RECYCLING 3D PRINTS

Enabling Material Reuse in Prototyping Facilities

Marc Aliana Guardia

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Delft University of Technology

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Marc Aliana Guardia

MSc. Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Supervisory team

Project chair
Prof. dr. A.R. Balkenende

Project mentor
Ir. A.L.M. Minnoye

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PREFACE

Before you lies the thesis 'Recycling 3D prints: Enabling material reuse in prototyping facilities' as the completion of the master of Integrated Product Design. As an industrial design engineer myself, I have been an avid user of 3D printing during my projects, especially during my journey at TU Delft. As a sustainability driven individual, the end-of-life of the prints I created in my projects always concerned me. This project has allowed me to dive further into this issue. That is why I would like to thank all the people who made this project possible.

First, I would like to thank my supervisors Ruud Balkenende and Sander Minnoye for giving me the opportunity to work on this project. Their guidance and constant support, especially at the very beginning of the project, helped me navigate through the challenges of working remotely and graduating during a pandemic.

I would also like to thank Mascha Slingerland, Adrie Kooijman and Tessa Essers, from the Applied Labs, for assisting me and teaching me how to use the facilities of the lab. Especially to Mascha and Adrie, who helped me troubleshoot the issues that emerged when producing recycled material.

Furthermore, I would like to thank the staff of the model making and machine lab (PMB), particularly to Don van Eeden, for arranging one of the FDM printers specially for this project and for the insights and feedback given.

Doing this project during the pandemic would have not been possible if it was not for the support of my family, especially my brother, and my friends.

Last but not least, thank you Stefanija for listening and supporting me no matter what, for being my co-worker during lock-down and for always being there.

EXECUTIVE SUMMARY

In Fused Deposition Modeling (FDM) for rapid-prototyping, the 3D printed parts usually have a short life, generating a constant stream of waste material and lost value. This issue becomes more relevant when FDM is used during the early stages of product development, where 3D printed prototypes become rapidly obsolete due to design iterations and advances in the project.

Amongst the materials used, Polylactic Acid (PLA) is one of the most popular in FDM, especially in early prototyping. As a result, prototyping facilities generate a constant waste stream of PLA from failed prints, support material and obsolete prints. A material stream that is not being reused, recycled or composted, as current recycling facilities are not capable of recycling or industrially biodegrade PLA.

This project investigates the opportunity of reusing this constant waste stream by recycling it back to FDM filament, closing the material loop in a prototyping facility context. Challenges such as material degradation, printability and the influence on the prototyping process are researched.

Theoretical research

In the initial theoretical research phase, the role of FDM in prototyping design for product development is explored, the most popular material and its current end-of-life scenario are analysed and the state of the art of recycling for FDM is presented. Additionally, insights from prototyping users and relevant industry experts on the material journey are collected. An opportunity is identified in low-fidelity prototyping, where high mechanical properties and high-quality prototypes are not always required.

Practical research

Then, the production and low-fidelity printability of recycled PLA from 3D printing waste is tested in practice. Experimentations are done first by producing recycled filament and second with several printability tests.

The printability results demonstrate that recycled PLA filament produced with a desktop recycling setup can be 3D printed with a desktop FDM printer, achieving similar low-fidelity prototyping capabilities for design projects as virgin PLA filament, thus enabling the use of recycled PLA from 3D printing waste for low-fidelity prototyping.

Solution development

The findings gathered in the research phase are converged and conceptualized into a future vision, a roadmap and a short-term solution to explore and facilitate its implementation. Additionally, a printing guide is created that summarizes the adjustments and recommended settings for future end-users.

Finally, a design case study demonstrates the feasibility of using recycled PLA in a design project for low-fidelity prototyping and it exemplifies how the design and prototyping process is affected. The solution is evaluated by a prototyping facility, highlighting concerns and challenges still to overcome before its implementation.

This research concludes with recommendations for further research and work required to achieve 3D printing material reuse in a prototyping facility.

GLOSSARY

AM	Additive Manufacturing, also generally known as 3D printing.
FDM	Fused Deposition Modeling, also known as Fused Filament Fabrication (FFF).
PLA	Polylactic Acid.
PRINTING PROFILE	List of the printer settings and printing parameters of a 3D printing file.
PROTOTYPING FACILITY	Workshop, lab or space destined to the small-scale fabrication of prototypes.
FABLAB	Fabrication Laboratory, small-scale workshop or prototyping facility providing access to digital fabrication.

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1 INTRODUCTION

3D printing has become an important manufacturing technology available almost everywhere. In the last 10 years, its popularity has risen and the technology keeps growing and evolving. Amongst other advantages in the manufacturing process and in product development, 3D printing could contribute to a better and more sustainable future. In particular, it could be a potential enabler for better production systems such as distributed manufacturing.

On the other hand, 3D printing also generates a negative impact on sustainability. One of the consequences is the use of raw material and the absence of material preservation cycles. Preserving materials and products' value through cycles or 'loops' is a keystone of the circular economy (Ellen MacArthur Foundation, 2013). Defined by Kirchherr et al. (2017), the circular economy "describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/ distribution and consumption processes …".

As stated by the European Commission (European Commission, 2015), a transition towards a circular economy is needed. Consequently, achieving a higher material value preservation in 3D printing is imperative. Whilst research is being done on new sustainable alternatives and circular materials (Sauerwein et al., 2020), no clear solution yet exists for closing the loop of the well established and commonly used 3D printing systems in a short-term.

Moreover, the issue of material value loss has an even bigger impact in 3D printing for prototyping. In rapid-prototyping, most of the 3D printed parts have an extremely short life, generating a constant stream of waste material that is usually not reused or recycled, losing its value.

Therefore, capturing the lost value of the material in 3D printing prototyping is essential to ensure a better and more sustainable and positive use of this growing technology. Additionally, focusing on the current materials would facilitate its implementation in the short term.

3D printing

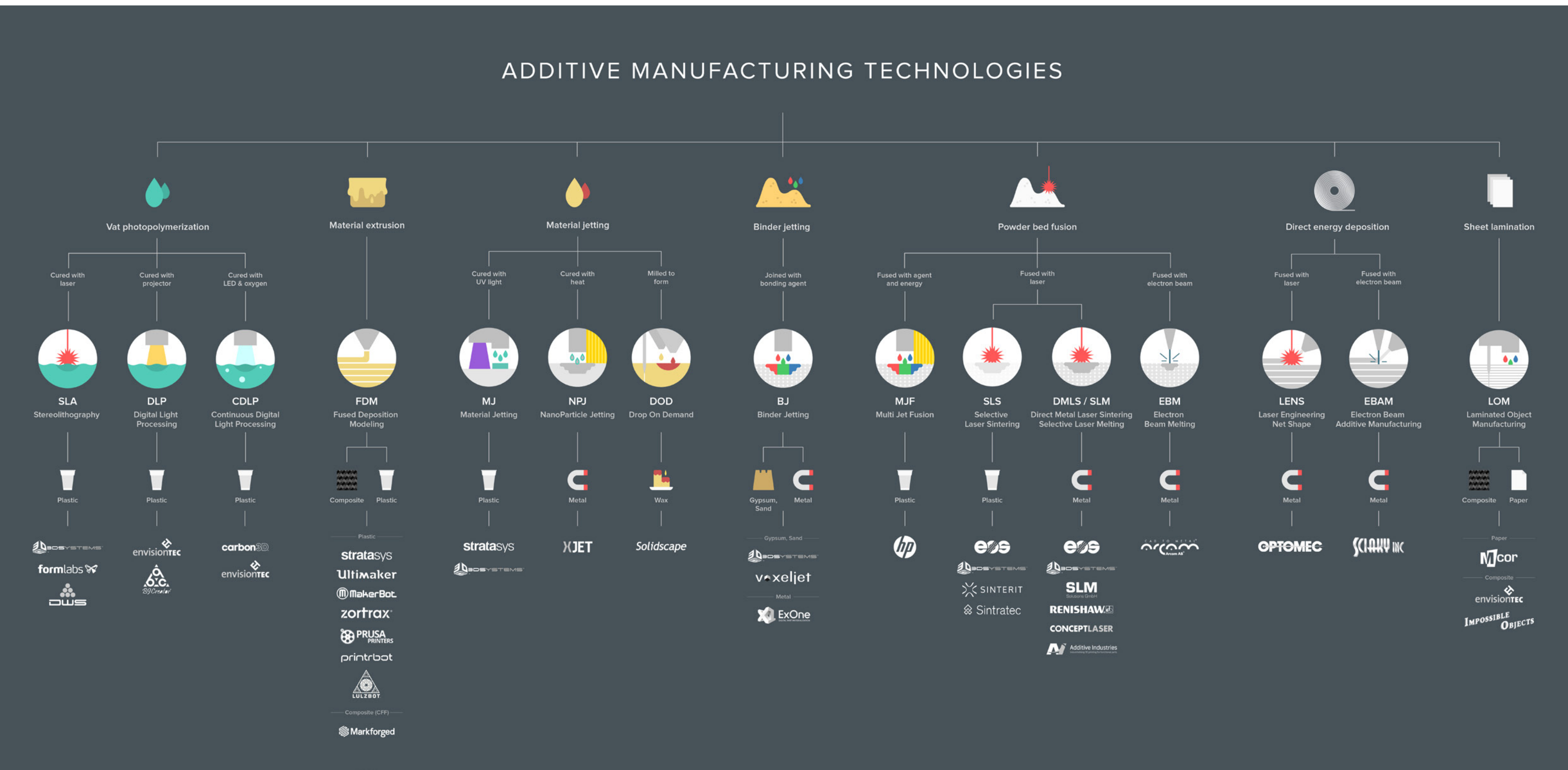
Additive manufacturing (AM), also known as 3D printing, is defined as the technologies that create physical objects by successive addition of material, based on a 3D model (International Organization for Standardization, 2015). The AM technologies can be categorized as shown in Figure 1. Those technologies are used globally in the engineering industry and other sectors like education, medicine or architecture.

Amongst the technologies within additive manufacturing (AM), Fused Deposition Modeling (FDM) is one of the most widely available across society. FDM, also known as Fused Filament Fabrication (FFF), is a material extrusion process that uses polymer filament as feedstock material. A moving heated print head melts and deposits the material through a nozzle into a build platform creating each layer, one on top of the other. In this way, a 3D object is formed. In order to print complex geometry, such as overhanging geometry, a support structure is needed for the melted material to be deposited. This support structure is usually printed with the same material as the 3D object. A schematic overview of an FDM printer is shown in Figure 2.

FDM is the most used technology amongst 3D printing users (Sculpteo, 2020). Its low cost, availability and simplicity of the process in comparison to other technologies might be some of the reasons why FDM is highly popular.

Generally, AM is mainly used for creating proof of concepts and prototypes, followed by production purposes, research purposes, spare parts and for personal projects (Sculpteo, 2020). But the use of 3D printing is -and it has been- continuously growing. The potential applications of AM and its benefits to different industries could increase even more its popularity and maintain its growth in the upcoming years.

Figure 1 Overview of the additive manufactruing technologies (3DHubs.com).



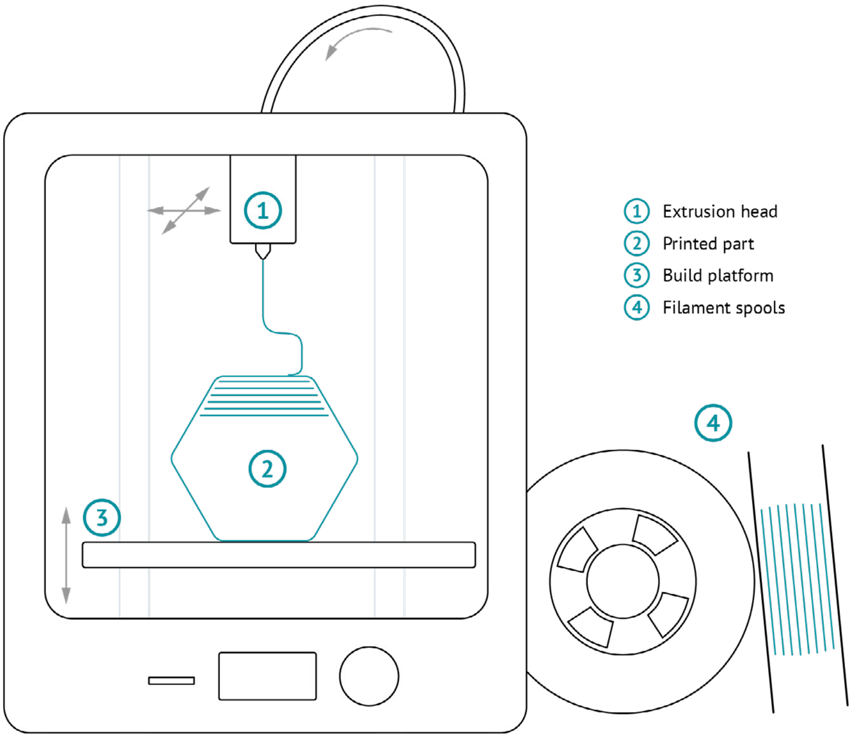


Figure 2 An schematic drawing of an FDM printer.

The local prototyping facility

Thanks to the growth of 3D printing, FDM machines have become one of the prototyping tools used by professionals, makers and educational institutes across the globe.

Prototyping refers to the methodology of using a physical model to study and test a product's behaviour, functionality, appearance and/or usability. It is a key problem-solving activity in industrial design and product development (Hallgrimsson, 2012). It is used throughout the development of a project, from the initial phases of concept design until the detailed and pre-production stages. A general overview of the types of prototypes for product development is shown in Figure 3 and Figure 4.

Many local prototyping facilities have acquired these machines to aid their users in their projects. These local prototyping facilities or hubs, such as FabLabs, Repair Cafes, companies' workshops, schools or universities, provide access to 3D printing to their communities and, sometimes, have more than one FDM printer to cover their demand.

In addition, 3D printing service companies, both on a global and local scale, have emerged providing access to this technology. By paying a fee, they produce the 3D printed object for you, either using their own production facilities or through a network of individual producers.

Whilst larger service providers usually offer different AM technologies and make use of bigger and more expensive machines, smaller companies usually rely on FDM printers for their production. Using multiple FDM printers, they can produce 3D printed prototypes for different users and with different colours and materials in parallel.

Figure 3 Loughborough ID cards, models (Evans & Pei, 2010).

Figure 4 Loughborough ID cards, prototypes (Evans & Pei, 2010).

The end of life of 3D printing material

The local prototyping facilities share a common issue: the end of life treatment of 3D printing material.

Although the printing process of FDM has become more reliable and has been highly optimized in recent years, sometimes the printing process can fail and generate unusable prints that end up as waste. Moreover, FDM material waste is generated not only by failed prints but also by the support material needed during printing. In addition, some local prototyping facilities throw away the last parts of the filament to avoid changing it halfway through the process.

Furthermore, properly 3D printed parts and products become waste at the end of their life. At present, little is known about the recyclability of 3D printed objects (Sauerwein et al., 2019). This issue becomes more relevant when FDM is used for rapid prototyping and testing during the early stages of a project, where the 3D printed parts become rapidly obsolete due to the advance in the project's development.

However, most 3D printed objects have one advantage: they are usually made of a single material. This mono-material character makes them potentially easier to recycle than other products. Although recyclability is the least preferred option when designing for a circular economy (den Hollander et al., 2017), it might be the only applicable strategy for rapid prototypes and material waste from the printing process.

Despite the recyclability potential, 3D print material still presents numerous challenges. An example would be the lack of labelling of the material. The limitations of the current plastic coding system and the absence of any identification in 3D printed objects could limit their recyclability even on a distributed recycling system (Hunt et al., 2015).

DRAM

Despite the sustainable impact of the waste material of 3D printing, AM also presents an opportunity: it can enable upcycling of waste streams in a circular economy. In particular, plastic waste could be used as feedstock material for AM to create new products, enabling a continuous flow of resources and contributing to the transition towards a circular economy.

One of the benefits of AM is that it makes possible local manufacturing. It reduces the entry barriers and capital investments required to create flexible and distributed production on a local level (Despeisse et al., 2017). An example of distributed production is the local prototyping facilities previously mentioned, where a product can be produced at a local prototyping facility if the production requirements of said product match with the production capabilities of the local prototyping facility.

In addition, this distributed manufacturing allows for distributed recycling of local waste streams (Despeisse et al., 2017). This concept is also known as Distributed Recycling via Additive Manufacturing or DRAM (Cruz Sanchez et al. 2020).

According to Cruz Sanchez et al. (2020), AM could work as a recycling tool to reuse thermoplastic waste material. In their recent research work, they identified and defined a 6 phases framework for DRAM: Recovery, Preparation, Compounding, Feedstock, Printing and Quality. Amongst those 6 phases, Recovery and Preparation presented the greater unknowns for the viability of DRAM.

However, homogenous waste streams like mono-material waste from industrial processes could present opportunities to ensure the effectiveness of local recovery and preparation phases. Using a controlled mono-material stream could reduce the requirements of the recovery and preparation phases. By using a so-called high-quality waste stream the feasibility of DRAM could be increased and implemented.

This is where the local prototyping facilities' waste presents itself as an opportunity to establish a local DRAM setup for its own generated 3D prints and waste. Recycling the material waste from FDM processes and obsolete FDM prints back to FDM filament could reduce the impact of the end of life of 3D printing.

The project brief

The present project aims at researching the feasibility of recycling FDM prints back to FDM filament in the context of a prototyping facility, to help reduce the plastic waste generated by those facilities. It will investigate the opportunities and concerns that this recycling scenario may present.

Challenges such as material degradation, printability, the effect that the recycled material might have on the printed prototypes and the influence of prototype design on its feasibility are expected.

The scope of the project is centred on prototyping for industrial design projects, where high mechanical properties and high-performance materials are not always required, thus creating a potentially more favourable scenario for reusing the material.

Therefore the mission of this project is to:

> “*Investigate ways in which reuse of 3D printed material used for prototyping can be enabled and how this depends on the design approach during prototyping; set up guidelines and demonstrate the feasibility in a prototyping facility context.*”

The project looks into a specific local prototyping facility that serves as a testing ground for the results and conclusions to be applied to other similar facilities. The selected prototyping facility is the Model Making Lab at the faculty of Industrial Design Engineering of TU Delft.

Case study

As mentioned in the project brief, this study looks into a specific local prototyping facility - a 3D printing facility in an industrial design faculty- as the testing ground for the research work. This particular case, and other similar prototyping facilities, present some interesting opportunities for reusing the material used for 3D printing prototyping, such relatively large 3D printing material waste and potentially better control of the waste stream.

The specific characteristics of the 3D prototyping setup at the faculty of Industrial Design Engineering of TUDelft, shown in Figure 5 and Figure 6, are described below.

- On average, the 3D printing prototyping facility has **12 FDM printers** running 24/7 all academic year
- Only one type of FDM printer is available: the **Ultimaker 2+**
- Only one material is used, across all printers: **white PLA from HotOrange**
- The access and use of the FDM printers is **free for all students**
- On average, **100kg of filament** is used every year

Currently, all the waste generated at this 3D prototyping facility is not recycled. Most of the waste comes from failed prints, support material and filament ends, which is around 20% of the total material used. However, the prototypes also end up as waste after being used by the students. If all is recycled, the amount of material being reused could potentially be of around 70-90% of the total material used in the facility.

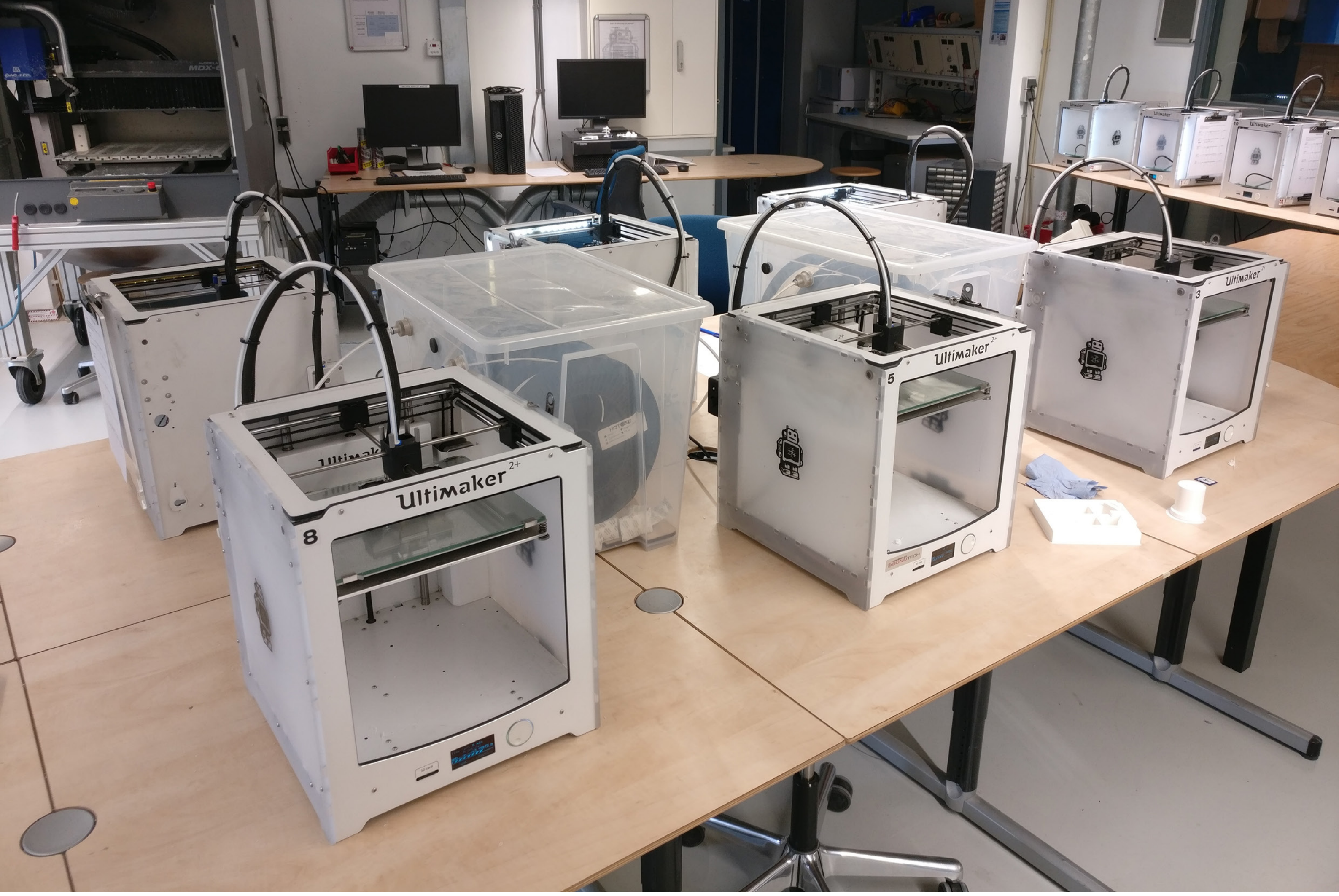
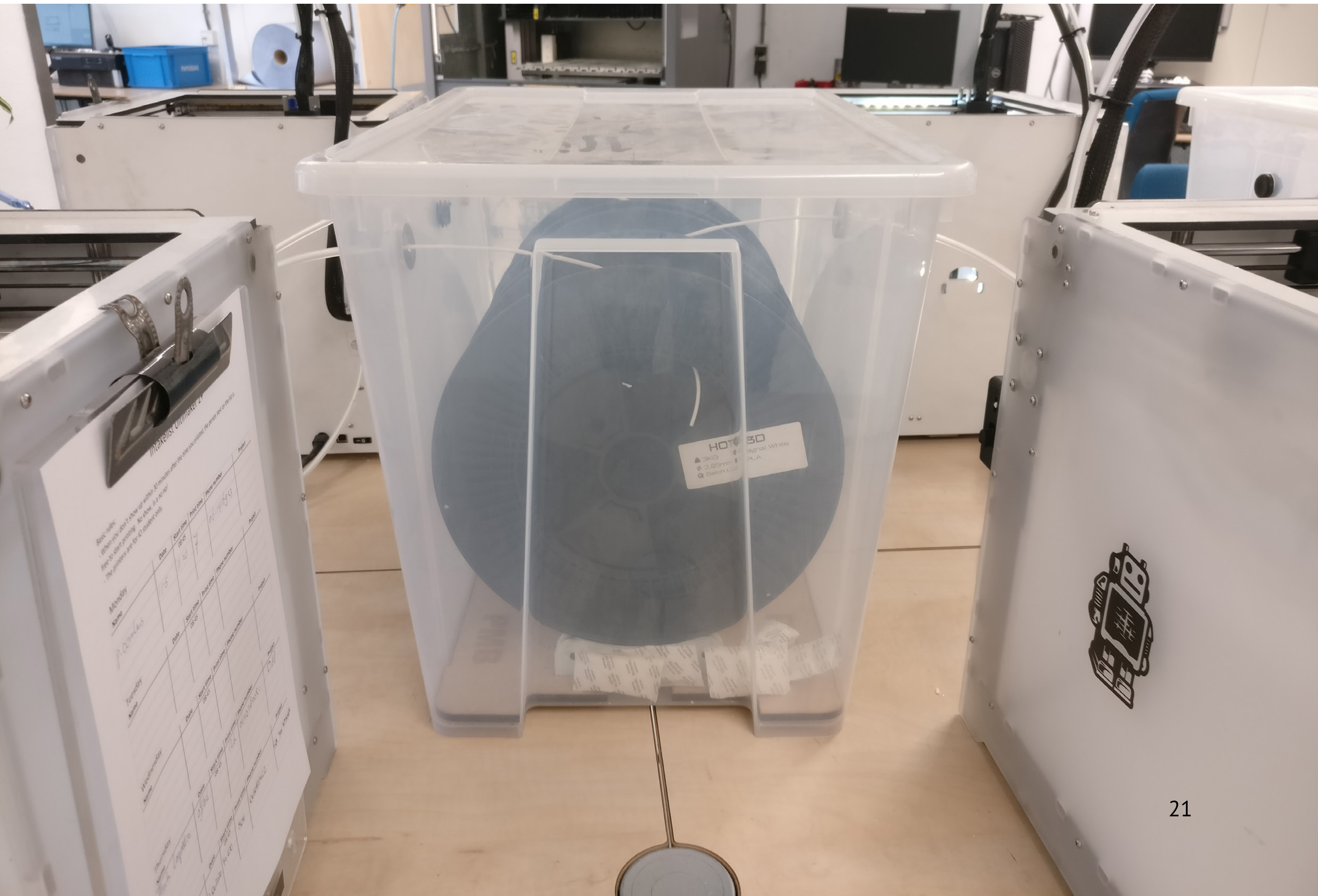


Figure 5 The 3D prototyping setup at the faculty of Industrial Design Engineering of TUDelft.

Figure 6 Detail of the filament used at the faculty of Industrial Design Engineering of TUDelft.



2 THEORETICAL RESEARCH

This chapter explores and presents the knowledge researched in the key relevant areas of prototyping in product design, FDM technology and materials, recycling for FDM and production of FDM filament, and provides industry and user insights across the 3D printing material journey.

2.1 PROTOTYPE DESIGN

This section describes how 3D printing prototyping is used in product development and design projects. It explains the differences in requirements of the several types of prototypes and describes the printing parameters that influence them.

2.1.1 Prototyping for product development

When prototyping for product development, the 3D printed parts have different requirements than other FDM applications. In particular, aspects such as prototype production time or prototyping costs become more relevant, making low-cost and low-quality prototyping more interesting for the early developing stages.

Focusing on product development for design projects, the design and requirements of the prototypes also vary according to the product development phases. These phases, as defined in the Loughborough ID cards (Evans & Pei, 2010), are:

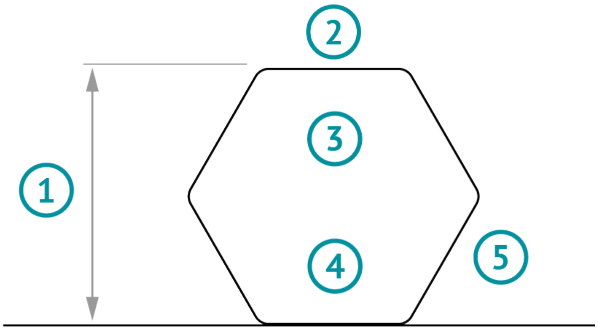
- Concept design
- Design development
- Embodiment design
- Detail design

In the initial phases, the exploration and the continuous development require quick and low-fidelity models whereas in the later stages detailed and high-fidelity prototypes can be more useful for evaluation and advanced testing.

In particular, the main purposes of 3D printed prototyping in each stage are:

- Concept design: evaluate the shape and form, proportions and dimensions of concepts.
- Design development: explore relationships between components and evaluate key functional features and ergonomics
- Embodiment design: represent accurately the appearance and evaluate the product manufacturability and production
- Detail design: combine all product functionality, appearance and production for testing before manufacturing.

2.1.2 Prototype design requirements



① Size & dimension accuracy
② Surface quality
③ Mechanical strength
④ Colour and material
⑤ Geometric features

Figure 7 Prototype design requirements.

In addition, 3D printed prototypes have specific design requirements. For example, good surface quality is an important requirement in an appearance model whereas its mechanical strength might be irrelevant. These prototype design requirements are determined by the main purpose of the prototype and can be established as follows.

Functionality

- Part size and dimension accuracy
- Mechanical strength
- Geometric features

Visual appearance

- Surface quality
- Colour and material

Some of these requirements are already restricted by the FDM technology and printer used, others depend on the material used or the printing parameters.

For early product development and for low-fidelity prototypes, the mechanical strength, surface quality, colour and material are usually less crucial.

2.1.3 Prototype printing parameters

When using FDM technology for prototyping, one of the key elements that influence the characteristics of the prototype is the printing parameters. These printing settings can influence aspects such as the surface quality, the mechanical strength or the production time.

Some of these printing settings are determined together by the user, the slicer —the software tool used to translate a 3D design into a printer-ready file— and the FDM printer. The user (or designer) usually can influence most parameters, but the most relevant ones that affect the prototype requirements are:

- **Layer height (printing quality)** › surface quality & strength
- **Infill** › strength
- **Wall thickness** › strength
- **Part orientation** › strength (isotropy)
- **Supports** › geometric features & surface quality
- **Filament material and colour** › strength & colour and material

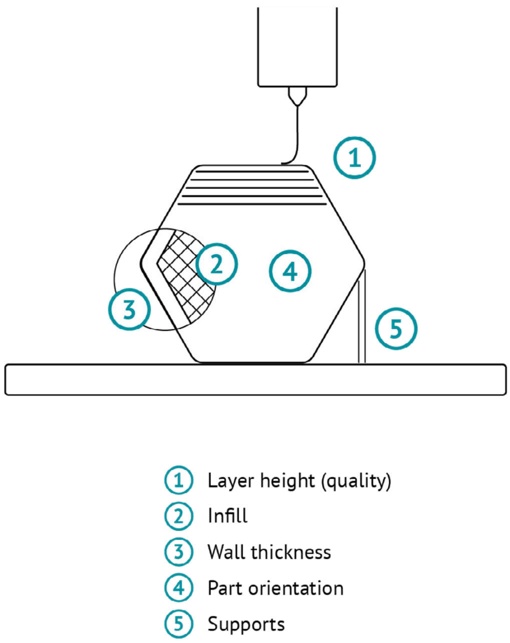


Figure 8 Prototype printing parameters.

Conclusion

The different purposes in product development require different prototype characteristics depending on their purpose and stage of the development. In FDM prototyping, the printing settings influence the prototype characteristics and, therefore, some printing profiles are better for high-fidelity prototypes (where higher strength and better surface quality is needed) while others are better for low-fidelity prototypes (where a faster printing speed might be more important than the strength or surface quality).

It is in these low-fidelity prototypes where there is a higher potential for recycled material, a material that could have less strength and lower printing quality than its virgin counterpart. Special attention should also be drawn towards how recycled material can produce geometric features as it might be a common requirement for both high-fidelity and low-fidelity prototyping.

2.1.4 Design process case study

To better illustrate prototyping for product development and the role of 3D printing in a product design project, a design study case is created. This study case serves as an example of the different 3D printed prototype characteristics used in each product development phase previously described.

The example project selected is the design of a computer mouse. A design process has mapped out, mainly focused on the first stages of product development, and the required prototypes have been defined.

In Figure 9, an overview of the prototypes of each phase of the project is shown. The models used to exemplify this process are the Royal IKEA Mouse model by Cryo_Frost (Alvin, 2020), the computer mouse design by B. Kromhout (Kromhout, 2020). and the Red Dragon M601 model by Sumanth Shekar (Shekar, 2018).

The prototypes' purpose and how they are printed are described according to each phase of the design process.

- **Concept design prototypes**

The main purposes of these prototypes are to evaluate the shape and proportions and have a first interaction of how the models feel in hand.

The mechanical strength and surface quality are not important and the absence of details make the print resolution insignificant. The material and colour used does not have any importance either, as the focus is on the shape.

Therefore, these prototypes are likely to be printed with normal or low-quality settings (with a layer height of 0,15 - 0,20 mm). The reduced printing time is a clear advantage without any drawback. It is likely for all 4 models to be printed in one go in the same printing session and with standard PLA.

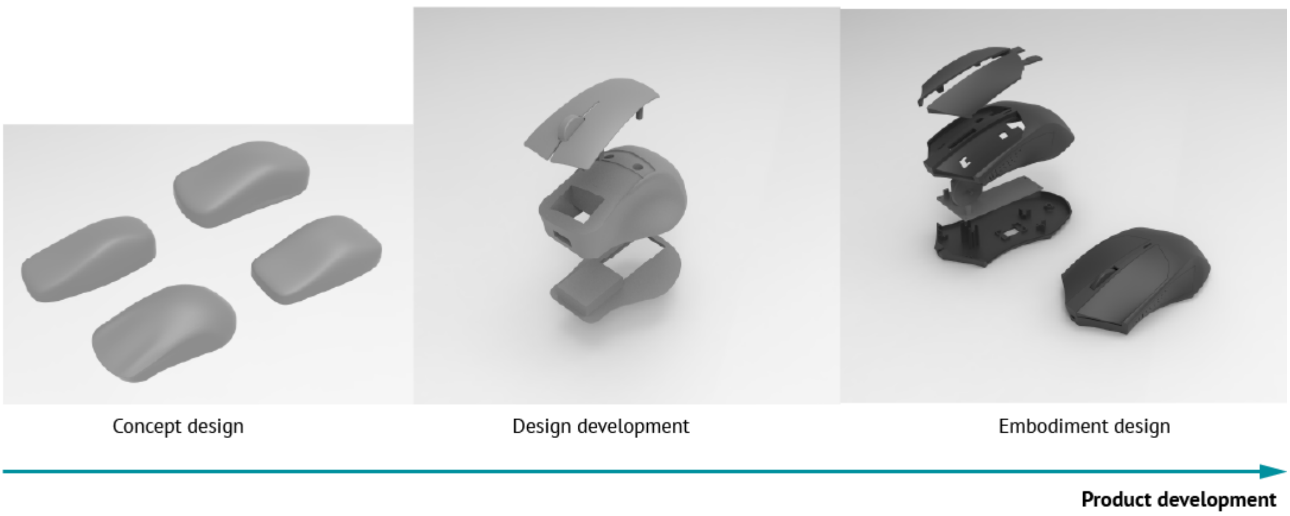


Figure 9 Prototypes in the product development process of a computer mouse design project.

- **Design development prototype**

The main purposes of this prototype are to explore relationships between components, to evaluate the ergonomics of the buttons and to also evaluate the shape and proportions.

Some parts of the prototype, such as the buttons, must resist some minor mechanical stress, as it is a part that should bend when pressed. The parts should also be relatively accurate and have no major dimensional deviations, not higher than a few millimetres, for the parts to be assembled correctly. Since the appearance is not evaluated, the surface quality and colour are not important.

Since this prototype does not have small relevant details, it is likely to be printed with normal settings (with a layer height of 0,15mm). And given that the appearance is not important, it is likely that all parts are printed in the same printing session in one go, using the same standard PLA material.

- **Embodiment design prototype**

The main purposes of this prototype are to validate the interaction of the different parts and the integration of electronics and components, to assess the functionality of the buttons and to represent and evaluate the appearance.

Most of the parts of the prototype require a relatively high mechanical strength for the screws and snap fits to properly function. A good dimensional accuracy is also needed for all the components to fit correctly and for a good evaluation of the buttons. Additionally, the surface details and quality is also important for the evaluation of the appearance details and overall looks of the design.

This prototype is likely to be printed more than once, either using a high quality setting (a layer height of 0.1mm or lower) or using another AM technology such as SLS or with SLA (for an appearance model). If FDM is used, it is likely that the parts are printed with different colours and with a stronger material than standard PLA.

2.2 THE FDM PRINTER

According to Ultimaker, one of the most popular FDM printer manufacturing companies, some of the applications of FDM are product development, architecture, education, production tooling and end-use parts (Ultimaker, n.d.). Most important, FDM printers excel in creating proof of concepts and prototypes due to its fast process and low cost, compared to other AM technologies, which makes them ideal for low-cost rapid prototyping. Additionally, around 79% of the 3D printer users use their printers for prototyping, as shown in Figure 11 by Ultimaker (2019).

Regarding the FDM printing process, a combination of parameters defines the outcome of the printer. The adjustment of these parameters depend on the particular FDM printer in use, but the most common ones are presented in Figure 10.

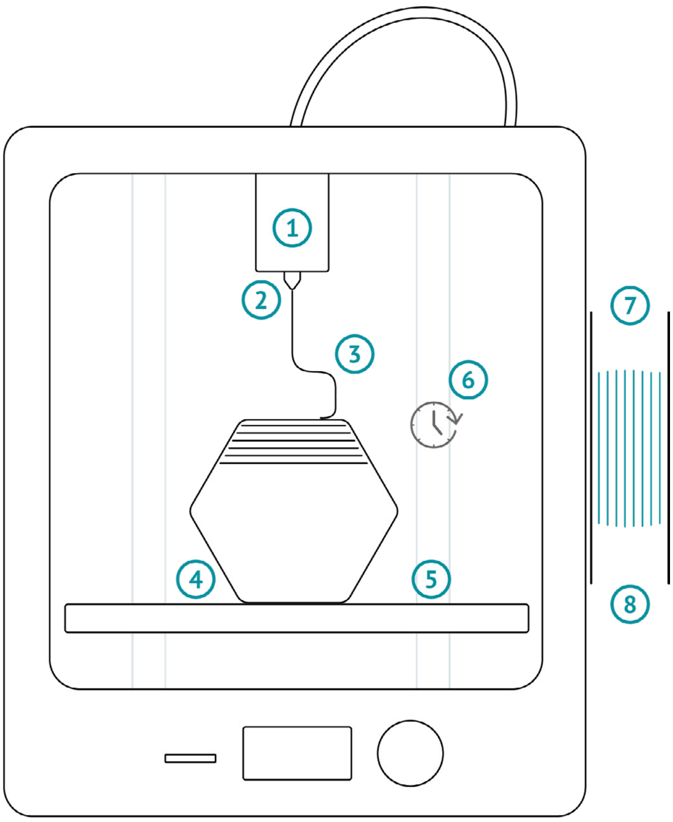


Figure 10 FDM printing parameters.

Additional aspects such as the build volume or the filament diameter also define the FDM printing capabilities and the type of filament to be used. Focusing on the prototyping facility of this study, the printers used are the Ultimaker 2+, a desktop FDM printer, shown in Figure 12. To have a better understanding of this FDM printer capabilities, the specifications of the Ultimaker 2+ are summarized:

- Build volume: up to 223 x 223 x 305 mm
- Compatible filament diameter: 2.85 mm
- Print head travel speed: 300 mm/s
- 0,4 mm nozzle (swappable)
- Layer resolution: 200 - 20 micron
- Geared feeder
- Build speed: < 24 mm^3/s
- Nozzle temperature: 180 - 260 °C
- Build plate temperature: 20 - 100 °C

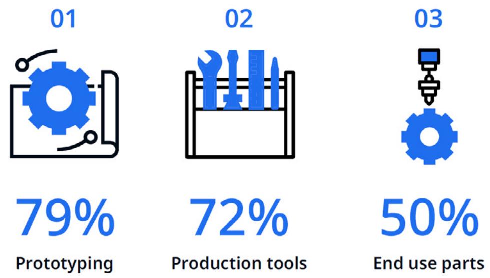


Figure 11 Ultimaker 3D printing Sentiment Index (Ultimaker, 2019).

Figure 12 The Ultimaker 2+ FDM printer (Ultimaker.com).

2.3 FDM MATERIALS

Nowadays, a broad range of thermoplastic filaments is available for FDM. PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PET (polyethylene terephthalate) and PETG (PET glycol-modified) and PA or nylon (polyamide) are amongst the most common materials.

The material is chosen considering its application after printing but also taking into account its price and its ease of use. The mechanical strength and flexibility requirements of the 3D printed part are some of the key properties that also determined the filament selection. An overview of the most common FDM materials is shown in Figure 13, an adapted version of the FDM material comparison from 3D Hubs (3D Hubs, n.d.-b).

In Table 1, a more detailed overview of the material and printing properties of FDM filaments is presented.

Figure 14 HotOrange PLA filament (Meer3D.nl)

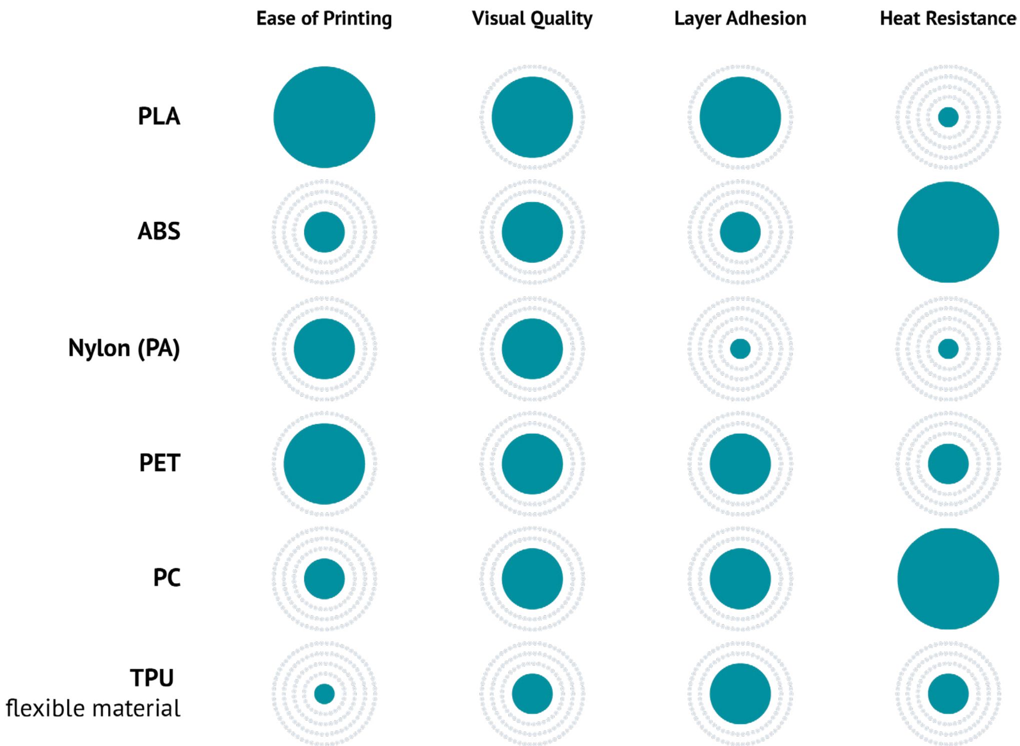


Figure 13 A comparison of the most common FDM materials, adapted from 3D Hubs (n.d.-b).

Material
Ultimaker PLA
HotOrange PLA
Ultimaker ABS
Ultimaker Nylon
BASF Ultrafuse PET
Ultimaker PC
Ultimaker PP
Ultimaker TPU 95A
Ultimaker PVA

PLA

PLA filament is one of the most, if not the most, popular filaments for FDM. PLA filament has a relatively low printing temperature (around 200 °C) and it does not require a heated bed (although it is recommended) which makes it suitable for most FDM printers. It is easy to print, meaning that it is unlikely to cause printability issues, and it is highly versatile due to its high dimensional accuracy and quality surface. Its mechanical properties, however, are not as good as other materials. It is also available in multiple colours and blends (All3DP, 2020).

At the local prototyping facility that this project focuses on, PLA filament is the material being used. According to the lab coordinator (D. van Eeden, personal communication, July 10, 2020), the material has been chosen because of its ease of use and because it emits less toxic fumes than other materials. The material used is the white PLA from HotOrange, shown in Figure 14. In Table 1, its properties can be compared with other FDM filaments.

For all these reasons, this study is focused on PLA as the main 3D printing material.

	MATERIAL PROPERTIES						PRINTING PROPERTIES		
Diameter	**Tensile modulus**	**Tensile stress at break**	**Flexural strength**	**Impact strength (ISO 180)**	**Hardness**	**Melting temperature**	**Printing temperature**	**Bed temperature**	**Cost (€/kg excl.tax)**
2,85 ± 0,10 mm	2346,5 MPa	45,6 MPa	103 MPa	5,1 kJ/m2	83 (Shore D)	145 -160 °C	200 - 210 °C	60 °C (recommended)	44,00 €
2,85 ± 0,10 mm	1320 MPa	52 MPa	108 MPA	-	95 (R-scale)	145 -160 °C	190 - 220 °C	46 - 60 °C	16,49 €
2,85 ± 0,10 mm	1618,5 MPa	33,9 MPa	70,5 MPa	10,5 kJ/m2	76 (Shore D)	225 - 245 °C	225 - 260 °C	80 - 90 °C	50,60 €
2,85 ± 0,05 mm	579 MPa	34,4 MPa	24 MPa	34,4 kJ/m2	74 (Shore D)	185 - 195 °C	230 - 260 °C	60 °C	72,67 €
2,85 mm	1933 MPa	33,4 MPa	66,7 MPa	2,1 kJ/m²	-	-	210 - 230 °C	60 - 80 °C	28,60 €
2,85 ± 0,05 mm	2134 MPa	76,4 MPa	111 MPa	4,1 kJ/m2	82 (Shore D)	-	260 - 280 °C	110 °C	72,67 €
2,85 ± 0,05 mm	220 MPa	-	13 MPa	27,1 kJ/m2	45 (Shore D)	130 °C	205 - 220 °C	85 - 100 °C	79,00 €
2,90 ± 0,13 mm	26 MPa	39 MPa	4.3 MPa	34,4 kJ/m2	95 (Shore A) 46 (Shore D)	220 °C	220 - 235 °C	70 °C	79,33 €
2,85 ± 0,10 mm	-	-	-	-	-	163 °C	215 - 225 °C	-	113,27 €

Table 1 Technical specifications of common FDM materials. (Meer 3D B.V., n.d.; Ultimaker, n.d.; BASF 3D, n.d.)

2.4 RECYCLING PLA FOR FDM

2.4.1 PLA recycling

Polylactic acid (PLA) is a bio-based aliphatic polyester produced from renewable sources such as sugar cane, corn or potatoes (Castro-Aguirre et al., 2016). It is considered biodegradable, which means that it can be decomposed into water, carbon dioxide, methane and biomass by microorganisms (van den Oever et al., 2017). However, biodegradability for PLA can only be achieved under certain environmental conditions. For example, PLA degradability in seawater is minimal and the degradation in landfill is very low (Haider et al., 2018).

Chemical recycling

In recent years, some advances have been made in the chemical recyclability of polymers and of PLA in particular.

Chemical recycling of polymers aims at creating a loop where the end-of-life polymer is transformed into building blocks for new polymers, usually by depolymerization and re-polymerization into virgin-quality material (Hong & Chen, 2017). The benefit of this process is that the material doesn't suffer quality loss. Regarding PLA, a recent study showed the viability of chemical recycling by using end-of-life PLA to create a new product (Román-Ramírez et al., 2020).

However, chemical recycling is still at its infancy and not industrially available yet. Moreover, it destroys the integrity of the material, creating a larger loop, which is not the most preferred value circle in a circular economy (Ellen MacArthur Foundation, 2019).

Mechanical recycling

On the other hand, the mechanical recycling of PLA, which also is a large loop, does not fully destroy the integrity of the material. One of its advwantages over chemical recycling due to less environmental impact (Cosate de Andrade et al., 2016). Additionally, general mechanical recycling is a more mature and available process than chemical recycling.

One of the biggest drawbacks is that each cycle causes material degradation in polymers. PLA is also affected by this (Haider et al., 2018). Mechanical recycling decreases some mechanical properties of PLA, such as its viscosity (Beltrán et al., 2018). This depletion could compromise the use of mechanical recycled PLA in some cases. To solve this, the use of additives could be a cost-effective method to improve the properties of mechanically recycled PLA (Beltrán et al., 2019).

Nowadays, PLA is mostly being incinerated, due to the low presence in the post-consumer waste stream (Haider et al., 2018). Some sorting waste methods do not work with PLA, and the ones that work, such as near-infrared technology processes, are not economically viable yet (van den Oever et al., 2017).

Conclusion

In a local prototyping facility, PLA waste counts as a big portion of the total generated waste. Smaller value circles that extend the life of a product such as repair, reuse or refurbish are not applicable due to the core purpose of prototypes as temporary short-life products, thus mechanical recycling seems to be the best option for tackling the end-of-life of PLA at the local prototyping facilities' waste stream and could potentially achieve closed-loop recycling of the material back to FDM filament. This presents an opportunity where recycling PLA might be feasible and interesting.

2.4.2 The recycling process

In order to mechanically recycle the 3D printing material back to FDM filament again, a series of processes are required. An overview of the process is shown in Figure 15.

Sorting out / cleaning scrap material

The first step is to sort the waste stream. In order to produce the best results, the waste stream has to be as homogenous as possible. This involves separating the plastic into different polymers (and colours) when they become waste. It is also recommended to clean it from dirt or impurities. This study is focused on a single material waste stream, hence this step might not be necessary.

Shredding

An essential process of recycling plastic is the shredding of large material scrap into smaller pieces called flakes. The plastic flakes can then be used for other processes, such as extrusion or injection moulding, amongst others. The size of the flakes and their homogeneity have an impact in those later processes, so using a shredder that can create small and consistent flakes is key.

The shredder (or granulator) uses a set of sharp blades that rotate around an axis, driven by a motor. Those blades break the material, fed through a hopper, into smaller pieces.

The plastic shredding process sometimes is divided into 2 separate stages:

- Shredding

  The scrap material is broken into pieces of around 10 to 20 mm of diameter, with low blade rotation speed (less than 100 rpm).

- Granulating

  The shredded flakes are ground into smaller flakes (less than 10 mm of diameter) with higher blade rotation speed. Usually, a sieve is used to filter the flakes into a homogenous size.

In some cases, only one step is used to simplify the process, sacrificing quality output.

Drying

After shredding, the plastic flakes must be dried to remove the moisture present in the material. The presence of water in the polymer can cause issues during the extrusion process, such as the presence of bubbles or nozzle clogging. The drying process can be achieved using a hot air dryer unit.

Regarding PLA, drying is not always a must, but most extruder providers recommend it.

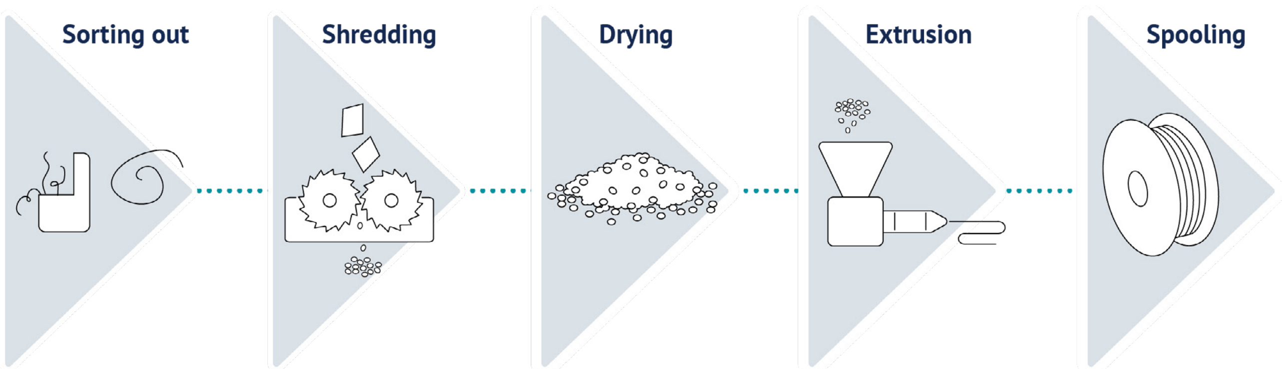


Figure 15 Overview of the process of making recycled filament.

Extruding

The key process for making FDM filament is the extrusion process. This process melts the plastic flakes into a continuous thin filament, usable by FDM printers. The flakes are fed into a heated barrel via a hopper, then a rotating screw compresses the melting flakes and pushes the material through a nozzle in a steady flow. An overview of the main parameters of an extrusion system is shown in Figure 16.

The barrel is usually heated in 2 to 4 areas, depending on each different extruder machine. The temperature depends on different parameters, such as the melting temperature of the material, its specific composition, the size of the barrel, the rotation speed of the screw, the ambient temperature, amongst others. Therefore, determining the ideal temperature for the process involves a considerable amount of trial and error.

The rotation speed of the screw has an influence on the output rate of filament, but also on the compression of the material inside the barrel. Consequently, the motor needs to deliver high torque to push the material through the nozzle and low rotation speed to let the material melt in the heater areas of the barrel. Again, the ideal rotation speed does not exist since it is influenced by other parameters of the extrusion such as the temperature in the barrel.

After the material has exited the nozzle, the filament is usually cooled down using fans or water/oil baths, depending on the material extruded. The diameter of the extruded filament is influenced by the nozzle size. However, to have better control of the diameter a puller is needed.

A puller is a device that, as the name indicates, pulls the filament as it comes out of the nozzle. By pulling at a constant speed, the diameter of the filament can be maintained constant, and by adjusting the pulling speed the thickness can be increased or reduced. To avoid marks on the filament, the puller is placed at the area where the filament has been cooled down and become more solid.

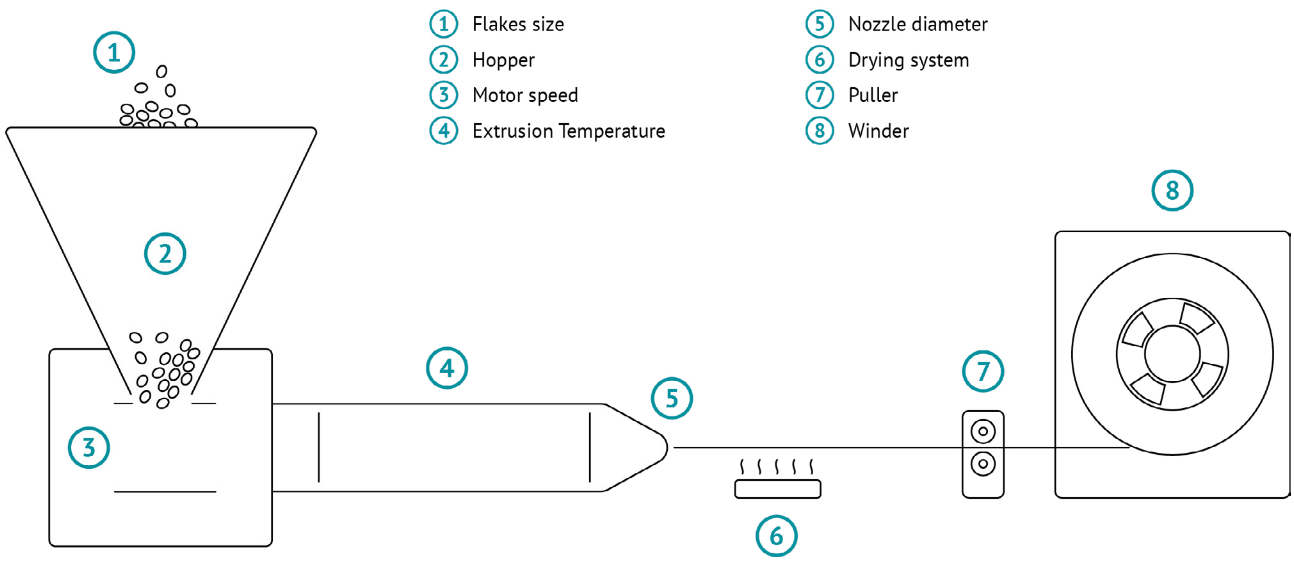


Figure 16 Overview of the general parameters of an extrusion system.

Spooling

The final step in the process of recycling plastic for FDM is the spooling of the filament. Once extruded, the filament needs to be winded into a spool so that the FDM machines can use it for printing. This can either be done manually or with a spooling device (winder) that helps distribute the filament evenly onto the spool. This second option avoids filament tangling and potentially more filament in a single spool.

Some winders are combined with a puller to create a more compact device.

Conclusion

To conclude, not all steps in the process of mechanical recycling for FDM are, apparently, equally important. The shredding and extruding processes seem to be key, so are the machines used on those steps. Using a puller device also seems to be critical to achieving good filament tolerances.

For PLA, the overall process might be simpler, as the melting temperature is lower than other polymers. No water or oil bath might be needed and a dryer might not be essential. However, further research has to be done in order to test these assumptions.

2.4.3 Material degradation in recycled PLA

Shredding and re-extruding 3D prints back to FDM filament could be an end-of-life solution for failed prints, support material or early prototypes that become obsolete during product development. Nonetheless, material degradation caused by 3D printing cycles could impact both printability and mechanical properties of the 3D prints. In addition, how many recycling and printing loops PLA can go through remains unclear. In this respect, there have been few studies that have analysed the effect of recycled PLA on FDM printing.

The results from Cruz Sanchez et al. (2017) showed a reduction in mechanical properties due to the 3D printing process, and therefore, the material could not be recycled as many times as in an injection process. The mechanical properties tested were elastic modulus, tensile strength at maximum stress, strength at break, tensile strain at maximum stress and nominal strain at break. Nevertheless, PLA was recycled and printed again for a total of 5 recycling loops. In addition, an increase in the elastic modulus was observed as more recycling loops were conducted. This could be caused by the reduction in the material viscosity, which caused a better homogenization of the layers and reduced the internal defects of the prints. For this study, a laboratory-scale extruder was used to make the filament and an open-source FDM printer for making the 3D printed specimens. A laboratory-scale cutting mill machine was used to shred the parts and it is unclear if the shredded flakes were dried before re-extruding them.

According to Zhao et al. (2018), viscosity is key for the printability in FDM. In their study, PLA could only be printed up to 2 cycles of recycling, due to significant deteriorations in the viscosity values. Recycled PLA was then blended with virgin PLA, with different rates, increasing its viscosity and enabling its printability in all cases. The mechanical properties analysed were tensile modulus, tensile strength, yield strength and elongation at break, according to ISO527e2:2012. The observed changes were similar to the results of Cruz Sanchez et al. (2017).

In the study of Zhao et al. (2018), a twin-screw laboratory scale extruder was used to produce the filament, a delta-pro FDM printer for the sample making, a laboratory-scale plastic mill for shredding and the plastic flakes were dried before extrusion.

Another study (Lanzotti et al., 2019) also showed a reduction in the mechanical properties of recycled PLA prints. At the third recycling loop, the values of short-beam strength were significantly reduced and presented high variability. However, both first and second loops showed similar short-beam values as specimens printed with virgin material. The machines used in this study were a desktop FDM printer and a homemade extruder. No indication of drying is mentioned and neither details of the machine used to shred the material.

Similarly, Anderson (2017) also encountered more variability in the mechanical properties of recycled PLA filament. The tensile, shear and hardness properties from the recycled specimens presented similar or slightly decreased values compared to the virgin specimens. Some printing difficulties were also observed during the FDM printing of recycled specimens, such as nozzle clogging. This study analyzed only one recycling loop. A desktop FDM printer was used to print the samples. The shredding and extrusion were done externally, by Filabot, a company specialized in making small-scale FDM filament extrusion machines. No details on the shredding or drying details are provided.

From all these studies it can be deduced that PLA material can be mechanically recycled for FDM, at least in laboratory conditions. Lower mechanical properties are expected and after 2 mechanical recycling cycles, printability issues are likely to appear. The viscosity of the material might be a relevant property to assess material printability.

Regarding the depletion of mechanical properties, it is not yet clear how this affects prototyping, since the mechanical requirements are usually low. Zhao et al. (2018a) have suggested using PDA coating as a method to improve the mechanical properties of FDM prints made from recycled PLA.

Conclusion

Printability could be more important for recycling PLA for prototyping than mechanical strength. Recycled PLA could be used for early prototyping where high mechanical properties are not needed. What is crucial is that the material is printable again.

However, from the studies mentioned, no further conclusions can be drawn regarding the printability of recycled PLA filament. Aspects such as the machines used for recycling and printing the material, the quality of the shredded flakes, the quality of the recycled filament and the presence of a drying process before extruding can all have an important impact on the printing process. In all studies analysed, different processes and machinery were used, plus some of them might not be available or difficult to achieve in a local recycling facility context.

2.5 STATE OF THE ART

2.5.1 Commercially available solutions

Large scale filament production has been developing since the beginnings of the FDM technology and the industry has developed into high efficient production of high-quality filament using large scale machinery and processes. However, in recent years, more companies making filament production machinery for small-scale setups have started appearing. Some examples can be seen in Figure 17.

Most of these companies are focused on lab-scale equipment extrusion systems for FDM filament production mainly for research purposes. Additionally, some have also started offering recycling machinery, like shredders, to produce the feedstock especially needed for the production of filament.

These small-scale filament production setups are interesting for the use case of this project because of their scale, flexibility and potential for distributed production scenarios. For this reason, an overview of these existing commercial solutions is presented in Table 2.

The available offering of desktop and lab-scale extruding systems differs on the production rate, the costs of each machine, the filament control systems offered, the overall size of the setup and the single-purpose or multi-functionality of each machine.

Overall, the costs of the machinery needed for a full recycled filament production setup is high. Depending on the production rate, the initial investment of an optimal setup ranges from 10.000€ up to around 20.000€. An optimal setup is defined as a setup where a puller and winder is used in the extrusion process, a 2 stage shredder is used and a dryer is included in the process. In sub-optimal setups such as the all-in-one ProtoCycler+, where no dryer nor 2 stage shredder is used, the initial investment is lower at expense of production rate, extrusion consistency and labour time.

Figure 17 Commercially available filament extruders (Filabot.com; Noztek.com; 3devo.com; Felfil.com)

The break-even point of the investment of an optimal extruder system, without considering running costs and other initial investments, would be after around 300 kg of filament, and between 700 and 1000 kg for higher production rate setups such as Noztek Xcalibur and Filabot EX6. However, labour costs have not been taken into account and they could have a relevant impact too.

2.5.2 Alternative solutions

Besides the commercially available solutions presented in the previous section, some open-source alternatives exist for producing recycled printing filament.

The most well-developed solution for extruding FDM filament is the Recyclebot, shown in Figure 18. It has been proven capable of producing printable filament from post-consumer polymer waste (Woern et al. 2018). A similar solution is the Precious Plastic extruder machine, shown in Figure 20. Unfortunately, it is not designed nor adapted to produce filament for FDM yet.

Regarding the shredding process, the Precious Plastic shredder, shown in Figure 19, is an interesting alternative. However, achieving the right plastic flake size for the FDM filament extruder system might be challenging, as it is designed to work with the Precious Plastic extruder which works with larger flakes. Nevertheless, it could be a feasible alternative after some adjustments.

Other more elementary shredder alternatives like kitchen blenders or paper shredders might be feasible in a Do-It-Yourself scenario but would likely not meet the scalability requirements of a prototyping facility.

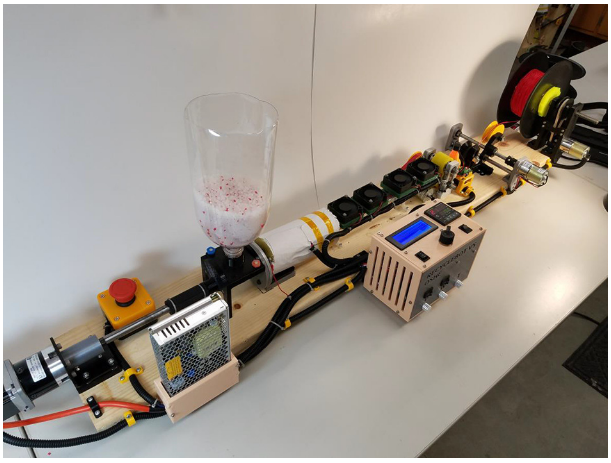


Figure 18 The Recyclebot (RepRap, 2019).

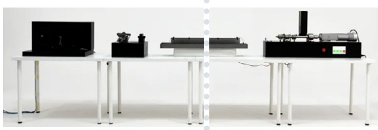
Figure 19 Precious Plastic shredder machine (Preciousplastic.com).

Figure 20 Precious Plastic extruder machine (Preciousplastic.com).

	RECYCLING		
	Shredder	Dryer	Extruder
3devo	SHR3D IT  2.973,00 €	AirID  2.500,00 €	Composer 350 (Material *Extruder + Puller + Winde* Precision 350 (High-flow *Extruder + Puller + Winde*
filabot	Reclaimer $5.849,00  Pelletizer $3.270,00	Plastic Pellet Dryer $6.143,00	EX2 Filament Extruder  $2.7 EX6 Filament Extruder  $10.8
ReDeTec	ProtoCycler+ *Shredder + Extruder + Puller + Winder* 		
FILASTRUDER			Filastruder Extruder  299
Felfil			Felfil Evo Extruder  719
noztek		Resin and Spool Dehydrator £1.250,00	Xcalibur Extruder  £7.9 Noztek Touch  £1.3

Table 2 Overview of commercially available solutions (3devo.com; Filabot.com; Redetec.com; Filastruder.com; Felfil.com; Noztek.com).

FILAMENT PRODUCTION

	Air/oil bath		Puller		Winder		Production rate (kg/h)	Extruder system investment	Break-even point [kg]
mixing) er						5.350,00 €	0,7	5.350,00 €	334
v) er						4.850,00 €	1	4.850,00 €	303
47,00	Airpath	$732,00	Spooler Puller + Winder			$2.347,00	0,91	4.893,84 €	306
347,00							4,5	11.697,84 €	731
						1.999,99 €	0,5	1.999,99 €	125
9,99 €					Filastruder Winder	169,99 €	0,125 - 0,2	469,98 €	29
9,00 €	Felfil Spooler *Fan array + Puller + Winder*					599,00 €	0,2	1.318,00 €	82
95,00	Noztek Water Bath	£495,00	Tolerance Puller	£3.950,00	Filament Winder 2.0	£1.750,00	2	15.892,80 €	993
85,00							0,5	7.935,20 €	496

2.5.3 Commercial available recycled filaments

Parallel to the appearance of recycled filament production solutions, new filaments branded as recycled have appeared in the market. These so-called recycled filaments are usually labelled as sustainable alternatives and can be available in different materials, from PLA to PET and ABS, amongst others. A list of commercial available recycled FDM filaments and its properties is shown in Table 3.

Despite most of them being called recycled materials, the source of the material they are made from and the rate of actual recycled content differ between each other. Regarding the source, the material origin can be divided into:

- Extrusion or filament production line waste
- Post-industrial waste
- Post-consumer waste

Brand	Nomenclature	Material	Source	Rate of recycled content
Filamentive	rPLA	PLA	Extrusion waste	55%
	ONE PET	PET	Post-consumer PET waste	100%
	rABS	ABS	Extrusion waste	64%
Formfutura ReForm	ReForm rPLA	PLA	Extrusion waste	100%*
	ReForm rPET	PETG	Post-industrial PETG waste	-
MCCP Nederlands	RPLA	PLA	Extrusion waste	100%*
	PIPG	PETG	Extrusion waste	100%*
	ONE PET @ Tridea	PETG	Post-consumer PET waste	100%
Replay 3D	Recycled PLA	PLA	Extrusion waste	100%*
Reflow	rPETG	PETG	Post-industrial PETG waste	100%
	rPLA	PLA	Post-industrial PLA (medical sector)	*In developmen*
Fishy filaments	Porthcurno - Recycled Nylon	Nylon 6 (PA 6)	Post-industrial waste (nylon fishnets)	100%
Refill	Recycled PLA	PLA	Post-consumer PLA packaging	100%
	Recycled PET	PET	Post-consumer PET bottles	100%
	Recycled HIPS	HIPS	Post-industrial waste from refrigerators	100%

A considerable number of “recycled” filaments come from the production waste of the filament producers, which might not even be considered recycling since the material has not been in use yet. Rather, one might identify it as a material optimization during production.

	MATERIAL PROPERTIES				PRINTING PROPERTIES		
Diameter	**Tensile modulus**	**Tensile stress at yield**	**Tensile stress at break**	**Impact strength (ISO 180)**	**Printing temperature**	**Bed temperature**	**Cost (€/kg excl.tax)**
2.85 ± 0.05 mm	3120 MPA	69.8 MPa		3.4 kJ/m2	190 - 220	0 - 60	29,99 £ (incl.VAT)
2.85 ± 0.05 mm		57 MPa		3.9 kJ/m2	240 - 260	80 - 100	43,99 £ (incl.VAT)
2.85 ± 0.05 mm	2030 MPa	43.6 MPa		58 kJ/m2	240 - 260	80 - 100	31,19 £ (incl.VAT)
2.85 ± 0.10 mm	3310 MPa		110 MPa	7.5 kJ/m2	200 - 230	0 - 60	20,62€
2.85 ± 0.10 mm	1940 MPa		50 MPa	7.2 kJ/m2	200 - 240	65 - 75	24,75€
2.85 ± 0.10 mm	3251 MPa	46 MPa	54 MPa	2.2 kJ/m2	200 - 220	0 - 60	
2.85 ± 0.10 mm	2050 MPa	46 MPa		4.9 kJ/m2	230 - 250	60 - 80	
2.85 ± 0.10 mm	2300 MPa	57 MPa		3.9 kJ/m2	250 - 270	80 - 90	
1.75 ± 0.07 mm	*Sold out/discontinued*						$27,99
2.85 ± 0.07 mm		50 MPa		6.2 kJ/m2	235 - 255	70 - 80	33,88€ (incl. VAT)
t							
2.85mm	2262 MPa	59 MPa	48 MPa	5.15 kJ/m2	250 - 270	60 - 80	80,00 £ (incl.VAT)
2.85 ± 0.10 mm	*Discontinued*						
2.85 ± 0.10 mm	*Discontinued*						
2.85 ± 0.10 mm	*Discontinued*						

Table 3 Commercially available recycled FDM filaments (Filamentive.com; Formfutura.com; Replay-3d.com; Reflowfilament.com; Fishyfilaments.com; Betterfuturefactory.com).

2.6 FUSED GRANULAR FABRICATION

A similar 3D printing process of FDM, Fused Granular Fabrication (FGF), is presented as a potentially better technology for distributed recycling of 3D printing waste (Alexandre et al., 2020). As shown in Figure 21, this process differentiates itself from FDM by directly using plastic flakes as feedstock for the print head, skipping the need for filament. Thus, in a closed-loop setup, the plastic undergoes fewer melting processes, potentially decreasing the depletion impact of this setup compared to an FDM setup.

However, this technology is still on its infancy, with almost no small-scale commercially available solutions. An example is the pellet extruder by Mahor XYZ (Mahor XYZ, n.d.) shown in Figure 22 and Figure 23, which replaces the print head and can be mounted in some desktop FDM printers. Despite that, some critical aspects are still to be solved, such as how to constantly feed the extruder with the material.

Conclusion

In conclusion, FGF has the potential to become a solution one day, but nowadays the technology is not ready to be applied in a local prototyping facility in the near future.

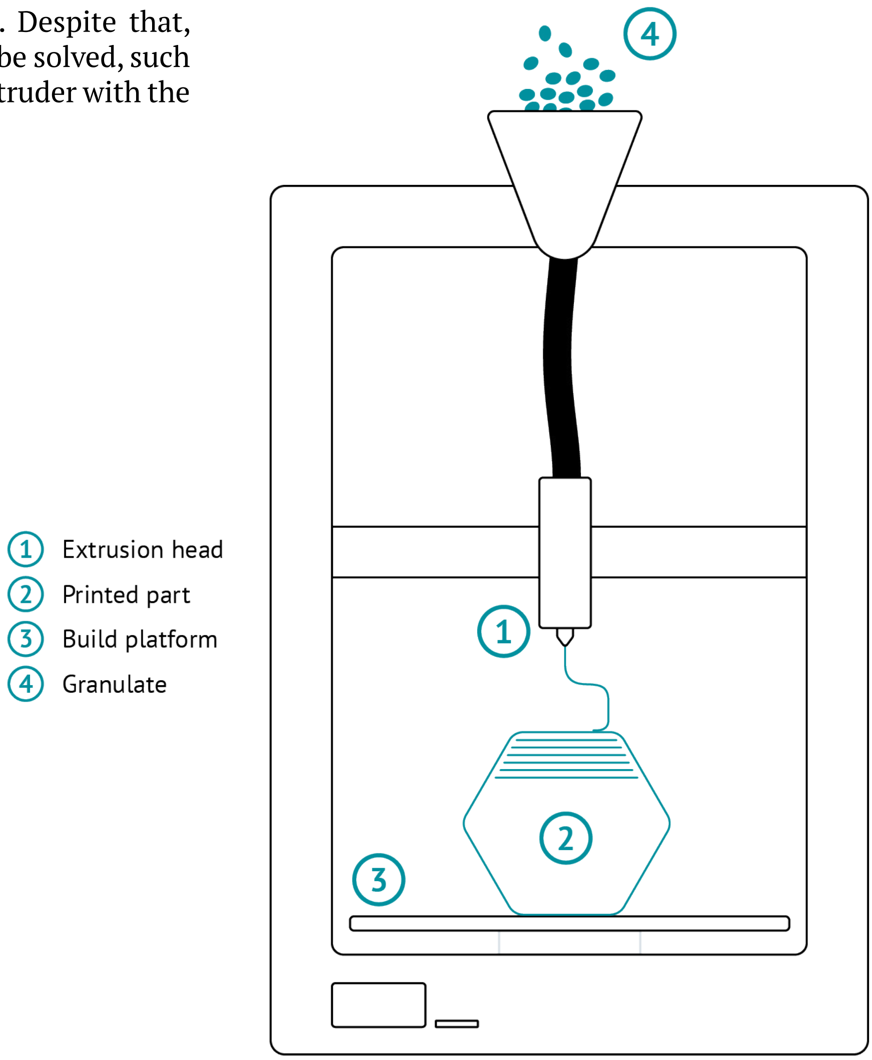


Figure 21 Skematic visual of an FGF printer.

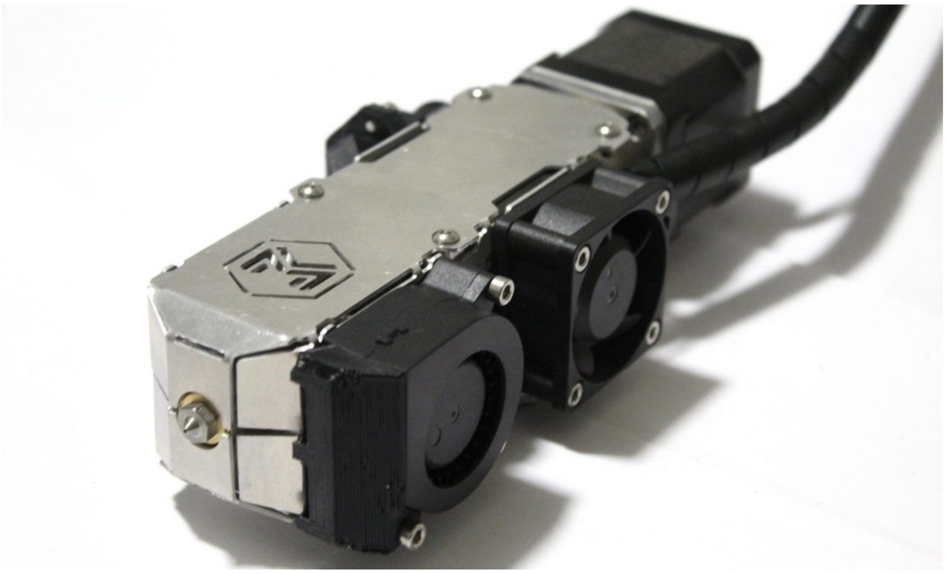


Figure 23 The FGF pellet extruder by Mahor XYZ (Mahor XYZ, n.d.).

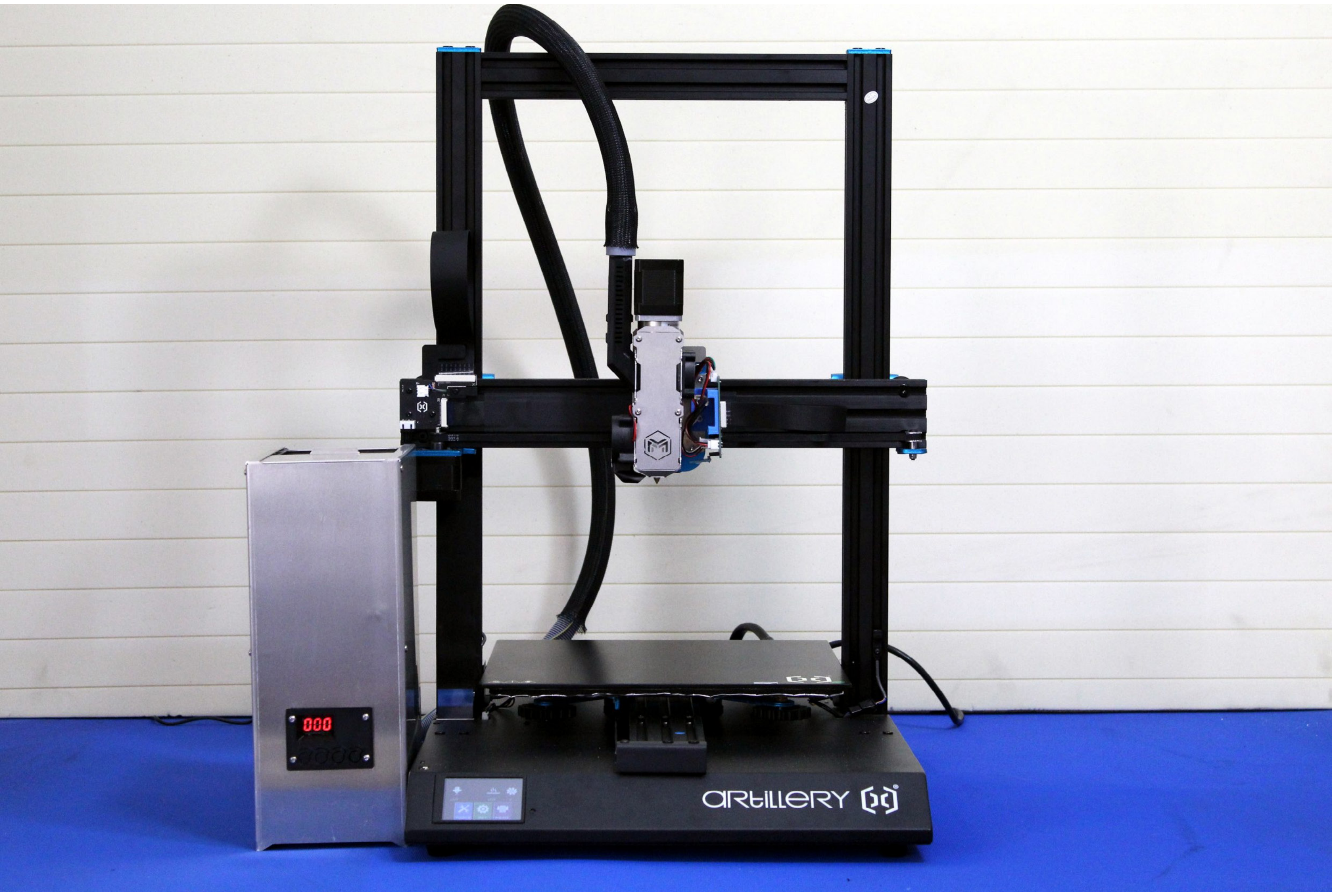


Figure 22 The FGF pellet extruder by Mahor XYZ, mounted on a FDM frame (Mahor XYZ, n.d.).

2.7 INDUSTRY INSIGHTS

As shown in the state of the art section, companies are starting to offer recycling solutions and recycled filament for FDM. Understanding the challenges, interests and concerns of different parties in the industry in regards to recycled filament is essential.

For this reason, a series of interviews with relevant parties and experts in the material journey and FDM industry has been done. Most of the interviews were done online or via phone call, some took place in the company following a company visit and some were done via email communication. The questions asked were tailored to each company's position in the supply chain. Figure 24 shows an overview of the companies interviewed.

Insights

- **Recycling/waste sorting**

Standard recycling processes, like infrared technology, sometimes can not sort bioplastics. Although there are new systems that can do it, **bioplastics are not economically attractive to recycle** due to the relatively low quantities in the general waste stream compared to other plastics and that bioplastics are not as easy to recycle as other plastics (L. van Keulen, Plastic Recycling Amsterdam, personal communication, August 19, 2020).

- **Filament producers**

The production of filament is always in bulk, of at least 300kg (R. Luiken, MCPP Netherlands, personal communication, August 21, 2020). This makes it easier to sort out and collect the **waste from their own production line**, which then can be reused after some testing to produce new filament, usually called recycled filament (R. Luiken, MCPP Netherlands, personal communication, August 21, 2020; Formfutura, personal communication, August 20, 2020).

"We'd love to buy waste and create materials from waste, but at this moment we are not strong enough to take responsibility for the whole recycling process" (R. Luiken, MCPP Netherlands, personal communication, August 21, 2020)

Figure 24 Overview of companies interviewed.

Other manufacturers are also **reluctant to produce recycled filament** due to a high chance of contamination (A. van Unen, Meer3D, personal communication, September 30, 2020).

- **Recycled filament providers**

Producing high quality filament from waste is technically more difficult (C. van der Meer, Better Future Factory, personal communication, August 24, 2020). **Controlling the whole recycling process is key** (collecting waste, sorting it out, and the whole recycling process) (J. Middendorp, Reflow, personal communication, September 1, 2020). Large batches are hard to control. When working with multiple parties, it is **harder to have total supplier control in the supply chain** to keep track where issues are happening (p.e. unexpected moisture) (C. van der Meer, Better Future Factory, personal communication, August 24, 2020). The **customer/user acceptance is key**. Users might be afraid to put lower quality filament into their printers. It is a constant battle of showing and proving the filament quality (C. van der Meer, BetterFutureFactory, personal communication, August 24, 2020).

- **Filament production machinery providers**

Recycling PLA into printable filament is possible. The drying process is highly recommended for PLA waste. Most of the machines sold are used primarily for material research or production (M. Gudelevicius, 3devo, personal communication, August 28, 2020).

- **FDM printer provider**

Recycled filaments are not usable like virgin filaments, they would **not be useful for their quality testing standards** as the material is compromised and different for every recycling batch (T. Rijnaarts, Ultimaker, personal communication, October 29, 2020).

- **3D printing services**

There is interest in reusing their waste. They are **experimenting with an FGF printer and downcycle alternatives**. Sorting out their waste by material and colour is easy and achievable. There is no demand for FGF, it works for personal projects but involves a lot of try and error (E. van Munster, MTB3D, personal communication, August 24, 2020).

2.8 USER RESEARCH

The users of the 3D printing prototyping centre are an important piece of the whole system. Learning about their desires, habits and current use of the 3D prototyping facility can help identify potential opportunities and concerns regarding the recyclability of the FDM material and its re-use for prototyping. The users can have an impact on the quality of the waste stream, on the amount of material that can be reused and how the material can be reused. Their prototype needs and prototyping habits between low-fidelity prototyping versus high-fidelity prototyping can have a substantial impact on the implementation of a material reuse solution. Therefore, insights from the users of the prototyping facility are investigated and collected.

Focusing on the case study of this project, the users of the prototyping centre are the students of the faculty of Industrial Design Engineering of TU Delft. In order to gather their insights, a tailored questionnaire is distributed amongst two representative groups of students: participants of the Advanced Prototyping minor and Integrated Product Design master students. They are likely to be familiar with 3D printing for prototyping and more likely to have used the 3D printing facilities at the faculty several times. A total of 22 students were surveyed.

The main topics addressed by the survey were:

- Experience with FDM technology
- Purpose and context of the prototypes
- Common 3D printed prototype characteristics and requirements
- Post-processing of prototypes
- End-of-life of prototypes

Insights

- **Experience with FDM technology**

  All surveyed users were familiar with FDM technology, more than 50 % use it often or always in their projects. All of them for university-related projects, while half of them also for personal projects.

- **Purpose and context of the prototypes**

  The most common purposes of the prototypes are to **evaluate the shape and form of a design (20/22)**, closely followed by development models (to explore and visualize component relations) and operational models (to evaluate key functional features).

  Around half of them print at home, but not exclusvely, since 12/22 also use the facilitites at IDE. It is worth pointing out that this result might be a consequence of the work-at-home faculty policy present at the time of the survey due to the Covid-19 pandemic.

- **Prototype characteristics**

  The most important prototype characteristics were **the overall shape and size** (95%) and dimension accuracy (77%). 81% of the contestants print their prototypes with **normal quality settings** (layer height of 0,15mm or higher). And most of the prototypes take between 3 and 8 hours to print.

- **Post-processing of prototypes**

  Most of the students usually only remove the supports and not do any further post-processing to the printed parts. **36% of the contestants never use paint or glue in their prints, while 50% only occasionally**.

- **End-of-life of prototypes**

  Most of the **prototypes become obsolete during the development of the project**. Students usually throw the prototypes to the **general waste outside of the faculty** or they keep them stored somewhere when they become obsolete. This suggests that a collection point for obsolete prototypes at the faculty might require students to bring back the prototypes.

2.9 MATERIAL JOURNEY

In order to have a better understanding of the waste stream of the 3D printing facility, but also to identify the origin and end-life of the material used, a material journey is mapped out.

Based on the materials journey mapping method by The Circular Design Guide (Ellen MacArthur Foundation & IDEO, 2018), the journey of the PLA filament used at the 3D prototyping facility at the faculty of Industrial Design Engineering of TUDelft is identified.

Several iterations of the material journey map are made, including new insights from the research and industry interviews done. The final version is presented in Figure 25.

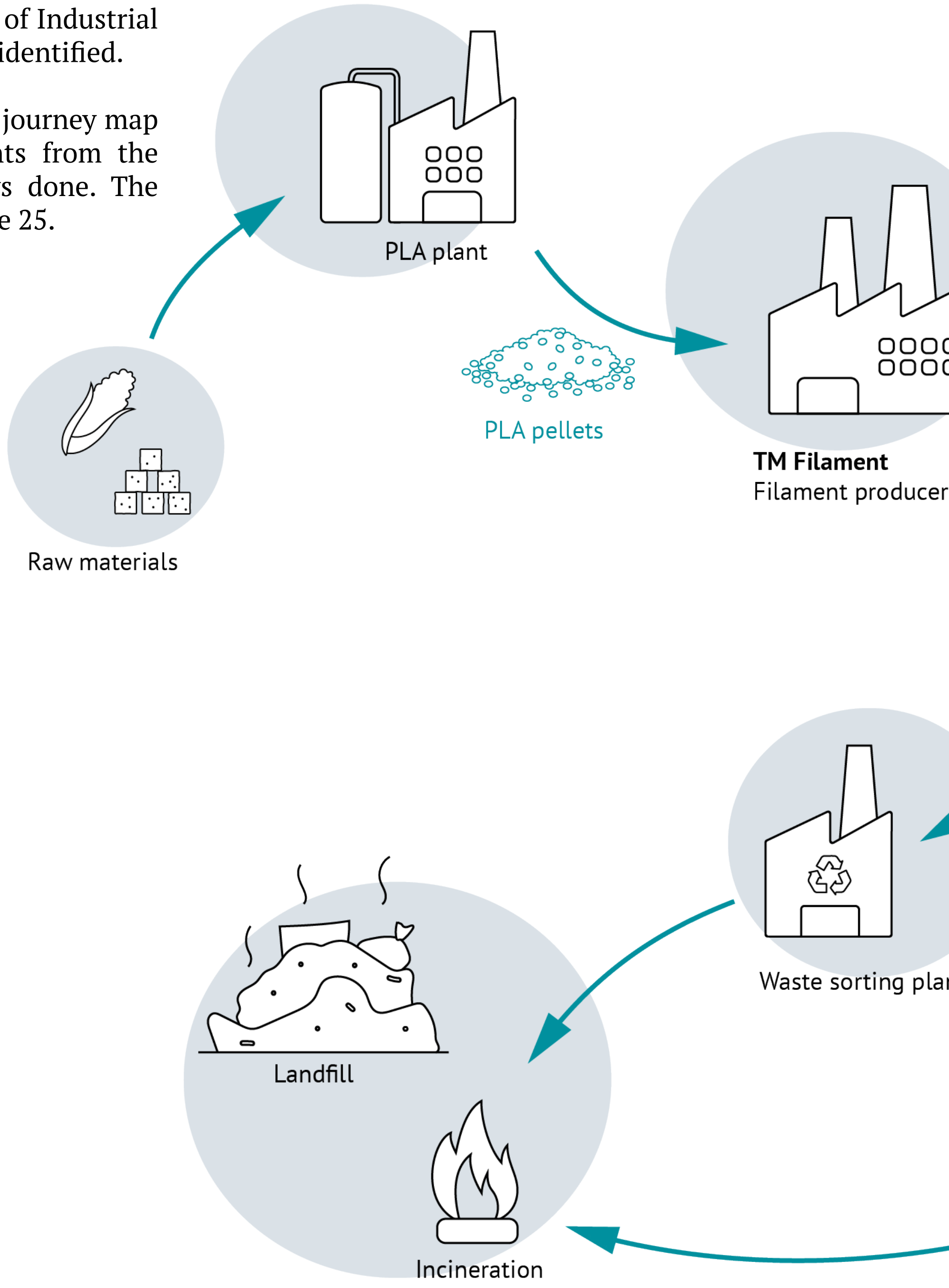
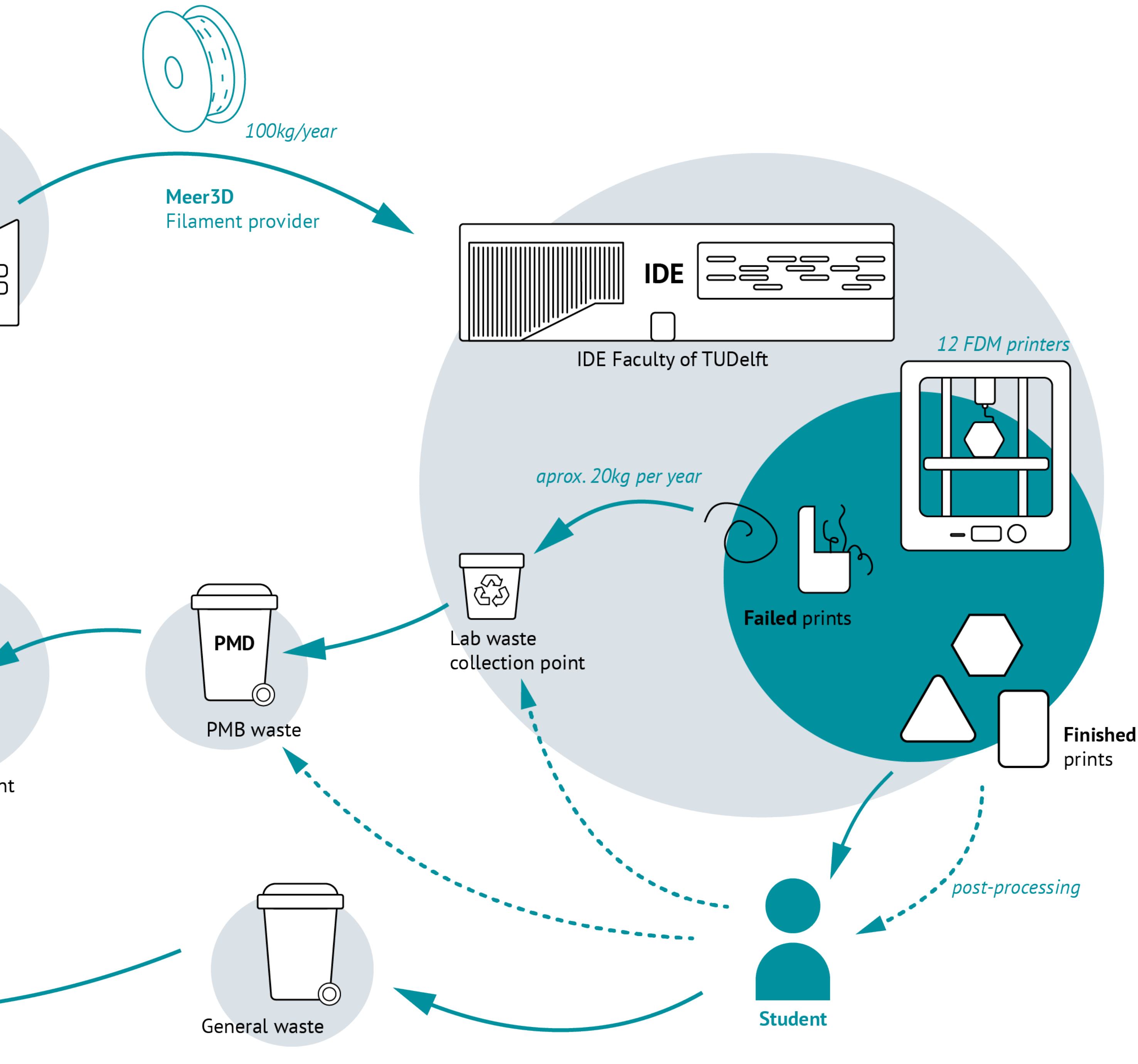
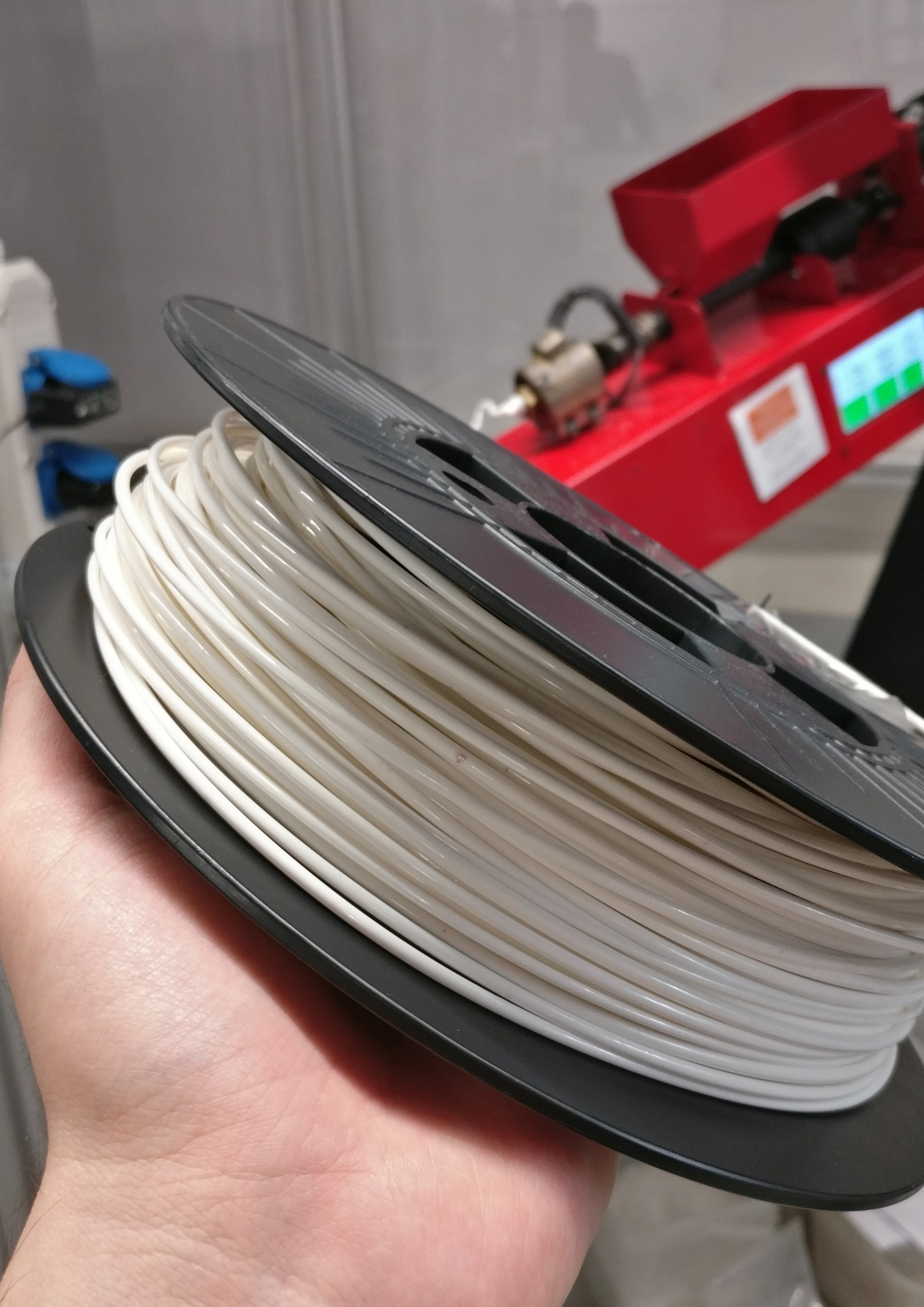
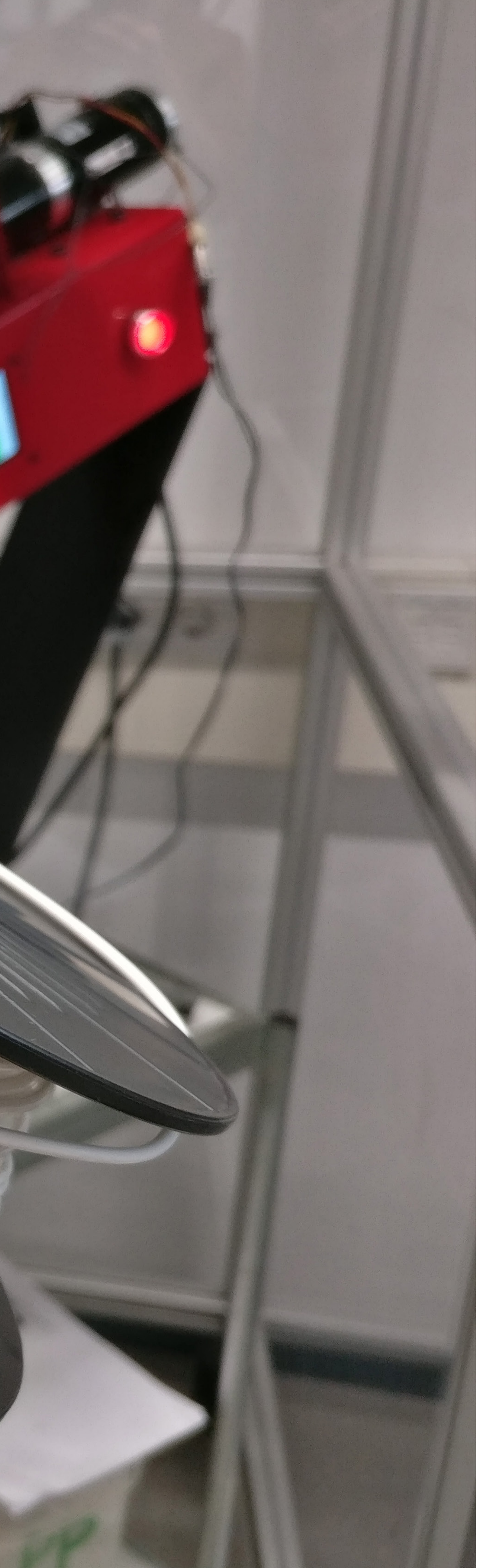


Figure 25 Material journey of the PLA for FDM printing at the IDE Faculty of TU Delft.







3 PRACTICAL RESEARCH

This chapter describes the experimenting approach and methods and it presents the results and discussions of the practical research done. First, an overall approach is presented. After that, the chapter is divided into two: the production of recycled filament and the printability of recycled filament.

3.1 RESEARCH APPROACH

The main goal of the practical research phase is to determine the printability of recycled PLA filament fabricated from PLA waste from 3D printing at a local scale. The material waste from the prototyping facility is recycled into FDM filament, following the process described in section 2.4, and then 3D printed using an FDM printer. The 3D printed specimens are then analysed and tested. The recycled filament is made out of 100% waste from the prototyping facility and it is referred to as **recycled PLA**.

The 3D printed recycled specimens are compared to two other sets of specimens. One set is printed with virgin PLA material, the same material and brand as the waste used for producing the recycled filament. It is referred to as **virgin PLA**. This is a direct comparison between virgin PLA and 100% recycled PLA.

To also evaluate the impact that the recycling process has in the printability, a third set of specimens is printed with virgin PLA that has been processed through the same recycling process as the PLA waste, but that has not been used for 3D printing yet. In other words, it is virgin PLA filament that has been granulated and re-extruded into filament. This third material is referred to as **re-extruded PLA**.

A visual summary of the tests is shown in Figure 26.

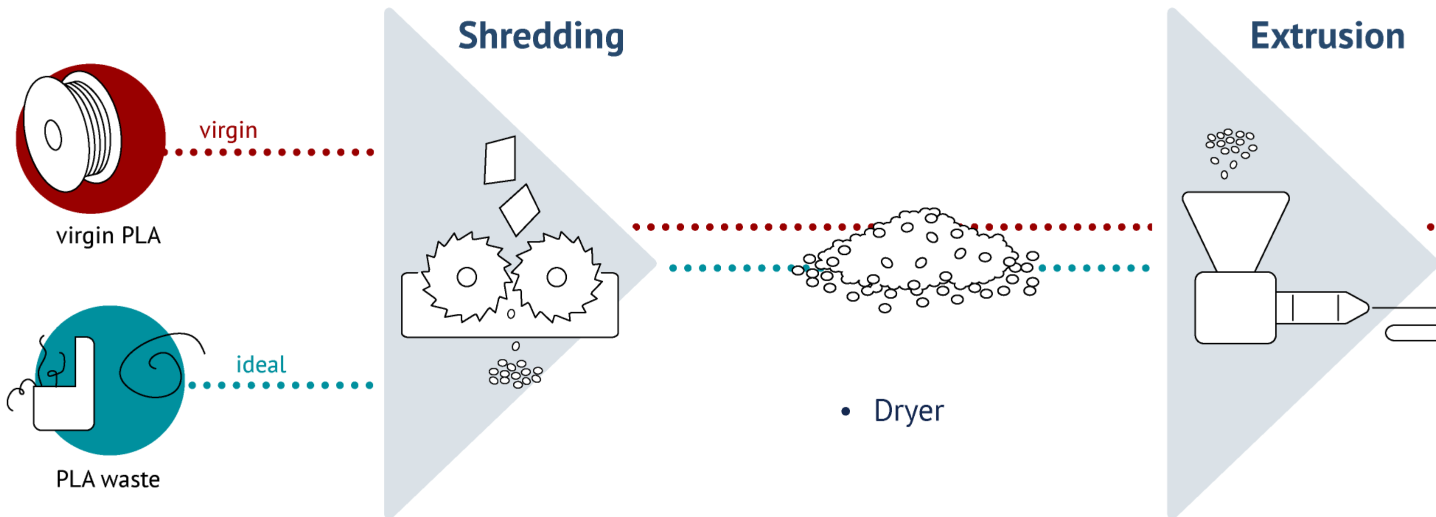
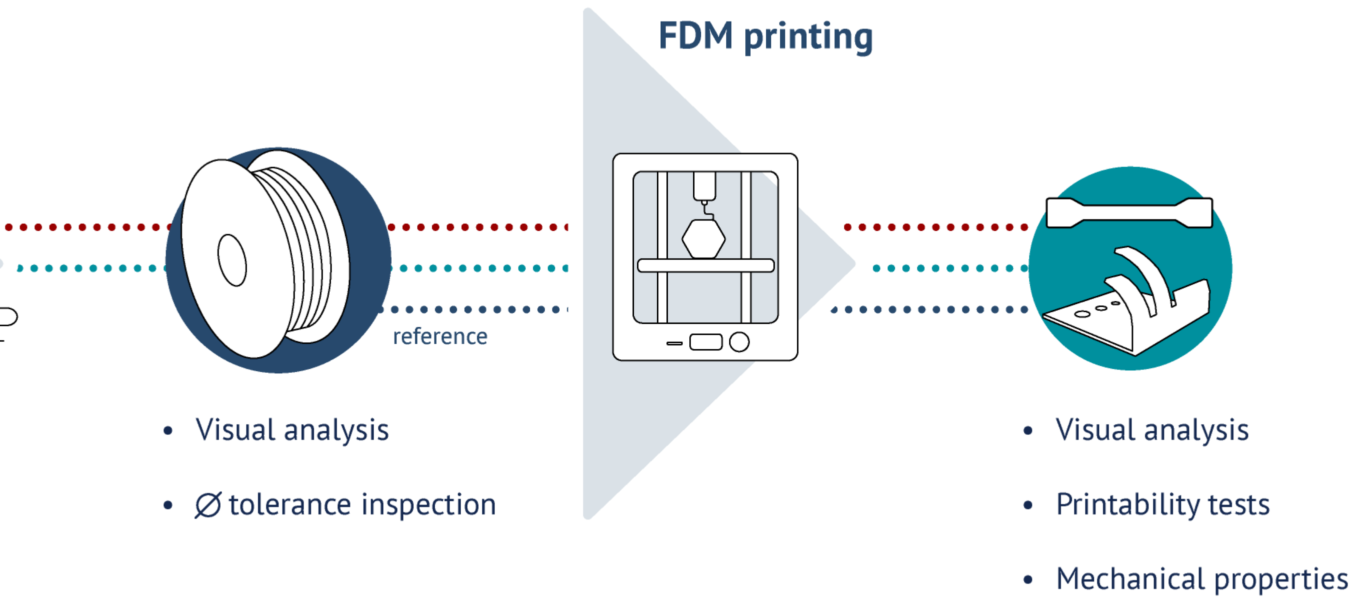


Figure 26 Overview of the practical tests approach.


FDM printing
reference
Visual analysis
∅ tolerance inspection
Visual analysis
Printability tests
Mechanical properties

3.2 PRODUCTION OF RECYCLED FILAMENT

In order to assess the printability of recycled PLA in a local-scale and its feasibility, the recycled PLA filament to be tested is also produced in a local-scale. Particularly, the process is carried on a desktop and small lab-scale setup.

The goal of these experimentations is first, to determine if producing recycled filament from the PLA waste of a local prototyping centre is possible, second, to produce recycled PLA filament to carry on the printability study, and third, to analyse the opportunities and challenges of producing recycled PLA filament in a local scale.

3.2.1 Method

The setup used for the production of recycled filament consists of a Zerma GSL 180 slow-speed granulator, a Noztek Touch desktop extruder and a Noztek 1.0 filament winder, shown in Figure 27. No puller, air-path nor oil bath was used. A filament dryer was used to dry the plastic flakes before extrusion.

- **Zerma GSL 180 granulator**

  Rotor speed: 150 rpm

  Rotor diameter: 180 mm

  Rotor knives: 10

  Drive capacity: 2,2 kW

- **Noztek Touch desktop extruder**

  Number of heated bands: 2

  Motor: adjustable speed control

  Drying system: integrated fan

  Nozzle diameter: 3 mm

Source of the waste

The PLA waste used for producing the recycled filament was collected at the local prototyping centre, with a designated bin situated next to the 3D printers. The majority of the waste collected was failed prints, support elements and some filament endings, all produced by the same filament brand and colour.

Shredding/granulating

The PLA waste was shredded using the granulator directly, without any cleaning, drying or cutting before using the granulator. Each batch of waste was processed through the granulator twice to ensure even flake sizes.

Processing time per kg of material › 10 min

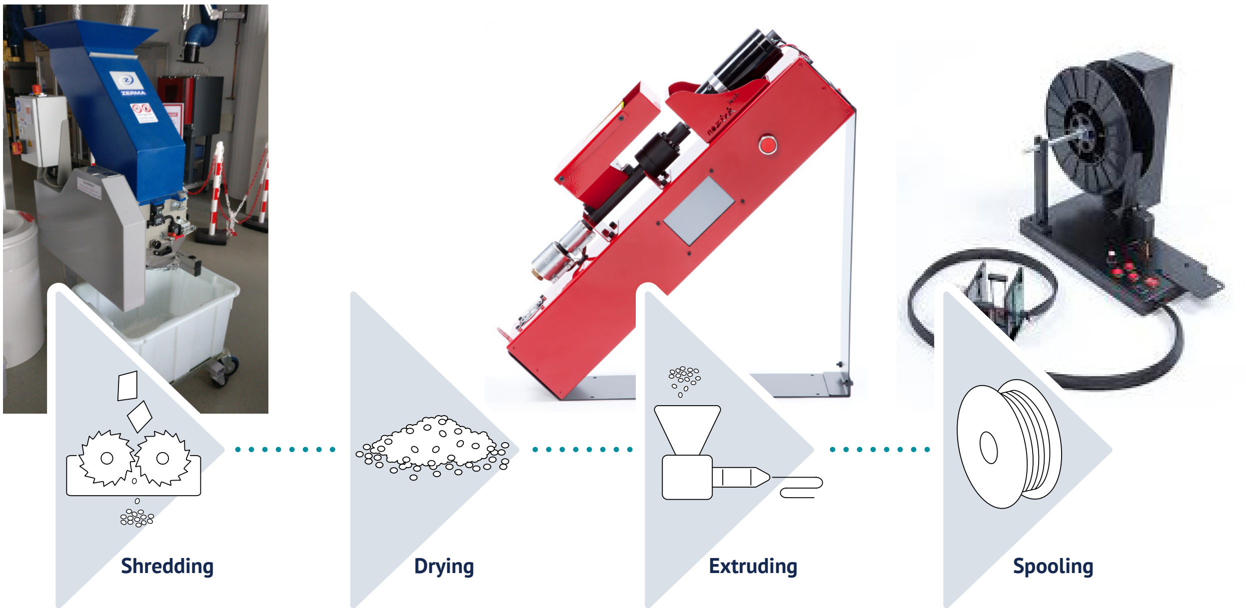


Figure 27 Noztek Touch extruder (Noztek.com), Noztek 1.0 filament winder (Noztek.com) and Zerma GSL180 granulator.

Drying

The shredded waste PLA flakes were dried using a filament dryer and a net bag.

Processing time per kg of material › 4 h

Extrusion

The first extrusion experimentations were done with virgin PLA filament granulated with the slow-speed granulator. The initial temperatures were determined by the extruder manufacturer, then a series of tests was carried, changing the extrusion temperature gradually until constant extrusion was achieved. Then the filament was fed into the winder and its thickness measured every 40 cm, with a calliper. The extrusion without a winder was also tested.

Once constant extrusion was achieved with virgin PLA filament granulated, the same parameters were used to test the extrusion of waste PLA. Then, more experimentation was done by gradually changing the extrusion temperature. The effect of drying the PLA waste prior to extrusion was also tested. The changes in the parameters were determined by the average diameter obtained in each test, aiming at producing the lower thickness variability possible and the closer nominal diameter to commercial virgin PLA filament.

Processing time per 1/2 kg of material › ~2 h

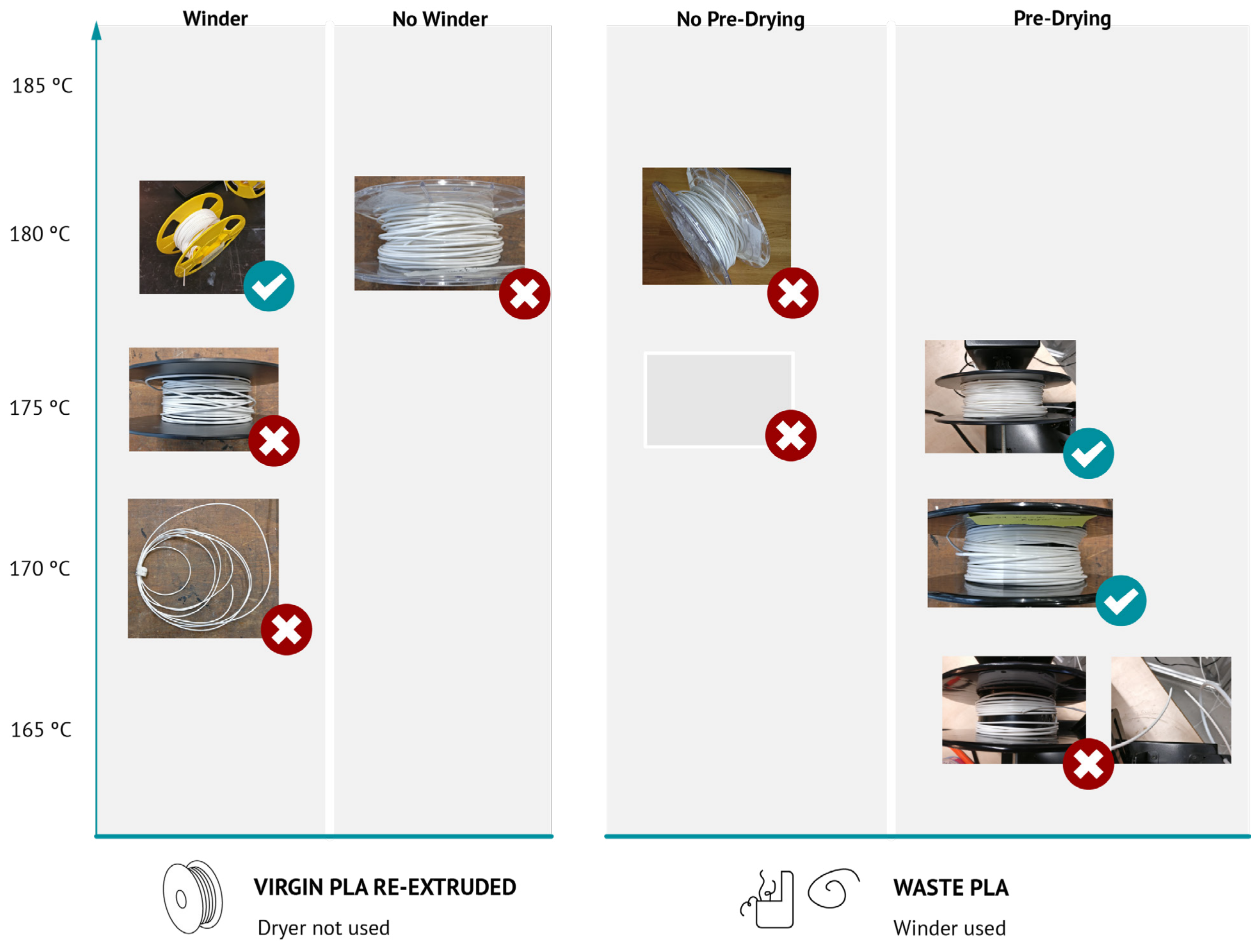


Figure 28 Overview of the extruded filaments.

3.2.2 Results

As shown in Table 4 and Figure 28, re-extruded virgin PLA filament showed the best results at **180°C** and **35 rpm**, with an average diameter of **2,73mm**. Using the filament winder achieved a more constant diameter and a filament spooled without tangling. Lower temperatures caused more irregular extrusion.

Recycled PLA filament showed the best results at **170°C** and good results at **175°C**, both at **35rpm** and with dried for 4h at 45°C prior to extruding. The average diameters were **2,47mm** and **2,41mm**, respectively.

The extrusion temperatures influenced the average diameter of the filament. At lower temperatures, a higher average diameter was obtained. However, unmelted flakes and impurities were present in the filament, which caused the filament to break during winding.

Extrusion from dried plastic flakes has less variability in diameter than without drying. Producing a constant diameter of 2,85mm was not possible with the setup used, not with PLA waste nor with virgin PLA filament granulated.

T1 - nozzle (°C)	T2 - barrel (°C)	Motor (rpm)	Material	Pre-extrusion drying	Average diameter (mm)	SD
170	170	40	Virgin PLA	No	Inconsistent extrusion	-
180	180	35	Virgin PLA	No	2,73	**0,06**
180	180	35	Virgin PLA	No	Inconsistent extrusion	-
175	175	35	Virgin PLA	No	Inconsistent extrusion, large presence of lumps	-
180	180	35	PLA waste	No	2,42	**0,26**
175	175	35	PLA waste	No	2,46	**0,22**
175	175	35	PLA waste	Yes	2,41	**0,11**
165	165	35	PLA waste	Yes	2,6	**0,12**
170	170	35	PLA waste	Yes	2,47	**0,11**
Filament sample from 3devo			PLA from pellets		2,61	**0,17**

Table 4 Extrusion tests results.

3.2.3 Discussion

The setup used for producing recycled filament from PLA waste was able to extrude recycled filament but with a lower nominal diameter and higher tolerances than commercially available filaments.

No major differences were observed between extruding PLA waste and virgin PLA filament granulated, only the optimal temperature was different. The average diameter obtained was higher using the virgin PLA filament granulated, but still below commercial standards. This suggests that the waste stream used was of enough quality to produce recycled filament without a cleaning process.

However, some issues were present in the process used. Bridging in the hopper was a constant issue using both PLA waste flakes and virgin filament granulate, although it was more present when using flakes. This caused interruptions in the stream of flakes or granulate feeding into the extruder barrel, which originated inconsistent extrusion rate. Manually moving the flakes was a must to keep a constant flow, making the extrusion process labour intensive and not autonomous.

Another issue was the lack of control on the filament diameter. The thickness of the extruded filament was dependent on the temperature and the nozzle size, which gave little control of the filament tolerances. A puller system with a diameter sensor might be needed to achieve the desired filament diameter.

Overall, the whole process was time-consuming and a large amount of try and error was needed before a constant extrusion was achieved.

Compared to the filament produced by another desktop extruder setup –the 3devo extruder–, the filament obtained had similar variability. The 3devo sample also had a low nominal diameter, between the re-extruded virgin filament and the recycled one. The 3devo sample was produced from virgin PLA pellets, from an unknown producer. However, no information was available regarding how optimized the 3devo extruder process was when the measured sample was produced.

Conclusion

From these experimentations, it can be concluded that the most important part of the setup and the limiting factor to produce recycled filament is the extruder machine. A reliable extrusion system with a puller-sensor system and a good feeding hopper system is key to produce recycled filament from PLA with the desired filament diameter and with a relatively autonomous and less labour intensive process. However, such an extruder setup has an important barrier: the high investment of the equipment.

That is why the printability tests of the recycled filament are focused on a low-quality and under-dimensioned filament.

3.3 PRINTABILITY TESTS

The printability of a prototype is determined by several factors, including the design of the prototype itself, the printer parameters and the material used. Achieving printability of a material can be referred to the capacity of an FDM printer to create a 3D object by extruding the material, yet it can also mean that the printed part fulfils the requirements for which was designed.

Regarding prototyping for design projects, chapter 2 identified a potential opportunity in low-fidelity prototypes for low-quality recycled filament. In this context, printability is defined as the capacity to produce a 3D object with the desired geometric features and where the mechanical properties and surface quality are not primordial, yet not completely ignored.

Based on these requirements, 4 tests have been designed and performed to assess the printability of recycled PLA.

- **Printing temperature test** › to determine and compare the optimal printing quality for recycled PLA.
- **Prototype quality test** › to assess the capability to print geometric features and the overall printing quality.
- **Print profile optimization** › to define an optimized printing profile for low-quality recycled PLA filament.
- **Mechanical properties** › to compare the mechanical properties of non-optimized and optimized recycled PLA prototypes to virgin PLA prototypes.

As explained in the practical research approach, recycled PLA is compared to virgin PLA and re-extruded virgin PLA. All specimens have been printed using the same FDM printer, an Ultimaker 2+, using a 0.4 mm nozzle.

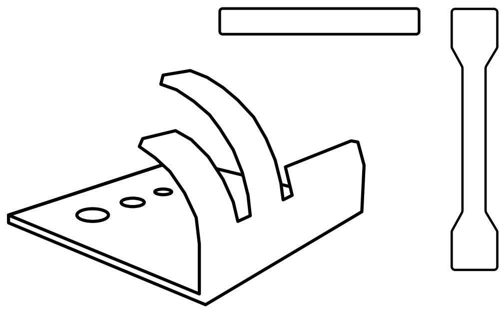


Figure 29 Overview of the printability test specimens.

3.3.1 Printing temperature

An important printing parameter with high influence on the printability of a material is the printing temperature. This is the temperature at which the material is extruded through the nozzle of the 3D printer.

Filament providers usually specify a range of temperatures in which a material can be printed. The 3D printer and the slicer software define the exact temperature of printing. In the case of the Ultimaker 2+, the printing temperature of generic PLA defined by the printer is 210 °C.

Recycled PLA may have a different range of printing temperatures. Additionally, the optimal printing temperature for recycled PLA may differ from the generic PLA setting. Optimizing the printing temperature might improve the overall printing quality of recycled PLA, and potentially enable a virgin-like printing quality.

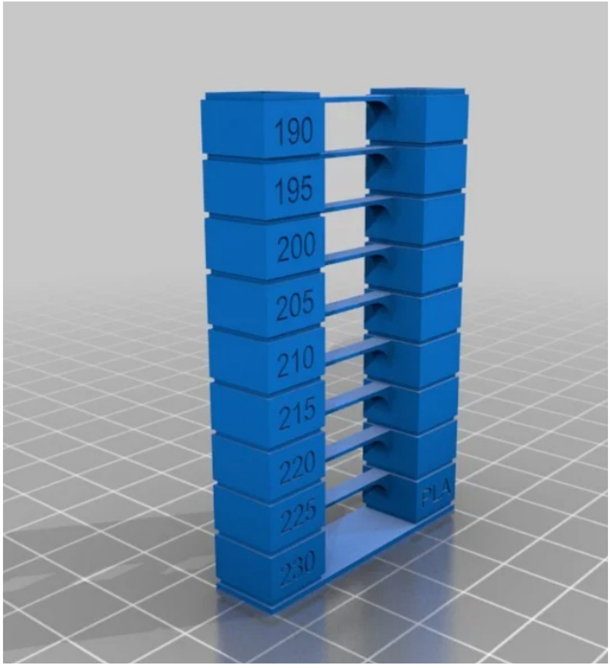


Figure 30 Temperature Tower for PLA, ABS, PETG by stoempie (Vranckx, 2017).

METHOD

To define and compare the range of printing temperatures between recycled PLA, virgin PLA and re-extruded virgin PLA, and to define the optimal printing temperature of recycled PLA, a temperature tower was used. A temperature tower (Figure 30) is a 3D printing test consisting of an element stacked vertically in which the printing temperature changes after a determined number of layers, resulting in the same element but printed with different temperatures.

The temperature tower selected was the Temperature Tower for PLA, ABS, PETG by stoempie (Vranckx, 2017), due to its compactness and low material use.

Two variations were printed: firstly a temperature tower with a range between 180°C and 220°C, and secondly a temperature tower with a range between 190°C and 230°C. The temperature range was selected based on the printing temperature range recommended by the virgin filament provider (Meer 3D, n.d.).

The specimens were printed with recycled PLA, virgin PLA and re-extruded virgin PLA using the recommended printing parameters by the creator of the test. The slicer used to configure the printing temperature profile was Cura 4.7.

- **Printing parameters:**

  Layer height = 0.2mm

  Bed temperature = 60°C

  Speed = 60mm/s

  Infill = 100%

  Flowrate = 100%

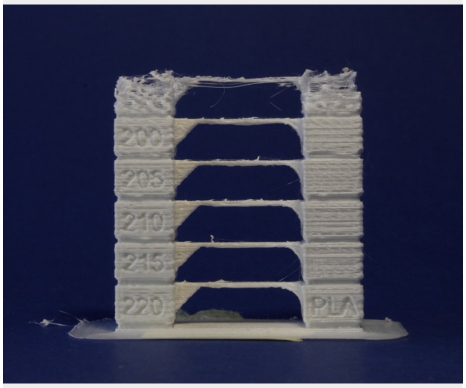
The recycled filaments were dried prior to printing. The virgin and re-extruded PLA were not dried prior to printing. After the specimens were printed, a visual inspection was done of each specimen.

RESULTS

The printed temperature towers are shown in Figure 31. **Recycled PLA** showed generally good printing results between **210 - 230°C**. Under 205°C, all recycled specimens showed important extrusion issues, like inconsistent extrusion and under-extrusion that caused the inability to fully print the element. One specimen (out of 4) already showed extrusion issues at 215°C. All recycled specimens showed a decrease in the under-extrusion issues at higher temperatures. At the maximum temperature tested, no issues were observed.

Re-extruded virgin PLA showed major extrusion issues at 215°C and lower temperatures, in both temperature towers printed. Between **220 and 230°C**, better results were obtained. Overall, re-extruded virgin PLA showed slightly worse results than recycled PLA, with less under-extrusion across the entire specimen.

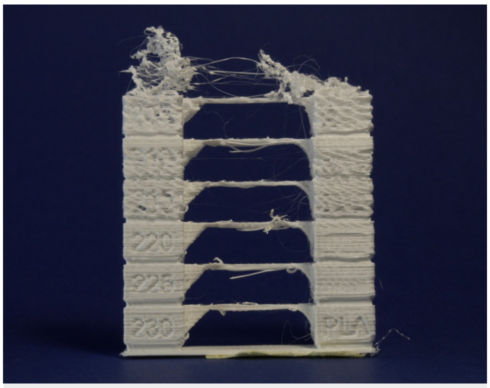
Virgin PLA showed good results between **205 and 220°C**. Virgin PLA was not tested at higher printing temperature than 220°C.



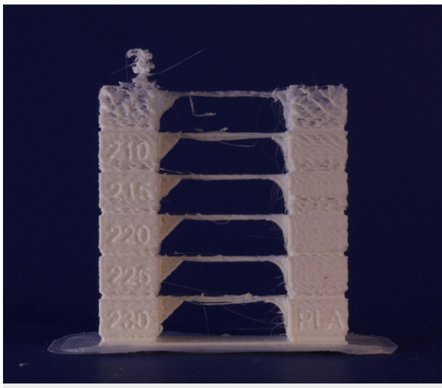
Temperature range › 180–220 °C
Best temperatures › **210–215 °C**

VIRGIN PLA

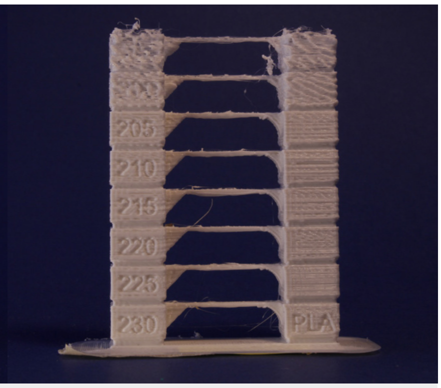
Figure 31 Printed temperature tower specimens results.



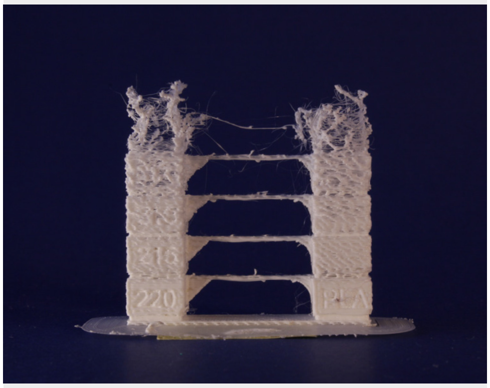
Temperature range › 190–230 °C
Best temperatures › **220–230 °C**



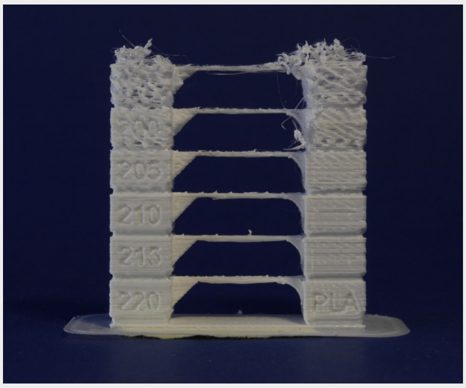
Temperature range › 190–230 °C
Best temperatures › **220–225 °C**



Temperature range › 190–230 °C
Best temperatures › **210–230 °C**



Temperature range › 180–220 °C
Best temperatures › **220 °C**



Temperature range › 180–220 °C
Best temperatures › **210–220 °C**

RE-EXTRUDED PLA

RECYCLED PLA

DISCUSSION

Overall the printing quality of both recycled and re-extruded samples was lower than the virgin sample. The range of temperatures in which no major issues were present was smaller in the recycled and re-extruded specimens.

Additionally, the printing quality changes were more gradual in both recycled and re-extruded samples. In the virgin sample, a difference of 5°C changed the printing quality drastically, from a fully printed element at 200°C to an unprintable element at 195°C. In the recycled samples, this changed happened gradually from 205°C to 195°C. In the re-extruded sample, this happened during an even larger range, from 215°C to 200°C.

A possible explanation might be the under-extrusion caused by the thinner filament diameters of both materials, also present in the prototype quality test. This under-extrusion might have masked the changes in quality caused only by the variation in temperature. Similarly, the good results from recycled PLA could be also caused by a particular section of the filament where the diameter was constant and no irregularities were present. However, these results were highly consistent across the different samples printed. Therefore, it can be concluded that at higher printing temperatures, the under-extrusion is less noticeable.

Conclusion

These results show a potential solution for extrusion issues when printing recycled PLA: printing it temperatures close to 220 °C, higher than used for generic PLA.

The better quality of the recycled samples over the re-extruded samples might suggest that the biggest impact on the printing quality comes from the process of producing filament, rather than from the difference in the source of the material used.

3.3.2 Prototype quality test

An important aspect of 3D printed prototypes is the printing quality. The printing quality usually refers to the capability of printing different geometric features, details and surface as accurately as possible. In Figure 33, an overview of the most relevant geometric features for 3D printing is shown.

The ability to print these geometric features can have an influence on the design of 3D printed prototypes, and therefore, an impact on the design process. Focusing on low-fidelity prototyping for design projects, aspects such as surface quality might not be as important as other geometric features, as indicated in chapter 2. On the other hand, the ability to print horizontal bridges, overhang geometry or embossed and engraved details are potentially more relevant for achieving good low-fidelity prototyping.

This means that the differences regarding printable geometric features between recycled PLA and virgin PLA can have an impact on the feasibility, desirability and usability of recycled PLA as a material for low-fidelity prototyping.

Additionally, comparing both materials can also help to determine possible adjustments to improve the printing settings with recycled low-quality filament.

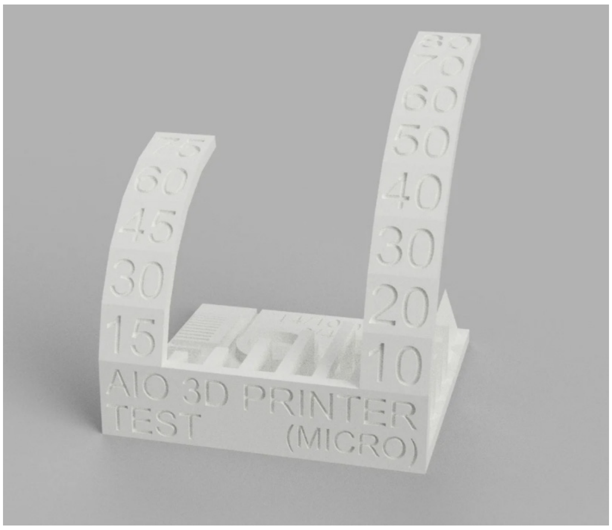


Figure 32 Micro All In One 3D printer test by majda107 (Trpkoš, 2018).

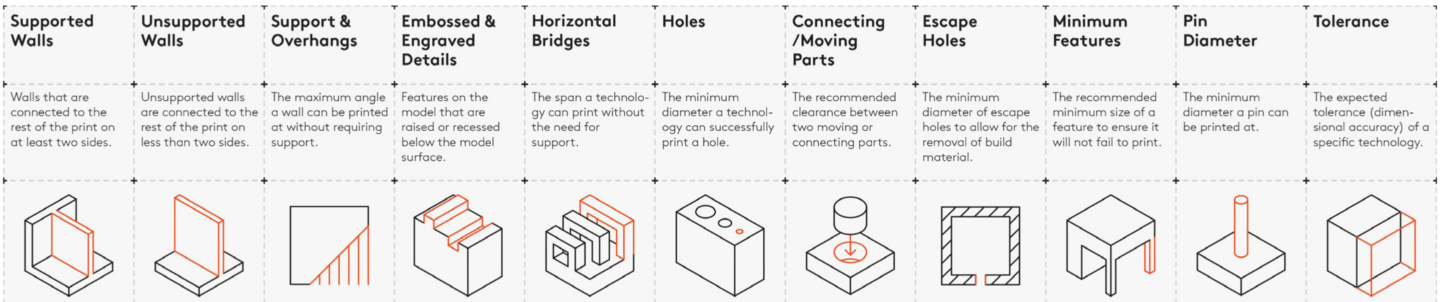


Figure 33 Geometric features overview, from the design rules for 3D printing (3D Hubs, n.d.-a).

METHOD

A 3D printer test model, also called torture test, has been used as the test specimen. Particularly, the specimen selected was the Micro All In One 3D printer test by majda107 (Trpkoš, 2018), shown in Figure 32. This compact specimen can be used to test the following geometric features: overhangs, tolerance, sharp corners, stringing, bridging and diameter accuracy.

The specimen was printed with recycled PLA, virgin PLA and re-extruded virgin PLA using the Fine printing parameters in Cura 4.7 for standard PLA, with exception of the Print Thin Walls parameter enabled and with 100% infill, as recommended by the author.

The filaments were not dried prior to printing,

After the specimens were printed, a visual inspection was done of each geometric feature of the model and individually compared with the other specimens.

- **Printing parameters:**

  Layer height = 0.1mm

  Printing temperature = 210°C

  Bed temperature = 60°C

  Speed = 50mm/s

  Infill = 100%

  Flowrate = 100%

RESULTS

A general overview of the printed specimens is shown in Figure 34 and a detailed description of each geometric feature can be found in Table 5. Part of the overhang geometry in the re-extruded PLA specimen broke at the ending of the printing process.

All 3 different materials achieved similar results, but under-extrusion was present in both the recycled PLA and the re-extruded virgin PLA specimens.

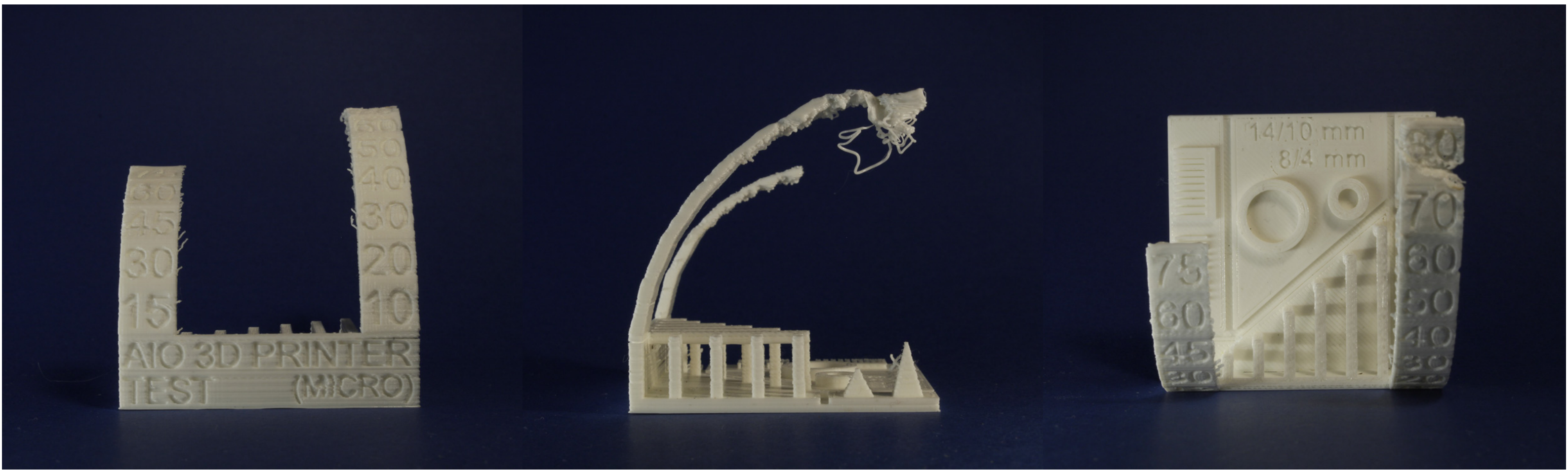
There were no differences between all 3 materials regarding the overhang geometry, sharp corners and bridging. No signs of stringing were observed in any of the samples either.

Similar measurements were obtained of the scale and diameter features. A slight difference was observed in the minimum printing tolerance of embossed details, Recycled PLA and Re-extruded PLA obtained a lower minimum detail (0.4mm, compared to 0.55mm of virgin PLA).

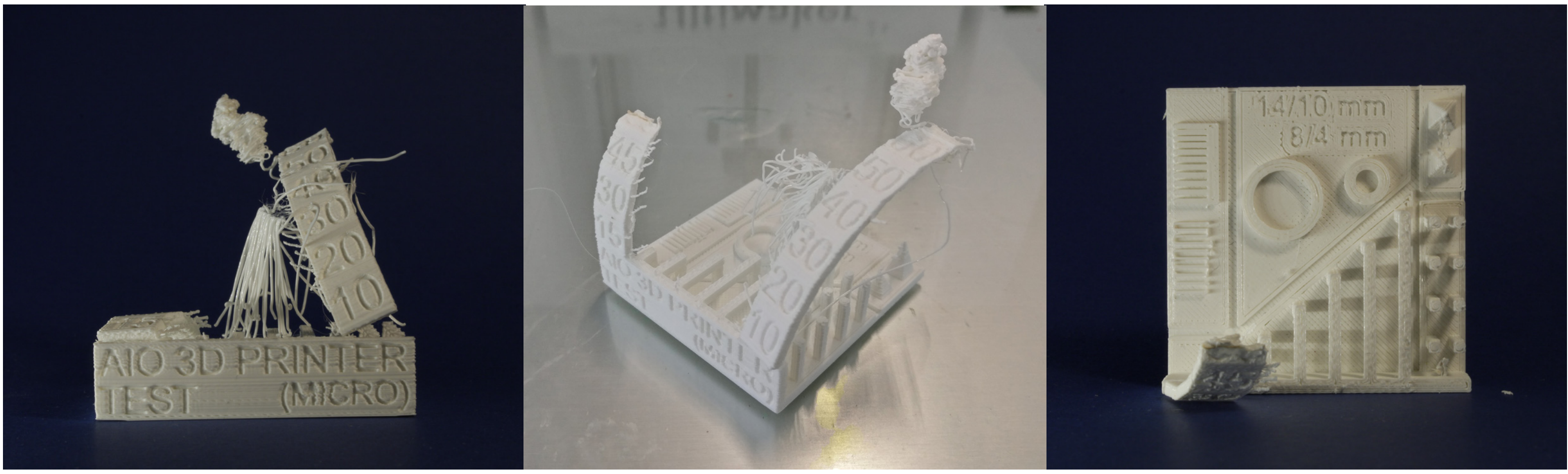
The major difference was observed in surface quality. In both re-extruded PLA and recycled PLA specimens, noticeable gaps were present between adjacent extrusions, a symptom of under-extrusion.

Overall, no differences were observed between Recycled PLA and Re-extruded PLA.

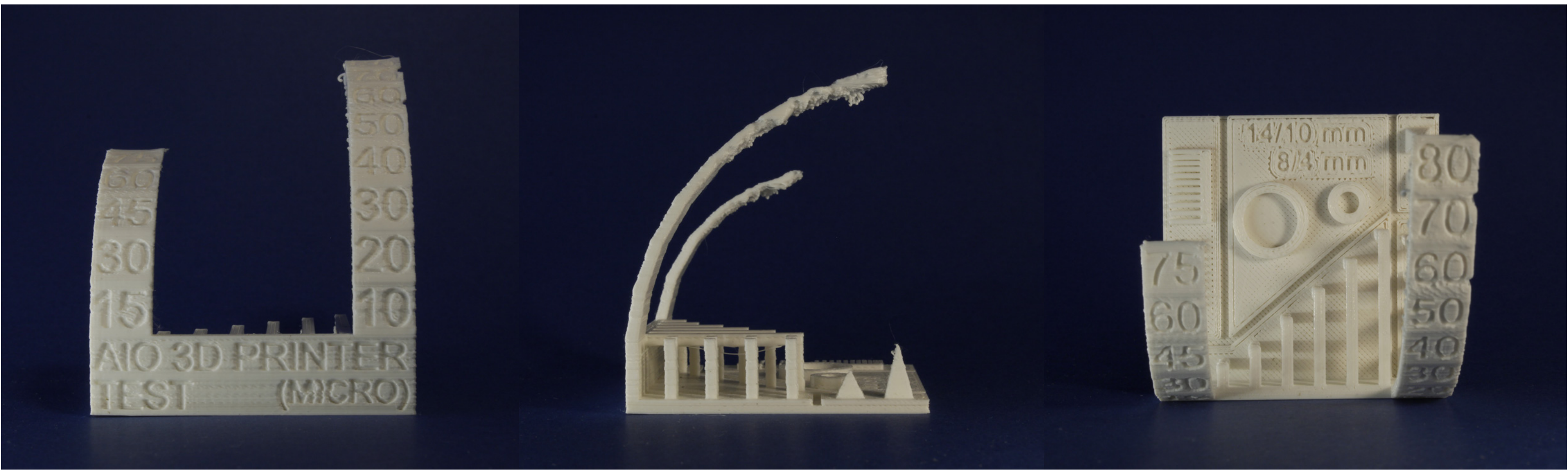
Figure 34 All-in-one 3D printer tests specimens.



Virgin PLA



Re-extruded PLA



Recycled PLA

	Overhangs	Bridging	Tolerance
Virgin PLA	At 45 and above surface imperfections on the underside start to appear.	Good results in all bridges, from 2mm to 25mm. No noticeable sagging, drooping or gaps are present in the bridges.	The minimum embossed detail is 0.55mm and the minimum engraved detail is 0.2mm.
Re-extruded PLA	At 45 and above surface imperfections on the underside start to appear. Part of the geometry got loose during printing.	Good results in all bridges, from 2mm to 25mm. No noticeable sagging, drooping or gaps are present in the bridges.	The minimum embossed detail is 0.4mm and the minimum engraved detail is 0.2mm.
Recycled PLA	At 45 and above surface imperfections on the underside start to appear.	Good results in all bridges, from 2mm to 25mm. No noticeable sagging, drooping or gaps are present in the bridges.	The minimum embossed detail is 0.4mm and the minimum engraved detail is 0.2mm.

Table 5 Detailed results of the geometric features tested.

DISCUSSION

Recycled PLA showed similar results as virgin PLA.

The slight difference in the embossed detail tolerance is likely to be caused by the general under-extrusion present across the recycled PLA and re-extruded PLA specimens. Likewise, the lower surface quality is another visible effect of this. This under-extrusion might be caused by the lower filament diameter of both recycled PLA and re-extruded PLA, compared to virgin PLA.

Despite the under-extrusion, Recycled PLA showed the ability to print the same geometric features and details as virgin PLA using the same printing parameters.

However, one can expect lower mechanical properties, especially lower isotropy likely due to weaker layer adhesion. Prototype printing orientation might have a higher impact when printing using recycled PLA.

Stringing	Scale (mm)	Sharp corners	Surface quality
No stringing	13.86/9.8 7.85/3.71	No visible issues	No major issues
No stringing	13.85/9.87 7.75/3.73	No visible issues	Underextrusion. Noticeable gaps between adjacent extrusions
No stringing	13.76/9.77 7.73/3.77	No visible issues	Underextrusion. Noticeable gaps between adjacent extrusions

Conclusion

The results obtained are promising. With the current recycling setup, only under-extrusion is an issue when using recycled low-quality filament. This confirms that recycled low-quality filament can be used for low-fidelity prototyping.

3.3.3 Print profile optimization

The prototype quality test and the printing temperature tests showed a common issue with recycled PLA: under-extrusion. To better compare recycled PLA to virgin PLA, a test is performed with the goal of optimizing the print profile for recycled and re-extruded PLA in order to reduce the extrusion issues. A print profile, also called material profile, is the collection of printing parameters defined by the slicer software or/and the 3D printer.

METHOD

To improve the under-extrusion, two parameters are selected according to their potential impact on solving this issue: the printing temperature, as concluded in the printing temperature tests, and the flowrate. The flowrate is a parameter that defines the amount of material flow that the nozzle extrudes. Since both materials to be improved have a thinner nominal diameter, the flowrate is adapted to overcome this difference in thickness.

A series of short tests are performed, varying the two parameters. The printing temperatures tested are based on the results of the printing temperature tests and the flowrate tested are based on the difference in thickness between the filaments.

The test specimen used was a thin wall box of 0.8mm thickness (2 times the nozzle size used), based on the Flowrate Calibration Method by petrzmax (Petrzak, 2019). This specimen (see Figure 35) allowed for quick iterations thanks to its low printing time and for a clear identification of extruding issues, thanks to its thin wall thickness.

After printing, a visual inspection was done and the average wall thickness of each specimen was compared to the specimen printed with virgin PLA. The tests were done with both re-extruded PLA and recycled PLA.

The recycled filament was dried prior to extruding. The re-extruded filament and the virgin filament were not dried prior to extruding.

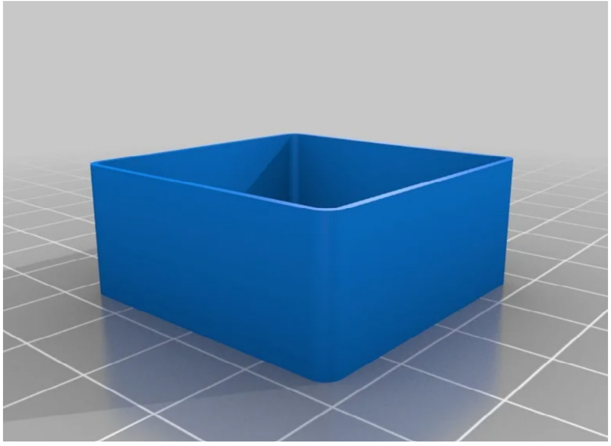


Figure 35 Flowrate Calibration Method specimen by petrzmax (Petrzak, 2019).

- **Printing parameters:**

  Layer height = 0.15mm

  Bed temperature = 60°C

  Speed = 60mm/s

  Infill = 0%

RESULTS

An overview of the specimens printed and their average wall thickness are presented in Figure 36. The best results obtained for **recycled PLA** was the sample printed at **230°C** and with **120%** of flowrate. Both the thickness and the printing quality were the most similar to virgin PLA. For **re-extruded PLA**, the best sample was at **220°C** and **110%** flowrate.

Increasing the flowrate without changing the printing temperature slightly improved the quality, however, under-extrusion was still present in the re-extruded samples. Increasing only the temperature caused fewer extrusion issues in both re-extruded and recycled samples, but the wall thickness was lower than the virgin sample.

In addition, in two specimens printed at 210°C (recycled PLA with 100% flowrate and re-extruded with 120% flowrate), the extrusion quality changed half-way the printing process, without any changes in the parameters. The same happened with the sample printed at 220°C and 120% flowrate.

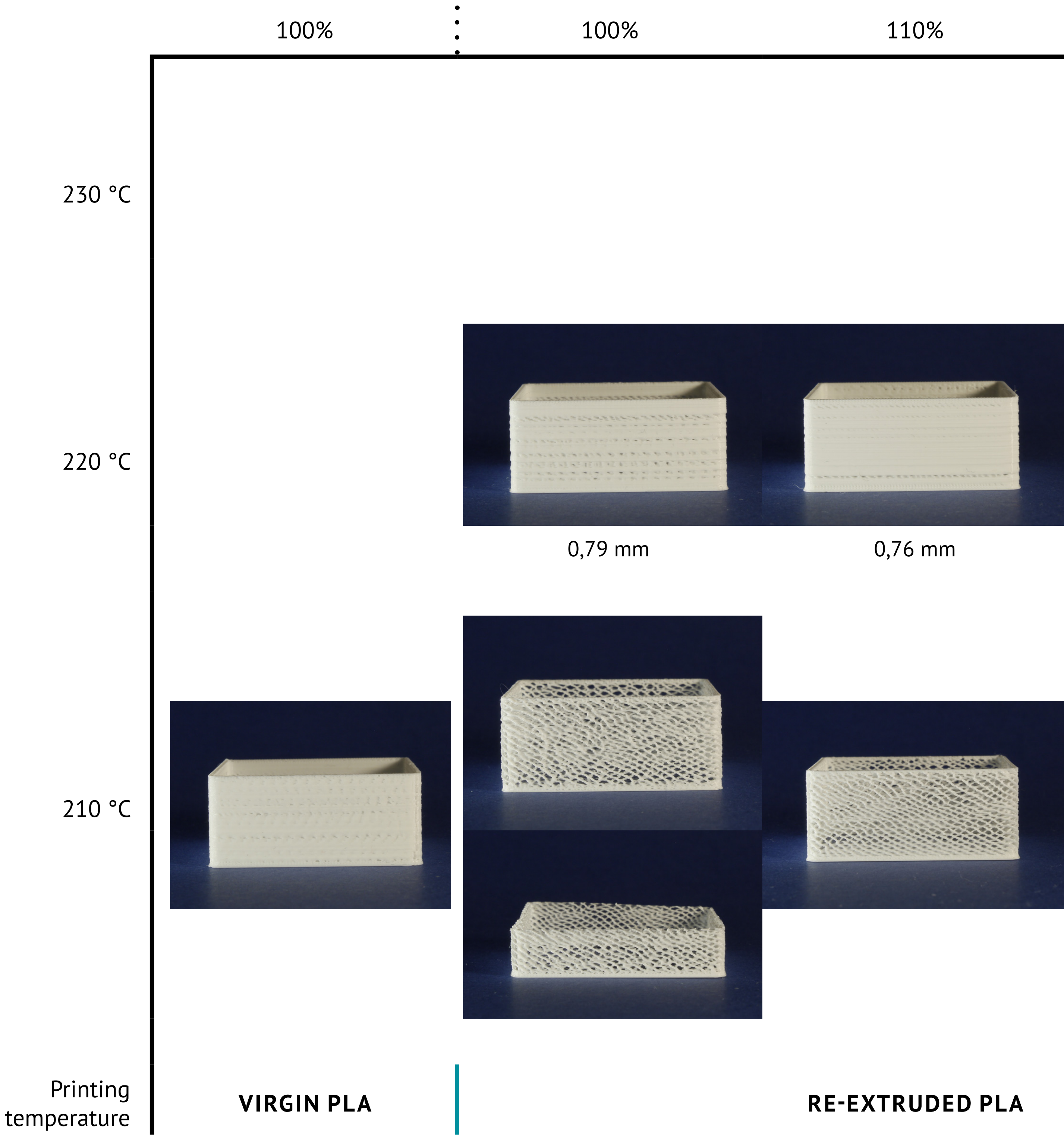
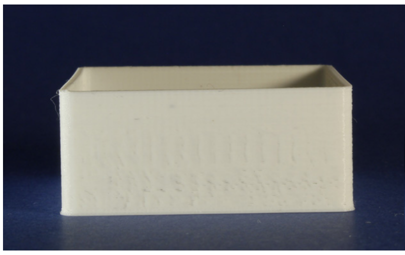
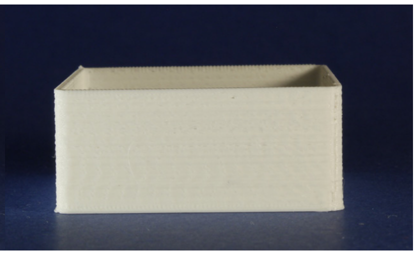


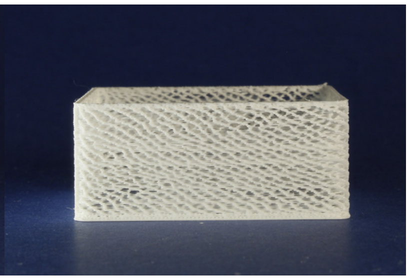
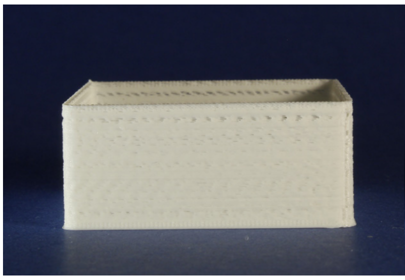
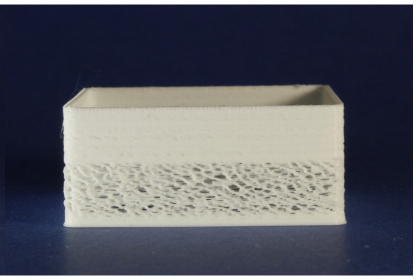
Figure 36 Print profile test results, including the average wall thickness.

120% | 100% | 120% | Flowrate

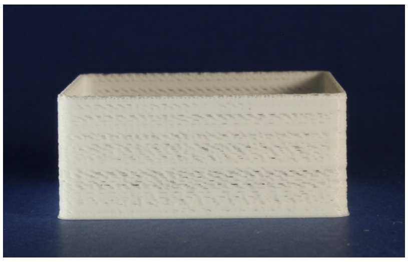



0,82 mm

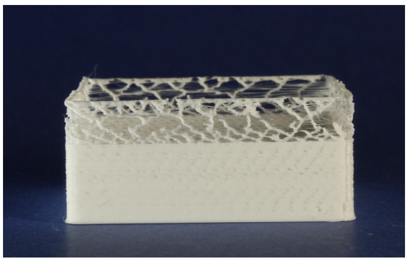
0,84 mm

0,77 mm



0,78 mm

RECYCLED PLA

DISCUSSION

Only adjusting the flowrate seems to have less impact on improving the under-extrusion. In addition, the flow was not constant in some specimens, which might have been caused by partial nozzle clogging.

Occasionally, when printing specimens, some issues in the geared feeder system were experienced, only with recycled and re-extruded filaments. This might also be causing the under-extrusion issues or the flowrate inconsistency observed in some specimens. At higher temperatures, the material flows easily through the nozzle, which might be the reason why higher temperatures achieve a more constant extrusion.

An interesting observation is that at 220°C, the optimal printing temperature defined in the printing temperature test, some extrusion issues appear at higher flowrates. A reason for this could be that with a higher flow rate, the material extrudes faster not allowing it to be heated up as high as at 100% flowrate.

Furthermore, at higher temperatures, there are less visible extrusion issues but under-extrusion is still present, as measured in the thinner wall thickness of the samples.

To fully assess the optimized printing profile, a specimen from the prototype quality test has been printed using the optimized settings. The result is shown in Figure 37 and Figure 38. Although the surface quality was still not in pair with the virgin specimen in section 3.3.2, no additional issues were observed. It is to be noted that this specimen was printed with a recycled filament badge less consistent and with more under-extrusion than the filament previously used.

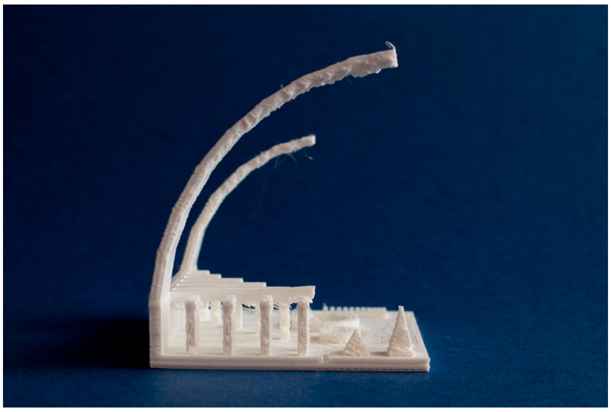


Figure 37 All-in-one specimen printed with optimized settings.

Figure 38 All-in-one specimen printed with optimized settings.

Conclusion

Combining a higher temperature with a higher flowrate that the standard settings can reduce the extrusion issues when using low-quality and under-dimensioned recycled and re-extruded filament.

3.3.4 Mechanical properties

A relevant characteristic of 3D printed prototypes is their mechanical properties. Although virgin PLA is generally already being used for prototypes where high mechanical strength is not a requirement, properties such as tensile strength and flexural strength are still significant for recycled PLA prototypes. A minimum mechanical strength is still expected from low-fidelity 3D printed prototypes.

Mechanically recycled polymers usually suffer from material degradation. Recycled PLA, in particular, suffers from material depletion of its mechanical properties (Haider et al., 2018). This could affect the strength and characteristics of the prototypes printed with recycled PLA compared to using virgin material and it could compromise the use of recycled material for 3D printing prototyping.

Additionally, the irregular extrusion during printing, caused by the low quality of the recycled filament, could also contribute to lower mechanical strength of the recycled PLA prototypes.

On the other hand, printing parameters are not optimized for maximum mechanical strength in low-fidelity 3D printing. Parameters such as layer height are more likely to be adjusted to obtain faster printing speed, affecting negatively the mechanical strength of the prototypes. It is in this specific scenario where the depletion of recycled PLA could have little to none impact compared to the other printing parameters, thus enabling the use of low-quality recycled filament for prototyping.

This is why the goal of this test is to analyse the tensile and flexural properties of recycled PLA prototypes printed with *normal* printing quality settings and compare them to virgin PLA prototypes, also printed with *normal* quality settings.

Figure 39 Zwick/Roell Z010 machine used.

METHOD

To test the tensile and flexural properties, two different tests have been done: a tensile 10kN test and a 3 point 10kN flexural test. All tests have been performed on a Zwick/Roell Z010 machine with 10kN grips, shown in Figure 39.

The specimens for testing the mechanical properties used are the ISO 527-2:2012/1A, for tensile properties, and the ISO 178:2019, for flexural properties. A set of the specimens printed can be seen in Figure 40.

Prior to printing, all filaments have been dried for 4 hours at 45°C using a filament dryer.

The recycled specimens are printed using two printing profiles: the *normal* profile in Cura 4.7 for printing PLA with a higher printing temperature defined by the temperature tests (Layer height=0,15mm, Infill=18%, T=220°C, Flowrate=100%) and an optimized printing profile defined by the flow rate tests to overcome under-extrusion (Layer height=0,15mm, Infill=18%, T=230°C, Flowrate=120%).

The non-optimized specimens are printed at 220 instead of 210 to avoid possible extrusion issues, observed in some specimens in the printing temperature tests.

Virgin PLA specimens are printed using the *normal* printing profile in Cura 4.7 (Layer height=0,15mm, Infill=18%, T=210°C, Flowrate=100%).

To compare the isotropy and the interlayer adhesion of the different specimens, the flexural specimens are printed twice each, one with the layer orientation perpendicular to the direction of the force during testing, and another one with the layer orientation parallel to it.

The virgin PLA and the non-optimized recycled PLA are tested 3 times each. The optimized recycled PLA is tested 4 times with the exception of the flexural test with parallel force, which is tested 2 times. The results show the average of the tests.

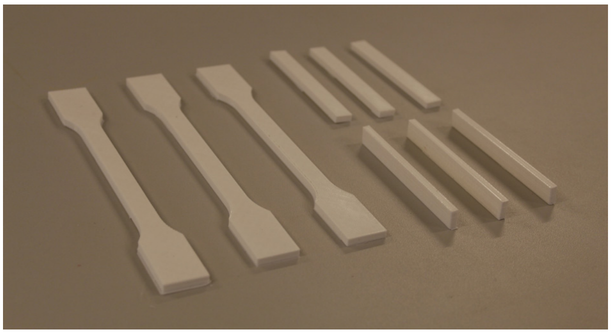


Figure 40 A set of the specimens tested, printed with virgin PLA.

RESULTS

Non-optimized recycled PLA performed worse than virgin PLA in both tensile and flexural tests, while optimized recycled PLA performed better than virgin PLA in some cases.

Tensile properties

The tensile properties results are shown in Table 6. Recycled PLA was more brittle than virgin in both optimized and non-optimized samples, breaking at the yield point in both cases. This differentiates them from virgin PLA, where the break occurred after yield.

Optimized recycled PLA showed higher tensile strength than virgin PLA and slightly lower elongation at break.

	Tensile modulus (MPa)	Tensile stress at yield (MPa)	Tensile stress at break (MPa)	Elongation at yield (%)	Elongation at break (%)
Virgin PLA	969,13	13,99	13,51	2,39	2,49
Recycled PLA T=220°C	573,47 (-40,83%)	8,12 (-41,95%)	8,12 (-39,91%)	2,01 (-15,98%)	2,01 (-19,32%)
Recycled PLA T=230°C fr=120%	1.174,77 (+21,22%)	17,92 (+28,12%)	17,92 (+32,62%)	2,32 (-2,61%)	2,32 (-6,49%)

Table 6 Tensile properties results.

Flexural properties

The flexural properties results are shown in Table 7. Optimized recycled PLA also performed better than virgin PLA in the flexural test, with higher flexural strength and flexural modulus in both parallel and perpendicular layer orientation. However, very brittle behaviour was observed. 3 out of 4 specimens with perpendicular layer orientation broke completely during the test, and on the 4th one, only the upper layer resisted the stress.

Non-optimized recycled PLA performed the worst of all 3 cases, but the perpendicular layer orientation specimens showed less brittle behaviour than the optimized samples. All 3 specimens did not fully break during the test. However, all 3 parallel layer orientation specimens broke, showing a very brittle behaviour similarly to the optimized samples.

Most of the virgin PLA specimens did not fully break, neither in perpendicular nor in parallel orientation specimens, with the exception of a single parallel orientation specimen. Virgin PLA showed the least brittle behaviour of all 3 cases.

Printing quality issues were observed in 3 specimens with perpendicular layer orientation that were printed together. This caused layer separation during the test (Figure 41). All 3 specimens were discarded for the determination of the flexural properties.

All printed specimens showed higher flexural strength printed with the layer orientation perpendicular to the testing force. Optimized recycled PLA had the highest difference in the flexural strength and higher flexural modulus difference than virgin PLA. Non-optimized recycled PLA had the least flexural strength difference between parallel and perpendicular layer orientation samples. Non-optimized recycled PLA had a different behaviour regarding the flexural modulus: the parallel layer orientation specimens showed higher flexural modulus than perpendicular ones, with the largest difference out of all cases.

	FORCE PERPENDICULAR TO LAYERS		FORCE PARALLEL TO LAYERS		COMPARISON PERPENDICULAR-PARALLEL ORIENTATION	
	Flexural strength (MPa)	Flexural Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)
Virgin PLA	37,12	1.309,52	28,92	1.234,24	-22,09%	-5,75%
Recycled PLA T=220°C	26,26 (-29,26%)	1.033,26 (-21,10%)	22,48 (-22,27%)	1.231,04 (-0,26%)	-14,39%	19,14%
Recycled PLA T=230°C fr=120%	56,25 (51,53%)	1.923,44 (46,88%)	42,17 (45,82%)	1.675,84 (35,78%)	-25,02%	-12,87%

Table 7 Flexural properties results.

Figure 41 Layer separation present in 3 virgin PLA specimens with perpendicular layer orientation.

DISCUSSION

Overall, recycled PLA showed more brittle behaviour than virgin PLA, especially with the optimized printing profile.

Even with a general printing profile that did not prioritize the mechanical strength of the specimens, recycled PLA still showed depletion in the mechanical properties. However, the optimized recycled PLA had higher tensile and flexural strength than virgin PLA.

This suggests that the lower tensile and flexural strength of recycled PLA is majorly caused by the extrusion issues, rather than from the depletion of the material after recycling.

Achieving similar tensile and flexural strength on low-quality prototypes using recycled PLA was demonstrated to be possible.

Conclusion

The results show that in order to achieve the mechanical strength of virgin PLA in low-quality prototyping, an optimized printing profile should be used. However, special attention should be given to the brittleness of the material, especially in flexural stress.

Recycled PLA might not be able to be used for prototyping elements that need some plasticity under flexural stress. The plasticity under flexural stress might be a necessary compromise if virgin-like tensile or flexural properties are required. This should be considered during prototype design.

3.3.5 Printability tests conclusions

The printability tests have shown that recycled PLA filament produced with a desktop recycling setup can be 3D printed with a desktop FDM printer, achieving similar low-fidelity prototyping capabilities for design projects as virgin PLA filament.

Recycled PLA filament is able to print the same geometric features as virgin PLA. An optimized printing profile with a higher printing temperature and flowrate is recommended to overcome the under-extrusion and lower mechanical strength when printing with low-quality recycled PLA filament.

Regardless of using an optimized printing profile, under-extrusion might still happen depending on how much thickness deviation is present in a specific filament portion. This might cause lower layer adhesion in specific printing moments, lowering the mechanical strength in some cases. Therefore, even though the results of the print-optimized prototypes showed high tensile and flexural strength comparable with virgin material, a general lower mechanical strength should be expected for recycled PLA printed prototypes.

Furthermore, nozzle clogging was detected 3 times during the printability tests, more frequently than when using virgin material. This suggests that more maintenance might be needed when printing with recycled PLA. More research is recommended to further determine the frequency of nozzle clogging when printing with recycled PLA.

During the printability tests, a common issue was present in both self-produced materials: grinding of the filament. This issue can generally occur in the FDM printers that use a gear system to feed the filament and control the extrusion. When the drive gear spins but the filament does not move, the gear can grind away the filament causing the filament to stop moving. This issue was present in both recycled PLA and re-extruded PLA filaments (see Figure 42).

The variability of the diameter or a potential difference in hardness of the filament used, compared to virgin PLA filament, might be the cause of this issue. At higher temperature, the material is likely to flow through the nozzle easily, which might be the reason why this is only observed when printing temperatures lower than 220°C. This might also be the cause of the irregularities in extrusion present in some tests and a possible explanation of why at higher temperatures the extrusion is more constant.

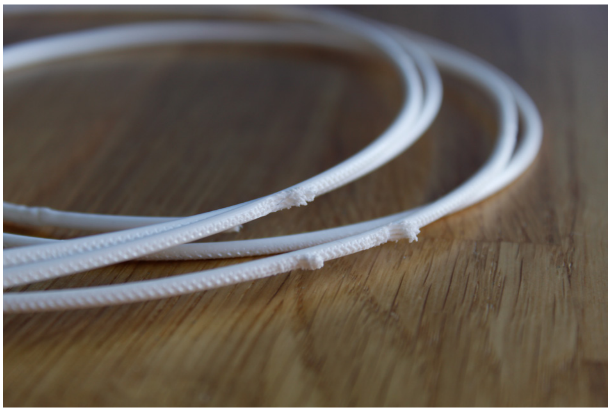
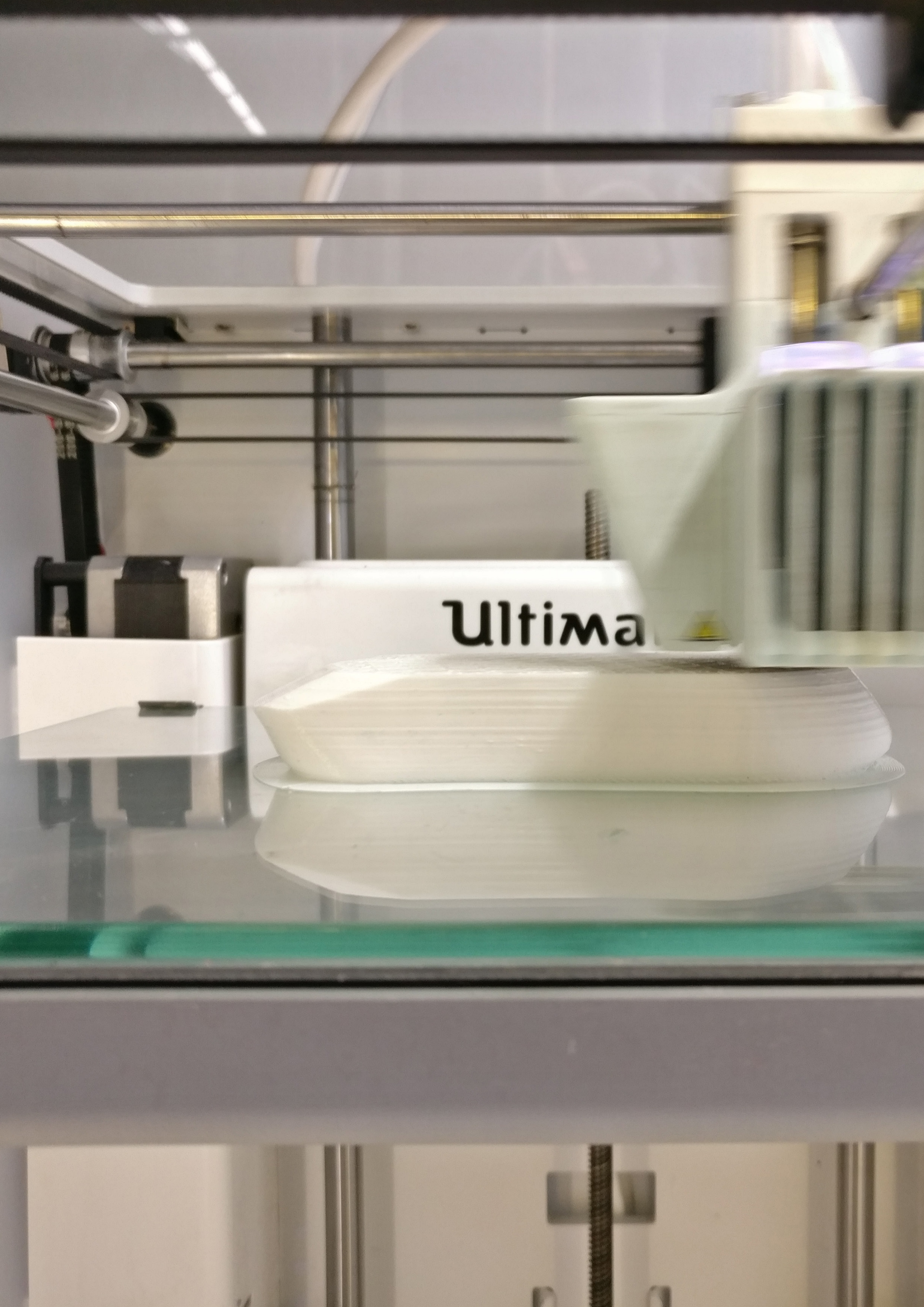


Figure 42 Filament grinding in recycled PLA filament.

On a different note, the lower mechanical strength of recycled PLA might suggest that using it as support only material could be another interesting application. However, nozzle clogging would still be an issue, causing virgin material prints to fail too when recycled PLA fails and still requiring more maintenance than with virgin-only prints. As it has been demonstrated, the lower mechanical strength does not impede using recycled PLA for low-fidelity prototyping. And by doing so, larger quantities of material can be reused than if it would be only used as support material.

Despite the encountered issues, it can be concluded that recycling 3D printing material for low-fidelity prototyping is possible, and the identified opportunity in the theoretical research is technically feasible.


Ultima

4 SOLUTION DEVELOPMENT

This chapter presents how recycling of 3D prints can be enabled. From the results of the research, a conceptualization phase is conducted, a roadmap towards the optimal scenario is created and the short-term solution further developed. Moreover, guidelines for printing with recycled PLA are established. Finally, the proposed solution is validated via a design case study.

4.1 DESIGN DRIVERS

After both theoretical research and practical research have been concluded, the findings have been summarized in a list of design drivers. These design drivers serve as the starting point for the ideation and the basis for the solution development phase.

They are divided into the two major processes: the printing setup and the recycling setup.

Recycling setup

- **Extruder system**

  - A puller and winder system highly recommended.

  To obtain a better and constant filament diameter and increase the autonomy of the process, a diameter control system is key.

- **Shredder system**

  - A 2-step shredder is recommended.

  For better extrusion, homogeneous and small size plastic flakes are needed. A 2-step shredder can achieve that.

- **Drying**

  - Plastic flakes must be dried before extrusion.

  To avoid extrusion issues and improve the filament obtained, drying the recycled plastic flakes is key.

Printing setup

- **Prototyping purpose**
  - Low-fidelity prototyping.

  The purpose of the prototypes printed with recycled material should be for development models, to evaluate the shape, form and explore relationships between components.

  - Low plasticity and flexural strength requirements.

  The mechanical requirements of the prototypes should be adapted to the characteristics of the recycled material.

- **FDM printing setup**
  - Ability to change printing profile.

  It should be possible to change the printing profile of the printing setup where recycled material is used.

  - Ability to adapt the geared feeder pressure on the filament.

  It should be possible to change and lower the pressure to reduce filament grinding.

- **Waste stream**
  - The material should always be the same.

  A constant material stream will ease and reduce production issues.

  - The waste material should be kept separated by material.

  Keeping the material streams separated reduces complexity and potential cross-contamination issues.

  - The waste material used for recycling should be free of any post-processing.

  Using only clean waste (without paint or adhesives) reduces the complexity of the processes needed to obtain recyclable material.

4.2 CONCEPTUALIZATION

4.2.1 Approach

First, a brainstorming session has been done with the goal of creating 8-10 different scenarios where recycling PLA can be enabled, exploring different set-ups and scales. Ideas were generated for multiple prototyping centres to expand the solution space.

Then, an initial selection was done according to the design drives previously defined. All selected ideas were clustered and new extra ones were generated. Finally, a selection of the 5 most promising ones was done regarding their potential impact and their feasibility.

Finally, each idea was explored by further defining the details and a scenario for each idea was visualized. Opportunities and concerns were indicated in each concept.

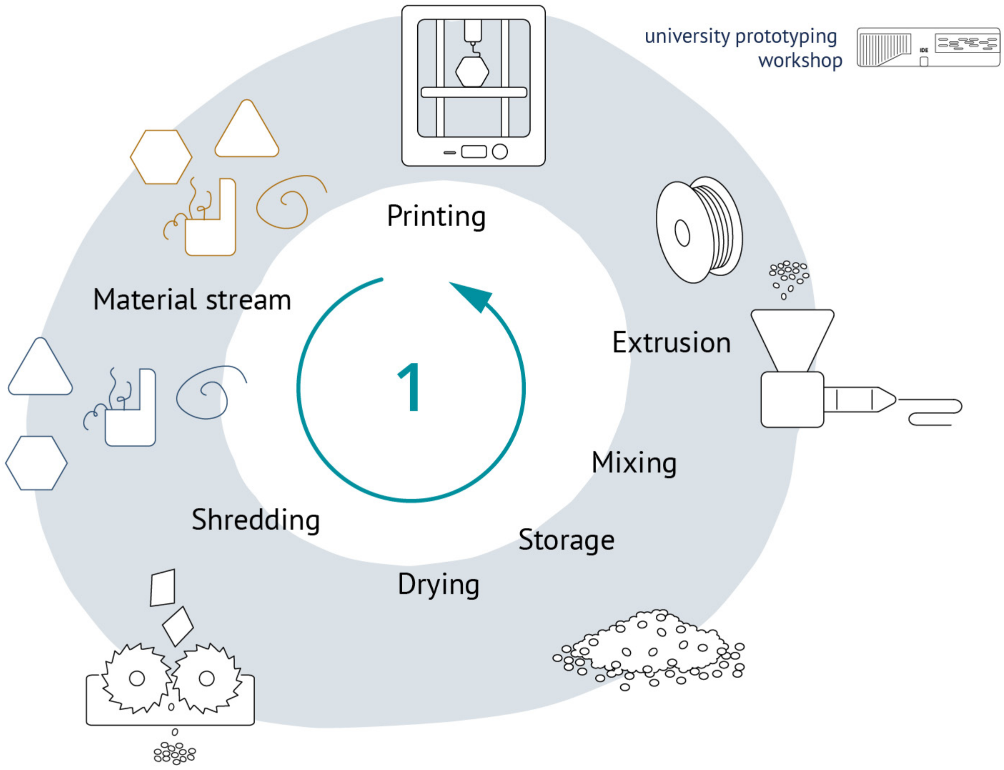
After the ideation phase, the concepts generated were compared using the Harris Profile methodology. The selected criteria for analysing each scenario were:

- System simplicity
- Material quality
- Sustainability impact
- Material reused
- User desirability
- Material costs reduction

4.2.2 Concepts

In this section, the detailed scenarios are presented. The five selected scenarios are:

- SCENARIO A. Single loop recycling at the prototyping centre (page 89)
- SCENARIO B1. Single loop recycling at a local makerspace (page 90)
- SCENARIO B2. Single loop recycling at a local recycling centre (page 91)
- SCENARIO C. Local recycled filament production workspace (page 92)
- SCENARIO D . Single loop recycling at a 3D printing service provider (page 94)



SCENARIO A. Single loop recycling at the prototyping centre

Harris Profile	- -	-	+	+ +
System simplicity			■	■
Material quality			■	■
Sustainability impact			■	
Material reused		■		
User desirability		■		
Material costs reduction			■	

System simplicity

- \+ No external parties involved
- \+ No minimum production volume
- \- In-house (human) resources needed for the process

Material quality

- \+ Homogeneous single waste stream
- \+ Full control of the material stream

Sustainability impact

- \+ Showcase setup to raise awareness
- \- Low replicability: difficult to implement to other prototyping centres (p.e. Fablabs)

Material reused

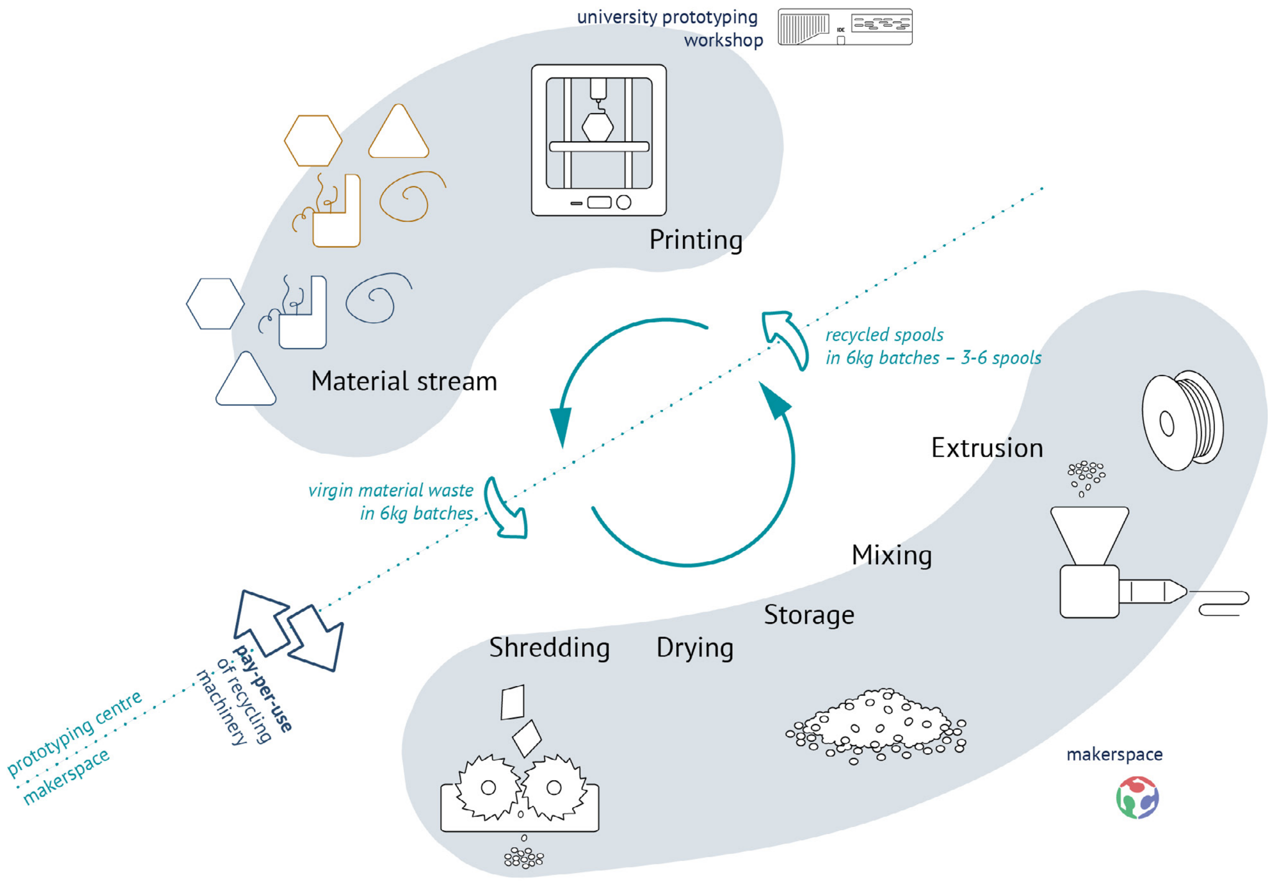
- \- A maximum of 50% of material can be reused
- \- Single recycling loop. More loops rise the complexity of the system

User desirability

- \+ Recycling setup might be useful for academic research and other purposes
- \- More day-to-day maintenance on the printing setup
- \- 2 parallel printing setups: more effort from the workers & extra decision for printer users

Material costs reduction

- \+ Reduction (up to 50%) on the amount of virgin material needed



SCENARIO B1. Single loop recycling at a local makerspace

Scenario B1	--	-	+	++
System simplicity			■	
Material quality			■	■
Sustainability impact			■	
Material reused		■		
User desirability	■	■		
Material costs reduction			■	

System simplicity

+ Only one extra party is needed
- Recycling facility demand: multiple users of recycling machinery are needed near the makerspace
- In-house (human) resources from the prototyping centre are needed for the process

Material quality

+ Homogeneous single waste stream
+ Full control of the material stream

Sustainability impact

+ Recycling setup can be used for other waste (p.e. PET bottles) but only on a small scale
- Low replicability: applicable only to other low-fidelity prototyping centres in the local area

Material reused

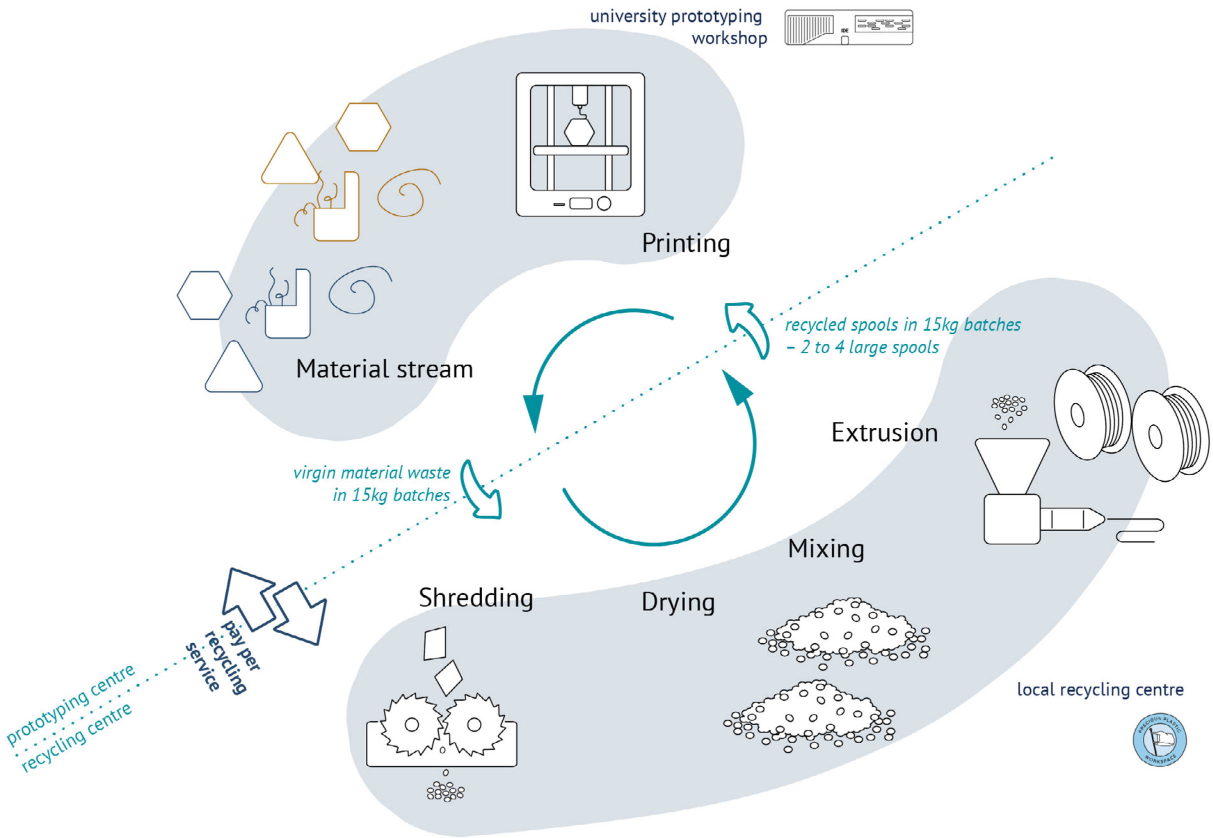
- A maximum of 50% of material can be reused
- Single recycling loop. More loops rise the complexity of printing setup

User desirability

- More day-to-day maintenance on the printing setup
- 2 parallel printing setups: more effort from the workers & extra decision for printer users

Material costs reduction

+ Reduction (up to 50%) on the amount of virgin material needed



SCENARIO B2. Single loop recycling at a local recycling centre

Scenario B2	- -	-	+	+ +
System simplicity		■		
Material quality			■	
Sustainability impact			■	
Material reused		■		
User desirability		■		
Material costs reduction			■	

System simplicity

+ No in-house (human) resources from the prototyping centre are needed for the recycling process
- Recycling service demand: multiple prototyping centres near the recycling centre have to be interested in a recycling service
- Short term feasibility: recycling centres are not widely available yet

Material quality

+ Homogeneous single waste stream
- No full control of the material stream by the same party. Contamination is possible

Sustainability impact

+ Recycling setup can be used for other waste (p.e. PET bottles) and on a semi-industrial scale
- Low replicability: applicable only to other low-fidelity prototyping centres in the local area

Material reused

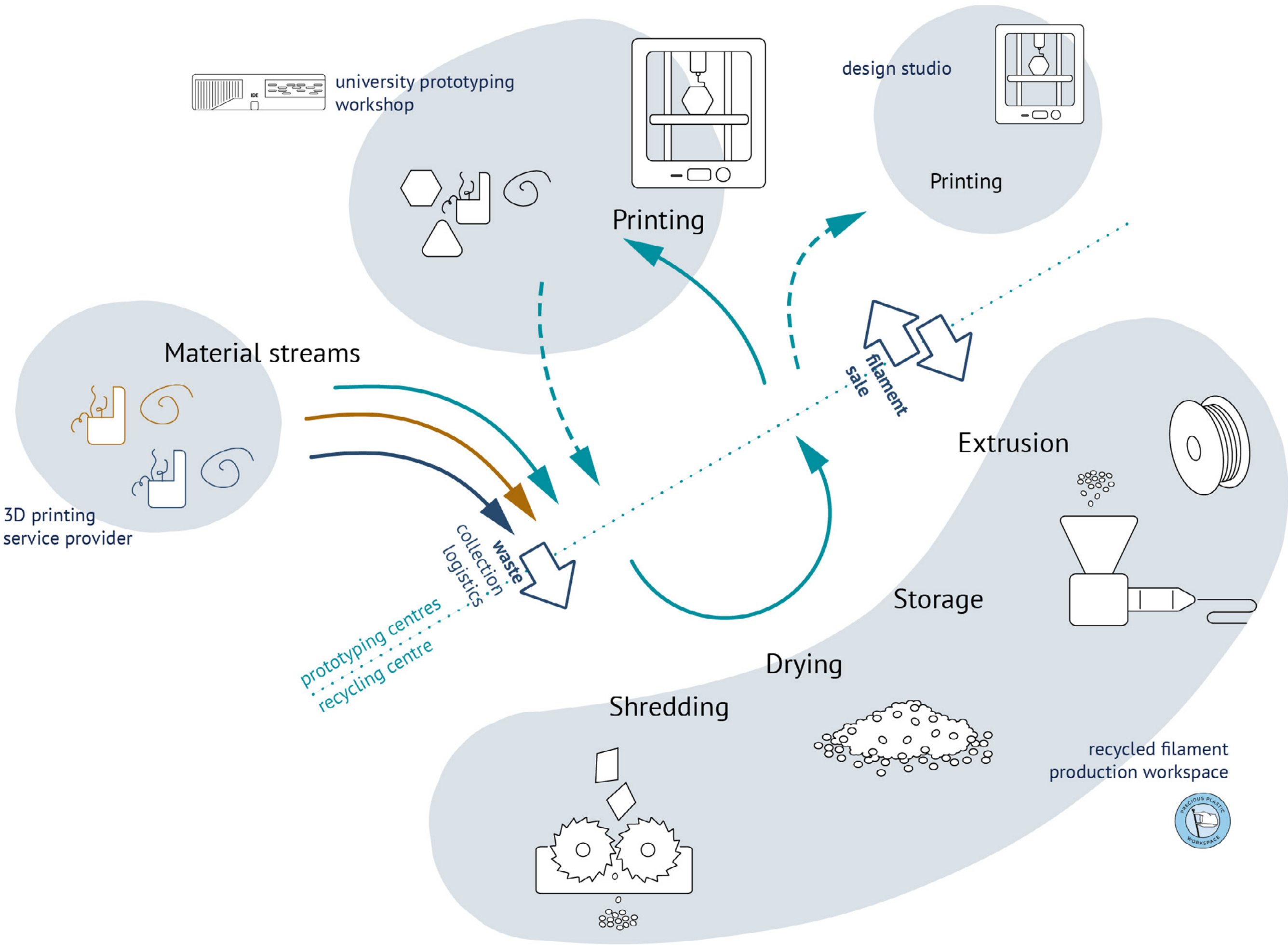
- A maximum of 50% of material can be reused
- More loops rise the complexity of printing setup

User desirability

+ Larger spools can simplify the printing setup
- More day-to-day maintenance on the printing setup
- 2 parallel printing setups: more effort from the workers & extra decision for printer users

Material costs reduction

+ Reduction (up to 50%) on the amount of virgin material needed



SCENARIO C. Local recycled filament production workspace

Scenario C	- -	-	+	+ +
System simplicity	■	■		
Material quality		■		
Sustainability impact			■	■
Material reused			■	■
User desirability			■	
Material costs reduction		■		

System simplicity

+ No in-house (human) resources from the prototyping centre are needed for the recycling process
- The viability of the local recycling centre depends on the revenue from low-quality recycled filament sales. Low-quality recycled filament demand is needed.
- Short term feasibility: recycling centres are not widely available yet
- Different material origins might need constant production parameters adjustment

Material quality

- No full control of the material stream by the same party. Contamination is possible.
- Potential differences between batches and printing profiles for each one due to different material origins

Sustainability impact

+ Recycling setup can be used for other waste (p.e. PET bottles) and on a semi-industrial scale
+ Reuse of material streams from prototyping centres, including the ones where loops are not possible

Material reused

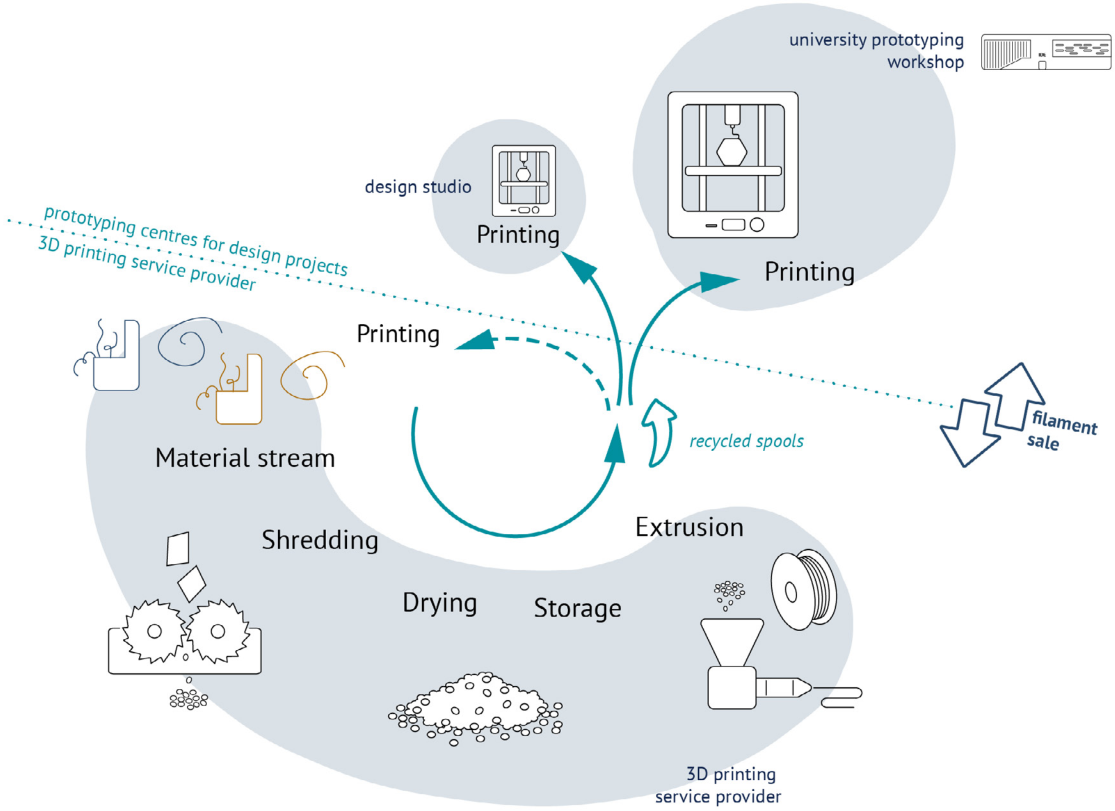
+ Reuse of material from multiple sources
+ All material can be reused at the prototyping centre
+ Extra material loops are possible without increasing the complexity of the printing setup

User desirability

+ Larger spools can simplify the printing setup
+ In some cases, recycled material could completely substitute the material used for low-quality printing, eliminating the need of an extra parallel printing setup
- More day-to-day maintenance on the printing setup
- Customer acceptance of low-quality filament could be a barrier

Material costs reduction

- Material costs dependant on the recycled low-quality filament price



SCENARIO D. Single loop recycling at a 3D printing service provider

Scenario C	- -	-	+	+ +
System simplicity		■		
Material quality			■	
Sustainability impact		■		
Material reused			■	
User desirability	■	■		
Material costs reduction		■		

System simplicity

+ Waste source and recycling process controlled by the same party
- The viability depends on the revenue from low-quality recycled filament sales. Low-quality recycled filament demand is needed
- In-house (human) resources needed for the recycling process

Material quality

+ Full control of the material stream from waste to recycling process
- Potential differences between batches and printing profiles for each one due to different materials used at the service provider

Sustainability impact

- Not possible to use the recycling setup with other waste streams

Material reused

+ All material can be reused at the prototyping centre
- Extra material loops are difficult to achieve

User desirability

- More day-to-day maintenance on the printing setup
- Customer acceptance of low-quality filament could be a barrier
- The only incentive to set up the recycling system is the filament sale

Material costs reduction

- Material costs dependant on the recycled low-quality filament price

4.2.3 SELECTED SCENARIO

The scenario C, a material reuse system between high and low fidelity prototyping centres on a local scale is defined as the vision, which also allows for more material loops and can be applied for other FDM materials. This scenario has a high sustainability impact as it can be extended to multiple prototyping centres. It also allows for a higher quantity of material being reused and enables the reuse of different material streams and for multiple cycles, if possible.

However, the selected scenario englobes a complex system that requires the trust and involvement of multiple stakeholders. Not all these parties are willing to invest resources into working towards the stated vision. They might be reluctant and uncertain of the feasibility of some particular aspects of the system.

Therefore, to implement the vision, further development is needed. In particular, being able to demonstrate its full feasibility in practice is key to convince stakeholders and potential parties and strive towards the vision. Thus, the ability to create a minimum viable system becomes key. A first version of the system, easier to implement and where learnings and constant iterations are possible, is seen as the first step towards implementing the full vision.

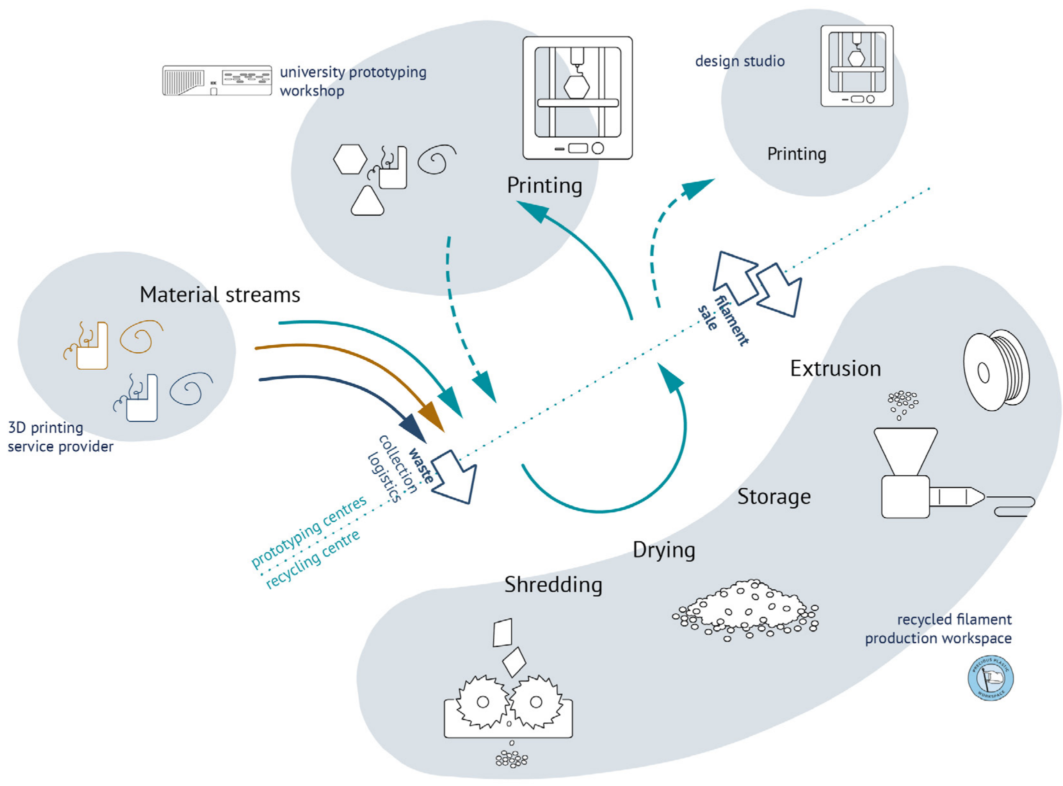


Figure 43 Scenario C Local recycled filament production workspace

4.3 ROADMAP

To define the steps needed to implement the vision, a roadmap has been created, as shown in Figure 44. A first version of the system, easier to implement and where learnings and constant iterations are possible, is seen as the first necessary step towards implementing the ideal scenario. Additionally, an in-between step has been created and the main objectives of all three steps have been defined.

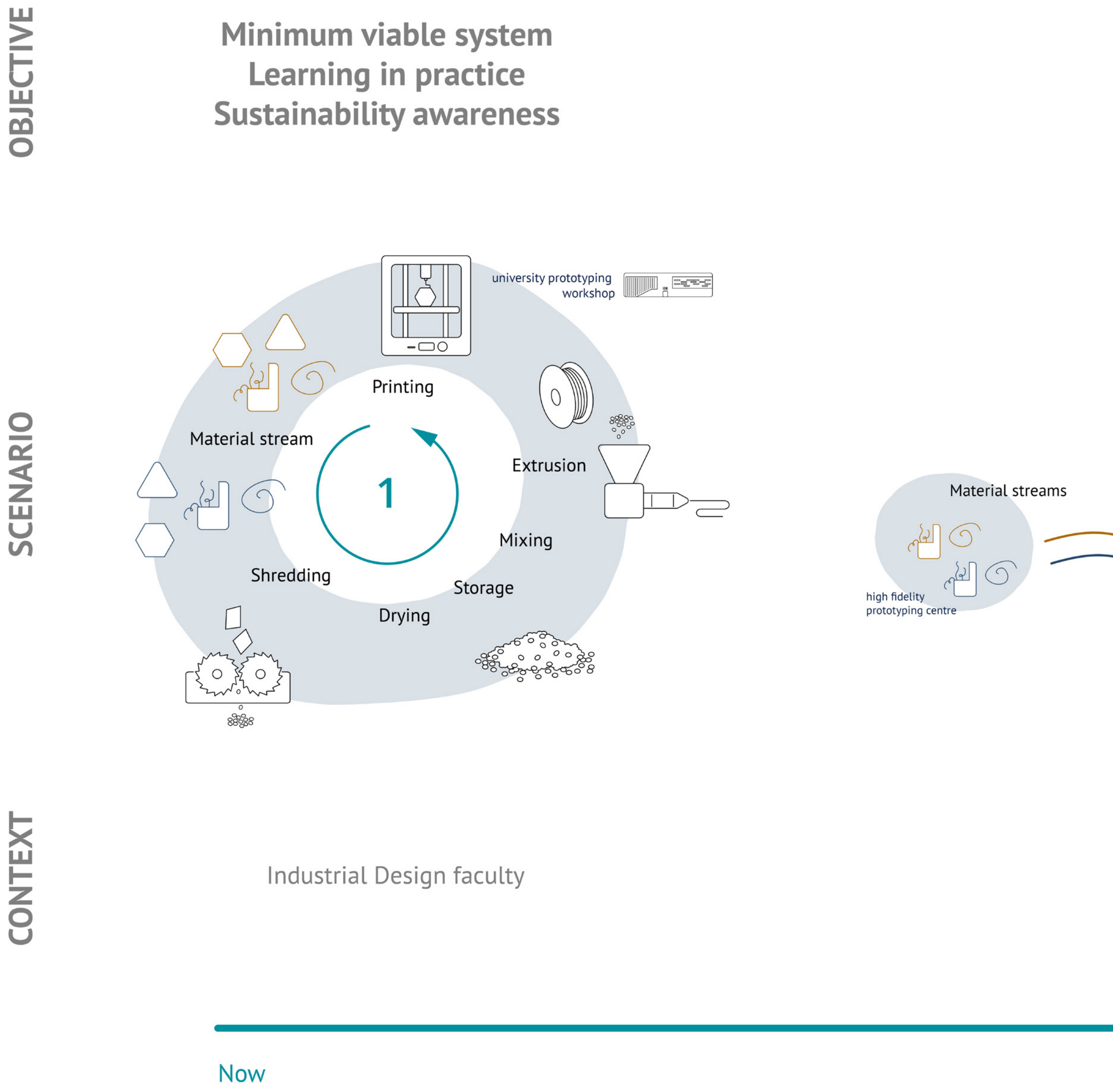
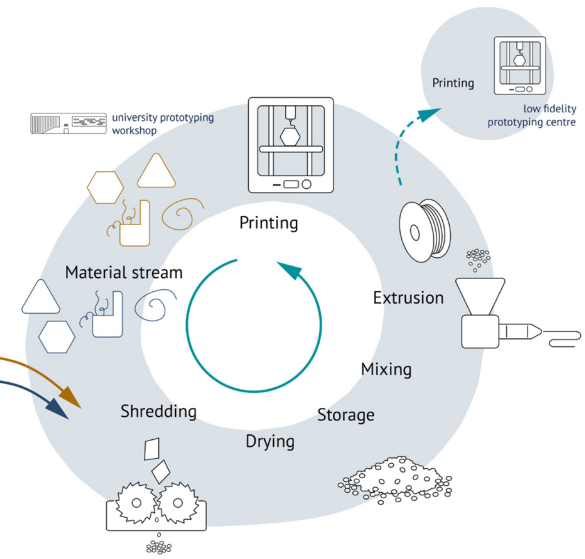


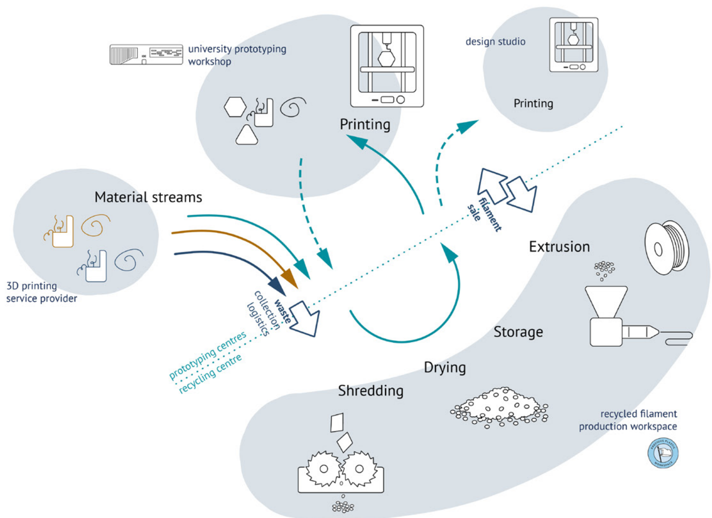
Figure 44 Roadmap towards the future vision.

External parties involvement
Learning in practice
Sustainability awareness



University campus and nearby prototyping centres

Customer acceptance
Replicability and scale up
Sustainability in practice



Distributed recycling centres (DRAM) and makerspaces

Future vision

4.4 SHORT-TERM SOLUTION

4.4.1 Workflow visualization

In order to further detail the first step of the roadmap, a new visualization of scenario A is created and presented in Figure 45. This visualization is a detailed overview of each step of the setup, workflows, machinery and roles of both the user of the 3D printing facility and the workshop staff. By visualizing the scenario in a more detailed level, new insights or concerns regarding its feasibility and implementation might become apparent.

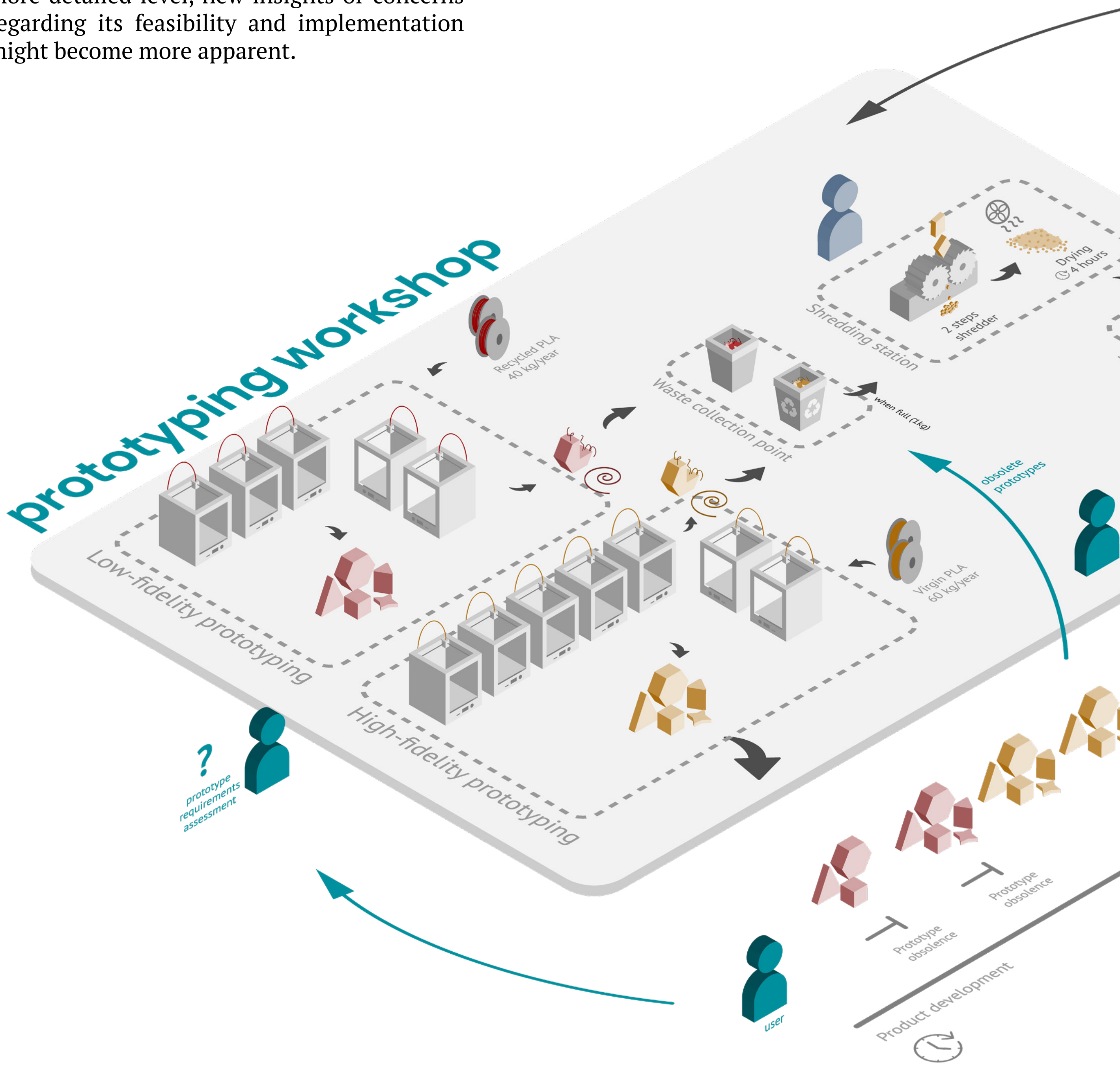
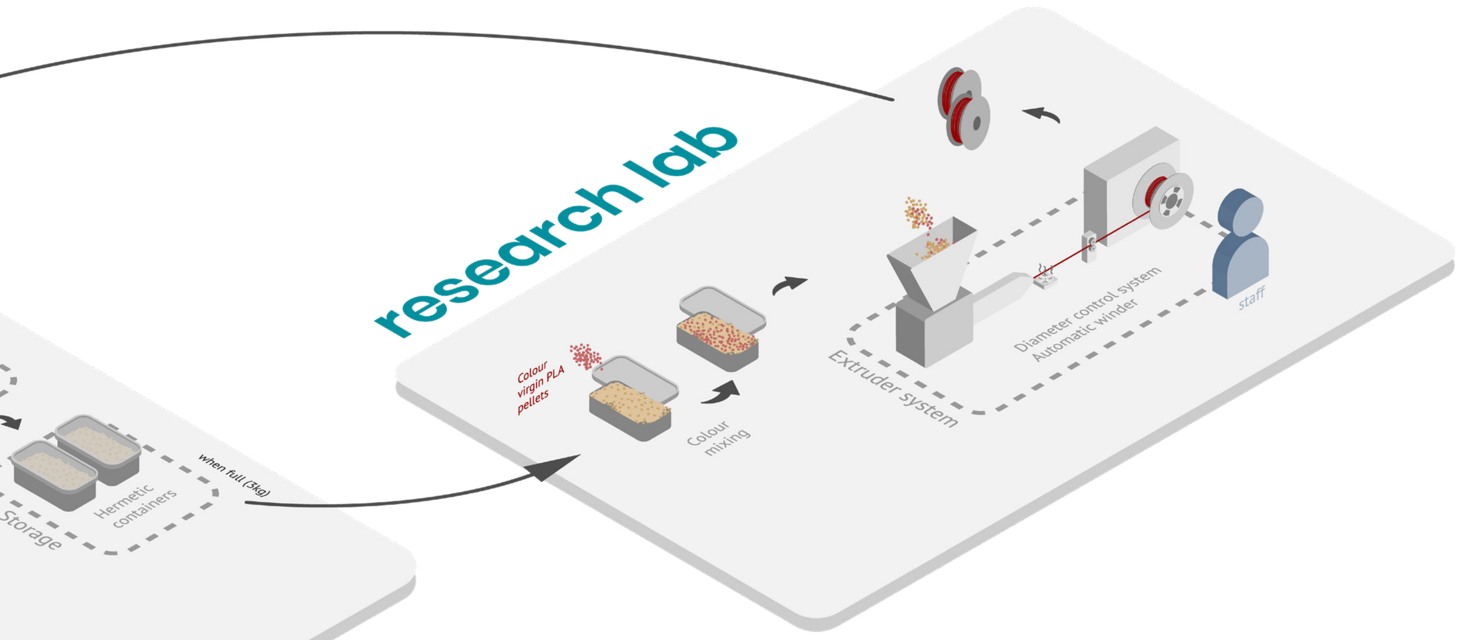
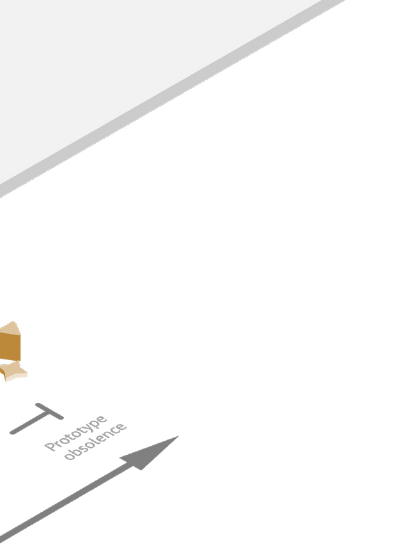


Figure 45 Short-term solution workflow visualization.





THE KEY ELEMENTS

- **Control of 2 material streams**

There should be 2 different printing setups at the prototyping facility: a low-fidelity setup that uses the recycled material and a high-fidelity setup that uses virgin material. The material should be kept separated at all times, including the waste collection point, with 2 different bins. That is why it is suggested to add colour to the recycled material, facilitating the identification of the material.

- **High-fidelity prototyping should always print more than low-fidelity**

This ensures that there is enough waste material to cover the low-fidelity setup.

4.4.2 Printing guidelines

To summarize the key findings from the research and the printing recommendations when using low-quality recycled PLA filament, a printing guide is created.

The guide includes a summary of the prototype capabilities printed with recycled PLA, the recommended printing settings and printer to use and the necessary steps and recommendations when preparing the printing file.

It is addressed to both end-users and prototyping facilities as a quick reference when using recycled PLA.

- **Mechanical Strength**

  The higher probability of under-extrusion might originate lower layer adhesion locally. This lower layer adhesion can affect the overall mechanical strength of prototypes. Therefore, lower mechanical strength is expected.

- **Brittleness**

  Prints of recycled PLA are more brittle than their virgin counterparts. Special attention is needed for those elements where plasticity is desired.

- **Surface quality**

  Similarly to the mechanical strength, the higher probability of under-extrusion can cause an uneven surface, with an overall low surface quality of the printed model.

- **Printing time**

  Due to a higher probability of nozzle clogging when printing recycled PLA, prints might fail more frequently. Avoiding large parts with long printing sessions can reduce the number of parts that have to be printed again if issues appear before printing is finished.

- **Preparing the printing file**

  When printing with recycled PLA, an additional step is needed to assess if the requirements of all parts are fulfilled according to the prototype capabilities of recycled PLA. If it is not the case, the elements with higher requirements must be printed with virgin material, since lowering the layer height will not result in better prototype capabilities.

  In addition, when more than one model has to be printed, it is recommended to split the printing file in multiple printing sessions to reduce the printing time, for the reasons mentioned above.

- **Printing settings**

  When printing with recycled PLA, a higher temperature and flowrate is recommended to reduce the under-extrusion issues.

  Since the benefits of using a low layer height, namely better surface quality and higher strength, would be hindered by the issues mentioned above, there is no reason to print with a lower layer height.

  Large printing nozzles are recommended to reduce nozzle clogging. A dynamic and adjustable geared feeder can reduce the filament grinding and work better with filaments with irregular thickness.

PRINTING GUIDELINES for **RECYCLED PLA**

PROTOTYPE CAPABILITIES

Mechanical properties

Strenght

How much stress can the prototype withstand under a pulling or flexing force.

Brittleness

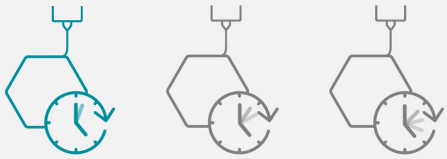
How easy an element breaks under tension, without deformation.

Surface quality

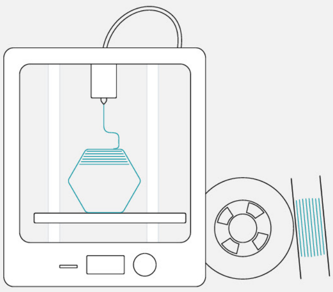
How smooth the surface of the protoype will be.

Printing time

How long a single print should take.



PRINTING SETTINGS



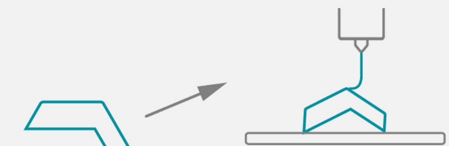
Layer height	>>	0.16mm or higher
Printing temperature	>>	220 °C- 230 °C
Flowrate	>>	100% - 120% *
Nozzle size	>>	0.4mm or larger
Filament feeder	>>	dynamic & adjustable geared feeder

*depending on the specific filament underdimension of each recycling setup

PREPARING THE PRINTING FILE

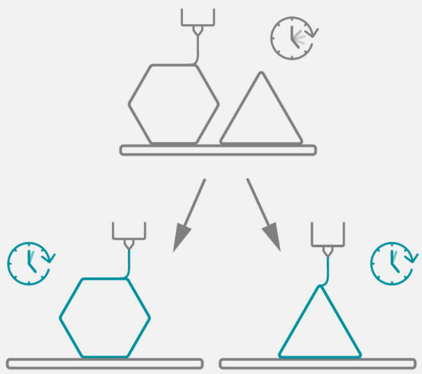
Part assessment

For **multiple-part prototypes**, assess the requirements of each part individually. If a part does not match the recycled PLA capabilities, print it separately with virgin material.



Multibody printing

Avoid long printing sessions by printing the models individually instead of all in one-go.



4.5 VALIDATION

4.5.1 Design case study

The computer mouse design case presented in the theoretical research chapter has been designated as a validation case of the proposed solution of using recycled PLA for low-fidelity prototyping.

This specific case shows how the design process has to be adapted when prototyping using the recycled filament setup described in the short-term solution section (page 98), compared to the usual process of 3D printing in product development using virgin material. In this way, the differences in the design process are highlighted and the capabilities and potential of recycling 3D prints are shown in an applied manner.

The process of prototyping with recycled PLA is described and showcased according to each phase of the product development.

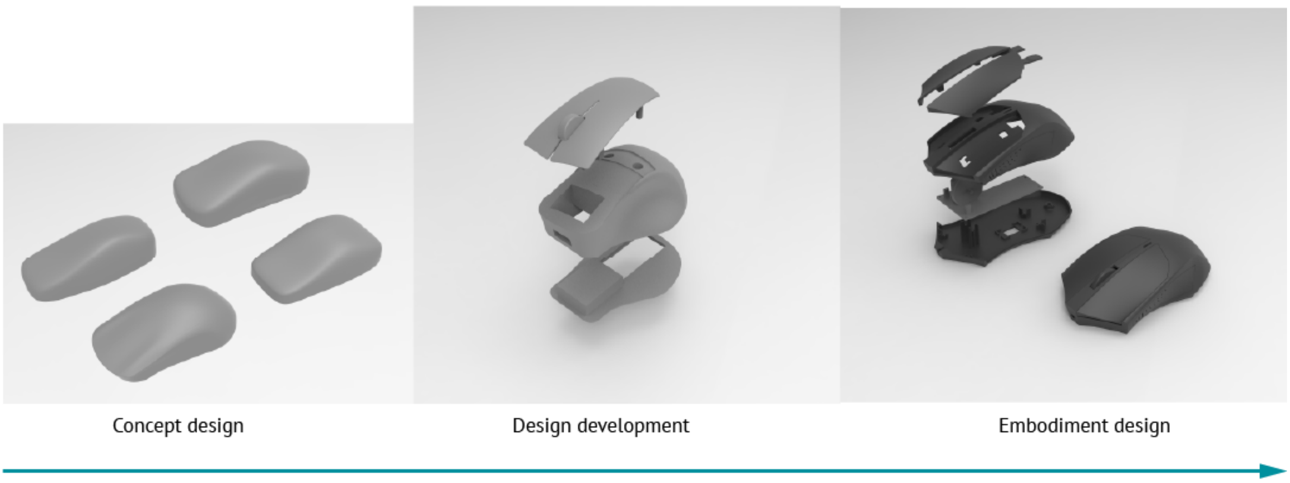


Figure 46 Overview of the prototypes in the computer mouse design case.

- **Concept design phase**

As described previously, these prototypes do not have any special requirement. Therefore, they are printed with recycled material.

As it is not recommended to print in long sessions, the 4 prototypes generated for this mouse design project have been printed individually instead of all models together, as seen in Figure 48. In this way, if any issues would have appeared, only one prototype would have had to be re-printed.

As shown in Figure 49, the surface quality is not perfect, but the prototype served its purpose «check the scale and shape in hand», as seen in Figure 50.

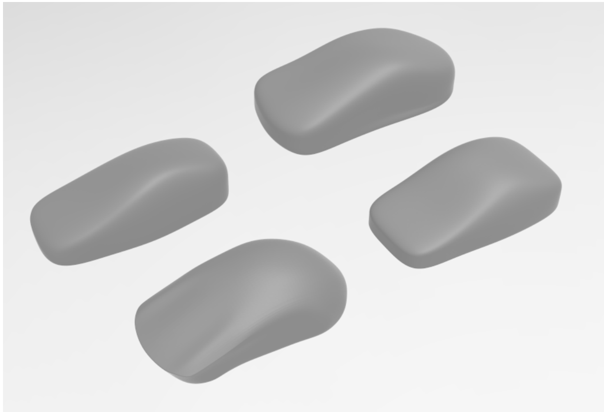


Figure 47 Concept design models of the computer mouse.

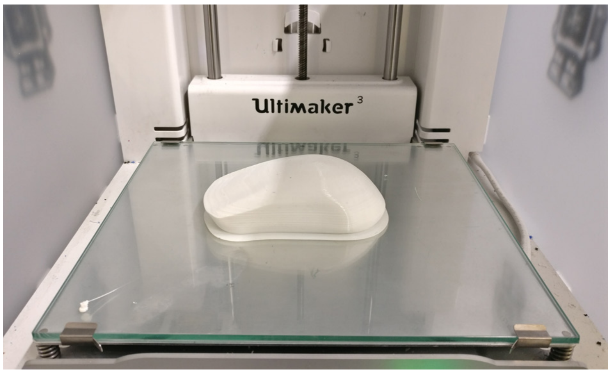


Figure 48 One of the concept prototypes printed individually.

Figure 49 Surface detail of one of the prototypes.

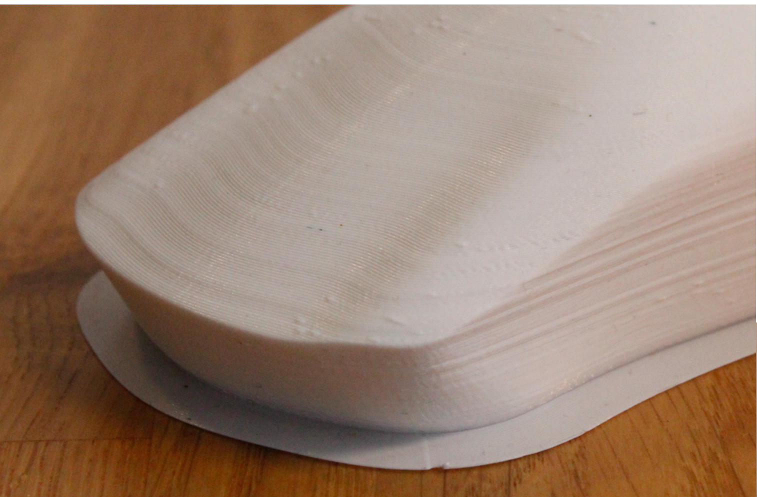


Figure 50 One of the concept prototypes being tested.

- **Design development phase**

As seen in Figure 51, an extra step is needed before printing when using recycled material for prototyping in this phase. Some parts might need specific requirements, not present in the concept design phase. When printing multiple parts of the same prototype, one has to assess and identify the parts that need extra mechanical properties, like the buttons in this specific prototype.

Then, instead of printing all the parts together in the same printer, two printing files are generated: one for the parts that have some special requirement and another one with the rest of the parts.

In the mouse project case, the buttons need some flexibility to correctly assess the prototype. Therefore, as seen in Figure 52, the parts are divided into two printing files. The button is printed with virgin PLA and the body and base with recycled PLA. Afterwards, they are assembled and tested as usual.

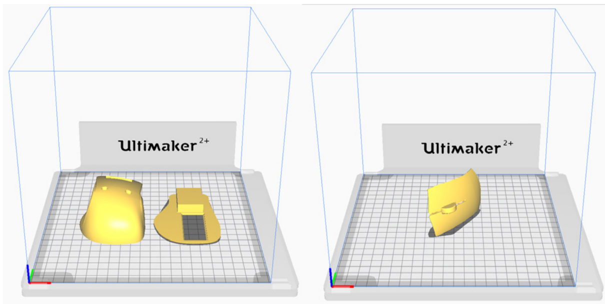


Figure 52 Prototype parts dived in two printing files, according to their individual requirements.

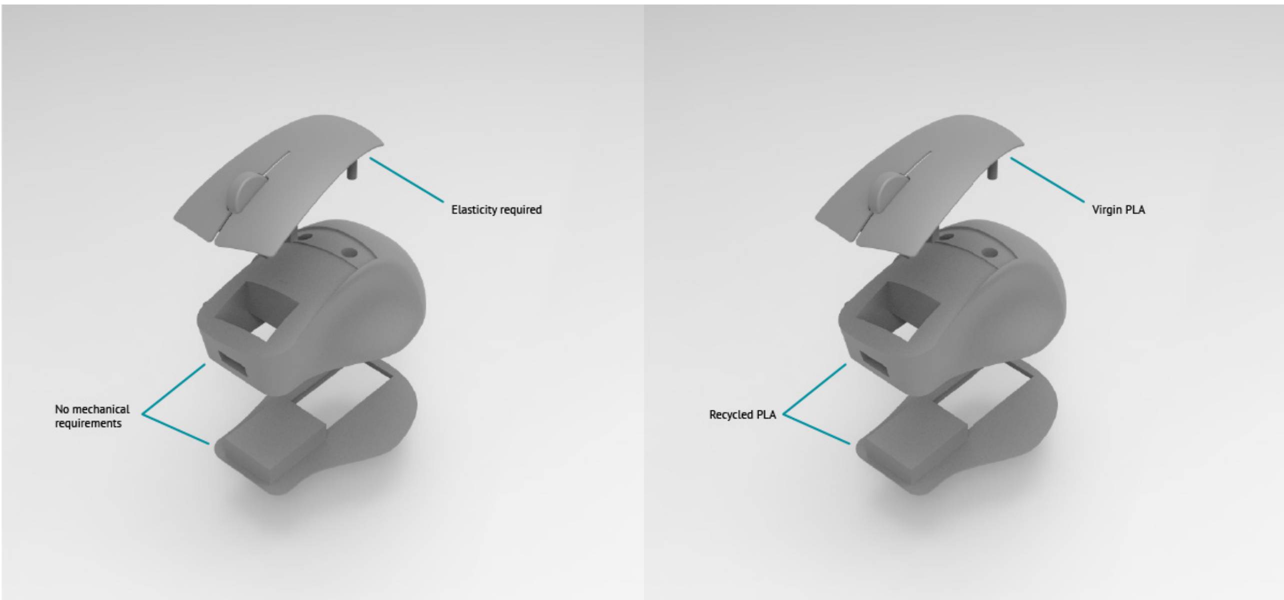


Figure 51 Part assessment step prior to 3D printing the prototype.

Figure 53 The parts of the mouse prototype.

Figure 54 Assembled prototype being tested.

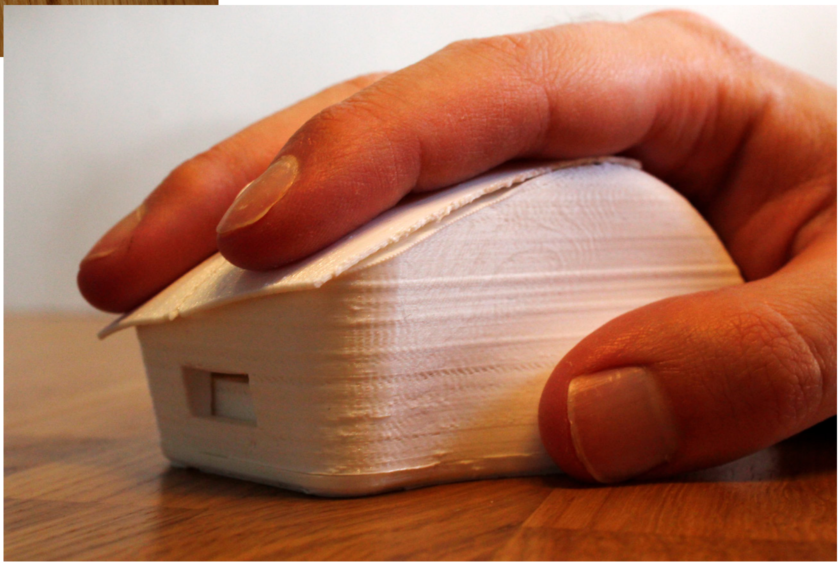
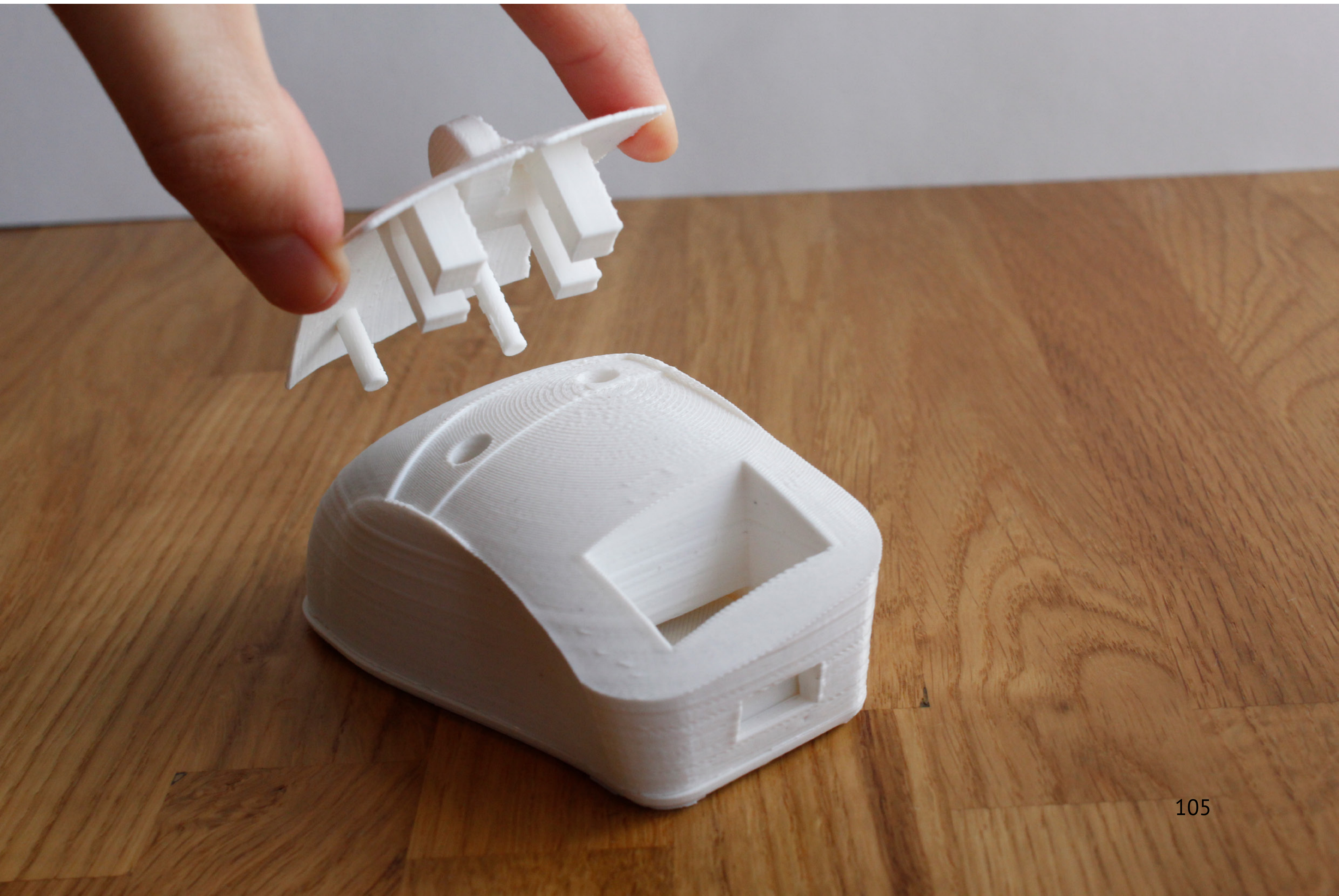


Figure 55 Buttons part being assembled together with the rest of the mouse prototype.



- **Embodiment design phase**

In the embodiment design phase, most of the prototype requirements, such as higher mechanical strength and good surface quality, can not be achieved with recycled PLA. Therefore, this prototype is not printed using recycled PLA.

Figure 56 Embodiment prototype of the computer mouse.

4.5.2 Prototyping facility: interest and concerns

The interest and concerns of the prototyping centre and their staff have an important role in fulfilling and implementing the short-term scenario described in section 4.4. Before being able to implement the recycled printing material set up, a pilot test might be needed for further testing.

That is why the results of this research project have been presented to the coordinator of the prototyping workshop of the IDE faculty of TU Delft and their thoughts and concerns have been gathered.

- **Lack of interest and no short-term benefits**

The current printing setup has been optimized to print fast and without issues, the students print on their own, reducing the staff time and effort to make it work. Using low-quality filament would go against this.

The potential savings in material might not be enough for the potential extra labour needed, making it not economically attractive. For example, the time needed to unclog a nozzle might already overcome any material cost savings when using recycled material.

- **Pilot feasibility**

Setting up a collection point for the waste is possible, where students could bring their obsolete prints too.

However, the staff does not have time for processing the waste and producing the filament.

Setting a printer to be used as a pilot test is possible, as long as the maintenance and tune-up of the machine are done by someone else.

5 PROJECT REFLECTION

This chapter evaluates the project results, outlines the recommendations and finishes with a personal reflection.

5.1 EVALUATION

The goal of this project was to investigate ways in which reuse of 3D printed material used for prototyping could be enabled, how this might depend on the design approach during prototyping and to set up guidelines and demonstrate its feasibility in a prototyping facility context, as framed in the project briefing in the introduction chapter. After the project completion, the outcomes are summarized and discussed.

First, the theoretical research phase provided insights on FDM for prototyping in product design development, on the most commonly used material and its current end-of-life solutions, on the current state of the art of production of recycled material for FDM and its challenges and available solutions; it provided relevant industry insights across the material journey of PLA filament and other FDM materials and presented the end-user priorities for FDM prototyping in product development projects.

An opportunity for recycled PLA in low-fidelity prototyping was identified and explored in the practical research phase. Through testing of production of filament and its printability, the feasibility of printing with recycled PLA filament fabricated from obsolete 3D prints and 3D printing waste was investigated. The key aspects and challenges were identified for both processes and its technical feasibility for low-fidelity prototyping was concluded to be possible. Prototypes printed with recycled PLA achieved similar prototype capabilities as their virgin counterparts.

In the solution development phase, the findings gathered in both research phases were converged into a future vision, a roadmap and a short-term solution. The scenarios suggested, in a prototyping facility context, the implementation of recycling of 3D prints back to FDM material. A workflow visualization detailed the short-term solution and highlighted the key elements for the implementation and a printing guide summarized the adjustments and recommended settings for future end-users.

Finally, a design case study demonstrated the feasibility of using recycled PLA in a design project and exemplified the 3D printing guidelines created. Furthermore, it showed how using recycled low-quality material affects the design and prototyping process.

The outcome of the project has been shared with a prototyping facility and the short-term solution evaluated. Its implementation still presents several concerns. For instance, the lack of short-term benefits for the prototyping facility in the initial phases of the solution is a major barrier that still needs to be resolved moving forward. Therefore, a list of recommendations is detailed in the next section.

Overall the project fulfilled its initial goals. It demonstrated the feasibility of reusing 3D printing material under low-fidelity prototyping conditions. Moreover, it defined and exemplified the effect that reusing the material has on the design and prototyping process.

Finally, it can be concluded that reusing 3D printing material for low-fidelity prototyping can achieve a high material value preservation in current 3D printing systems. This might suggest that the solution presented in this project might be the foremost solution for implementing material value preservation in 3D printing. However, further research is needed to assess its long term implications, such as the total number of cycles that the material can withstand, the rate of printing failure or the economic feasibility of the process to help bridging the gap between its technical feasibility and its real-life long-term implementation.

5.2 RECOMMENDATIONS

Regarding the experimentations conducted during this project, an additional test is needed. A mechanical properties test of re-extruded virgin PLA, to fully assess the impact of the extrusion system compared to the material degradation effect on the mechanical strength of low-fidelity prototypes.

Similarly, using a better extruder setup for testing the extrusion of recycled and re-extruded filament will allow to better evaluate the importance and impact of the extruder system. The biggest impact on the printability of the recycled material in the results of this project has been the low quality of the filament. An extruder setup with some diameter control system and a better feeder system might improve significantly the printability of recycled material.

One issue was identified when printing both recycled filament and re-extruded filament: filament grinding caused by the geared feeder of the FDM printer. Further research into whether this is caused by the deviation of diameter or by a reduction of the hardness of the filament is recommended as it might be relevant not only for PLA but other low-scale produced recycled filaments.

In order to bridge the gap between research and implementation, knowing the rate of printing failure when using recycled material compared to virgin material would help to better evaluate the economic feasibility. Likewise, more printability tests can be done varying the printer nozzle to reduce potential printing issues caused by impurities.

Further research in the printability of recycled material after a second (or more) recycling loops might be interesting from a material depletion perspective, but a new system to control the material stream should then be drafted, as the material cannot be indefinitely recycled. Additionally, exploring the recycled material behaviour when mixed with different rates of virgin material should only be done if a better extrusion is achieved and the relative impact of the recycling process is lower, making the impact of the material depletion more relevant.

Recommendation for implementation at the IDE faculty

Before trying to implement the short-term solution at the prototyping facility at the IDE faculty, further research is needed. A pilot to gather more insights on the long-term and day-to-day use of the system can be a starting point. Additionally, it could help to demonstrate its feasibility and to convince the prototyping facility staff.

Due to the lack of benefits and incentives for the prototyping facility and their staff at the initial stages of the implementation, the pilot project might have to be driven by a research project, without the day-to-day involvement of the prototyping facility staff. Likewise, the labour needed for the production of recycled filament might need to come from other sources rather than from the prototyping workshop, such as a student assistant from a research department or from student initiatives like GreenTU.

Nevertheless, before introducing a pilot at the prototyping facility, the filament production setup should be improved. The current setup requires too much labour to scale the production towards a pilot and the simplicity of the machine difficults a constant extrusion. The setup could be improved by acquiring a more complete solution, such as the 3devo extruder or the Filabot extrusion setup. Otherwise, a series of improvements on the current setup are suggested:

- Automatic winder. Modifying the winder so it can automatically adapt to the extrusion rate.
- Filament puller with diameter control. Developing a diameter sensing control system that pulls the filament to achieve the desired diameter.
- Bigger extruder nozzle. Using a bigger extruder nozzle would enable the use of a puller to achieve better consistency and it would reduce the under-dimensioning of the filament.
- Melt filter. Adding a melt filter in the extruder could prevent impurities larger than the printer nozzle to end up in the filament, avoiding clogging of the printer's nozzle.
- Improved hopper. Adapting the hopper to a higher capacity and adding a constant stirring element to reduce bridging can increase the autonomy of the extrusion process and create a more constant filament diameter.

Finally, setting a pilot or initial setup to recycle the material back to filament at the faculty could have a beneficial impact for the students' perception and awareness regarding sustainability and circular solutions, potentially overcoming the extra resources and research needed to implement it.

Even if the faculty decides not to continue this project, exploring other solutions for the end-of-life of 3D printed prototypes should not be discarded. Fused granular fabrication could be an alternative if advances in the current available solutions are done. In addition, downcycling alternatives such as producing PLA sheets from shredded prints for laser-cutting can still be worth exploring.

5.3 PERSONAL REFLECTION

The biggest limitation of the project has been the restrictions due to the Covid-19 pandemic. Although I was still able to do the tests and experimentations at the faculty, the informality and casual discussions about the day-to-day work that used to happen at the faculty were very limited or non-existence. The frequent coffee-talks used to be a common source of new insights, inspiration and motivation between students, which now, after completing this project, I realize how important and helpful they sometimes were. Moreover, there was less room for improvisation and experimentations, since all the visits to the faculty had to be justified and the tests planned in advance. In addition, although I am very thankful to my supervisors for making the effort of making the meetings less formal, I feel like the contact with the supervisors was colder than usual due to not being able to meet in person.

Looking back on this project, I appreciate the learning journey I have been through, especially regarding my ability to manage and run a project on my own. Most of the projects I have been involved in the past were strongly team-oriented. Hence, this project has given me the perfect opportunity and, with the coaching of the supervisors, I have become better at planning and self-managing.

This project has also helped me in better balancing the bigger picture with the detailed views. I sometimes get myself lost too much into small details and technicalities of the projects, losing a bit the overall picture and main focus. Even though this slightly happened during the initial research phase of this project, I feel I have managed to keep a broader perspective throughout the project and overall became a better industrial design engineer.

6 REFERENCES

3D Hubs. (n.d.-a). Design rules for 3D printing. https://www.3dhubs.com/knowledge-base/key-design-considerations-3d-printing/

3D Hubs. (n.d.-b). FDM 3D printing materials compared. Retrieved 18 September 2020, from https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared/

Alexandre, A., Cruz Sanchez, F. A., Boudaoud, H., Camargo, M., & Pearce, J. M. (2020). Mechanical Properties of Direct Waste Printing of Polylactic Acid with Universal Pellets Extruder: Comparison to Fused Filament Fabrication on Open-Source Desktop Three-Dimensional Printers. 3D Printing and Additive Manufacturing. https://doi.org/10.1089/3dp.2019.0195

All3DP. (2020). 2020 PLA Filament Buyer's Guide. https://all3dp.com/1/pla-filament-3d-printing/

Alvin, T. (2020). Royal (IKEA) Mouse (3D printed shell for g304/305) by Cryo_Frost. Thingiverse. Retrieved December 2020, from https://www.thingiverse.com/thing:4266102

Anderson, I. (2017). Mechanical Properties of Specimens 3D Printed with Virgin and Recycled Polylactic Acid. 3D Printing and Additive Manufacturing, 4(2), 110–115. https://doi.org/10.1089/3dp.2016.0054

Beltrán, F. R., Infante, C., de la Orden, M. U., & Martínez Urreaga, J. (2019). Mechanical recycling of poly(lactic acid): Evaluation of a chain extender and a peroxide as additives for upgrading the recycled plastic. Journal of Cleaner Production, 219, 46–56. https://doi.org/10.1016/j.jclepro.2019.01.206

Beltrán, F. R., Lorenzo, V., Acosta, J., de la Orden, M. U., & Martínez Urreaga, J. (2018). Effect of simulated mechanical recycling processes on the structure and properties of poly(lactic acid). Journal of Environmental Management, 216, 25–31. https://doi.org/10.1016/j.jenvman.2017.05.020

BASF 3D. (n.d.). Standard filaments - technical data. Ultrafuse FFF. Retrieved 18 September 2020, from https://www.ultrafusefff.com/material-data/standard-filaments/

Castro-Aguirre, E., Iñiguez-Franco, F., Samsudin, H., Fang, X., & Auras, R. (2016). Poly(lactic acid)—Mass production, processing, industrial applications, and end of life. Advanced Drug Delivery Reviews, 107, 333–366. https://doi.org/10.1016/j.addr.2016.03.010

Cosate de Andrade, M. F., Souza, P. M. S., Cavalett, O., & Morales, A. R. (2016). Life Cycle Assessment of Poly(Lactic Acid) (PLA): Comparison Between Chemical Recycling, Mechanical Recycling and Composting. Journal of Polymers and the Environment, 24(4), 372–384. https://doi.org/10.1007/s10924-016-0787-2

Cruz Sanchez, F. A., Boudaoud, H., Camargo, M., & Pearce, J. M. (2020). Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. Journal of Cleaner Production, 264, 121602. https://doi.org/10.1016/j.jclepro.2020.121602

Cruz Sanchez, F. A., Boudaoud, H., Hoppe, S., & Camargo, M. (2017). Polymer recycling in an open-source additive manufacturing context: Mechanical issues. Additive Manufacturing, 17, 87–105. https://doi.org/10.1016/j.addma.2017.05.013

den Hollander, M. C., Bakker, C. A., & Hultink, E. J. (2017). Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. Journal of Industrial Ecology, 21(3), 517–525. https://doi.org/10.1111/jiec.12610

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. Technological Forecasting and Social Change, 115, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Ellen MacArthur Foundation. (2013). Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

Ellen MacArthur Foundation. (2019). Circular Economy System Diagram. https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic

Ellen MacArthur Foundation & IDEO. (2018). The Circular Design Guide. The Circular Design Guide. https://www.circulardesignguide.com/

European Commission. (2015). Closing the Loop – An EU Action Plan for the Circular Economy. Brussels, 2.12.2015 COM(2015) 614 final.

Evans, M. A., & Pei, E. (2010). ID Cards. Loughborough University.

Haider, T. P., Völker, C., Kramm, J., Landfester, K., & Wurm, F. R. (2018). Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society. Angewandte Chemie International Edition, 58(1), 50–62. https://doi.org/10.1002/anie.201805766

Hallgrimsson, B. (2012). Prototyping and Modelmaking for Product Design. Laurence King Publishing.

Hong, M., & Chen, E. Y.-X. (2017). Chemically recyclable polymers: a circular economy approach to sustainability. Green Chemistry, 19(16), 3692–3706. https://doi.org/10.1039/c7gc01496a

Hunt, E. J., Zhang, C., Anzalone, N., & Pearce, J. M. (2015). Polymer recycling codes for distributed manufacturing with 3-D printers. Resources, Conservation and Recycling, 97, 24–30. https://doi.org/10.1016/j.resconrec.2015.02.004

International Organization for Standardization. (2015). ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology. ISO. https://www.iso.org/standard/69669.html

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kromhout, B. (2020). Transcended Manufacturing: The Mass-production of One-of-a-kind Products. Delft University of Technology.

Lanzotti, A., Martorelli, M., Maietta, S., Gerbino, S., Penta, F., & Gloria, A. (2019). A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. Procedia CIRP, 79, 143–146. https://doi.org/10.1016/j.procir.2019.02.030

Mahor XYZ. (n.d.). Pellet Extruder V4. https://www.mahor.xyz/

Meer 3D B.V. (n.d.). 3D printer kopen of leasen, of laten printen in 3d door onze 3d print service. Meer 3D. Retrieved 18 September 2020, from https://meer3d.nl/

Petrzak, A. (2019). The Best Flowrate Calibration Method! by petrzmax. Thingiverse. Retrieved October 2020, from https://www.thingiverse.com/thing:3397997

RepRap. (2019). Recyclebot - RepRap. https://reprap.org/wiki/Recyclebot

Román-Ramírez, L. A., McKeown, P., Shah, C., Abraham, J., Jones, M. D., & Wood, J. (2020). Chemical Degradation of End-of-Life Poly(lactic acid) into Methyl Lactate by a Zn(II) Complex. Industrial & Engineering Chemistry Research, 59(24), 11149–11156. https://doi.org/10.1021/acs.iecr.0c01122

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production, 226, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Sauerwein, M., Zlopasa, J., Doubrovski, Z., Bakker, C., & Balkenende, R. (2020). Reprintable Paste-Based Materials for Additive Manufacturing in a Circular Economy. Sustainability, 12(19), 8032. https://doi.org/10.3390/su12198032

Sculpteo. (2020). The State of 3D Printing Report: 2020. https://www.sculpteo.com/en/ebooks/state-of-3d-printing-report-2020/

Shekar, S. (2018). Functional Mouse- Red Dragon M601 by sumanthshekar. Thingiverse. Retrieved December 2020, from https://www.thingiverse.com/thing:3218917

Trpkoš, M. (2018). *MICRO* All In One 3D printer test by majda107. Thingiverse. Retrieved October 2020, from https://www.thingiverse.com/thing:2975429

Ultimaker. (n.d.). Materials. Retrieved 18 September 2020, from https://ultimaker.com/materials

Ultimaker. (2019). 3D Printing Sentiment Index 2019. https://3d.ultimaker.com/Ultimaker-3D-Printing-Sentiment-Index van den Oever, M., Molenveld, K., van der Zee, M., & Bos, H. (2017). Bio-based and biodegradable plastics : facts and figures : focus on food packaging in the Netherlands (No. 1722). Wageningen Food & Biobased Research. https://doi.org/10.18174/408350

Vranckx, M. (2017). Temp Tower PLA,ABS,PETG by stoempie. Thingiverse. Retrieved October 2020, from https://www.thingiverse.com/thing:2493504

Woern, A. L., McCaslin, J. R., Pringle, A. M., & Pearce, J. M. (2018). RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament. HardwareX, 4, e00026. https://doi.org/10.1016/j.ohx.2018.e00026

Zhao, P., Rao, C., Gu, F., Sharmin, N., & Fu, J. (2018). Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. Journal of Cleaner Production, 197, 1046–1055. https://doi.org/10.1016/j.jclepro.2018.06.275

Zhao, X. G., Hwang, K.-J., Lee, D., Kim, T., & Kim, N. (2018a). Enhanced mechanical properties of self-polymerized polydopamine-coated recycled PLA filament used in 3D printing. Applied Surface Science, 441, 381–387. https://doi.org/10.1016/j.apsusc.2018.01.257

7 APPENDIX

APPENDIX A Project Brief

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Aliana Guardia 4273

initials: M given name: Marc

student number:

street & no.:

zipcode & city:

country:

phone:

email:

Your master programme (only select the options that apply to you):

IDE master(s): ★ IPD ◯ DfI ◯ SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: ◯ Honours Programme Master

specialisation / annotation: ◯ Medisign

◯ Tech. in Sustainable Design

◯ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: A.R. Balkenende dept. / section: SDE, CPD

** mentor: A.L.M. Minnoye dept. / section: SDE, M&M

2nd mentor:

organisation:

city: country:

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

TUDelft

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair A.R. Balkenende date 13 - 07 - 2020 signature

CHECK STUDY PROGRESS
To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 32 EC
Of which, taking the conditional requirements into account, can be part of the exam programme 32 EC
List of electives obtained before the third semester without approval of the BoE

★ YES all 1st year master courses passed
NO missing 1st year master courses are:

name J. J. de Bruin, SPA-IO date 14 - 07 - 2020 signature J. J. de Bruin, SPA Digitally signed by J. J. de Bruin, SPA Date: 2020.07.14 10:08:41 +02'00'

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED NOT APPROVED
Procedure: ★ APPROVED NOT APPROVED

- adapted version approved

comments

name Monique von Morgen date 21 - 07 - 2020 signature

Initials & Name M Aliana Guardia 4273 Student number
Title of Project Recycling of 3D printing material used for prototyping

Recycling of 3D printing material used for prototyping — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 02 - 07 - 2020 — 17 - 12 - 2020 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

FDM or Fused Deposition Modeling is the most widely available additive manufacturing process, mainly used for low-cost prototyping and design verification. FDM printing is highly versatile for prototyping, but large amounts are wasted after testing and early prototyping. Therefore an interesting test case to explore the recyclability of 3D printing materials.

This project will be focused on the specific case of FDM for prototyping in the early stages of a design project, tackling the issue of material waste created during those stages. Early prototypes are usually part of a continuously developing process, where prototypes quickly become obsolete when improved versions are generated. In addition, these early prototypes can have different material properties requirements than prototypes in later stages of development.

This is why the research group Circular Product Design and the Center of Design for Agile Manufacturing want to look into the FDM printing process for design projects and explore the possibilities of recycling the base material.

As a test case, 3D printing facilities at the IDE faculty will provide a suitable case to explore solution directions. At the IDE faculty, the most commonly used prototyping method is the FDM printers from Ultimaker, operating using polylactic acid (PLA) filament and producing prototypes 24/7 for a large variety of projects.

The research group Circular Product Design focuses on enabling the design of products that are used more than once, exploring strategies such as product life-extension, reuse, remanufacturing and recycling.

The Center of Design for Advanced Manufacturing areas of expertise are both the product design and the design process enabled by the possibilities within advanced manufacturing, including digitalization, computational design, digital fabrication and human-robot co-production.

space available for images / figures on next page

introduction (continued): space for images

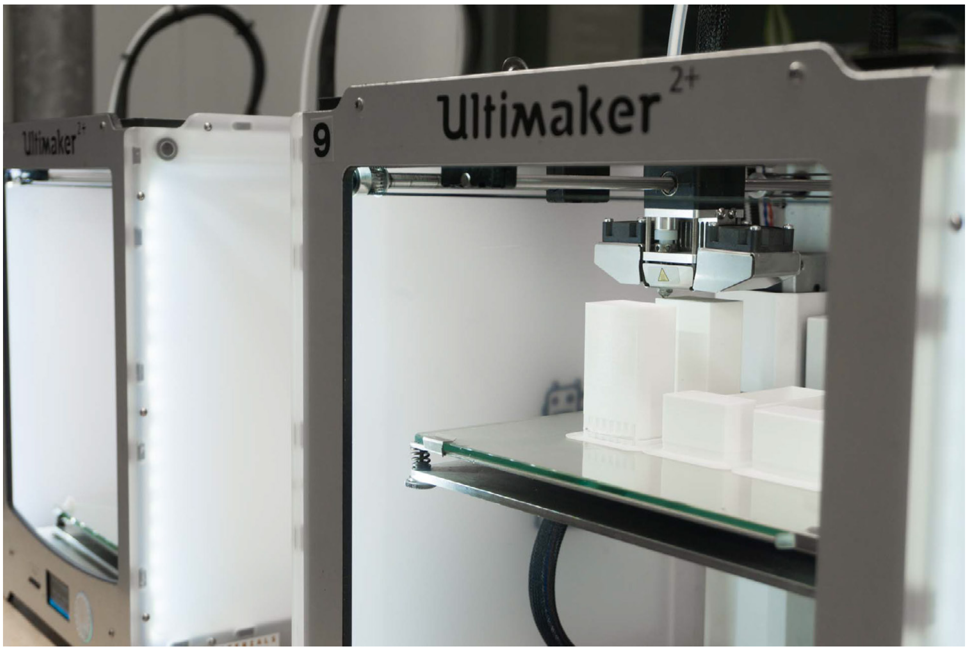


image / figure 1: A prototype being printed in a FDM desktop 3D printer at the IDE faculty.

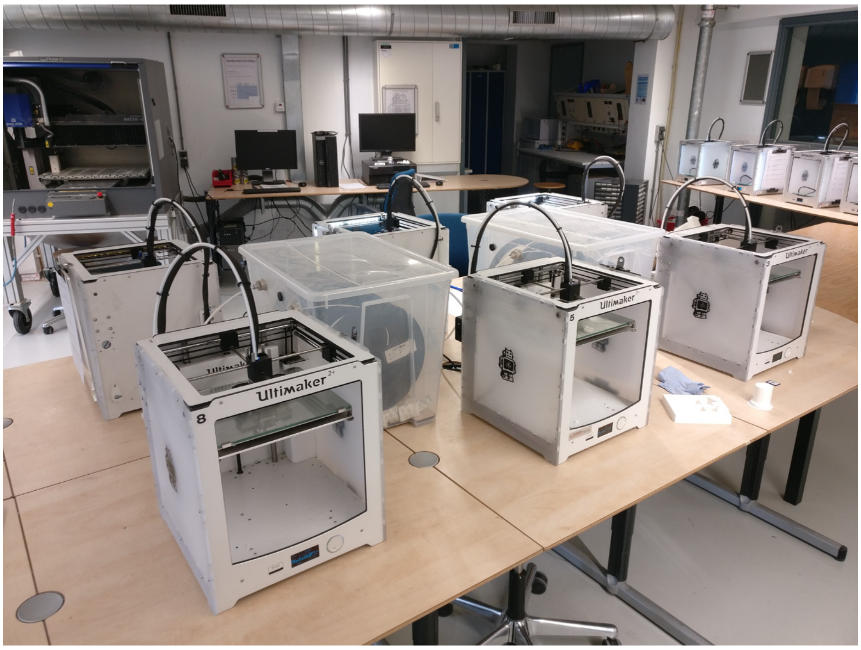


image / figure 2: Current 3D printing setup of the Model Making and Machine Lab (PMB) at the IDE faculty.

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Solutions need to be found to reduce the waste of 3D printing material in FDM. An opportunity arises to recycle the material and reuse it in the same 3D printing process.

However, most materials used for FDM deteriorate upon recycling. Recycled material filament may behave differently than virgin material, it will likely have different material and printing properties altering the outcome of the 3D printers. Moreover, it could affect their printability after one or more recycling loops.

To this day, how (prototype) design, material quality and printer settings affect the functionality of 3D printed products made from recycled material is largely unexplored.

In this project, these issues will be tackled with a special focus on the use case of FDM in design projects.

ASSIGNMENT **

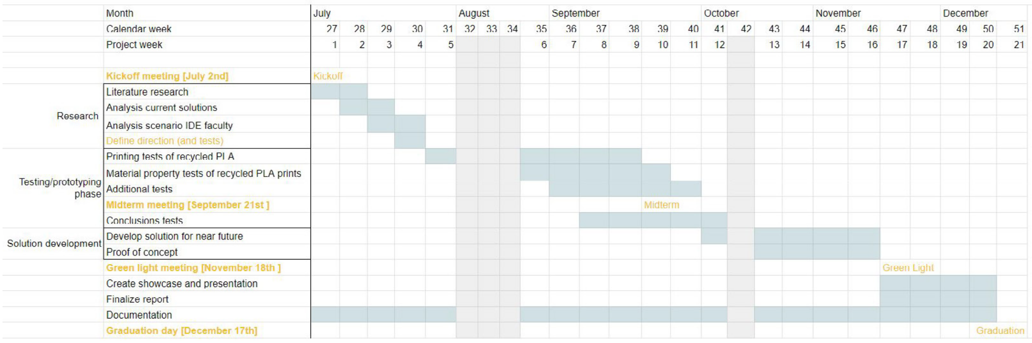
State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Investigate ways in which reuse of 3D printed material used for prototyping can be enabled and how this depends on the design approach during prototyping; set up guidelines and demonstrate the feasibility in the context of IDE prototyping.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 2 - 7 - 2020 | 17 - 12 - 2020 end date



Main activities to undertake:
- Analysis of current solutions/methods of PLA recycling for 3D printing
- Identify possible solutions for the specific scenario of usage of the IDE faculty
- Test material and printing properties of recycled material for 3D printed prototypes.
- Define the impact of one (or multiple) material cycles on 3D printed prototypes.
- Identify critical points/challenges within the recycling process.
- Propose an optimal solution for the near future for a specific usage case.
- Build a demonstrator or proof of concept of the proposed solution.

The project starts with a research phase to analyze current solutions and research that has already been done about the problem. The specific scenario of the faculty will also be analyzed, mapping out the most common uses of the 3D printers. During this phase, some attention will be dedicated to seeking possible collaborations to facilitate prototyping on the next phase. A direction(s) will be defined as a main focus for the testing phase.

During the testing phase, various prototypes will be tested to analyze both printing and material properties of recycled PLA, and how different variables affect 3D printed prototypes. Further testing may be also required to assess the whole process of recyclability (p.e. shredding, filament extrusion…). Conclusions from the tests will be drawn and iterate over.

Finally, a near-future solution will be developed as a result of the conclusions of the testing phase. To support and to assess its viability, a proof of concept will be built.

Initials & Name M Aliana Guardia 4273 Student number

Title of Project Recycling of 3D printing material used for prototyping

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

This project is set up in a way it matches both my background and my interests. I consider myself a technical industrial design engineer who's driven by solving specific problems and who enjoys transforming ideas into reality.

I am very much interested in circular product design, specifically in the more technical areas, that also match my engineer background. I strive to empower sustainable design solutions that contribute to a circular future.
Thanks to an internship and courses like Sustainable Business Models and Sustainable Product/Service Systems, I have learned about sustainability on a broader level. Now, I want to focus more on learning by doing, on solving specific sustainability issues with my work.

During the IPD master, I have had the opportunity to dive into additive manufacturing on a regular basis, to the point that now I consider 3D printing a part of my usual design process. Being a frequent user has awakened my interest to learn more about the printing process, which I am looking forward to diving into.

This project can add expertise to my career in the areas of sustainability and circular product design and help me define my future steps.

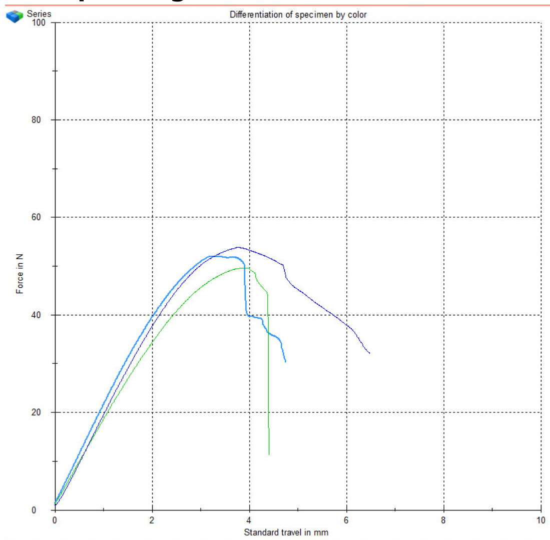
FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

APPENDIX B Mechanical tests graphs

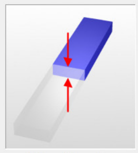
3 points Flexural 10kN test

Recycled PLA - printing direction X



No.	Date/Clock time	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
1	29-10-2020 17:28:25	52,0	3,3	31,2	4,7	102,22	3,94	9,62	37,90	29,15
2	29-10-2020 17:30:28	49,7	3,9	29,1	4,4	121,42	3,9	9,59	37,40	27,13
3	29-10-2020 17:32:29	53,8	3,8	32,3	6,5	124,46	3,94	9,58	37,75	39,57

Series n = 3	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
$\bar{x}$	51,8	3,7	30,9	5,2	116,03	3,927	9,597	37,68	31,95
s	2,08	0,3	1,59	1,1	12,06	0,02309	0,02082	0,26	6,67
V} [%]	4,02	9,43	5,16	21,42	10,39	0,59	0,22	0,68	20,89

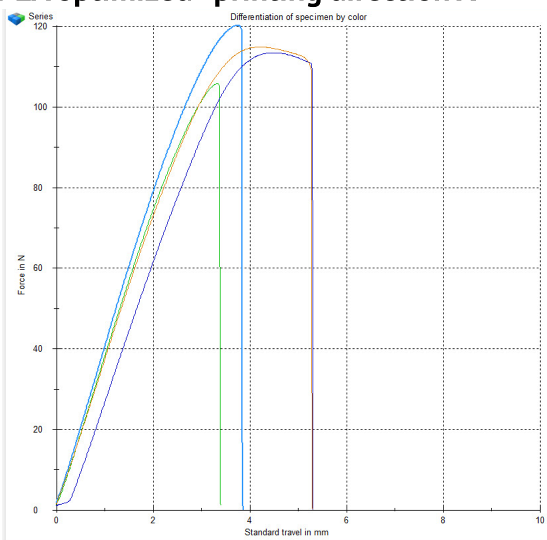


Thickness of the specimen

Specimen thickness 3,94 mm

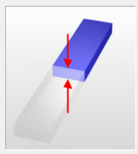
Specimen width 9,62 mm

Recycled PLA optimized - printing direction X



No.	Date/Clock time	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
1	29-10-2020 17:47:14	120	3,7	71,5	3,8	261,29	3,96	9,72	38,49	23,80
2	29-10-2020 17:49:25	106	3,3	63,4	3,4	199,08	3,95	9,84	38,87	21,05
3	29-10-2020 17:53:49	113	4,5	66,9	5,3	294,53	3,91	9,76	38,16	32,54
4	29-10-2020 17:56:23	115	4,2	67,1	5,3	297,91	3,94	9,72	38,30	32,43

Series n = 4	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
$\bar{x}$	114	4,0	67,2	4,4	263,20	3,94	9,76	38,45	27,46
s	5,96	0,5	3,30	1,0	45,83	0,0216	0,05657	0,31	5,92
V} [%]	5,24	13,31	4,91	22,19	17,41	0,55	0,58	0,80	21,55

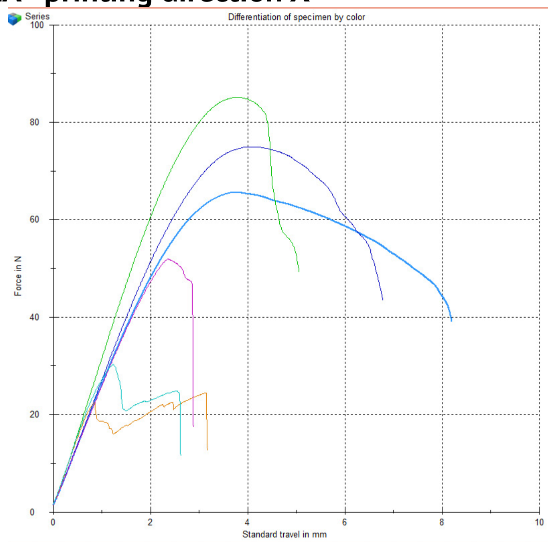


Thickness of the specimen

Specimen thickness 3,96 mm

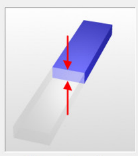
Specimen width 9,72 mm

Virgin PLA - printing direction X



No.	Date/Clock time	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
1	29-10-2020 16:23:14	65,6	3,8	39,3	8,2	155,90	3,93	9,75	38,32	246,67
2	29-10-2020 16:29:53	85,1	3,8	51,1	5,0	200,25	3,97	9,69	38,47	30,95
3	29-10-2020 16:38:17	75,0	4,1	45,0	6,8	193,76	3,98	9,61	38,25	41,28
4	29-10-2020 16:45:00	24,5	3,1	23,3	3,2	57,66	3,96	9,69	38,37	19,69
5	29-10-2020 16:57:17	51,9	2,4	31,0	2,9	68,73	3,91	9,59	37,50	18,01
6	29-10-2020 17:05:55	30,3	1,2	20,1	2,6	21,88	3,95	9,73	38,43	16,42

Series n = 6	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
$\bar{x}$	55,4	3,1	35,0	4,8	116,36	3,95	9,677	38,22	62,17
s	24,4	1,1	12,3	2,3	76,46	0,02608	0,06408	0,36	90,88
V} [%]	43,99	35,55	35,07	48,41	65,71	0,66	0,66	0,95	146,19

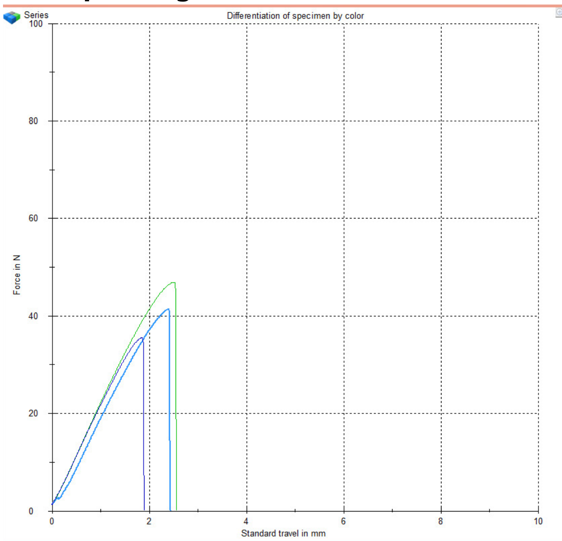


Thickness of the specimen

Specimen thickness 3,93 mm

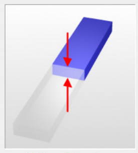
Specimen width 9,75 mm

Recycled PLA - printing direction Y



No.	Date/Clock time	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
1	29-10-2020 17:37:23	41,4	2,4	31,8	2,4	53,06	3,74	9,73	36,39	15,32
2	29-10-2020 17:39:31	46,9	2,5	35,6	2,5	66,22	3,77	9,77	36,83	16,03
3	29-10-2020 17:41:06	35,5	1,8	27,0	1,9	36,47	3,76	9,76	36,70	12,09

Series n = 3	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
$\bar{x}$	41,3	2,2	31,5	2,3	51,92	3,757	9,753	36,64	14,48
s	5,67	0,4	4,31	0,4	14,91	0,01528	0,02082	0,23	2,10
ν} [%]	13,75	15,59	13,68	15,49	28,71	0,41	0,21	0,62	14,49

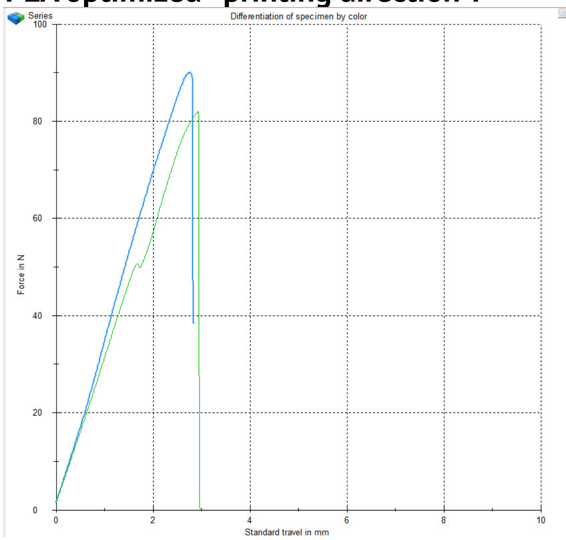


Thickness of the specimen

Specimen thickness 3,74 mm

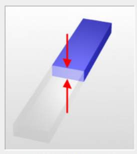
Specimen width 9,73 mm

Recycled PLA optimized - printing direction Y



No.	Date/Clock time	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
1	29-10-2020 18:01:42	90,0	2,7	53,3	2,8	130,60	4,01	9,86	39,54	17,73
2	29-10-2020 18:03:24	82,0	2,9	48,1	2,9	128,17	3,88	9,78	37,95	18,46

Series n = 2	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
$\bar{x}$	86,0	2,8	50,7	2,9	129,38	3,945	9,82	38,74	18,09
s	5,63	0,1	3,68	0,1	1,72	0,09192	0,05657	1,13	0,52
ν} [%]	6,55	4,56	7,25	3,02	1,33	2,33	0,58	2,91	2,87

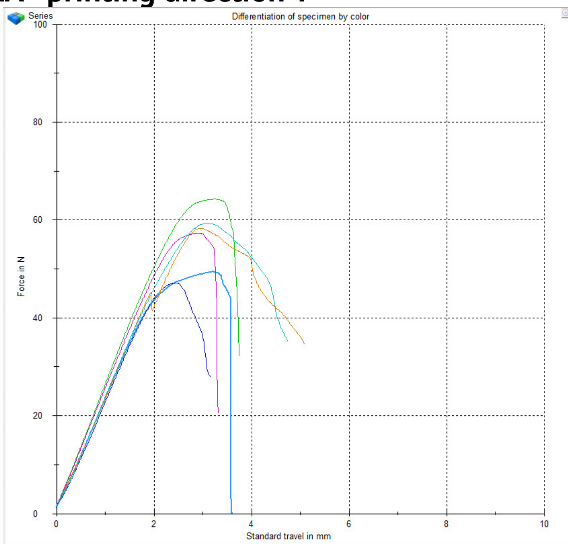


Thickness of the specimen

Specimen thickness 4,01 mm

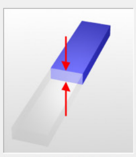
Specimen width 9,86 mm

Virgin PLA - printing direction Y



No.	Date/Clock time	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
1	29-10-2020 17:11:26	49,4	3,2	33,6	3,6	103,23	3,78	9,81	37,08	22,22
2	29-10-2020 17:14:49	64,2	3,3	38,5	3,7	129,27	3,87	9,85	38,12	23,14
3	29-10-2020 17:17:58	47,1	2,4	28,3	3,1	64,94	3,79	9,82	37,22	19,59
4	29-10-2020 17:20:17	58,3	2,9	35,0	5,1	96,56	3,88	9,84	38,18	31,21
5	29-10-2020 17:22:04	57,3	2,9	34,3	3,3	100,18	3,86	9,82	37,91	20,51
6	29-10-2020 17:23:36	59,3	3,1	35,6	4,7	107,34	3,85	9,84	37,88	29,15

Series n = 6	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	W to F_{max} Nmm	a_0 mm	b_0 mm	S_0 mm²	t_{Test} s
$\bar{x}$	55,9	3,0	34,2	3,9	100,25	3,838	9,83	37,73	24,30
s	6,45	0,3	3,36	0,8	20,79	0,04262	0,01549	0,47	4,76
ν} [%]	11,53	10,29	9,84	20,25	20,74	1,11	0,16	1,24	19,61



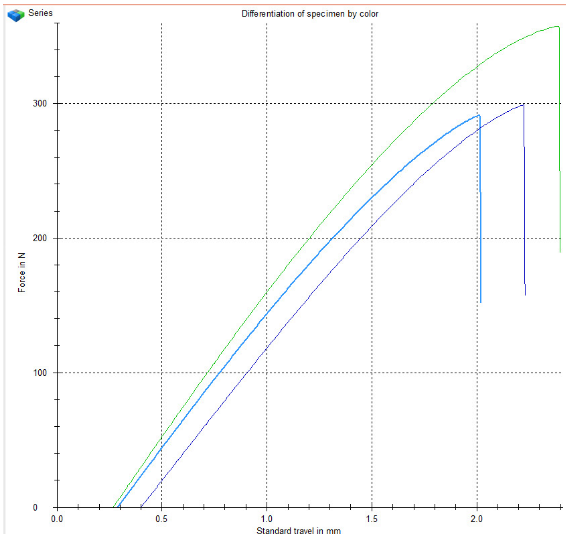
Thickness of the specimen

Specimen thickness 3,78 mm

Specimen width 9,81 mm

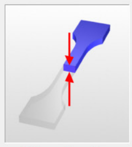
Tensile 10kN test

Recycled PLA



No.	Maximum extension mm	Test speed mm/min	Pre-load N	Specimen no.	h mm	b mm	A_0 mm²	Peak detection N	Date/Clock time	L_0 CH mm
1	3	5	0,1	1	3,89	9,93	38,63	291,08	29-10-2020 15:18:26	110,15
2				2	3,94	9,98	39,32	357,47	29-10-2020 15:21:54	110,15
3				3	3,9	9,91	38,65	299,06	29-10-2020 15:25:41	110,15

Series n = 3	Specimen no.	h mm	b mm	A_0 mm²	Peak detection N	L_0 CH mm
x	2	3,91	9,94	38,87	315,87	110,15
s	1	0,02646	0,03606	0,39	36,25	0,00
ν} [%]	50,00	0,68	0,36	1,01	11,48	0,00

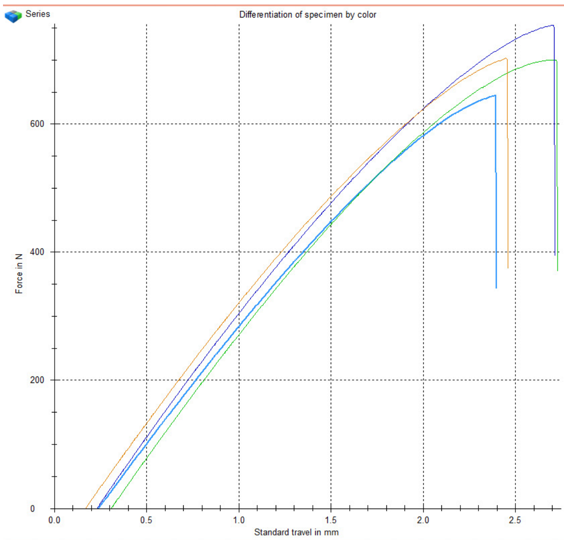


Thickness of the specimen

Specimen thickness 3,89 mm

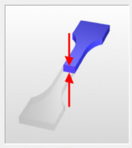
Specimen width 9,93 mm

Recycled PLA optimized



No.	Maximum extension mm	Test speed mm/min	Pre-load N	Specimen no.	h mm	b mm	A_0 mm²	Peak detection N	Date/Clock time	L_0 CH mm
1	3	5	0,1	1	3,89	10,05	39,09	644,73	29-10-2020 15:45:47	110,15
2				2	3,86	10,07	38,87	700,00	29-10-2020 15:48:55	110,15
3				3	3,9	10,1	39,39	754,05	29-10-2020 15:53:33	110,15
4				4	3,86	10,08	38,91	702,32	29-10-2020 15:56:51	110,15

Series n = 4	Specimen no.	h mm	b mm	A_0 mm²	Peak detection N	L_0 CH mm
x	3	3,878	10,08	39,07	700,27	110,15
s	1	0,02062	0,02082	0,24	44,65	0,00
ν} [%]	51,64	0,53	0,21	0,61	6,38	0,00

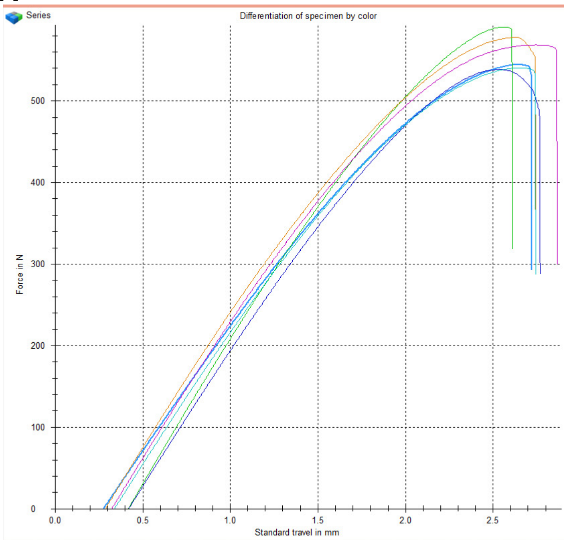


Thickness of the specimen

Specimen thickness 3,89 mm

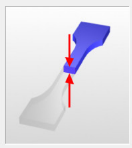
Specimen width 10,05 mm

Virgin PLA



No.	Maximum extension mm	Test speed mm/min	Pre-load N	Specimen no.	h mm	b mm	A_0 mm²	Peak detection N	Date/Clock time	L_0 CH mm
1	3	5	0,1	1	3,97	10,5	41,69	544,69	29-10-2020 14:23:36	110,15
2				2	4,01	10,61	42,55	590,72	29-10-2020 14:27:53	110,15
3				3	3,85	9,95	38,31	538,49	29-10-2020 14:32:03	110,15
4				4	3,9	10,01	39,04	578,31	29-10-2020 14:50:49	110,15
5				5	3,91	10,04	39,26	568,84	29-10-2020 14:54:45	110,15
6				6	3,94	10,07	39,68	540,65	29-10-2020 14:59:29	110,15

Series n = 6	Specimen no.	h mm	b mm	A_0 mm²	Peak detection N	L_0 CH mm
x	4	3,93	10,2	40,08	560,28	110,15
s	2	0,05621	0,2825	1,66	22,04	0,00
ν} [%]	53,45	1,43	2,77	4,13	3,93	0,00



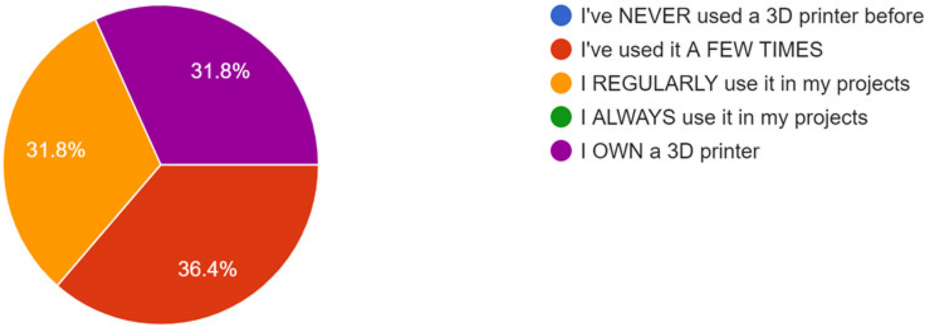
Thickness of the specimen

Specimen thickness 3,97 mm

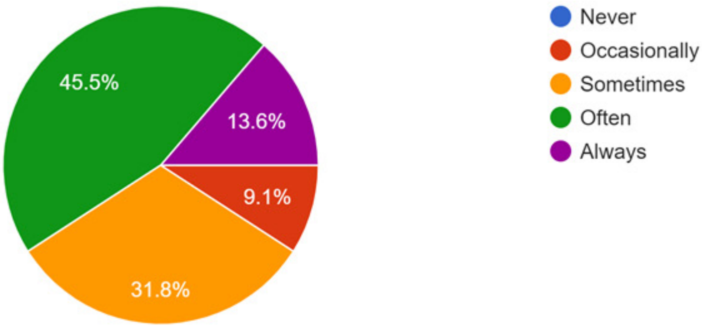
Specimen width 10,5 mm

APPENDIX C Users Questionnaire

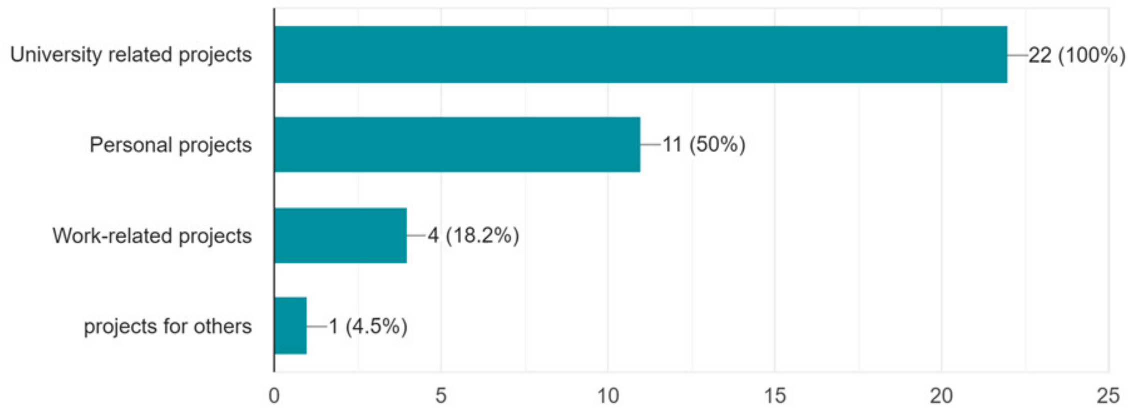
How familiar are you with (FDM) 3D printing?
22 responses



How often do you use (FDM) 3D printing in your projects?
22 responses



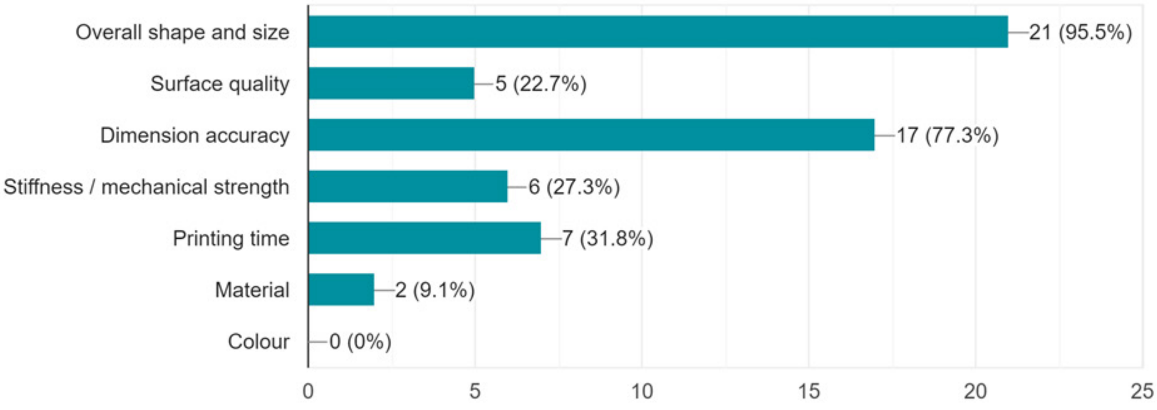
What projects do you usually use (FDM) 3D printing for?
22 responses



Your 3D printed prototypes

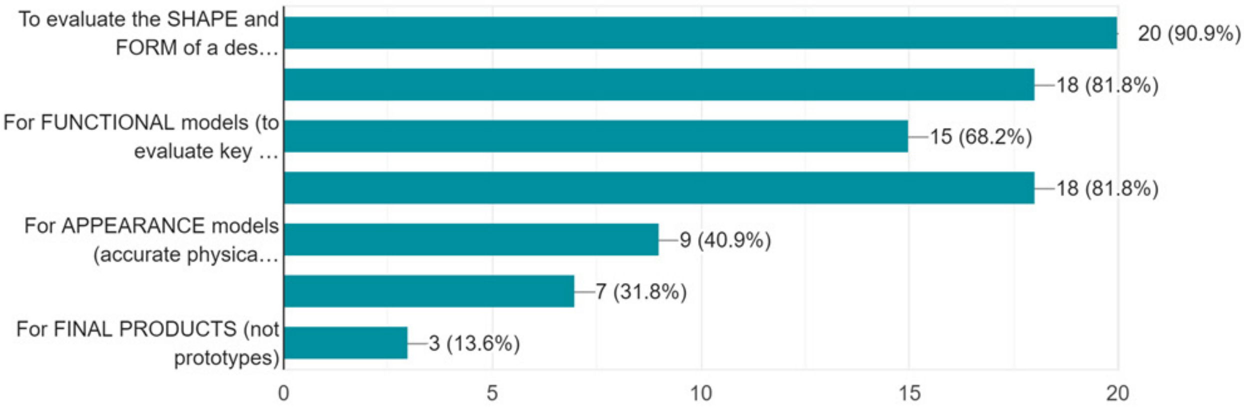
What is the most important aspect of your printed prototypes?

22 responses



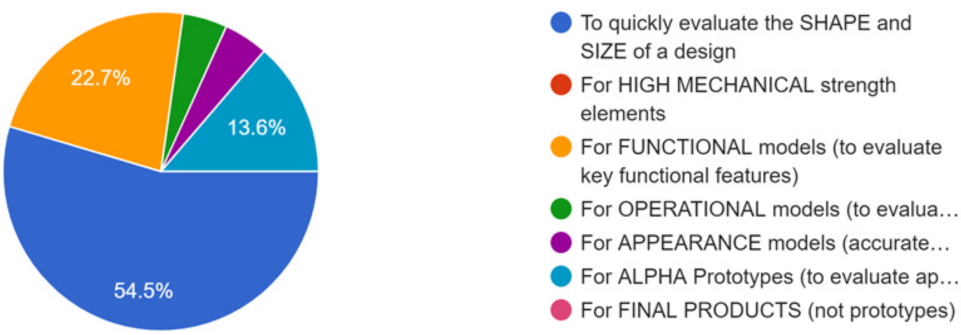
For what purpose do you use (FDM) 3D printing?

22 responses



For what purpose do you use (FDM) 3D printing THE MOST?

22 responses

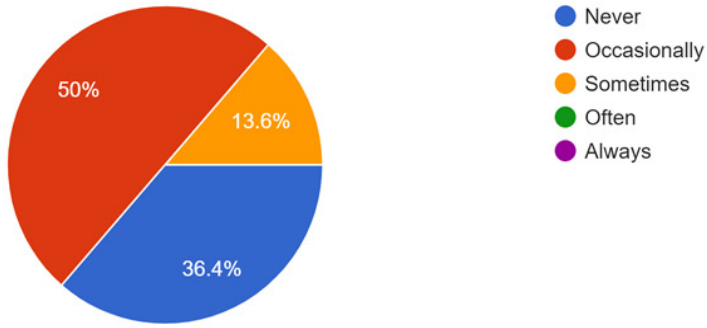


Do you usually post-process your 3D prints?

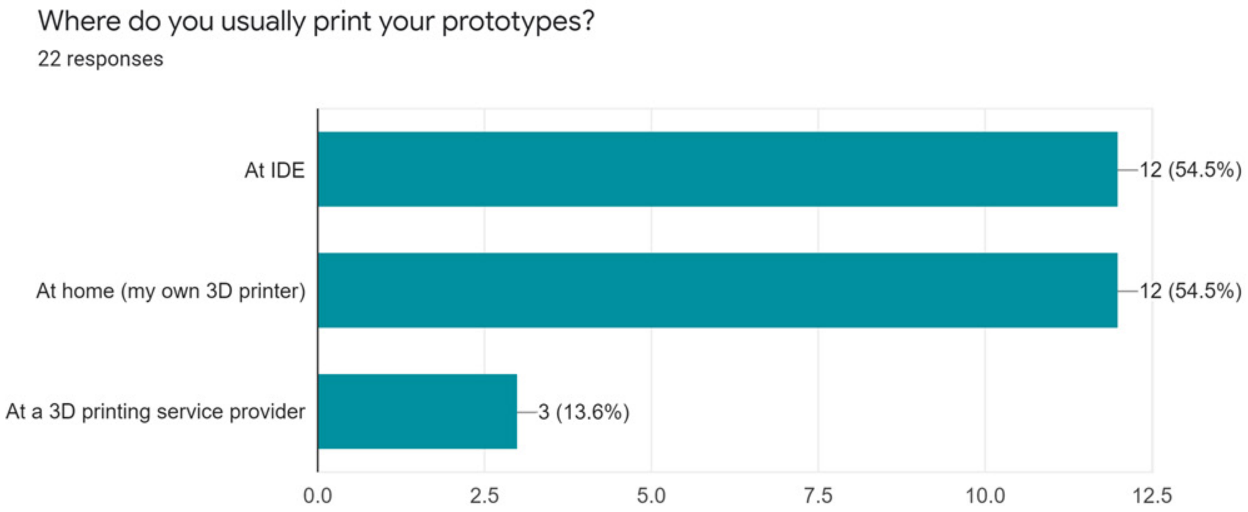
22 responses

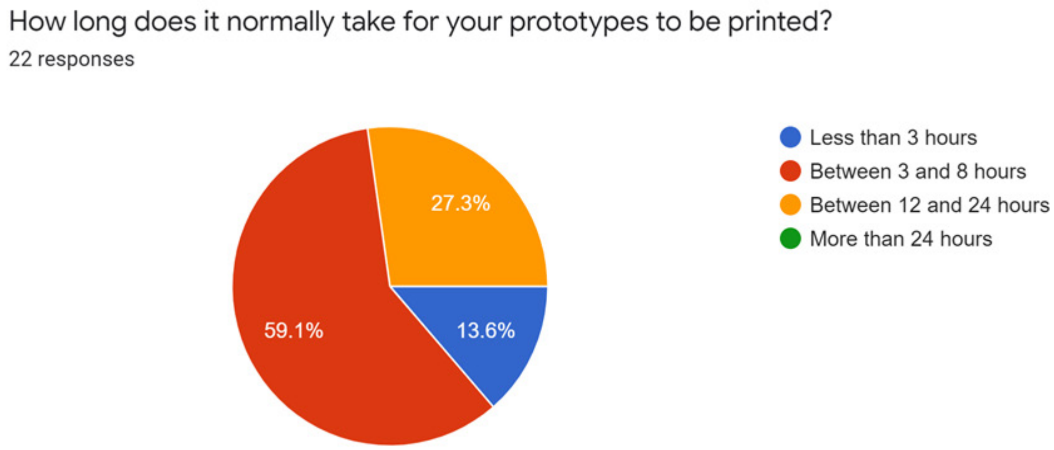
How often do you paint or glue your prints?

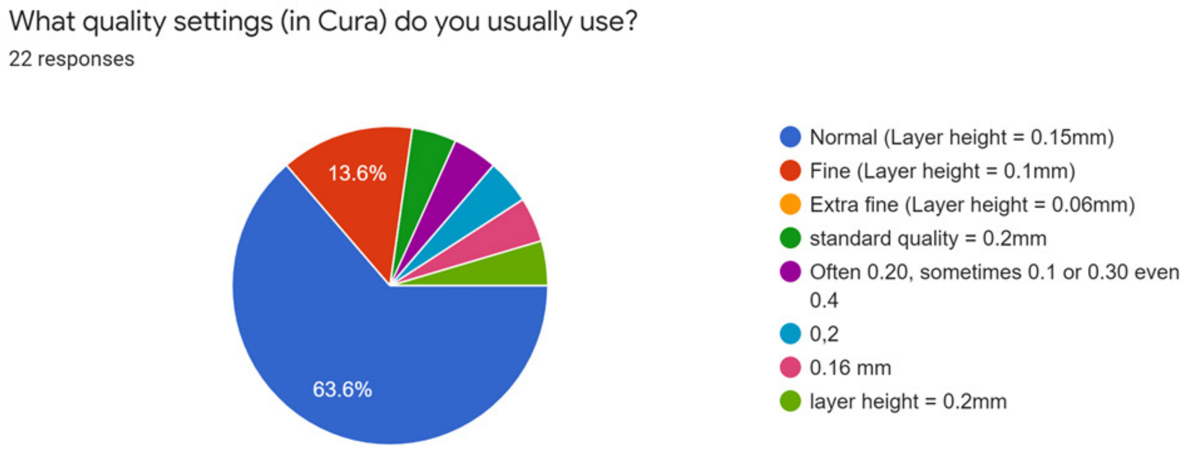
22 responses



Printing your prototypes

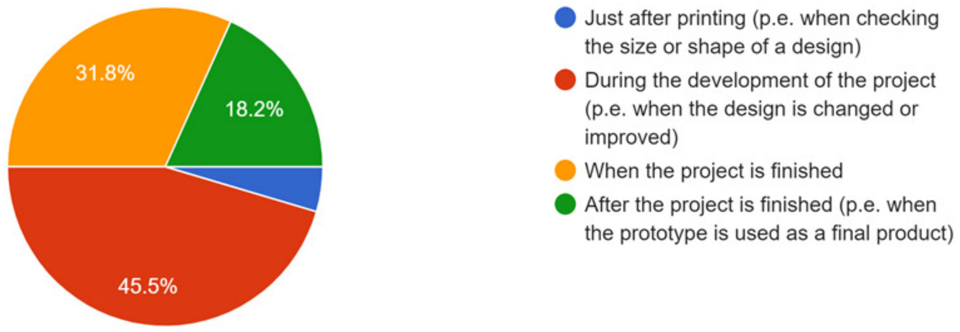




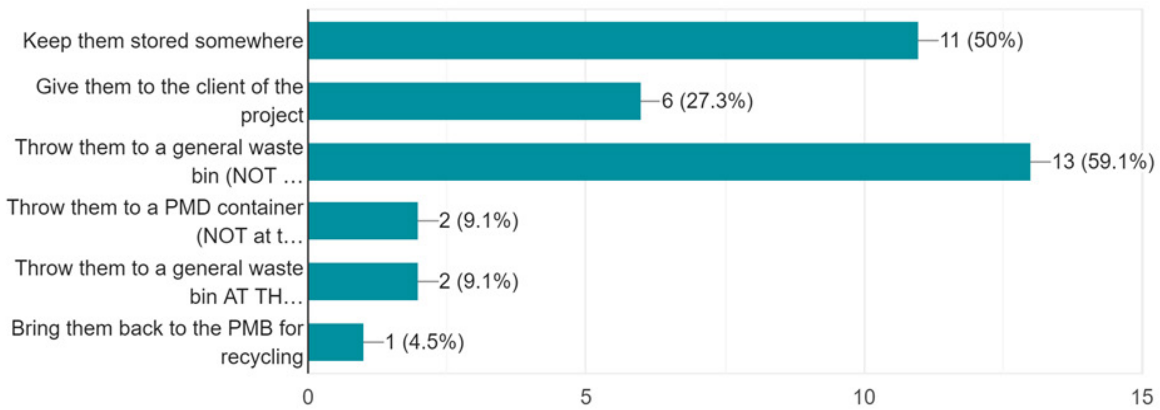


End-of-life of 3D prints

When do your prototypes usually become obsolete?
22 responses



What do you usually do with your obsolete 3D prints?
22 responses



Master Thesis
February, 2021

Marc Aliana Guardia

MSc. Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology