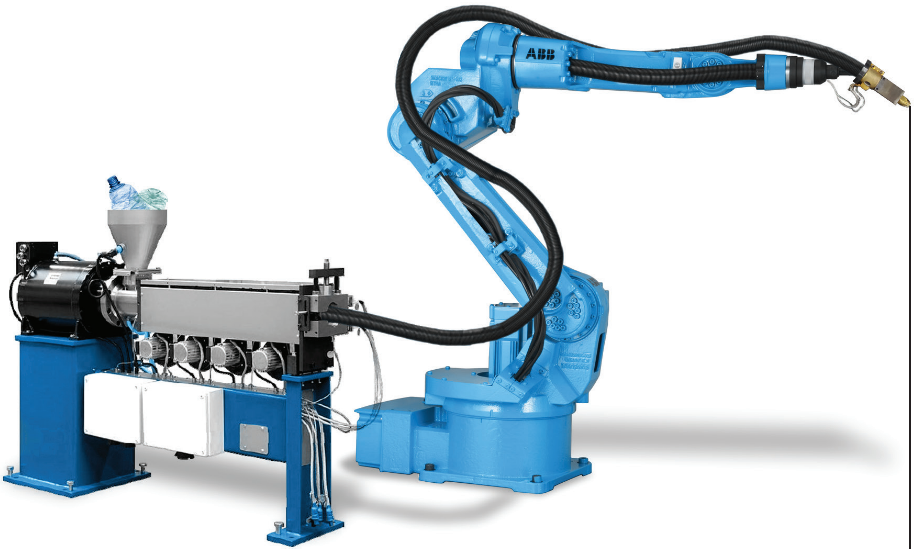
3D Printing of Large Objects with PET Flakes



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3D Printing of Large Objects with PET flakes

Graduation Project - Integrated Product Design

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Figure 1: Inadequate (plastic) waste management in rural Africa.

Summary

“3D Printing of Large Objects with PET Flakes” is the Graduation project of Daniël Eikelenboom of the Faculty of Industrial Design Engineering of the TU Delft for the Rotterdam based company 3D Robotprinting. The project focusses on the development and implementation of an ‘all-inclusive’ PET bottle recycling unit containing a large-scale 3D printer as made by 3D Robotprinting and the development of a preliminary set of guidelines for manufacturing products using the 3D printer. The aim is to enable the 3D printer to use PET flakes gained from bottles as feedstock. Therefore, the 3D printer was adapted and guidelines for manufacturing were developed.

An iterative approach is followed, in which the exploration of the ‘novel’ source material and defining the design guidelines for manufacturing are at the heart of the project. After defining the context, the 3D printer was analysed and a literature study was performed, from which was concluded that the current polymer extrusion machine is likely too small to process the initial flake sample.

With an initial sample of the material, experiments were performed in order to examine directions for a possible solution and to determine the most important properties, like flake material density, particle size distribution and funnel flow behaviour. By increasing the polymer extrusion screw channel depth at the feeding zone to 8 mm and compression ratio to 4:1 (resulting in a screw diameter of 30,4 mm), the 3D printer should be able to process PET flakes with a diameter up to 4 mm. To ensure the material does not contain particles larger than 4 mm in diameter, it should be shredded, granulated with a 3 mm mesh and sifted using a 4 mm sieve consecutively.

Using literature of previous experiments, preliminary design guidelines for creating products with the 3D printer from 3D Robotprinting were set up. From a set of ideas gained from context analysis, a children’s slide was chosen to experiment on. Multiple prototyping rounds were done to perfect the slide’s printing performance and to refine the design guidelines.

The project’s final results are:

- Advised dimensions on the most important part of the system: the polymer extruder.
- A list of preliminary design guidelines for optimizing a product for manufacturing on the 3D printer.
- A children’s slide showing the application of the design guidelines.

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Introduction

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1.1. Project motivation

While working on a project in Tanzania, Africa I noticed the amount of plastic being disposed improperly (see Figure 1 on page 4). It usually ends up on the ground littering the cities and villages or being burned (Climate & Clean Air Coalition, 2015), affecting the health of people and environment, while letting valuable resources go to waste. Most African countries are even amongst the world's worst plastic waste managers, together with the Middle East and Asia (Figure 2). It is known that recycling waste plastic is beneficial for the environment (Gu, Guo, Zhang, Summers & Hall, 2017) and living amongst high amounts of waste is bad for your health (Tomita, Cuadros, Burns, Tanser & Slotow, 2020). The waste mismanagement in areas like this is often linked to a lack of infrastructure (Jambeck et al., 2018). As giving people an economic incentive to commit proper waste management is more effective than social influence (Xu, Ling and Wu, 2018), I believe that it is possible to give value back to these waste plastics. In doing so, the amount of mismanaged plastic waste can be reduced drastically while encouraging infrastructure improvement, improving both the environment and the living conditions.

When I met 3D Robotprinting, a match in our vision was found. They expressed their desire to locally process PET waste from bottles directly into products and were working on a recycling unit based on their 3D printer.

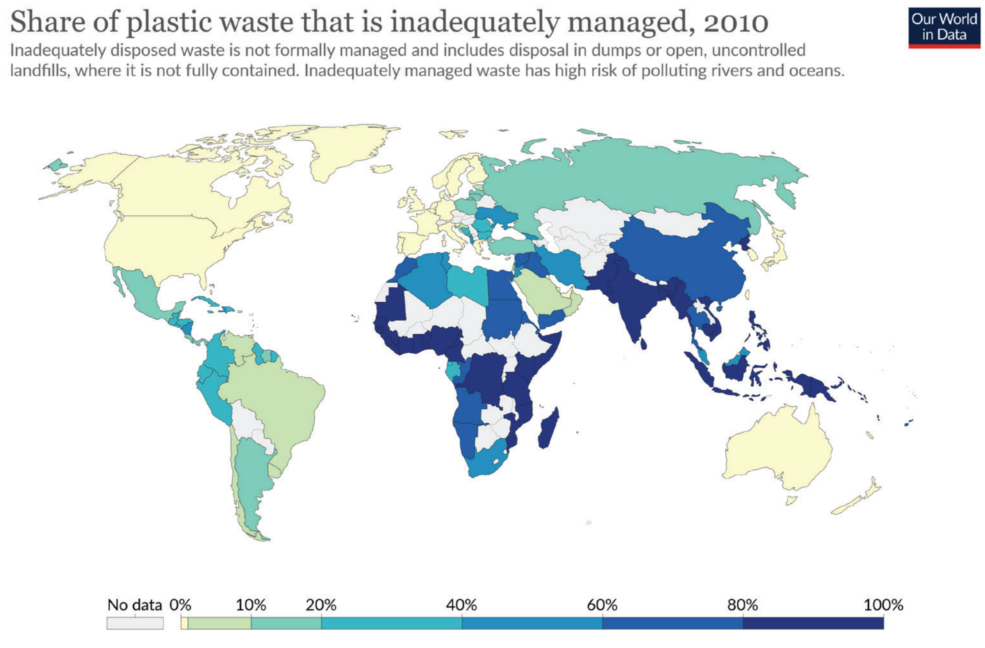


Figure 2: Plastic waste management across the world (Ritchie & Roser, 2018).

1.2. 3D Robotprinting

3D Robotprinting is a Rotterdam based company that develops 3D printers using industrial robotic arms and plastic extrusion machines. Their printers are capable of printing large sized objects. Past projects include (parts of) a wind tunnel, train simulators, tram/metro simulators, large flanges and several art objects, as can be seen in Figure 3. Materials used include TPE, PMMA, PET and PLA. However, glass-fibre reinforced PP with optional additives for colour or fire retardant is most commonly used.

According to 3D Robotprinting, the large size of the printer causes it to require less consistency of the input material in comparison to other 3D printing techniques, which could be beneficial in processing PET bottle waste. Connecting this technique to locally sourced waste plastics could create a huge opportunity for the 3D printing and recycling industry. It has the potential to connect remote areas to a wide range of products, including items only available in industrial high-tech facilities, while also adding value to waste plastics in areas where it is needed most.

Figure 3: Past 3D printing projects from 3D Robotprinting.

1.3. The project

1.3.1. Goal & scope

This project aims to 3D print using PET flakes gained from bottles as feedstock. Therefore, preliminary research has been performed, the 3D printer was adapted for use with the PET flake material and preliminary guidelines for manufacturing reliably were set up.

> *"Design an extruder and/or process to enable the 3D printer to use PET bottles as a feedstock and develop (preliminary) design guidelines for manufacturing products with the 3D printer by printing a product that highlights the potential of 3D printing for localized recycling."*

The system to be designed should be a complete recycling unit, which processes the waste PET bottle into an object using the 3D printing technique as developed by 3D Robotprinting. The scope of this project will include a part of the production chain, starting from the waste material and ending at the material processing part of the 3D printer. The robotic arm of the 3D printer is outside the scope, as is the printing technique used (as expressed by the client).

The timespan to develop the machine should be short: feasible in months rather than years.

The focus of this project lies on the interaction between the preparation of the waste material and (the dimensions and design of) the extruder as well as on the design of products with the adapted equipment.

1.3.2. Approach

Throughout this project, an iterative cycle based on the Basic Design Cycle by Roosenburg and Eekels (1995) is followed (Figure 4). In this report, each chapter contains sections that are linked to the five phases of the cycle. These phases are listed separately and consecutively. In practice however, this process is better described as a continuous loop, in which each step is passed multiple times for each chapter.

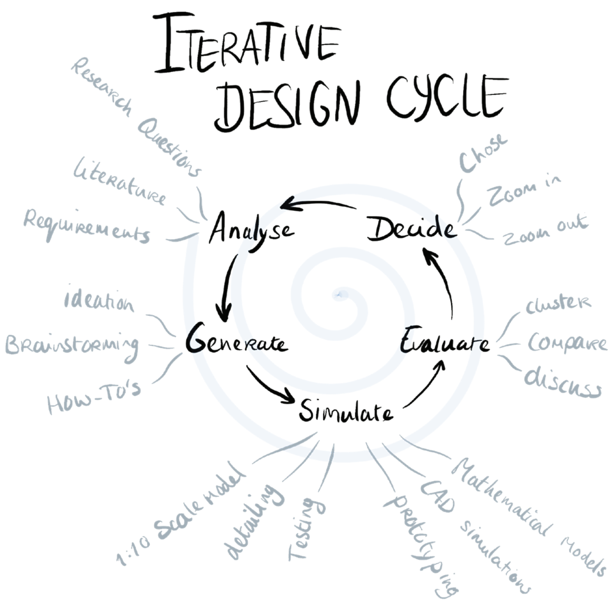


Figure 4: Iterative cycle based on Roosenburg & Eekels' (1995) Basic Design Cycle.

Context & Research

2

2.1. Introduction

In this chapter the context, the 3D printer and the printing technique were analysed. Knowledge on 3D printing, polymer extrusion and handling of flake material was combined to form a hypothesis on the cause of the observed critical failures of the 3D printing system. Finally, the technology required to build a successful recycling unit has been analysed.

The sub-questions for this chapter:

1) Where and by whom will the PET recycling unit be used?

2) What design rules are posed on products when designing for the 3D printer?

3) Where, when and why does the current system fail to use PET bottles as feedstock?

4) How can PET bottles be recycled to 3D printing feedstock?

2.2. Method

From client interviews and desk research a short context analysis was done.

A literature study on desktop 3D printing techniques was performed.

A client interview and observation was performed where test shapes were 3D printed using the printer and PET flakes. A direct extruder setup was used for the observation. The extruder used in this observation is a print extruder by CEAD with a polymer extrusion screw diameter of 25mm. Material is transported to the print head from a sealed hopper next to the machine using air (comparable to a vacuum cleaner). Before, during and after the observation, an unstructured client interview was performed . More information on the observation of this experiment can be found in appendix C. As the observation experiment was performed using a mixture of 50% virgin PET and 50% recycled PET flakes, an additional explorative experiment was performed using a sample of 100% recycled PET flakes on a Noztek Touch desktop filament extruder located at the Applied Labs at the faculty of Industrial Design Engineering at TU Delft (appendix B).

A literature study was performed on the properties of PET and the application of polymer extrusion on flake materials. Using a function analysis, the recycling system was broken down into four sub-functions. The sub-functions of the system were then developed into requirements for existing machinery.

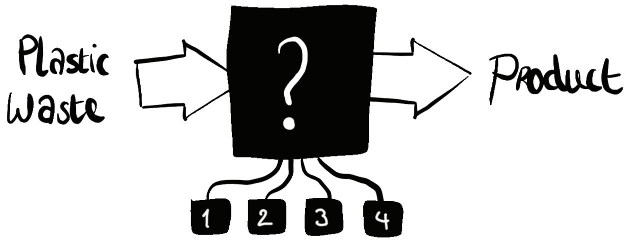


Figure 5: The main function of the recycling unit can be subdivided in four sub-functions.

2.3. Context

As a first step to reach a circular material stream, a machine was envisioned which transforms PET bottle waste into products. A machine like this could be useful in different scenarios, ranging from remote military bases (using PET bottles for drinking water) to refugee camps to (touristic) cities in Africa -- where waste management is non-existent. Together with the client, three possible context areas were chosen to focus development on.

Context area 1: An army base in countries where drinking water is supplied through sealed PET bottles. The first context area was introduced by the client. In this context the recycling unit will be transported to an army base in an area where safe drinking water is not readily available. Daily, around 300 kg of PET waste is generated, caused by these water bottles. The waste management is currently limited to burning. The machine has to be transportable by boat and truck. The client expressed desire to fit the recycling unit inside a climate-controlled shipping container permanently. Boredom amongst (off-duty) soldiers is an issue in the camps.

Context area 2: Refugee camps. Based on stories by refugee help organisations like UNHCR, Oxfam-Novib and Unicef (UNHCR The UN Refugee Agency, 2018; Ferguson, 2018; Mora, 2021; Dunmore, 2015; UNHCR The UN Refugee Agency, n.d.; Oxfam Novib, n.d.), the context of a refugee camp was chosen as possible use scenario, especially if drinking water needs to be trucked in (UNHCR The UN Refugee Agency, n.d.). In refugee camps waste management consists of people collecting and sorting the waste for a minimum wage (Oxfam Novib, n.d.). The camp pays the people from money made by selling the waste, but not all waste is sellable. Refugee camps are also a place rich of entrepreneurship (Mora, 2021; Dunmore, 2015).

Context area 3: Cities in third world countries (with lacking waste treatment infrastructure). Inspired by Blok, Eikelenboom, Van Der Schaaf & Schouten (2018), the context of an African city was chosen. Waste management infrastructure is often lacking in African cities, causing a high amount of mistreated waste (Tomita et al., 2020; Jambeck et al., 2018). Especially in touristic areas, water is mainly consumed from sealed PET bottles. At the same time, streets are littered with plastic. From Blok et al. (2018) and Xu, Ling & Wu (2018) was also seen that peoples' actions are mostly driven by financial incentives.

For this project processing 300 kg of PET per day will be used as guideline. As local machine operators are likely novices, products to be printed should be designed with this in mind. Other important conclusions are that the recycling unit is contained within a climate-controlled shipping container and will be transported by truck or boat. A standard shipping container internal size is 5,71m x 2,35m x 2,38 m (Northern Container Sales, n.d.) and has to fit all machinery. As the container is climate-controlled, environmental influences will be neglected for this project.

2.4. Printing technique & design guidelines

3D Robotprinting's 3D printer uses a printing technique comparable to an upscaled version of Fused Deposit Modeling (FDM) or Fused Filament Fabrication (FFF) and can, like FDM/FFF, be classified as Additive Manufacturing. In this technique, the machine stacks material in layers to form a 3D shape (see Figure 6). As the layers are stacked from the bottom up, some geometries are impossible to create without a piece of support structure. On FDM/FFF and Additive Manufacturing, extensive research is done into design rules and knowledge banks of this data can be found easily online ("3D Printing & Additive Manufacturing – A Complete Overview", 2021; 3Dprinting.com, n.d.; 3D insider, n.d.).

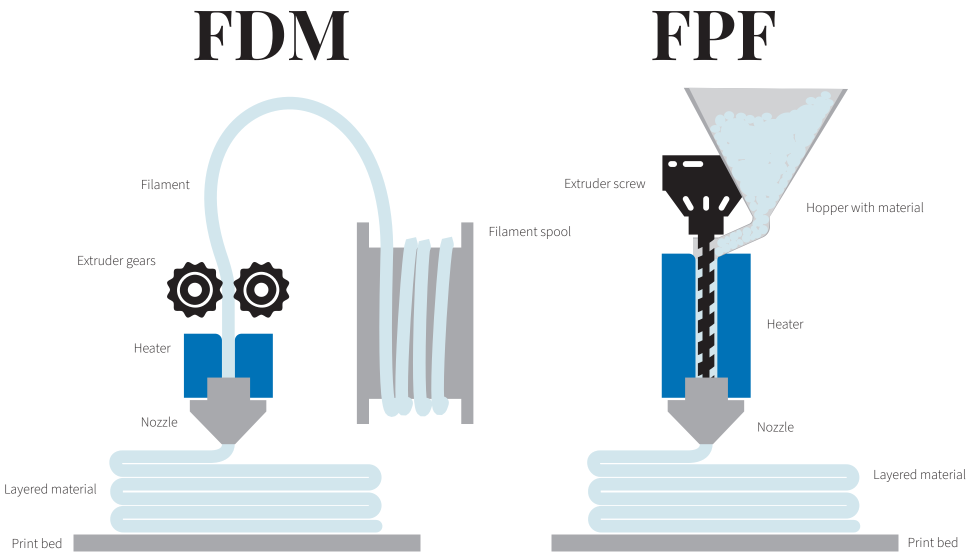


Figure 6: FDM/FFF vs. FPF printing technique.

Where desktop 3D printers commonly use filament, a thin strand of plastic, to build the layers, the 3D Robotprinter uses small polymer particles (also called pellets or granules) as input material. This technique is called Fused Particle Fabrication (FPF).

The two most important differences between the printing technique of the 3D Robotprinting printer and a commonly used FDM/FFF printer are the increased size and the use of granules instead of filament as feedstock (Figure 6). Further testing is needed to determine if and how these differences affect printing rules.

In Table 1, the dimensions of important parts for printing are compared to desktop printers.

Setting	*Desktop FDM/FFF printing*	*3D Robotprinting FPF printing*
Nozzle size	0,4 mm*	4-8 mm
Layer height	0,1-0,3	1-3 mm
Layer width	0,4 mm*	3-10 mm
Feedstock	1,75mm or 2,85mm filament strands	Pellets/Granules
Common print speed	60 mm/s	150 mm/s
	*Most common, other options available ("How FDM/FFF 3D Printing Technology Works?", 2018)	

Table 1: Important dimensions in FDM and FPF printing.

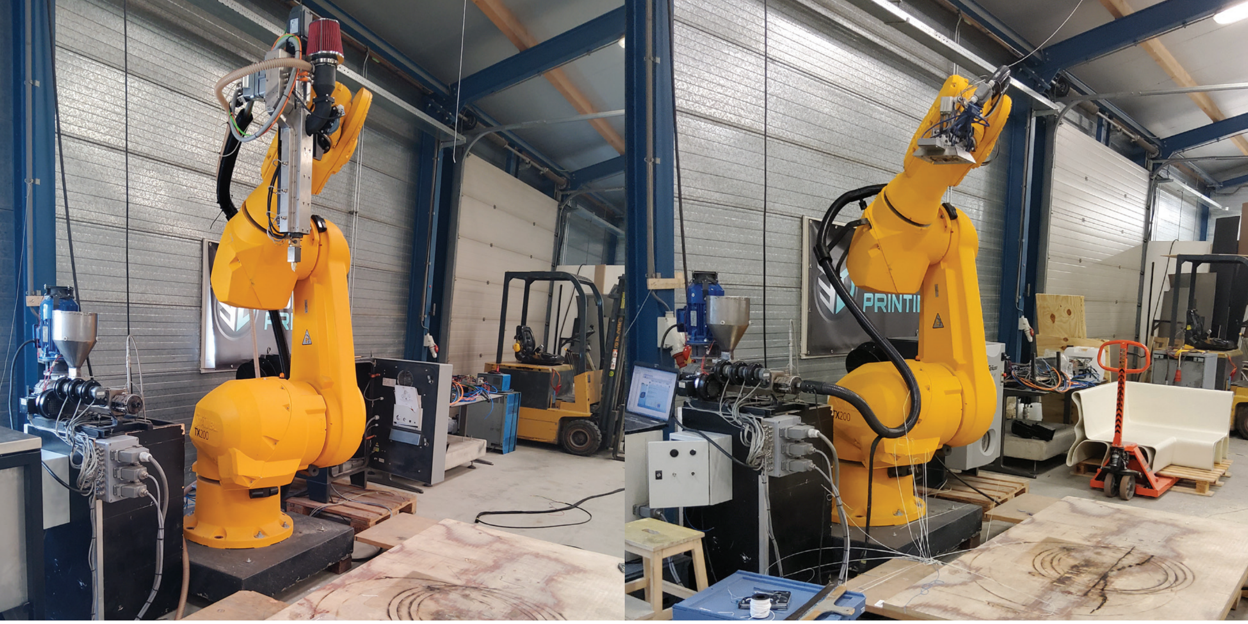


Figure 7: The 3D printer setup: Left, a direct extruder; right, extruder connected with a heated tube.

2.5. 3D Robotprinting and their machine

2.5.1. The company’s past experiments

In the past 3D Robotprinting has experimented with printing with flakes from shredded post-consumer PET waste. However, the printing performance is not comparable with virgin material. Observed issues are for example, the machine clogging up. The machine has trouble pulling the flakes into the extruder, possibly because flake particles are shaped differently and seem lighter than virgin polymer pellets. However, what precisely causes these jams and how to solve these problems, is unknown. As a current work-around, they mix at least 50% virgin PET granulate with the recycled flakes.

2.5.2. The 3D printer with flakes

Next to building machines, 3D Robotprinting also own their own machine for experiments and to print products for consumers and companies. The 3D printer consists of a small polymer extrusion machine connected by a heated tube to the printing head on an industrial robotic arm. For certain applications and materials, such as high temperature polymers, a different extruder is mounted directly to the moving end of the robotic arm. In Table 2, the pros and cons of each configuration are listed. For the recycling unit in this project, a 3D printer setup with heated tube is used for financial reasons.

	Stationary extruder with heated tube	Direct extruder mounted on arm
Pros	Flexible extruder size, orientation and position Light (= cheaper robotic arm)	Less output delay High max temperature Short polymer residence time at high temperature (= less degradation)
Cons	Hose is fragile (cannot move when polymer is not fluid) Max temperature of 250 °C	Small hopper on extruder Hard to refill while in use Heavy (= expensive robotic arm)

Table 2: Pros and cons for different extruder setups

The printer is fitted with a 3,6 mm nozzle and is capable of 3D printing objects all around its base. By extruding up to 10 kg/h (of glass filled PP) in layers around 1,2 mm in height and between 3 and 6 mm wide large scale 3D prints are created. The polymer extruder has an 18 mm plastic screw inside. Connected to it, is a flexible heated tube capable of reaching up to 250 °C. At the end of the heated tube, a flow stopper is installed to reduce material leaking from the print head when the tool head is moved without outputting material. Optionally, a print cooling system can be mounted on the print head.

From the observation (appendix C) multiple problems surface: Because of the transport of flakes through the tube, the flakes become statically charged. Especially the smaller particles stick to the walls of the plastic hopper on the extruder and on the sensors, crippling the system's refill process (Figure 8). The built-in vibration motor is not capable of removing the static dust from the hopper walls. To continue the experiment, the system had to be rebuilt in the heated tube configuration.

Figure 8: Small, statically charged particles sticking to the sensors and hopper walls.

In the lab experiment with a desktop extrusion machine (appendix B), a sample of 100% PET bottle flakes was used. The shape and weight of the flakes were found to cause issues like bridging and rat-holing on a regular basis, resulting in too little material being fed into the extrusion screw (starve feeding). Too little material input decreases pressure build-up in the barrel, resulting in inconsistent output flow, as was observed.

2.6. A bottle recycle system

2.6.1. Introducing PET

PET is a common thermoplastic polymer and is used at a large scale for synthetic fibres and bottles (Ansys Granta Edupack, 2020). The bottles are made in two steps: first pellets are heated and moulded into a preform. The preform is then heated again and moulded to shape by blowing air inside the hot preform. By using chemical additives or adjusting the way PET is processed, the properties of the final product can be influenced. For example, cooling it quickly will reduce the forming of crystals, thus creating a material with less crystallinity (Zander, Gillan & Lambeth, 2018). PET is usually semi-crystalline and by influencing the amount of crystals formed inside the material, properties such as the melting point and material strength can be adjusted to fit its product's purpose. When highly crystalized, PET appears opaque. PET with a moderate amount of crystallinity keeps its transparency (Zander et al., 2018). The length of the polymer chains influences the intrinsic viscosity of the material (Flory, 1940). Interestingly, this value is different for carbonated soft drinks bottles than for regular water bottles (Gupta & Bashir, 2002), suggesting the polymer chain length of the material used in carbonated soft drink bottles is not the same as in flat water bottles. Polymer chain length and its influence on viscosity is important, as it affects the ability to extrude the plastic (Zander et al., 2018). According to Zander et al. (2018) as well, material from carbonated soft drink bottles and flat-water bottles can be mixed without much trouble as, apart from polymer structure, their chemistry is identical. Contamination with other polymers (eg. PVC) can however induce degradation (Paci & La Mantia, 1998) and must thus be avoided.

The melting point of PET is with 250 degrees Celsius quite high for a polymer. For certain applications, the melting temperature can be lowered by additives. For example, the ethylene glycol part of PET can be replaced with a much larger cyclohexanedimethanol (CHDM) part. This lowers the melting temperature and creates what is known as PETG, which is often used in 3D printing. In the context of this project, adding CHDM to improve printing performance is undesirable though, as CHDM is likely hard to find in a context as described in section 2.3.

PET is susceptible to degradation. Degradation causes chain scissions,

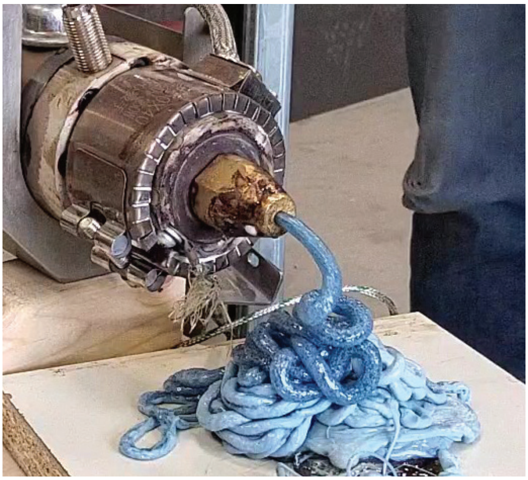


Figure 9: Bubbles in output and opaque PET: the result of hydrolysis when processing undried PET.

poor performance and processibility, as well as the formation of acetaldehyde and cross-links (gelation) (Wu, Lv, He & Qu, 2019; Arhant, Le Gall, Le Gac & Davies, 2019; Franciszczak, Piesowicz & Kalnins, 2018). As the polymer length has an influence on the viscosity (Flory, 1940) and thus the extrusion of the material, it is important to prevent degradation as much as possible to keep a consistent and predictable print result. The print results are expected to be more brittle than virgin PET, as was observed with PETG by Franciszczak et al. (2018).

For this project, the most important forms of degradation are thermal (oxidative) and hydrolytic degradation.

Thermal & thermo-oxidative degradation

One of the main issues on recycling polymers, is degradation upon repeated heating and cooling. According to Assadi, Colin & Verdu (2004), PET can show gelation after 3 extrusion runs. Degradation can also occur when using temperatures above 300 °C and long barrel times ("Polyethylene Therephthalate", 2020). Waste polymer shows a lower degradation temperature than the virgin polymer (Singh, Biswaji Ruj & Sadhukhan, 2019), further amplifying this process. To successfully use a circular material stream, it is key to make sure the polymer is heated as short as possible and to keep the number of heating-cooling cycles as low as possible.

To preserve as much of the material quality as possible, it is thus preferred to print directly with the PET bottles without any additional heating steps.

2.6.2. PET and water

PET is a hygroscopic material. When heated, absorbed moisture causes the chemical bonds inside PET to break, thus degrading the material and reducing its viscosity (Zander et al., 2018). Upon extrusion of undried PET, vaporising moisture can be observed in the extrudate (Figure 9; Zander et al., 2018) as well. Therefore it is common practice to dry PET before processing at high temperatures. The second sub-function of the system is thus to dry the material before heating it and can be phrased as "to adjust the material's moisture level".

This process, hydrolysis or hydrolytic degradation, can also happen during the drying process, as hydrolysis can occur when PET is heated above its glass transition temperature (60-84 °C (Ansys Granta Edupack, 2020)). It would be preferred to dry

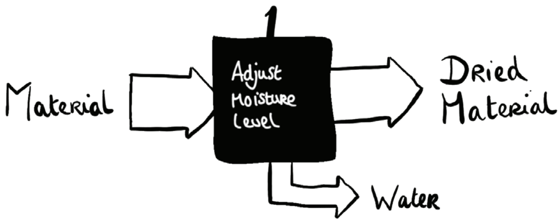


Figure 10: The first sub-function: adjust moisture level.

Figure 11: Example of a stand-alone drying machine

PET at a temperature below the glass transition temperature, but it is more common to dry PET around 160 °C for at least 4 hours (Haynie, n.d.). Reducing the drying temperature is likely to increase the residence time in the dryer drastically. According to Baird & Collias (2014) water can also be removed using a vented extruder, however Haynie (n.d.) advises drying PET before heating it to prevent degradation. For this project, an external dryer unit is thus advised, as a vented polymer extrusion screw would increase complexity, cost and development time of the extruder and is worse at preventing material degradation.

2.6.3. Sizing the plastics

As mentioned in section 2.5, the flake sample used appears to be too big for the extruder, highlighting the importance of the size of the material. The second sub-function of the system thus could be “Adjust the material size”.

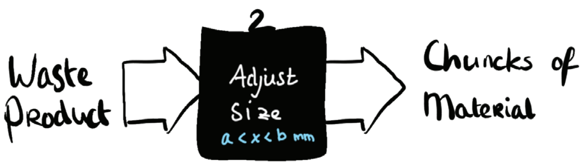


Figure 12: The second sub-function of the recycling system: to adjust the material size.

To reduce the size of the material input of the machine to a workable size, shredders and granulators are used in current recycling plants. While a shredder often features two axes with slow moving blades and generally can process material sized as big as its input slot allows, a granulator features a single axis of quickly spinning blades

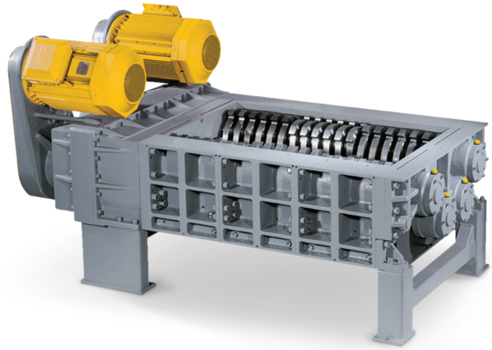


Figure 13: left example of a shredder (with removed funnel); right, example of a granulator (open).

combined with a sieve and is only capable of processing relatively small sized material particles. The output of a granulator is more controllable, as a screen with holes is used to size particles to their desired size. In some setups, both machines are combined into a single machine, as the output of a shredder is usually well suited for a granulator machine, while the accuracy of the granulator ensures (relatively) equally sized particles in the end material.

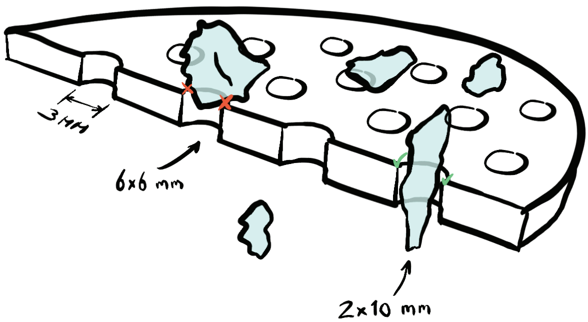


Figure 14: Oversized flakes passing the granulator screen.

In this project, the material used was shredded and granulated with a screen size of 3 mm. In practice, this means that granulate with two out of its three dimensions smaller than 3 mm can fall or be forced through the filters. Since PET flakes are usually roughly a millimetre thick, this means that once they are less than 3 mm wide, they can reach lengths longer than that and are also prone to folding once force is applied inside the granulator. This was confirmed by an industry expert, who stated that a granulator screen of 7 mm in practice results in the majority of the particles being smaller than 10 mm.

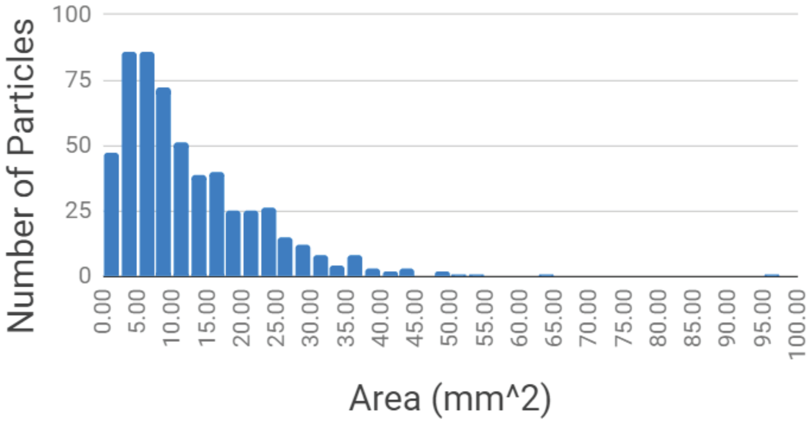


Figure 15: Particle distribution of a PET water bottle flake material (Little et al., 2020).

According to Little et al (2020), sifting the material created with a 5,84 mm hole diameter granulator screen and a 5 mm sieve yields 60% (by weight) of the material. Is does also effectively decrease the number of oversized particles as can be seen in Figure 16. It is thus plausible that the forces applied to the material inside the granulator play a role in oversized particles escaping through the screen.

Little et al (2020) also indicate that a reduction of the particle size can be useful to improve the '3D printability' of PET from recycled bottles. Next to sifting, heating the flakes to 100 °C can reduce the average particle area of the flake material effectively. Combining both methods showed even better results, but also suffers from both the disadvantages tied to each method. Where sifting generates 40% (by weight) waste material, heating the material adds a heating cycle to the process.

For this project, removing only the largest particles with a sieve might be interesting. For example using a 5mm sieve with a granulator screen of 3 mm. This could decrease sifting waste, while filtering out the outliers. Another option might be to reprocess the sifting waste using the granulator. The effects of sifting with a larger sieve and the processing of the oversized 'left-over' flakes is a subject for follow-up research.

Another disadvantage of the shredder/granulator machines is their lack of control on the minimum particle size. There is no lower limit for how small a particle can be. As can be seen in Figure 15, a significant part of the particles has an area smaller than 5 mm^2, but the largest particles are over 90 mm^2. In section 2.5, even particles as small as dust were observed, creating a wide range in particle sizes within a single material batch.

According to Principles of Polymer Processing (Tadmor & Gogos, 2006), fine particles are in general more difficult to feed into processing equipment, as was observed in section 2.5.

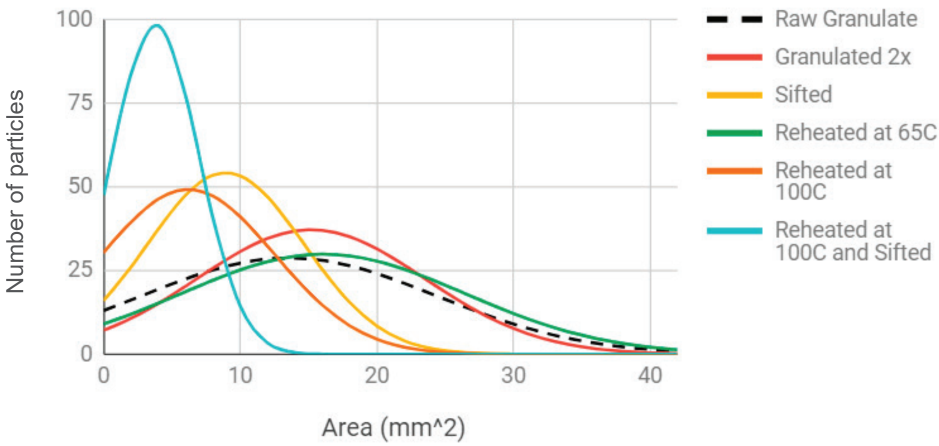


Figure 16: Size distribution of flakes after different processing methods (Little et al., 2020).

2.6.4. Particulate solids

Before it is molten and extruded, the material needs to pass through several machines. The second sub-function of the recycling system is thus to 'adjust the position' of the material.

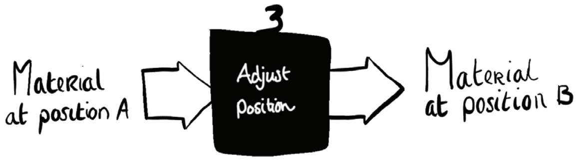


Figure 17: The third sub-function of the recycling system: to adjust material position.

The material resulting from the shredding and granulation of a bottle consists of a large number of small solid particles. This regrind has some interesting properties. The particles individually are solid, but together behave partially like liquids and partially like solids (Tadmor & Gogos, 2006). Similar behaviour can be found in sand, rice or grains. These materials are called Particulate Solids. In Figure 18 an overview of the most important properties of particulate solids can be found.

Particulate solids can flow like fluids, but are more susceptible to flow disruptions due to their nature to resist shear forces. Blockages can take shape in two distinct ways, as illustrated in Figure 19.

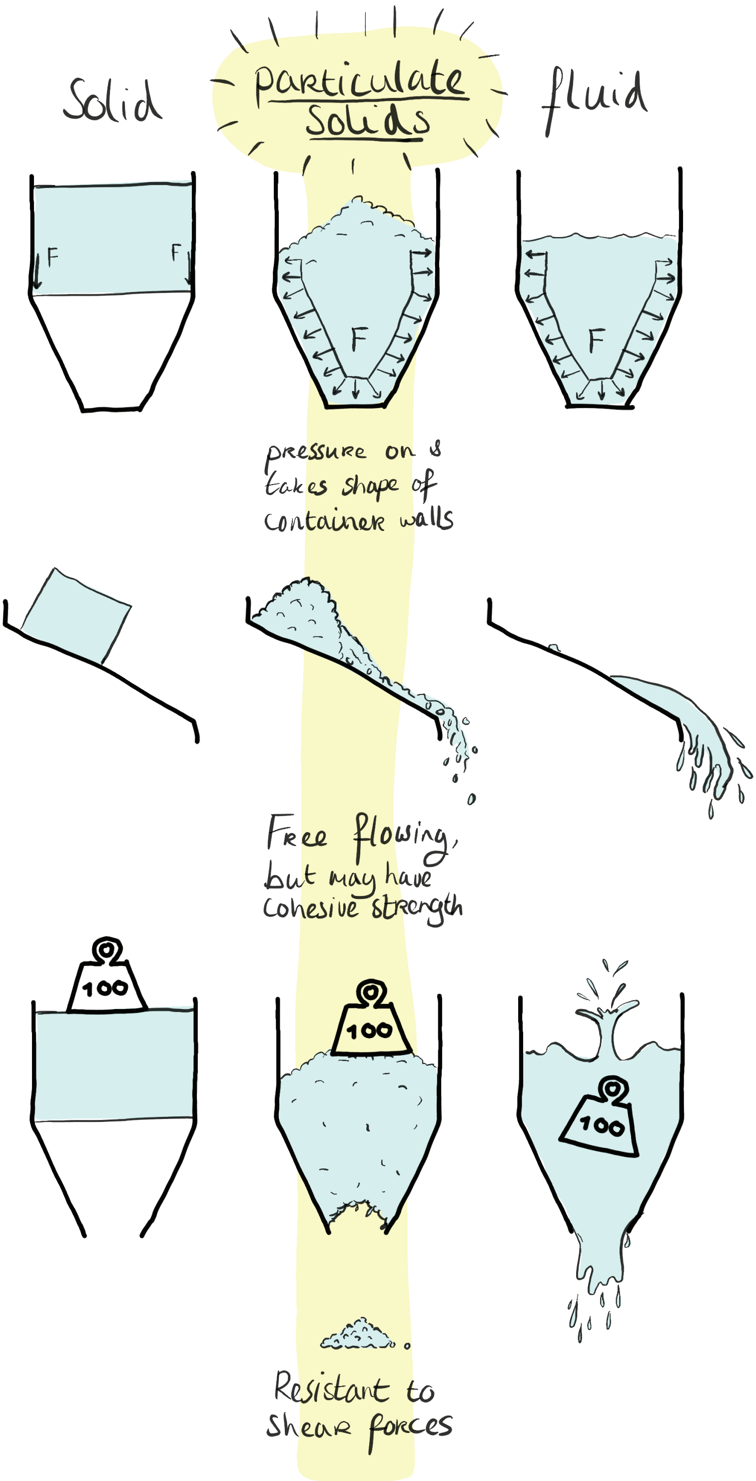


Figure 18: Particulate solids compared to fluid and solid materials.

To make sure to reduce agglomerates and blockages to a minimum, this set of guidelines can be followed when designing funnels, storage containers or other transport and storage solutions:

- For polymers a funnel slope angle of 60 degrees is sufficient (Syntron Material Handling, 2019)
- Smallest opening must be twice the diameter of the largest particle for irregular sized materials (Syntron Material Handling, 2019).
- As a particulate solid resists shearing forces, axial stress drops exponentially with distance (Tadmore & Gogos, 2006).

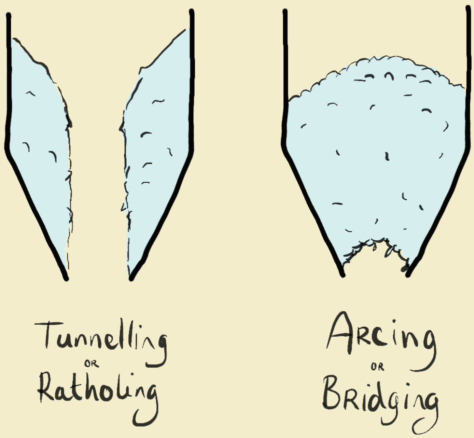


Figure 19: Two common types of flow disruptions: ratholing and bridging.

If preventing blockages is not possible, devices to 'break' blockages could be used. Examples are hammer machines, vibration motors, air cannons or fluidization systems.

2.6.5. The 3D printer

The last step is to create a product using the 3D printer from the dried flakes. The last sub function thus is to change the physical form of the material into a desired shape.

Extruder design

Consistent material output is essential for 3D printing, as inconsistencies can cause weaknesses or failure of the print. Next to properties of the material, the extrusion machine is of significant importance.

Figure 20: Example of a medium sized extrusion machine.

Extrusion machines consist of at least a barrel with a polymer extrusion screw inside. The barrel is equipped with multiple heating elements and sensors to allow for individual control of each zone. The zones allow for a controlled and gradual polymer melting process. Additional functions can be added if desired, such as improved mixing or gas removal sections.

The extrusion screw

The extrusion screw is the core of an extrusion machine and is often custom-made for use with a certain material or process. The simplest screws have three zones, the feed zone, the compression zone and the metering zone. In the first zone, the material enters the barrel and screw. The screw's channel depth (see Figure 21) at the feed zone is advised to be at least twice the size of the largest particle to ensure proper feeding (Griff, 2016). After the feed zone, the material enters the compression or melting zone. The channel depth decreases gradually to 25-50% of the channel depth at the feed zone, melting the material with heating elements and friction. The third zone, the metering zone, mixes the molten plastic and pressurizes it towards the exit. The channel depth is constant at 25-50% of the channel depth in the feed zone. The difference in depth of the channel at the feed zone in comparison to the metering zone, gives the compression ratio of the screw. General purpose extruders usually

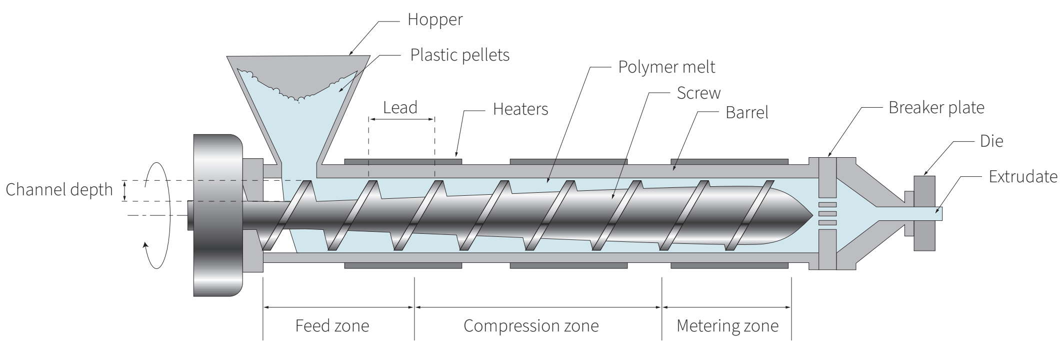
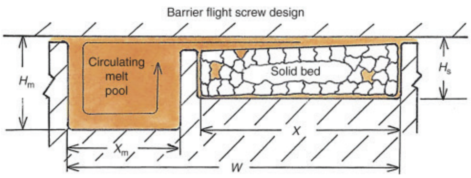


Figure 21: Layout of a typical extrusion machine and the most important dimensions.

have a compression ratio between 2,5:1 and 3:1, depending on the type of polymer and application (Reifenhäuser Reiloy, 2021; Extrusion Guide Book, 2015).

More complex screw geometry is possible to, for example, eliminate air or gas build-up during processing or to achieve improved mixing properties. When more output is desired, the diameter can be increased. Increasing the length of the screw is usually done to accommodate additional zones for vented extrusion (removal of gasses), but can also result in increased output (Griff, 2016).



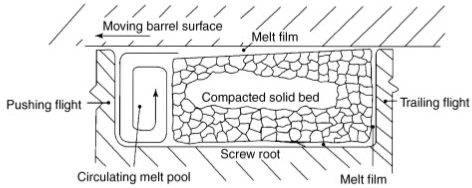
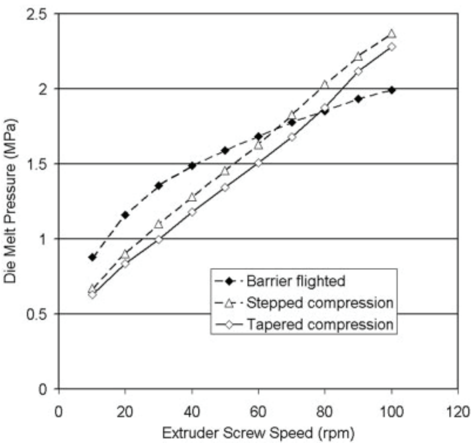


Figure 22: A zoomed-in cross section of a barrier flighted screw (left) vs a 'normal' screw (right) design.

A barrier flighted extrusion screw separates the molten plastic from the solid particles during the melting process (Figure 22). According to Kelly, Brown and Coates (2006), the barrier flighted screws are more consistent in die pressure and melt temperature at different rotational speeds (Figure 23).

In the design of the screw, a lot of parameters can be fit to suit the goal of the extruder perfectly. Baird & Collias (2014) provide theory and mathematics on extrusion screws and single screw extruders. However, the calculation is heavily dependent on a large set of assumptions making it unreliable, especially with a "non-standard" material such as PET flakes. Therefore, the exact dimensions will not be calculated. The channel depth, diameter and compression ratio will be estimated to provide a starting point for further development. It is necessary to consult an expert on screw and extruder design for the production of a final extruder.



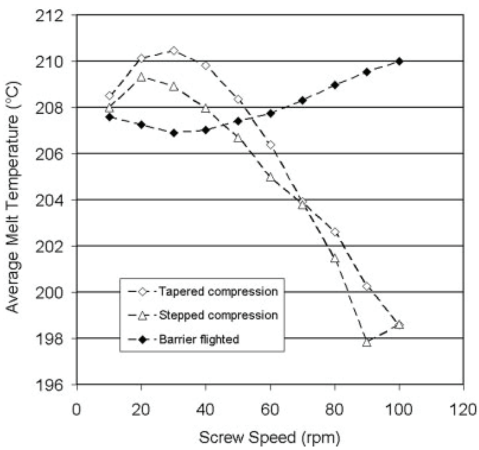
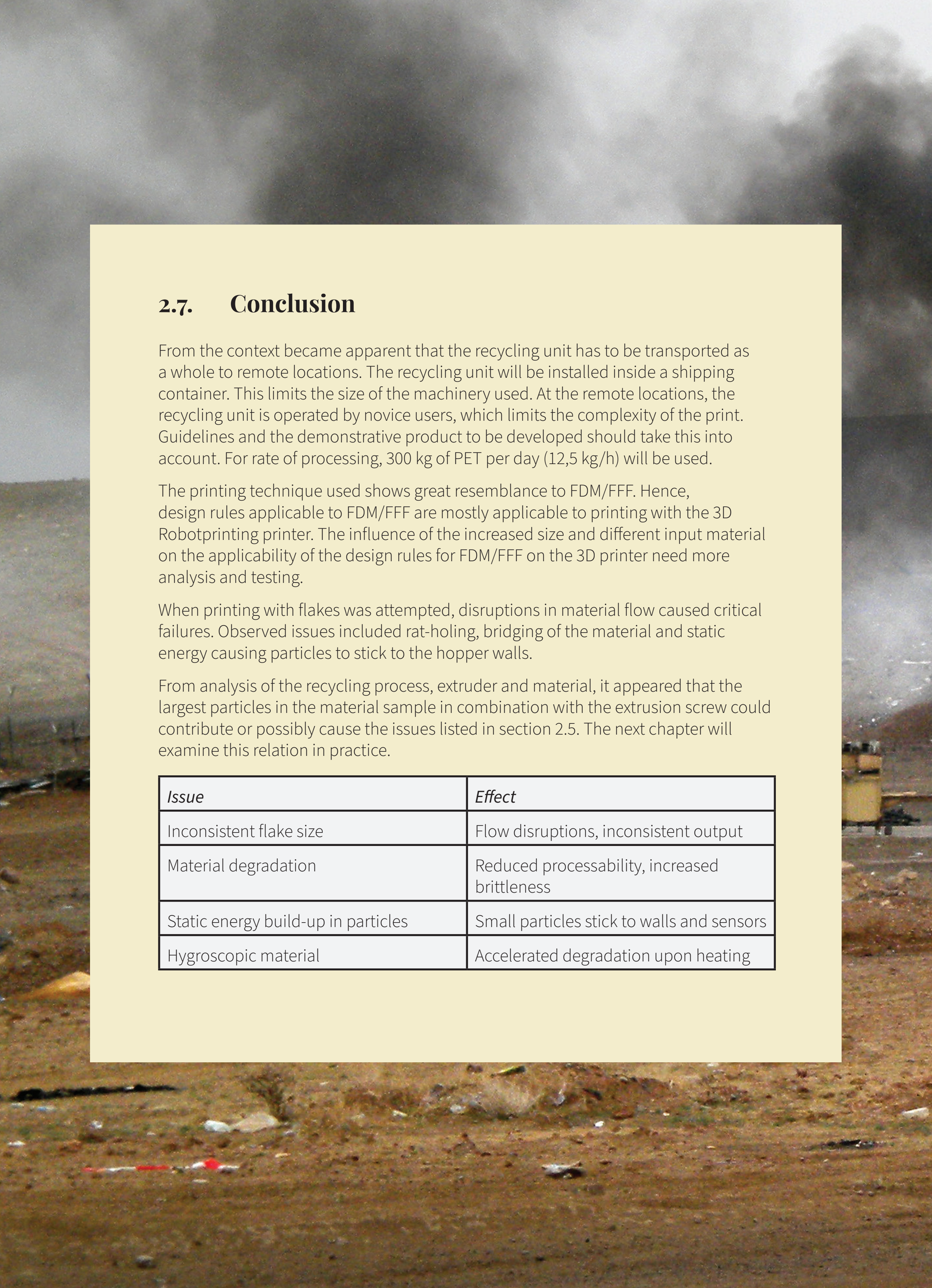


Figure 23: Die pressure (left) and average melt temperature (right) versus screw speed of barrier flighted and standard extrusion screws (Kelly et al., 2006)



2.7. Conclusion

From the context became apparent that the recycling unit has to be transported as a whole to remote locations. The recycling unit will be installed inside a shipping container. This limits the size of the machinery used. At the remote locations, the recycling unit is operated by novice users, which limits the complexity of the print. Guidelines and the demonstrative product to be developed should take this into account. For rate of processing, 300 kg of PET per day (12,5 kg/h) will be used.

The printing technique used shows great resemblance to FDM/FFF. Hence, design rules applicable to FDM/FFF are mostly applicable to printing with the 3D Robotprinting printer. The influence of the increased size and different input material on the applicability of the design rules for FDM/FFF on the 3D printer need more analysis and testing.

When printing with flakes was attempted, disruptions in material flow caused critical failures. Observed issues included rat-holing, bridging of the material and static energy causing particles to stick to the hopper walls.

From analysis of the recycling process, extruder and material, it appeared that the largest particles in the material sample in combination with the extrusion screw could contribute or possibly cause the issues listed in section 2.5. The next chapter will examine this relation in practice.

Issue	*Effect*
Inconsistent flake size	Flow disruptions, inconsistent output
Material degradation	Reduced processability, increased brittleness
Static energy build-up in particles	Small particles stick to walls and sensors
Hygroscopic material	Accelerated degradation upon heating

Figure 24: Burn pit in Camp Holland near Tarin Kowt, Afghanistan.

From Waste Bottle to Product

3

3.1. Introduction

While some examples of 3D printers printing with PET flakes were found (Van Plestik, 2020; Inhabitat, 2012), scientific literature on the matter is scarce. This chapter will aim to develop a preliminary extruder suitable for extruding PET flakes. An estimation will be made on the print quality to be expected from a flake-fed machine which will be used to develop the design guidelines (in the next chapter).

For this section of the project, the scope will be zoomed in to the extruder assembly and material preparation. The presumption that the majority of the issues are caused by the extruder being sized improperly will be tested (partially) in practice. The maximum particle size in a PET flake sample will be examined and compared to the advised preliminary values of important parameters of the extrusion screw.

In this project the machine will not be optimized, but only made suitable for use with flakes.

Research questions:

1) What properties has the PET flake material in practice?

2) How can the extruder be adjusted to process flakes?

a) What changes in extruder and/or feed geometry are necessary?

b) What changes in screw parameters (compression ratio, channel depth and/or lead) are necessary?

c) What will be the effect of said changes on extruder size and output?

3) What quality can be expected from printing with PET flakes?

3.2. Method

A material sample produced in a desktop shredder-granulator machine (a 3D EVO Shred-It) with a 3 mm sieve was received from the client and was used in the experiments.

To determine the density and particle size distribution of the flake material, a small experiment was performed. Several small sieves with hole sizes ranging from 1x1 mm to 5x5 mm were 3D printed (on a desktop 3D printer) to sort the particles by size. These sieves were stacked and filled with a small sample of the material. After shaking the sieves until no more flakes dropped trough their levels, the sieves were unstacked and their contents compared. This was repeated multiple times. More info on this experiment can be found in appendix A.

To determine the density of the bulk material, three samples between 1000 and 1500 mL of flakes were weighted on a kitchen scale. The container was shaken afterwards, to measure the influence of shaking on the density of the bulk material. This data was compared to data on PET from the Ansys Granta Edupack (2020) database. More info on this experiment can be found in appendix A.

In the ideation phase, multiple brainstorms were performed to generate ideas using the 'How-To' format. Subjects included "how to make flakes go down (in the extruder)" and "how to size bottles to equal flakes".

A series of experiments originated from ideas and concepts from the ideation were performed. A set of funnels were 3D printed and tested on flow properties. Funnels tested all had wall angles of 60 degrees, 20 mm holes, but different bottom outlet shapes and angles: two funnels with a round outlet hole, a tilted funnel and a slotted funnel. These tests were repeated with an added extrusion screw and flow aids. Two types of improvised screws were used: a 20 mm metal drill with a large channel depth and lead, and a 18 mm concrete drill with a small channel depth and lead. As flow aids some steel wire, kitchen tools, pressurized air and a ruler were used. More info on this experiment can be found in appendix D.

To decide on a concept direction, additional feasibility tests were performed. A prototype was built using a 60mm ‘ground drill’ and 70 mm PVC plumbing pipe with screwable end caps at both ends. The caps had holes to fit the drill shaft on one end and a 3D printed funnel on the other. These funnels were printed with different hole sizes, angles and shapes: a funnel with a 10 mm round hole, one with a hole twice the surface area, one with a slotted hole sized the same as the extruder inlet. Using this setup a cold extrusion was performed to test the flake acceptance of a large screw and ability to force feed an existing extruder. For the latter, the prototype was connected to a CEAD polymer extruder using a 3D printed connector. As one of the concepts was hard to test in practice, an expert in the field was contacted to judge on the feasibility of the concept based on a concept drawing. More info on this experiment can be found in appendix F.

In an experiment by 3D Robotprinting, a series of extrusion tests with glass filled PP on different speeds and using different nozzles were done. The weight extruded was recorded. For this project, an analysis on the data gained in this experiment was performed to estimate the effect of a larger extrusion screw on print performance. The extruder used in the experiment is a CEAD extruder for 3D printing and has a screw with a channel depth of 5,3 mm and a screw diameter of 25,0 mm. The screw lead is 24,4 mm. At the metering zone, the screw has a channel depth of 1,75 mm, which means it has a compression ratio of 3:1. These dimensions were recorded in the “Extruder Disassembly” experiment in appendix E. Attached to the extruder is a five metre long heated tube with 16 mm internal diameter. The tool head features an interchangeable printing nozzle of 3,6 mm or 8 mm (hole diameter). This data is combined with a mathematical model by Baird & Collias (2014) to estimate the material increase by increasing the barrel diameter.

Figure 25: Flake size distribution from a 3mm granulator (Left to right: 5 mm, 4 mm, 3 mm, 2 mm and 1 mm, square hole size).

3.3. Flakes in practice

When sieving a sample of flakes is was expected that most of the material would be smaller than 3 mm in diameter as the sieve size of the shredder-granulator machine was 3 mm. In Figure 25 can clearly be seen that the majority of the flakes were smaller than 4 mm, but that there are particles sized larger than 5 mm. From 117 grams of sifted material, 16 grams was caught in the 4 mm and 5 mm sieves (combined). To develop an extruder for all the particles, even an extruder with a channel depth of 10 mm is not suitable, as the channel depth is advised to be twice the diameter of the largest particle. In multiple sieving runs, the largest particle measured was 16x15x4 mm and was a crumpled up, long flake. To make the extruder suitable for material of this size, an immense increase in extrusion screw diameter would be necessary.

This experiment does acknowledge that when using a sieve, the largest particles can be filtered out even though the flakes have passed through a sieve during granulating. Possibly, the absence of force during sifting decreases the likelihood of oversized flakes passing the sieve. An industrial sifting machine is thus advised to be added to the recycling unit.

By weighing multiple samples of the flakes, an average density of 0,258 g/cm3 was measured. 24% reduction in volume (average) of was measured after shaking the sample.

Combined with the data from Ansys Granta Edupack (2020), a calculation for the screw compression ratio can be made. If an output of 3,5 g/s (300 kg per day) is desired, a volume of 2,6 cm3/s of solid PET needs to be output. Taking in to account the reduced density of PET flakes, a volume of 13,5 cm3/s (uncompacted) or 10,8 cm3/s (compacted) needs to be input to keep the extruder fed. This means that the amount of volume reduction inside the barrel, the compression ratio, needs to be 4:1 if the material enters the screw perfectly and is compacted before entering the screw. In practice, a higher compression ratio might be desired to account for inconsistencies and imperfect feeding. This is higher than what is used in generic polymer extruders, but within the range of possibilities for custom extrusion screws. Due to time and financial constraints, the extrusion screw with a compression ratio of 4:1 was not tested.

PET bottle flake properties (3mm sieve)

- Density of Flakes: 0,2581 g/cm3 (measured)
- Density of flakes compacted: 0,3355 g/cm3 (measured)
- Density of solid: 1,29 – 1,39 g/cm3 (Amorphous, Ansys Granta Edupack (2020))
- Melting point: 250 °C
- Glass transition temperature (T_g) = 60-84 °C
- E = 2800 – 3100 MPa
- σ = 55-75 MPa, (FDM) 3D printed PET: 27-47 MPa, for rPET: 29,62 MPA
- Intrinsic viscosity: 0,70-0,85 (0.70-0.78 normal to 0.78-0.85 carbonated)
- Smallest particle size (observed): Dust (not measurable)
- Biggest particle size (observed): 16x15x4 mm

Take-aways from this section:

- To increase consistency in output, more material input is required
- Flake density can be increased by shaking the storage bin
- Screw compression ratio of 4:1 (or more) is advised
- Sifting is effective to reduce particle size and filter outliers

3.4. Extruder requirements

Operation & Transport

- The machine must be operable by a novice (context)
- The whole system is installed in a standard shipping container (context)

Funnels & Containers

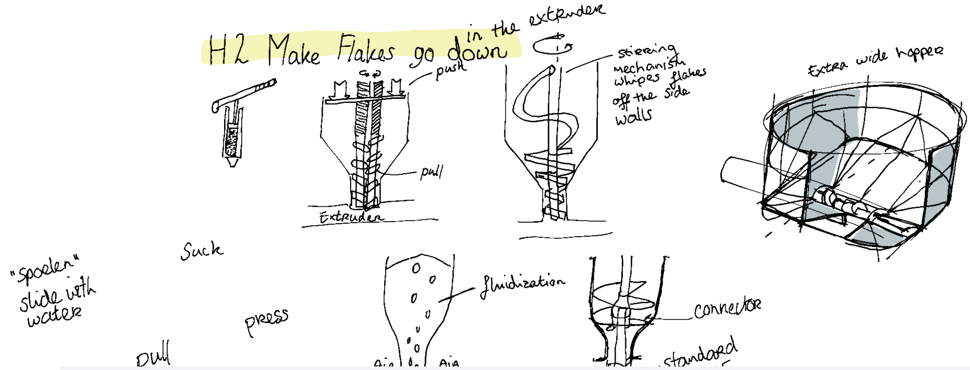
- Wall angles must be at least 60 degrees (from the horizontal plane) to prevent flow blockages (literature)
- Hoppers and bins must be electrically grounded to prevent build-up of static charges during movement of the material (observation)
- The smallest hole in the system must be larger than twice the diameter of the largest particle (literature)

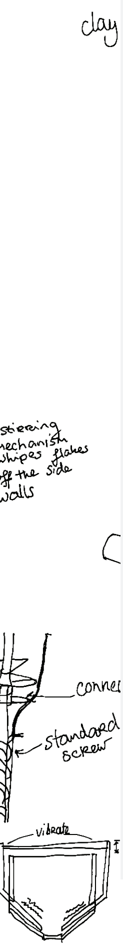
Material treatment & storage conditions

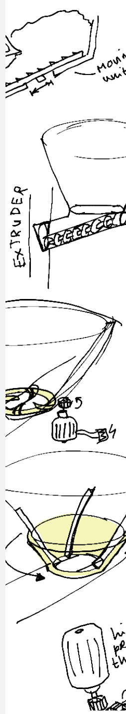
- The material must be dried before heating (literature)
- Material transport under axial pressure should be kept to a minimum, as axial stress drops exponentially over distance (literature)
- The material should be stored away from humidity (after drying) (literature)

Extruder Design

- Polymer extrusion screw compression ratio at least 4:1 (calculations)
- Channel depth must be larger than twice the diameter of the largest particle (literature)







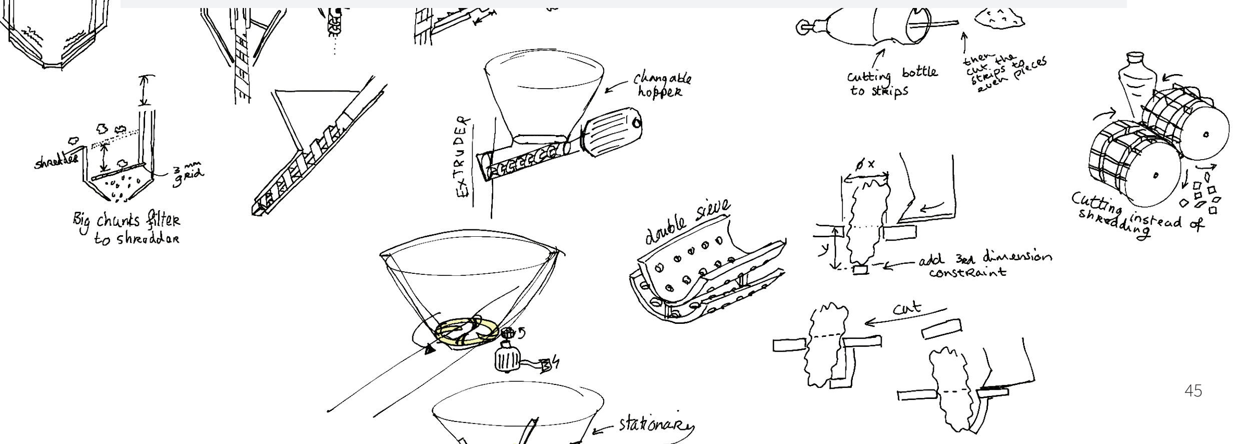
3.5. Ideation

While exploring the material, an initial ideation on extruder designs was done. Working principles behind the ideas were tested in quick and simple tests. After testing the ideas, three promising ideas were picked and detailed.

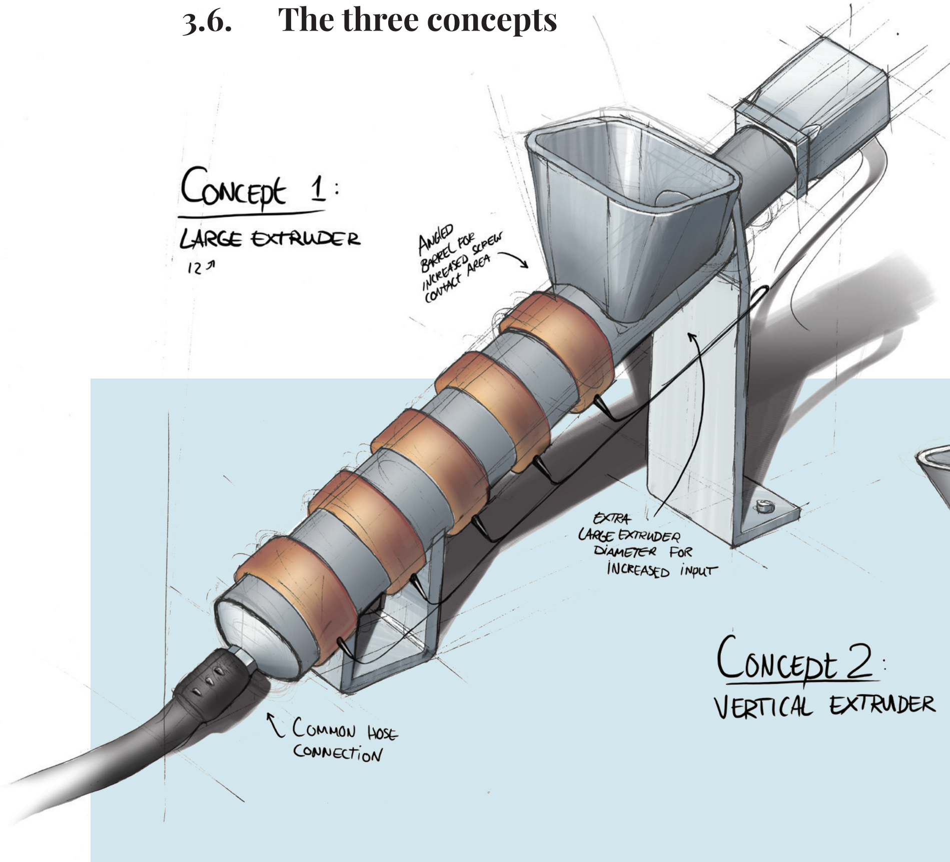
From the experiments following the ideation, the tilted funnel showed promising results. Especially when using the 18mm concrete drill, the output was consistent and high. The funnels using vertical screw setup were easy to connect to flow aid systems in the hopper, such as a rotating steel wire, thanks to the circular hopper shape. As the outlet hole is the smallest of the three, the hopper does not empty without aid when removing the drill. Also, in the vertical orientation severe ratholing around the screw-drill was observed. When emptying the hopper, flakes stuck to the angled plastic walls.

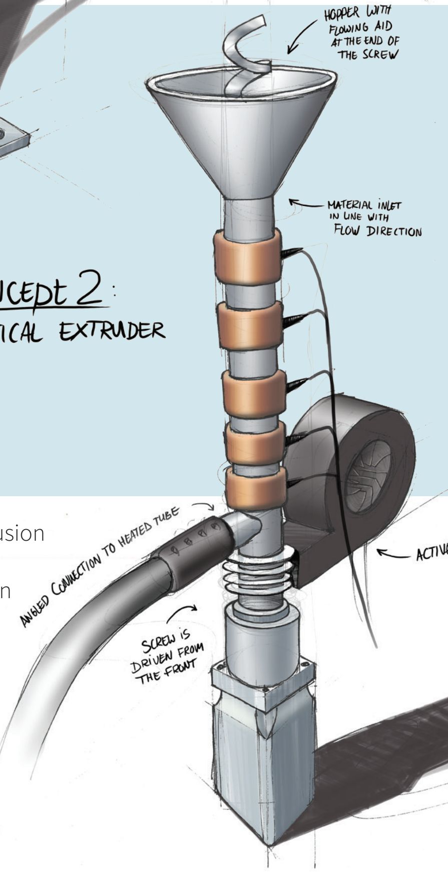
The 20 mm metal drill proved to be the better flake conveyer per revolution thanks to its bigger channel depth in most cases. It was observed that a larger volume of flakes was transported per revolution. The setup with the largest observed output, was the 30 degrees tilted screw with slightly larger diameter and the concrete drill. This could be due to larger area of flake-screw contact combined with the loose tolerances leaving more space for large particles to enter the funnel without being forced into the small concrete drill channels. Gravity could also contribute to flake flow due to the angled funnel outlet.

From these findings three concept designs were developed. In appendix D a more elaborate description of these experiments can be found.



3.6. The three concepts

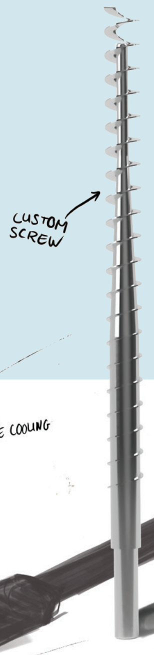




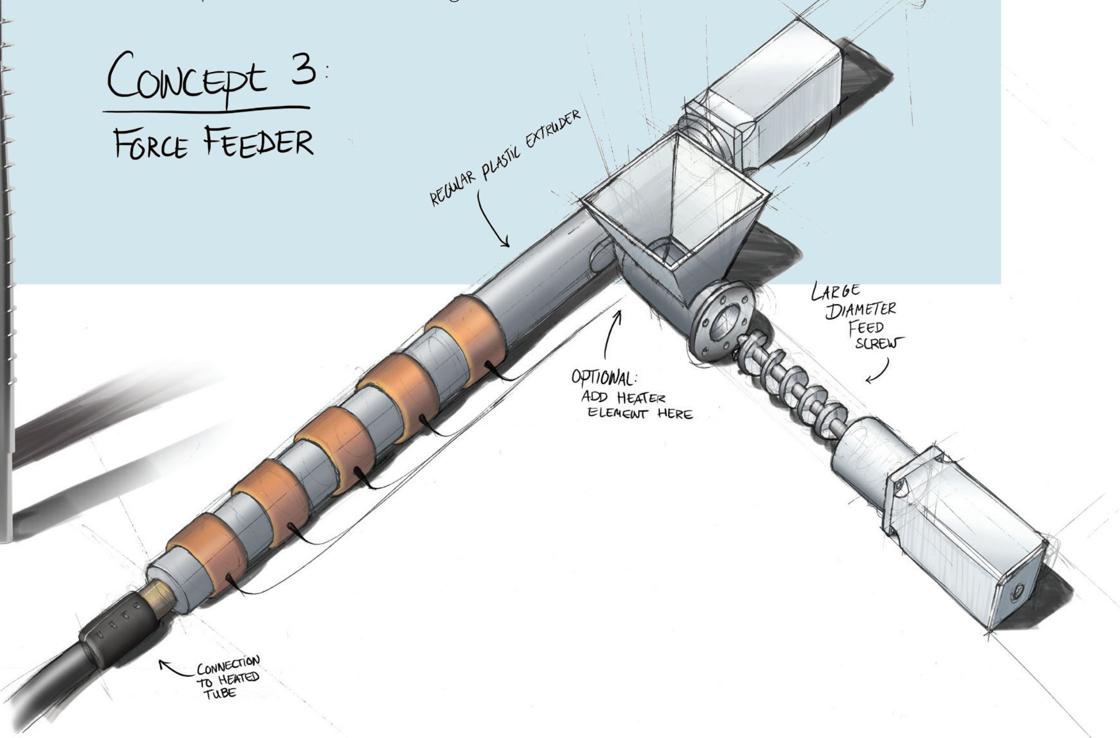
Concept 1, the large extruder, is based on the theoretic conclusion that a higher diameter extrusion screw should be enough to enable the extruder to consistently input flakes. As observed in the experiments in section 3.3, tilting the extruder could be beneficial to the flake acceptance of the extrusion screw. Advantages of this concept include the high number of standardized parts and simple implementation.

Concept 2, the vertical extruder, makes use of gravity to guide flakes to the extruder. It uses a pulling motion to pull flakes into the extrusion screw. At the same time, the upper end of the custom extrusion screw functions as a flowing aid inside the hopper. Due to the vertical orientation and flow aid inside the hopper, the gearbox and motor driving the screw have moved to the opposite end of the material input, which is quite novel and needs some research before judgement is made on the feasibility. Advantages include improved feeding, a single motor drives the whole design.

Concept 3, the force feeder, is a design to enhance a stock extruder. It consists of a force-feeding section with a large diameter and connects to the small input on the stock extruder. Flakes are thus forced to enter the barrel. An optional addition might be to heat the funnel at the end of the force feeder. The biggest advantage of this concept is that is uses an existing extruder. It does however require and extra motor and gearbox.



Concept 3: Force Feeder



	The Large Extruder	*The Vertical Extruder*	*The Force Feeder*
Pros	Large extrusion screw and high compression ratio Tilted setup for increased flake-screw contact High number of standardized parts Simple implementation	Flow aid inside hopper without extra motor and gearbox Gravity aided screw feeding Small horizontal footprint (space)	Very large feeder screw possible Addition to standard extruders Easy implementation Low start-up time
Cons	Increased material output Increased start-up time	Unusual extrusion screw Requires research to implement Tight tolerances required in manufacturing	Additional motor and gearbox require operation Requires heated funnel to function

Table 3: The three concepts compared

3.6.1. Prototype tests

From the experiments performed using the cold extruder prototype, it became clear that it is hard to force the flakes through a funnel. With steep funnel angles and a high force some flakes were extruded. Since flakes resist shearing forces, there was only very little pressure left at the end of the funnel. When the force feeder prototype was connected to an extruder, the system worked worse than when directly feeding the flakes into the screw opening. The sound of the motor indicated starve feeding was occurring, causing the barrel pressure to drop. The concept could provide a benefit if the flakes were pressed against a heated funnel to melt the flakes to decrease their ability to resist compressing forces.

As a stand-alone extruder, the prototype did function properly. The transport of the flakes through the tube showed no issues at all. The large prototype was capable of emptying the hopper with a consistent flow, which is promising. A more detailed description of this experiment can be found in appendix F.

Figure 26: The simplified extruder prototype.

3.6.2. Expert feedback

The second concept, The vertical extruder, has two main feasibility concerns. The pressure and temperature of the molten material is the highest near the end of the extruder due to the screw pressing the melt through the heated tube. The polymer should not enter the bearings and gearbox compartment located there. Therefore, some sort of high pressure, high temperature seal is required. Secondly, the polymer melt is usually transported through the extruder in a linear path. By using a sideways exit, the path contains a 90°angle. This could create spots where residue could be left behind.

According to E. Tempelman (personal communication, October 5, 2020) from the TU Delft faculty of Industrial Design Engineering, molten plastic has such a high viscosity, that even with the high pressures and temperatures near the barrel end, a seal should be possible. By using tight tolerances, a gap can persist which is too small for the melt to be pushed through, but allow for movement of the screw. This is comparable to an injection moulding machine's air vent channels. He considers concept 2 technically feasible.

According to Lau (2017) and Upmold (2017) the venting slot depth is dependent on the viscosity of the material. For PET the venting depth is 0.013 to 0.018 mm. These tight tolerances increase the manufacturing cost, as it will require designated equipment and skill to manufacture products at such an accuracy. As it is common in injection moulding, it is not impossible though.

An interesting remark by E. Tempelman (personal communication, October 5, 2020) was that plastics need a lot of energy to warm up, as they are terrible heat conductors. By increasing the barrel size, the start-up time likely increases.

According to S. Bakker (personal communication, Juli 11, 2020) from extruder selling company Xtrusion, it is easier to extrude PET flakes with a larger extruder, confirming the prototype tests and previously found literature.

3.6.3. Concept choice

Concept 1: The Large extruder will be pursued further for this project, due to the ease of implementation and high number of standardized parts, making a functional model on short timescale possible. For future projects, concept 2 might be interesting to continue research on.

3.7. Final concept evaluation

While a large extruder diameter and channel depth is likely to solve the flake feeding issue, it will likely increase the extruder length and output as well. As the extruder is housed inside a shipping container, the space available is limited. In this section an attempt is made to balance increasing the extruder size without increasing the size and output too much.

In this section data from an experiment performed by 3D Robotprinting will be analysed and compared to a mathematical model to examine if an increased screw diameter leads to increased output and what the influence is on the abilities of the 3D printer. Finally, suitable extruder parameters will be determined.

3.7.1. Extruder behaviour in practice

From the data of the experiment performed by the client, it became clear that the maximum output of the extruder in the printer configuration is around 9.8 kg/h 30% glass filled PP, an equal volume to 11.7 kg of PET, at max speed (167 RPM) when using an 8 mm nozzle.

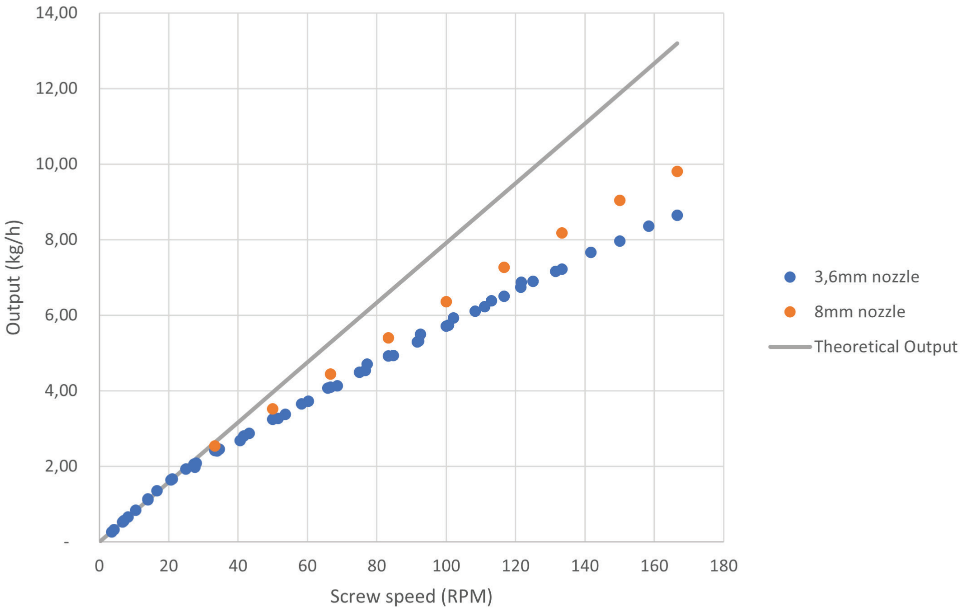


Figure 27: Expected theoretical output vs measured output.

The experiment also showed that the volume extruded per revolution was not constant at different speeds. The amount of material extruded per revolution decreases slightly as RPM increases, as can be seen in Figure 27 and Figure 28. It is known that generic extrusion screws can perform unreliably at higher speeds (Kelly et al., 2006). For extruding at higher RPM, a barrier flighted screw will increase pressure consistency resulting in a more linear weight per revolution over different revolution speeds. The 'normal' extruder used by Kelly et al. (2006) shows a linear relation between amount of material extruded and RPM. This is an indication that there is something else influencing the 3D printer's extrusion system, which was not present in the experiment by Kelly et al. (2006). By Kelly et al. (2006), a die with a relatively large cross-sectional area was used, causing a low die head pressure. Increasing the cross section of the parts after the extruder, could thus decrease the pressure required for output.

For the 3D printer, an increase in material flow is thus not simply the result of an increase in extruder diameter. Neither does a larger nozzle increase the output linearly. If a higher output is desired, a closer look needs to be taken at the effects of the size and length of the heated tube and the nozzle size.

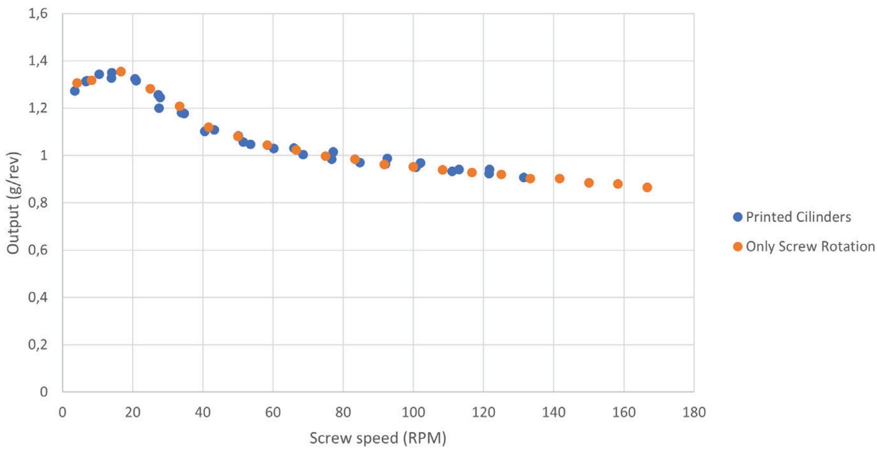


Figure 28: Output for moving vs stationary tool head

Data from the experiment by the client showed that there was no influence on the rate of output when printing or when stationary, which can thus be ruled out (Figure 28).

From the results shown in Figure 29 can be seen that the nozzle size has an influence on the output of the machine. The 8mm nozzle shows an increase in output, but the difference is marginal for an increase of more than double the nozzle diameter. A larger nozzle size thus increases the output, but only slightly.

The inner diameter of the heated tube is of influence as well. The Darcy-Weisbach equation states a high flow velocity, small diameter and a long tube length increase the friction on material flow. Due to time constraints, the influence of the heated tube is not tested in practice, but based on the Darcy-Weisbach equation can be assumed that transporting a high viscosity polymer melt through the heated tube has a significant limiting influence on pressure and flow rate.

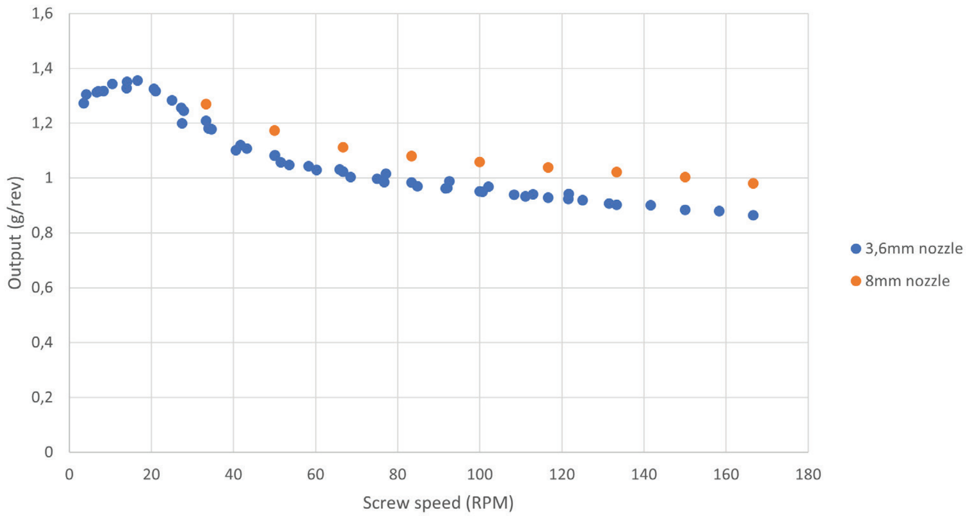


Figure 29: Output for a 3,6 mm nozzle vs an 8 mm nozzle

The combination of pressure instability of the screw at high rotational speeds and the high heated tube and nozzle resistance explains the reduced output seen in the data. If material throughput increases further due to an increased extruder diameter, these factors could increase even further. An increase in diameter could however also allow the extruder to be used at lower rotational velocity, reducing pressure issues in the extruder.

3.7.2. Final screw dimensions

By using the data gained from the experiment by 3D Robotprinting and the mathematical model for extrusion screw output (by Baird & Collias, 2014) an attempt will be made to estimate the increase in output when a larger screw diameter is implemented.

A sifting step is necessary to ensure the majority of the particles larger than 4mm in diameter are removed. By sifting the largest particles, the extruder size increase is minimal. To design the extruder for the remaining particles, a **channel depth at the feeding zone of 8 mm** (increase of 2,7 mm) or more is required. If the feeding section core diameter remains unchanged, the screw **diameter will be 30,4 mm** (increase of 5,4 mm). Using a **4:1 compression ratio** (previously 3:1) results in a 2 mm channel depth at the metering section (increase of 0,25 mm).

Based on the simplified calculation and data from the experiment, the estimated **increase in output is around 23%** (at low screw velocity). The increase will be less in reality, as the resistance of the heated tube increases at higher flow rates and the effectivity of the screw decreases at high velocity.

If the material is not compacted before entering the screw, a **compression ratio of 5:1** should be used. The estimated **output will then be roughly equal** to the current output (-2%).

The polymer extrusion screw has many more tweakable variables that influence and can contribute to proper PET flake extrusion (Frankland, 2013). Hence, it is strongly advised to engage an expert in polymer screw design upon further development for the final production of this part of the recycling unit.

3.8. Conclusion

The extruder currently in use is not suitable for processing flakes and will never be. However, when building a new printer, adjustments can and should be made. For short lead time and financial reasons, a simple, large extruder design is desired. In the table below, the advised adjustments are listed. These numbers should serve as a starting point for extruder development. Involving engineers in polymer screw and extrusion techniques is critical for the best possible extruder.

Adjustments

- Sifting machine with 4 mm sieve added to the chain
- Channel depth increased to 8 mm
- Screw compression ratio increased to 4:1 (when compacted) or 5:1
- Barrier screw design
- Vibration motor inside hopper
- Metal, grounded hopper

Product Development

4.1. Introduction

To draw up the preliminary 3D printing guidelines, a product will be developed for 3D printing with flakes. During the development, 3D printing tests will be executed to search for the best solution to design problems. To determine a product direction, scenarios were created based on the context. After brainstorm sessions to ideate on possible directions, a product to print was chosen.

4.2. Method

Three Scenarios based on the contexts from chapter 2 were created. From the scenarios user needs were mapped, which were used to guide the brainstorm sessions during ideation. The ideas were rated on three factors: their relevance for the context, their printability on the machine and the required print quality to function. From the resulting plot, three ideas were picked and compared, from which a final idea to pursue was chosen.

4.3. Scenarios

Below three written scenarios in the shape of a small story are listed. These scenarios are based on the context analysis in chapter 2 and were created based on information from the client (scenario 1), stories by refugee help organisations UNHCR (UNHCR The UN Refugee Agency, 2018; Mora, 2021; Dunmore, 2015; UNHCR The UN Refugee Agency, n.d.), Oxfam-Novib (Oxfam Novib, n.d.) and Unicef (Ferguson, 2018; Ulin, 2013) (scenario 2) and a previous project performed by the author (Blok et al., 2018) and Climate & Clean Air Coalition (2015), Tomita et al. (2020) and Jambeck et al. (2018) (scenario 3) and depict the current situation.

The scenarios have two things in common: The need for proper waste disposal and the scarcity of anything but basic products. The (most interesting) waste consists of PET from used water bottles.

Scenario 1: NAVO army base, Uruzgan, Iraq.

"Peter is a soldier sent to Iraq to assist in local operations. In between shifts, he is required to stay inside the walls of the settlement as much as possible. However, inside the walls is only little entertainment. Activities performed are often sports or reading. However, after being stationed there for four months, Peter is longing for something different. Peter and his colleagues need to drink bottled water, as the water supply in the settlement is limited and not suitable for drinking. As Peter is stationed in a settlement with 1200 other soldiers, a large number of used bottles are collected daily. As there is no infrastructure to get rid of their waste, all the bottles are burned at the waste disposal location at the edge of the camp."

Scenario 2: Refugee camp near border of Uganda.

Yassmin is a refugee, who fled the war in neighbouring country Sudan with her three children. Back in Sudan her husband used to be a dentist, a useless profession in a refugee camp. Now, they spend their days hanging out in their tents or outside in shady spots. To keep their environment clean, she burns their waste in a nearby dirt pit, which causes a smell to linger over parts of the camp. As clean drinking water is limited, it is supplemented with bottled drinking water. The drinking bottles represent a large part of the waste Yassmin burns daily.

Scenario 3: Dar Es Salaam, Tanzania.

David belongs to the poorest in the city of Dar Es Salam. Every day he sleeps in the with plastic littered local slumps. During the day he tries to carry luggage for tourists arriving by boat to cabs. This is work offers little money and is very uncertain. Some days he spends hours waiting for a tourist to assist near the small shop of a friend of his. Every day is a gamble if he can make the ends meet. In a touristic, big city like Dar Es Salam, a high number of tourists pass every day. As tourists only drink bottled water, there is a lot of waste from bottles, caps and cellophanes used for packaging.

Working with 3D printers usually involves post-processing. When working with plastic as a material, it is important to make sure residue from post processing does not end up in the environment that is being cleaned by the recycling unit. Post-processing steps such as sanding, sawing and drilling are known for creating large quantities of small particles. This plastic dust is very hard to collect, especially in these scenarios. Therefore, the post processing of the 3D print should be limited, so the creation of this plastic dust is prevented.

As in all scenarios the recycling system is stationed in a remote area, it is undesirable for the product to rely on materials sourced elsewhere. Examples could be bearings, hinges or other parts which need to be imported. A single part print is thus encouraged.

In a remote setting, it is also unlikely that technical experts on 3D printing and/or the machine are available for support. The product should be designed with this in mind.

4.4. Product criteria

The product must: (Requirements)

- Serve a purpose in one or more of the scenarios (context)
- Be printable by a novice machine operator (context)
- Contain geometry which is not too simple nor too complex
- Require no post processing (due to release of micro-plastics) (context)

The product is preferred to: (Wishes)

- Increase material value as much as possible by function or form
- Serve a social purpose
- Show benefit of recycling: cheap material; create value from nothing/waste,
- Showcase the possibilities of the 3D printer: On demand production; Customizable products; Flexible in product nature/no initial investment

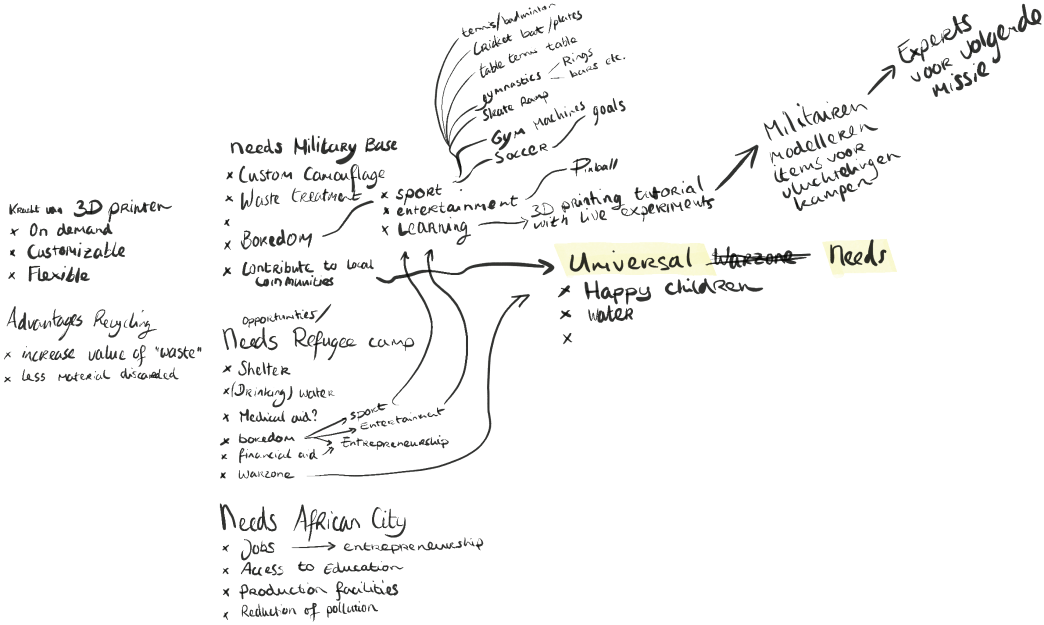


Figure 30: The needs identified and connected.

4.5. Ideation

From the scenarios proposed in section 4.3, specific user needs for each scenario were identified (Figure 30). From this list, connections were made between the user needs in different scenarios to find out if there were common grounds to explore further. An example of a shared need would be 'reduce boredom', present in scenario 1 and 2. For shared needs like this one, small brainstorm sessions were performed. Where possible, needs were combined to create more relevant directions for all scenarios. This resulted in a mind map of possible idea directions, which were used as a starting point for a brainstorm. Parts of the result can be seen in Figure 31.

Figure 31: Part of the Brainstorm

4.6. Comparison & concepts

In Figure 32 the ideas are arranged based on their relevance for the context, if they are likely to be adapted into a printable model for 3D printing and what print quality would be required for the object to function.

The ideas were clustered based on three factors: their relevance for the context, their printability on the machine and the required quality to function.

To be relevant for the context, the product needs to serve a purpose in one or more of the scenarios.

For the printability, the ideas are ranked based on the simplicity of their geometry, the amount of detail in their shape and if the geometry has hard-to-print features, such as large overhangs.

The required quality to function is based on the requirements posed on the item for it to function, like structural integrity, material purity, tolerances or if post-processing is required.

As an example, a vase is not particularly relevant for the provided context, is easy to make into a printable model and can be printed coarsely and still function as a vase. A water purification column however is relevant in the provided context, the geometry is likely printable, but it would require an uncontaminated material and relies on water tight seals between parts to function and thus needs fine manufacturing on the print quality scale.

In chapter 3, was concluded that a decent quality was likely to be achieved, thus 3D printing a simple vase will not be interesting. In Figure 32, the area of interest is marked green. The ideas in this area are complex enough to print, while also being tied to the context.

The ideal product should be found in the green area as displayed in Figure 32 or be increased in complexity to fit in the green area.

Figure 32: Printability vs context vs quality

From the ideas, three directions were selected as most interesting:

Direction 1: Design Furniture

While outside the green area in Figure 32, furniture could be made interesting enough by adding complex design features. The furniture could be designed by a famous designers or artists remotely across the world and printed near big African cities, such as Dar Es Salam. Designer furniture can be sold to hotels, lodges and other tourist-rich places. As part of the value of the design comes from branding, a higher value increase of the material is realised with limited extra costs, thus creating a higher economic incentive.

+ Increase material value by branding

- Only applicable near tourist industry

- 3D printing furniture has been done a lot

Direction 2: PET Playground

3D printed slides or seesaws are applicable almost anywhere. Could be designed and/or customized by (military) trainees as a course on location. As kids are involved, print quality should be consistent enough for the objects

+ A nice gift to local communities: Social purpose

+ Balance in complexity versus printability

Direction 3: Dentist/barber chair

On demand production of scarce items required for hygiene/medical purposes, such as a barber chair in a refugee camp. Could stimulate entrepreneurship and self-reliance.

+ Stimulate entrepreneurship: Social purpose

- Only for specific people (barbers/dentists) at specific locations

- Might be too complex

The PET Playground is chosen as it has a clear positive goal applicable to all specified contexts and offers freedom in the design of the geometry to create a printable object.

4.7. The final product

Within the playground theme multiple directions were considered. As the prints size is limited by the print bed, small objects were preferred. Depending on the achieved print quality, multi-part designs could be interesting. Using prior knowledge of FFF/FDM printing, two items were chosen for this concept: the slide and the seesaw. Both can be printed large and small, dependent on printer properties.

As 3D Robotprinting offers courses in 3D printing with their robot, the complementary concept of a learn-by-doing course could be a valuable addition. To let military personnel develop 3D modeling skills and the basics of design for 3D printing, the slide and seesaw can be used as an example project.

As the focus of this project lies on the development of guidelines and technology to enable printing with PET flakes, only the slide was developed further. The decision for a small scale children's slide was made based on the printer limits and to allow multiple units to be printed and be of use in local societies.

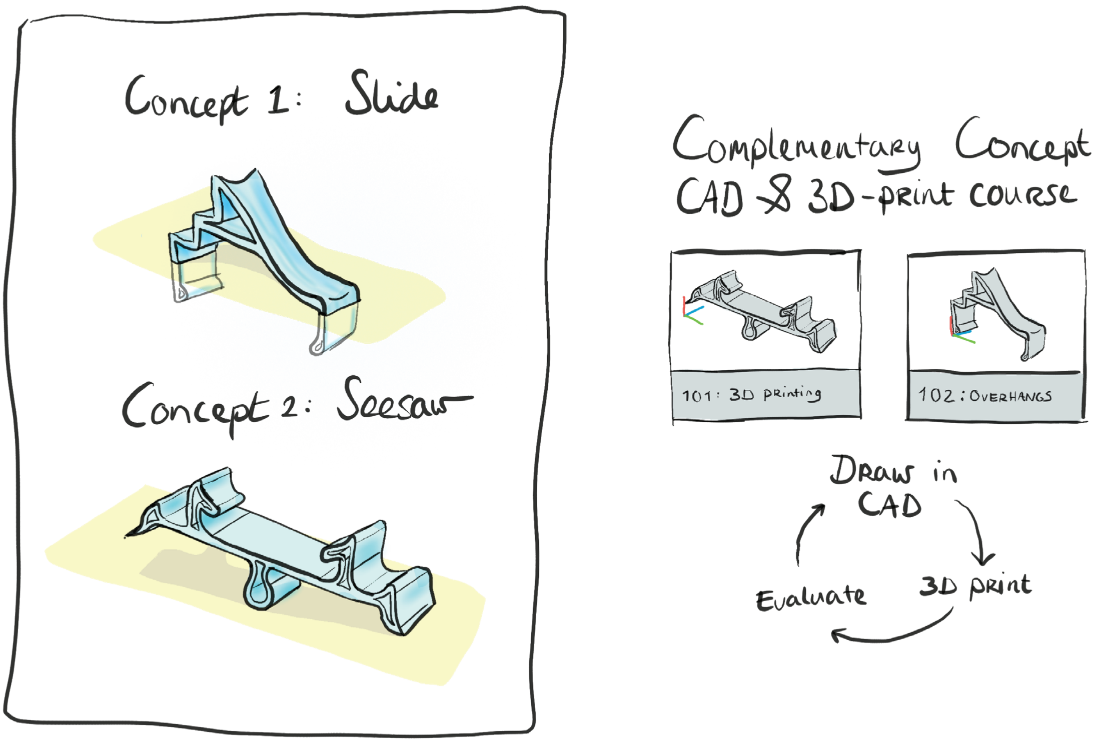


Figure 33: The two playground concepts

Design for 3D printing

5

5.1. Introduction

The two most important differences between the printing technique of the 3D Robotprinting printer and a commonly used FDM/FFF printer are the increased size and the use of granules instead of filament as feedstock (see section 2.4). A some design rules developed for FDM/FFF printing can thus be applied directly when optimizing designs for the 3D Robotprinting 3D printer, but some cannot. This chapter will focus on the identification of preliminary 'replacement' guidelines for incompatible design rules from FDM/FFF.

5.2. Method

By developing and printing a children's slide, the printing process is studied. First, the developer of the slicing software was interviewed on how to design for the printer and results of a previous experiment were studied. The experiments were performed by students in commission of 3D Robotprinting with virgin PET. Using the take-aways from this study, a brainstorm session on the slide geometry was performed. After settling on a preliminary slide geometry, the first full-scale print test was performed using glass filled PP pellets, 5 mm layer width, 1.6 mm layer height, 150 mm/s print speed, with Spiralize Outer Contour setting enabled and the slicer set to surface mode. The model was tested to hold approximately 80 kg on each step of the stairs (consecutively, not simultaneously). Following up on the first print test, two test models were printed to test the properties of different loop connections using the same settings. As the new extruder has not been produced, the final slide was printed in (virgin) PET pellets instead of recycled flakes. The final prototype in virgin PET was printed for approximately 50%, but was strained equally to the first print. These FPF prints were sliced using Cura 3.6.0, with a custom printer profile provided by the client.

Before each full-scale slide print, an FDM/FFF print was made. The prints were prepared using Cura 4.8.0 and printed on a Wanhao Duplicator i3 V2.1 (0.4 mm nozzle, 0.16 mm layer height, 75mm/s print speed, 110% material flow and in PLA). To study the forces working on the slide, four 1:10 scale models of the last iteration and final design with widths of 50 mm and 60 mm were put under strain. A digital scale and a clamp were used to put around 20N of force on the second step and 40N on the top step of the stairs of each model. As the top step of the stairs was curved, a piece of foam tubing was used to even out the pressure. The deflection was photographed perpendicular to the side of the slide. Using Adobe Photoshop the images of the unstrained models were combined with the images of the strained model and the deflection measured.

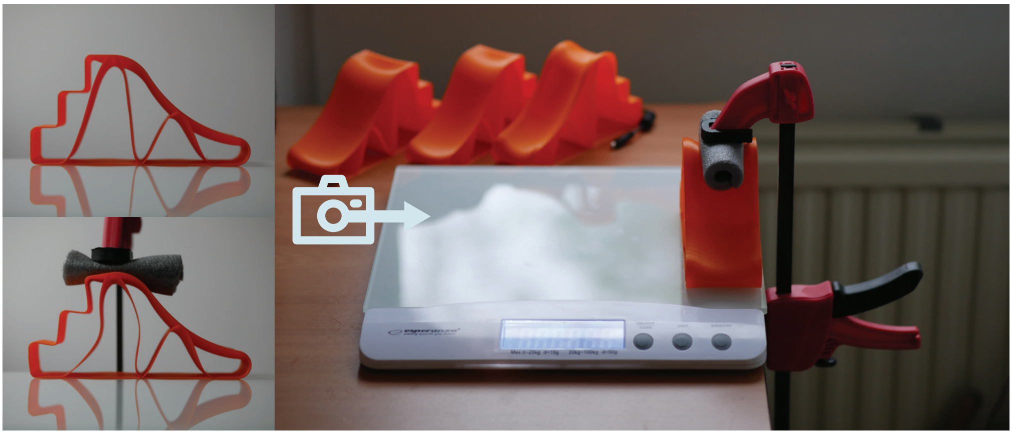


Figure 34: Two images before combining (left); Test setup (right).

5.3. Manufacturing analysis

From the interview, the literature and from the observational research (chapter 2), differences in six areas surfaced: the use of support structure, bridging and overhang capabilities, the use of top and bottom skins, contour and use of infill, the first layer protocol and warping of the print.

5.3.1. Support

Although 3D printing offers a lot of flexibility, both FDM/FFF and FPF have weaknesses to account for when designing object geometry. Since the objects are printed from the bottom up, certain features cannot be printed, as parts cannot start in mid-air. In FDM/FFF printing, support structures are often used to circumvent this. These structures are printed in a way that lets them support the structure, while adhering only a little to the final product, making them easy to break away. This requires tight tolerances and well-tuned settings of both the 3D printer and the tool path software, the slicer.

The 3D Robot printer is accurate; however, the use of removable support structure is undesirable in the current context. When using a support structure on a print, it fuses to the model. As a result, extensive post processing is required to separate the support structure from the model (Brans, Gilhuis, Hensen & Van Der Ven, n.d.). Likely due to the high volume extruded by the printer, the layers remain at a higher temperature after extruding and thus adhere much better upon contact when compared to regular 3D printing. The surface contact area is also significantly bigger, thus increasing the layer bond.

5.3.2. Bridging & overhangs

On desktop 3D printers, depending on the quality of the printer and slicer settings, gaps of relatively large sizes can be bridged. However, as the material remains fluid much longer after extrusion than in small desktop 3D printers, the FPF printer is incapable at bridging gaps. On an FDM/FFF desktop 3D printer, any overhang above 45 degrees usually require a support structure to prevent saggy lines on the outside of the model, but values up to 70 degrees can be achieved. For the 3D Robot printer, the tested limit using PET was 55 degrees and using PP 45 degrees before sagging layers were visible, according to Brans et al. (n.d.).

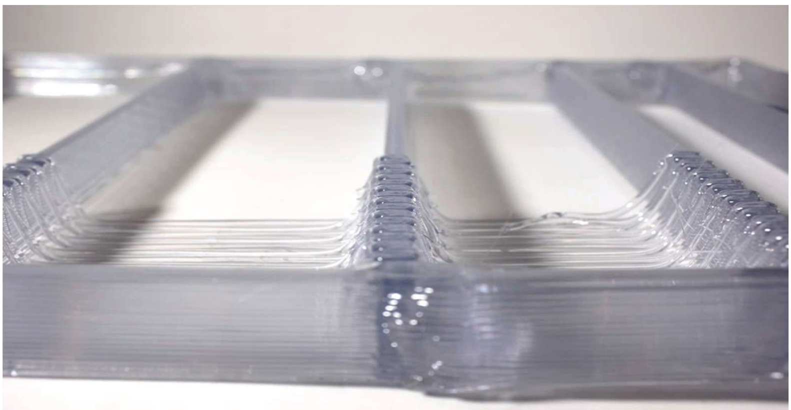


Figure 35: Briding test performed by Brans et al. (n.d.).

The performance can be increased somewhat by cooling the material as soon as it leaves the nozzle, but as the PET is extruded in thick lines and is a natural heat insulator, cooling the material thoroughly using external coolers is difficult.

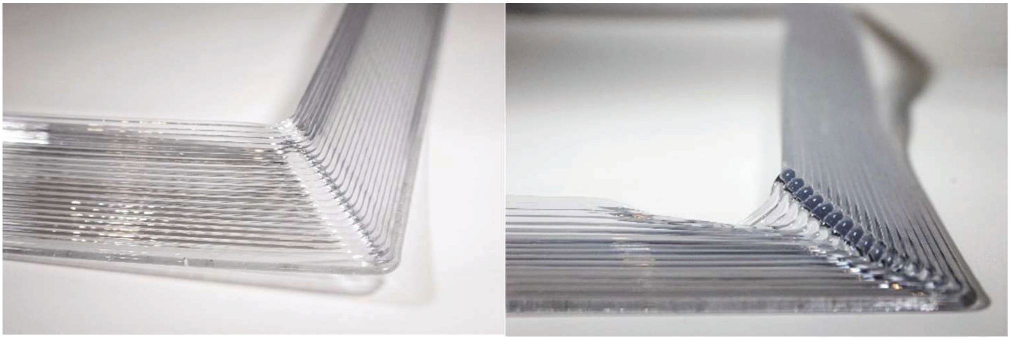


Figure 36: 55 degrees (left) and 60 degrees (right) overhang printed with PET (Brans et al., n.d.)

5.3.3. Top & bottom skins

As a result of the lack of bridging capabilities, it is impossible to print the top horizontal surface of a model, as it would require the model to be printed solid, which would result in extensive sagging, shrinkage and warping due to uneven cooling. When printing a small, solid bar during the observation (appendix C) sagging was observed and the print required extensive cooling by hand between each layer to finish successfully. Additionally, the solid printed test bars were stuck to the wooden print bed, as when printing items solid, the contact area with the print bed is large. Upon removal from the print bed, the bed was damaged lightly. Therefore, printing a solid bottom layer is thus also not advised.

5.3.4. Contour & infill

To successfully 3D print infill patterns generated by the slicer, tool head movements without extruding plastic are necessary. However, due to the heated tube setup and the high volume of extruded material, it is hard to start and stop the flow of plastic accurately. Therefore, it is desirable to print a model in a single loop to keep the extruder working continuously. If infill is desired, the infill should be designed to allow the machine to still print the design in a single loop. If that is impossible, a high amount of polymer residue in the tool head travel path (known as stringing) can be expected. If the travel path crosses printed surfaces, the oozing tool head often leaves marks on the model that require post processing to remove.

While the slide can be printed without any tool head travel, during the print tests occasional tool head travel was observed. After multiple rebuild of the 3D model, the issue persisted. The tool head travel appears to happen around ten times in the slide (see Figure 37). The second iteration slide model (Figure 42, left) was the only model which was sliced successfully without tool head travel, suggesting the increased complexity of the model might have an influence. As the design is highly optimized for easy printing, the travel does not cause a critical failure, but does leave small oozing marks.

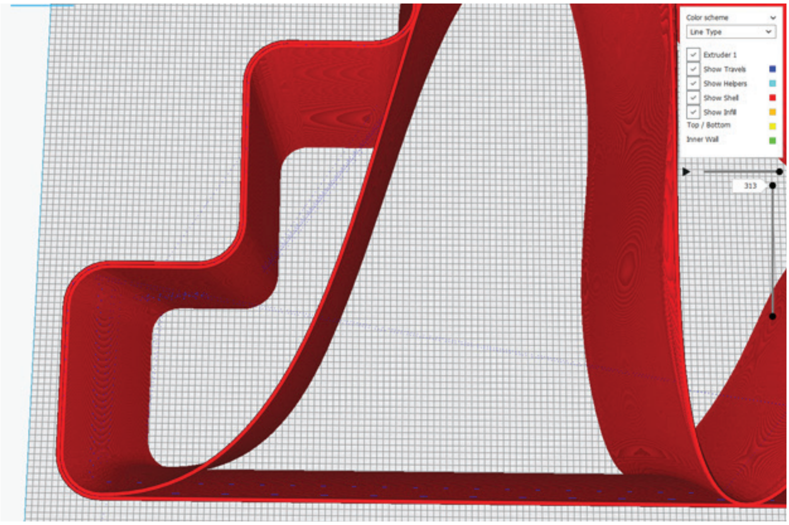


Figure 37: Blue lines indicating tool head travel routes present in the tool path.

5.3.5. First layer

While printing a solid horizontal surface as a first layer results in too much print bed adhesion, printing just the contour often provides too little adhesion, especially after the plastic has cooled down. On FDM/FFF machines, the first layer is usually thicker than the following layers to account for small inconsistencies and misalignments in the print bed. The robot 3D printer uses the same principle, but it is not set in the slicing software. To ensure proper first layer adhesion, the speed of the tool head is controlled by the operator during the first layer, while the material output remains constant. At visually perceived adhesion issues or difficult parts in a print, the tool head is slowed down to make sure the first layer is adhering properly. Currently, the prints are stapled to the print bed after two layers to make sure the print sticks to the bed. The staples leave visible marks or occasionally damage the print, as can be seen in Figure 38. On products where a high level of surface finish is required, the first couple of layers are usually sawed off. As post-processing is undesirable, this damage should be accounted for in the design.

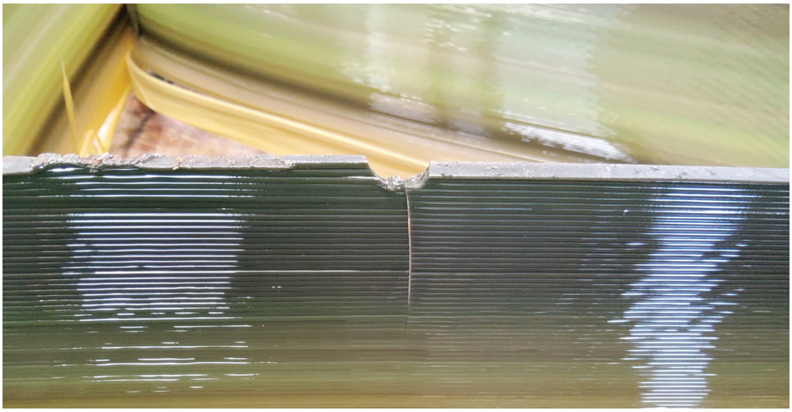


Figure 38: Damage from a staple ripped through the material by the forces induced by warping.

5.3.6. Warping

Like in FFF/FDM printing, prints from the 3D Robot printer are susceptible to warping. While no significant issues during the print tests in PP were seen, the PET print was more sensitive to warping.

The most visible issues were:

- Partial release from the print bed during printing
- Forceful release when stapled at specific locations, causing damage.
- Upward curling of sections and corners

Warping is caused by uneven cooling of the extruded material. As the 3D robot printer prints more then 100 times as much material as FFF/FDM printers, the effects of uneven cooling are enlarged.

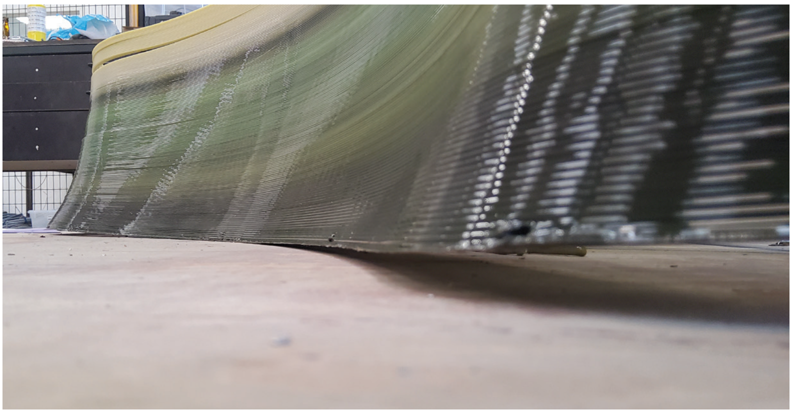


Figure 39: Warping of the print is clearly visible after removing the staples.

Warping can be prevented (in FFF/FDM printing) in three ways (Singh, 2018):

- Increase bed adhesion
- Print in an enclosure
- Adapting the geometry
- Eg. Subdivision of the bottom layers (Singh, 2018)
- Eg. Divide the model into sections (Guerrero-de-Mier, Espinosa & Domínguez, 2015)

The take-aways from section 5.3:

- Standard slicer support structure: not possible (in current context)
- Maximum overhang angle: 55 degrees (PET)
- Bridging: not possible
- Top surface: not possible
- Bottom surface: Possible, but causes too much bed adhesion
- Model shell and infill tool path should form a single closed loop
- Use a buffer zone in the first (+-10) layers to account for damage from bed adhesion techniques
- Only staple the print to the bed at low-strain points
- Warping is increased at high wall thicknesses

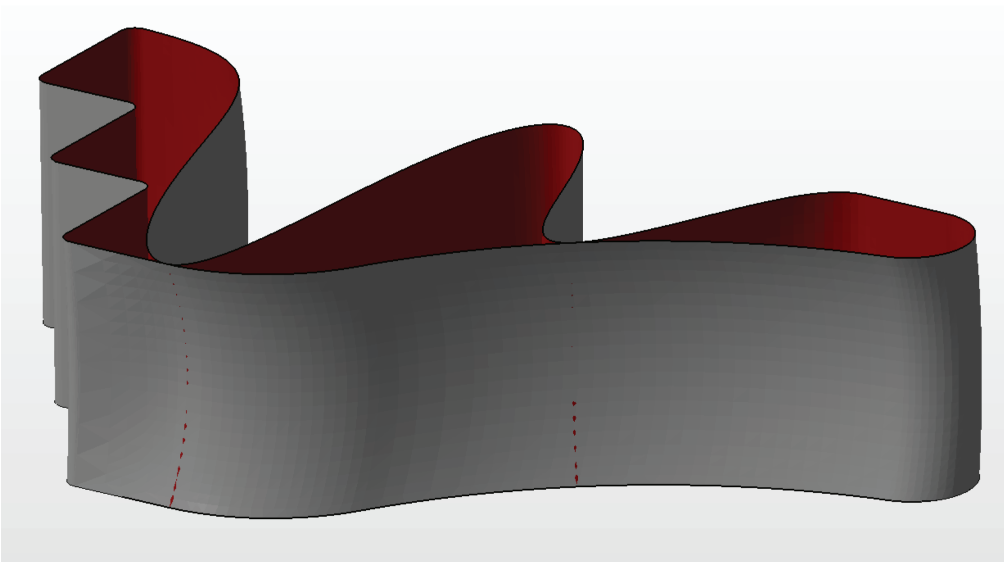
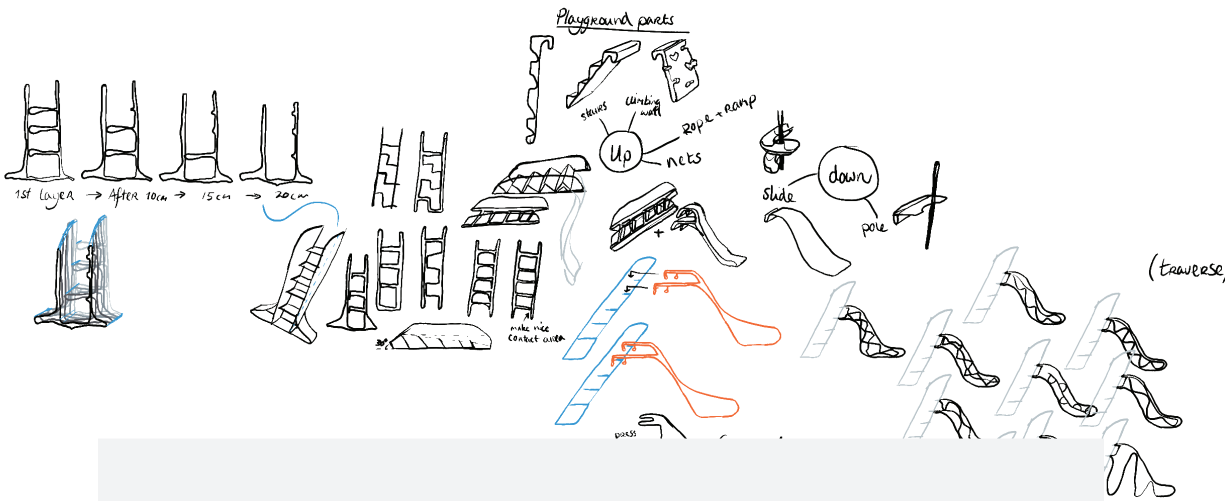


Figure 40: The red areas visible through the gray surface can cause errors in tool path generation.



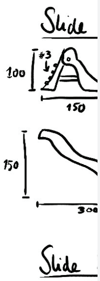
5.4. Slide shape development

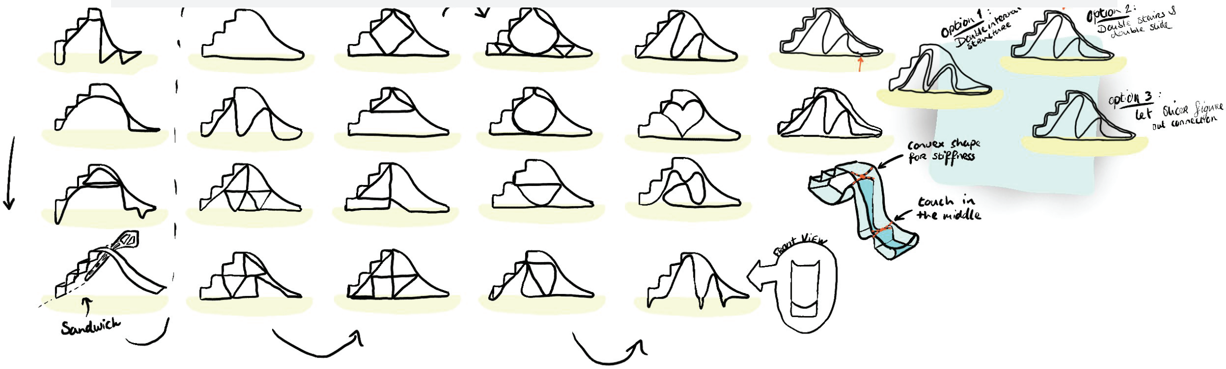
5.4.1. Connecting and intersecting faces

The digital model to generate the tool path for the slide was made using a looped surface describing the tool path precisely.

On the slide it is desired to connect the wave part of the loop to the slide deck part of the loop for structural integrity. As a digital surface has no thickness and is used to model a wall of 5 mm wide, a connection could be made by creating two digital surfaces with a gap less than the layer width. From the test print was concluded that when designing a surface intersection, it is important to never 'mathematically' intersect the paths to prevent errors when generating the tool path in the slicer (Figure 40).

When designing a connection between two parts of the tool path, it is important to account for the power and weight of the robotic arm. Its acceleration is limited, which causes 90-degree corners to become slightly rounded. In the experiments, it was observed that two sharp 90-degree corners with 'touching elbows' do not connect, as can be seen in Figure 41 (top). A radius of 1-2 cm was observed on sharp corners. As the tool head speed increases, the radius increases. A minimum radius of 10 mm was observed at a tool head speed of 150 mm/s.

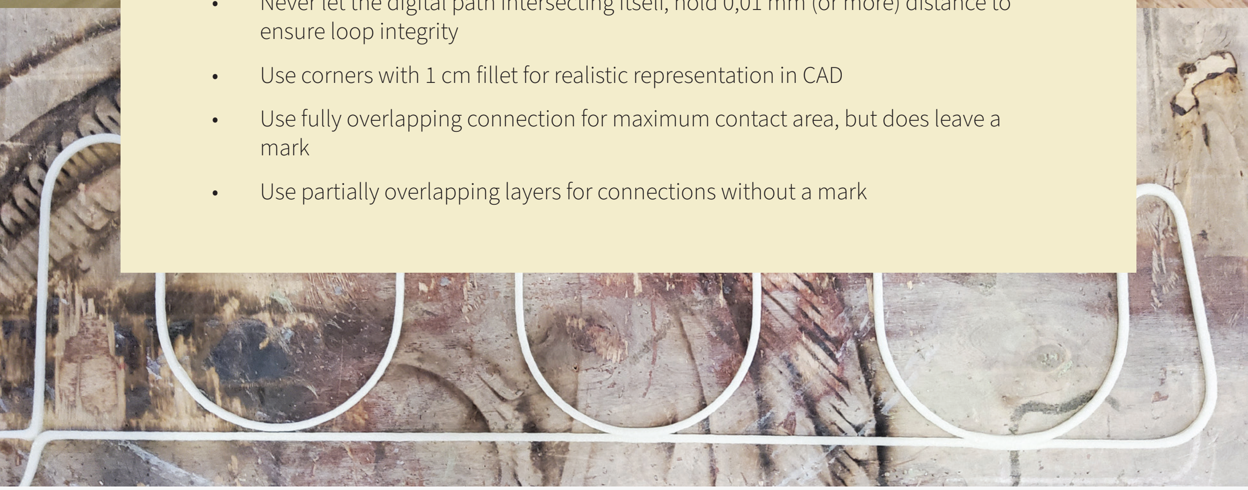




In Figure 41 can be seen that a mark is visible through the surface at the fully overlapping connection. Overlapping half the layer width shows no mark, but has less contact area between the surfaces. The connection with 5 mm line distance is barely connected and could be separated easily.

With the specified settings, the intersections on the slide can be made properly in the following ways:

- Never let the digital path intersecting itself, hold 0,01 mm (or more) distance to ensure loop integrity
- Use corners with 1 cm fillet for realistic representation in CAD
- Use fully overlapping connection for maximum contact area, but does leave a mark
- Use partially overlapping layers for connections without a mark



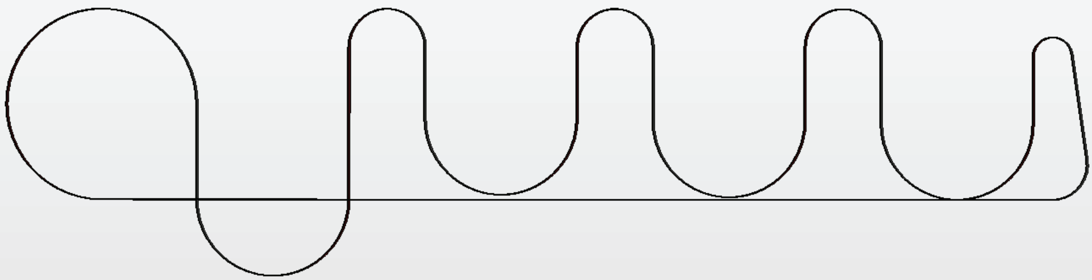


Figure 41: Intersections test model (from left to right): crossing, just touching (5 mm line distance), 2,5 mm overlap (2,5 mm line distance) and full overlap (0,01 mm line distance). CAD (bottom) and print result (middle and top).

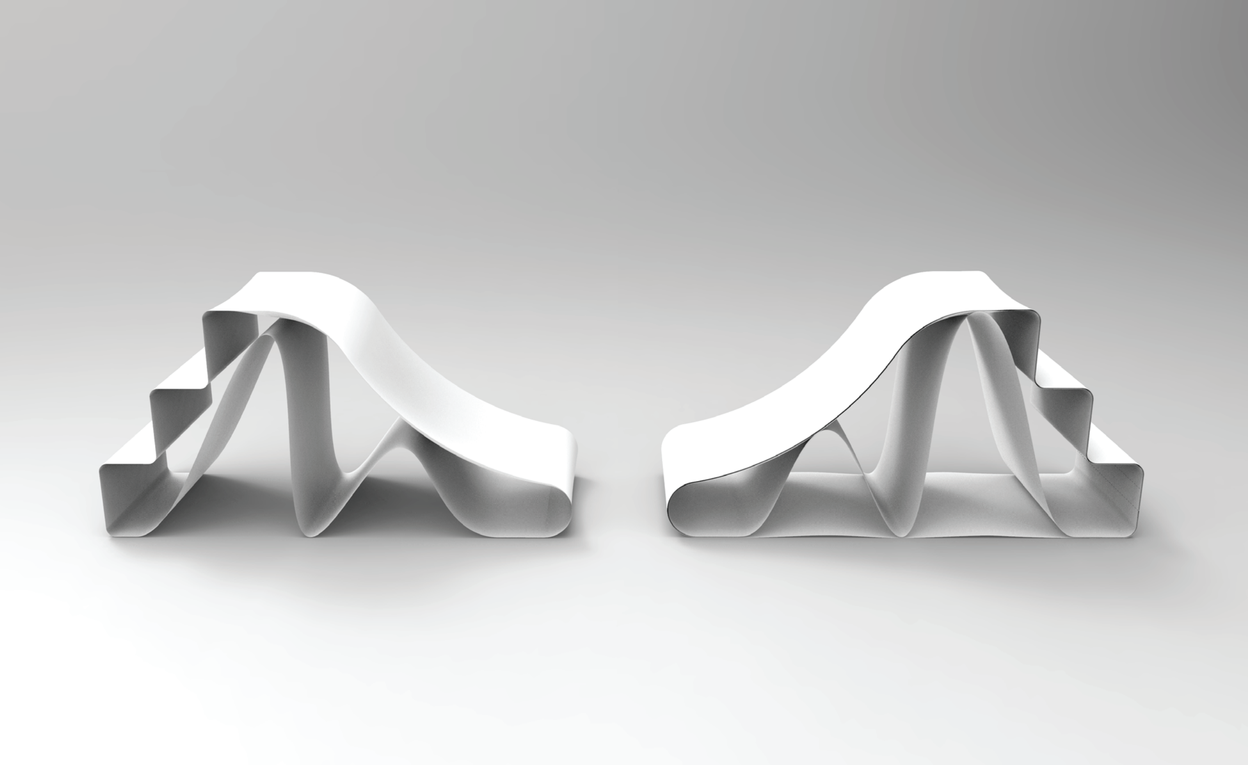


Figure 42: The single loop iteration (left) and the double loop iteration (right).

5.4.2. Connecting inner and outer loops

When under strain, the model bend in the middle section. As (recycled) PET is more brittle than virgin glass filled PP, the model would likely break when printed in PET. An additional shell should be added around the model to strengthen it while maintaining the aesthetic.

By adding an outside shell, an inner and an outer loop formed: The outer loop is the contour or the shell of the model, while the inner loop functions as custom infill and ensures structural integrity. The loops should be connected to prevent stringing and travel marks on the slide surface.

To test some shell and infill connections for the slide design, a test model was printed (Figure 43). This model showed two unreliable connections and three functional loop connections for the specified settings. Each connection method has distinct advantages and disadvantages, which are listed in Table 4.

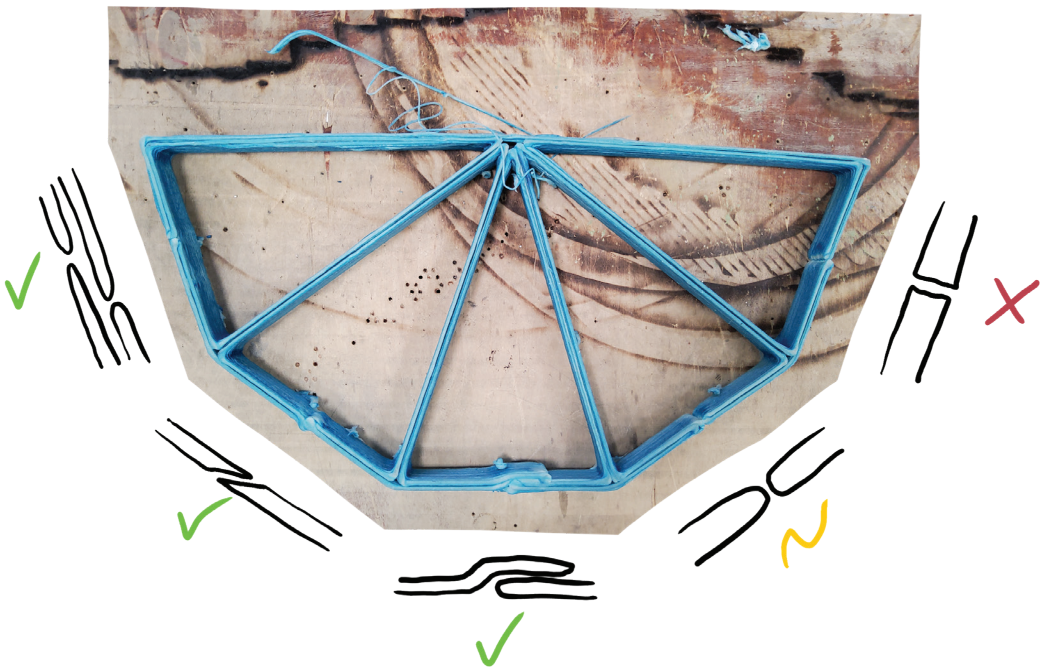


Figure 43: The test print with applied connection types.

Connection	*Disadvantages*	*Advantages*
Consecutively overlapping the connection point by the next layer, by shifting the connection point between layers (Figure 44)	Reduced strength at connection, hard to generate in CAD-software, can induce errors in slicing software	Aesthetically interesting, uniform wall thickness
Use a sharp cornered connection (without fillet)	Small lump of material around connection, quality influenced by tool head speed	Easy to generate in CAD-software, simple connection
Increase horizontal path overlap area	Large lump of material and sagging layers around connection	Fool-proof, high surface contact

Table 4: (Dis)Advantages of the different connection methods.

Figure 44: A crack at the overlapping loop connection point (left); The overlapping loop connection point shifting every five layers (right).

5.4.3. Deflection analysis

The first and second (Figure 42, left) full-scale prototypes were made from a single wall. Under strain, the slide buckled at the points connecting the top of the slide surface and the supporting wave. The PP second prototype was strong enough to support an adult using the slide, if the supporting wave's movement was limited, hence a bottom surface was added to the design.

The final full-scale print in (virgin) PET was completed for 50%, which reduced its strength. Due to the increased brittleness of PET, the print snapped at multiple spots across the slide when applying pressure to the stairs. To further analyse the influence of the stairs and the model width on the deflection behaviour of the slide, 1:10 scale models were used.

The strained and unstrained slide models were combined and colourized using photo editing software, to show the deflection more clearly. At locations of deflection, the unstrained model is coloured blue, while orange shows the strained model. The dark area's indicate spots free of deflection.

While the results cannot be translated directly to full scale, these tests show the front of the slide is the least strained section (Figure 45). The increase of model width by 10 mm (scale 1:10) reduces the deflection, especially at the 'middle wave'. Connecting the wave structure to the stairs is effective at reducing the deflection. From these tests it appears plausible that the updated, 60 cm wide, full-scale model will be strong enough in PET for use as a slide.

Old geometry - 50 mm wide

Load: 21N on second step

Max (M): 7,6 mm

At force point (F): 4,7 mm

Final geometry - 50 mm wide

Load: 21N on second step

Max (M): 4,8 mm

At force point (F): 3,5 mm

Old geometry - 50 mm wide

Load: 42N on top surface

Max (M): 11,5 mm

At force point (F): 5,6 mm

Final geometry - 50 mm wide

Load: 43N on top surface

Max (M): 4,4 mm

At force point (F): 2,2 mm

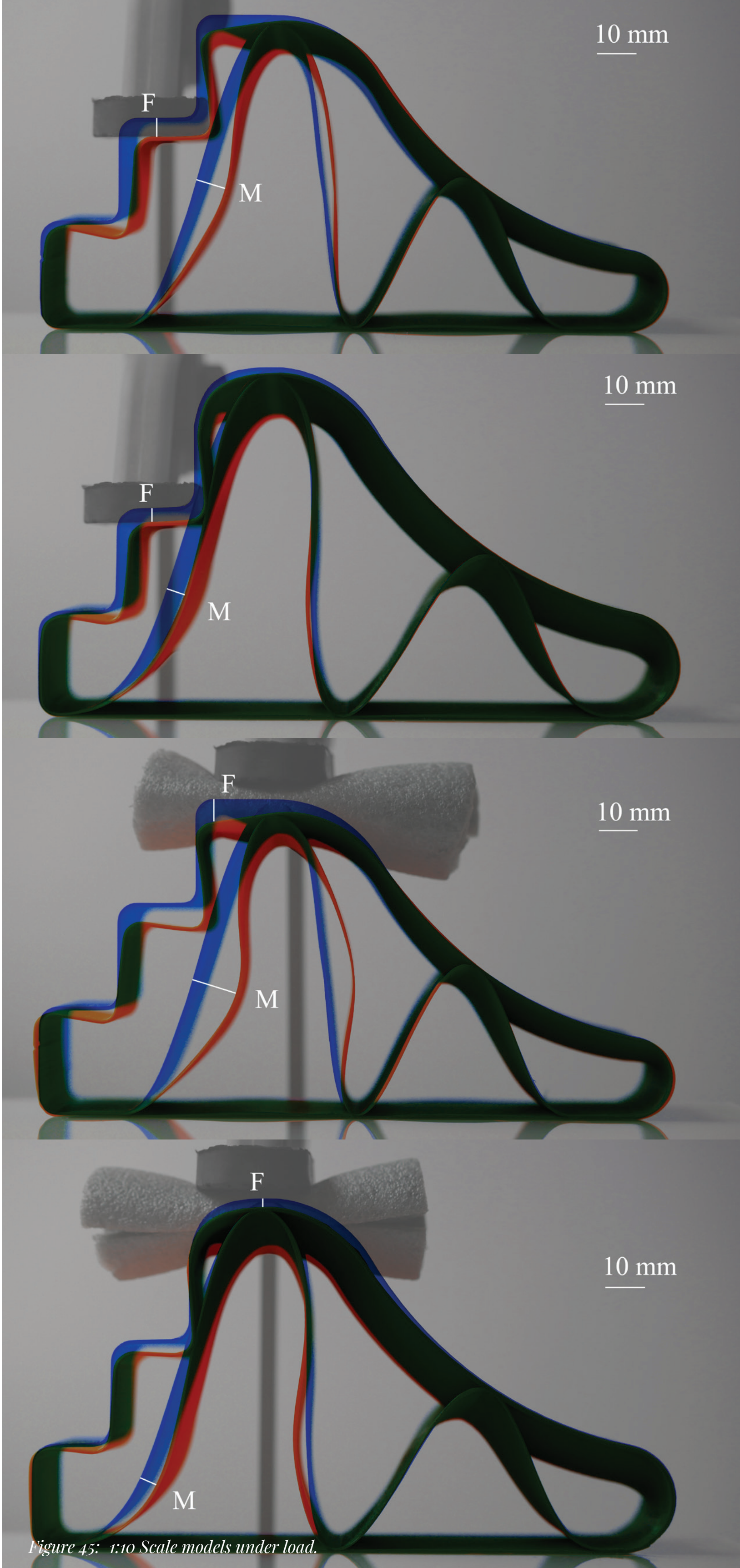
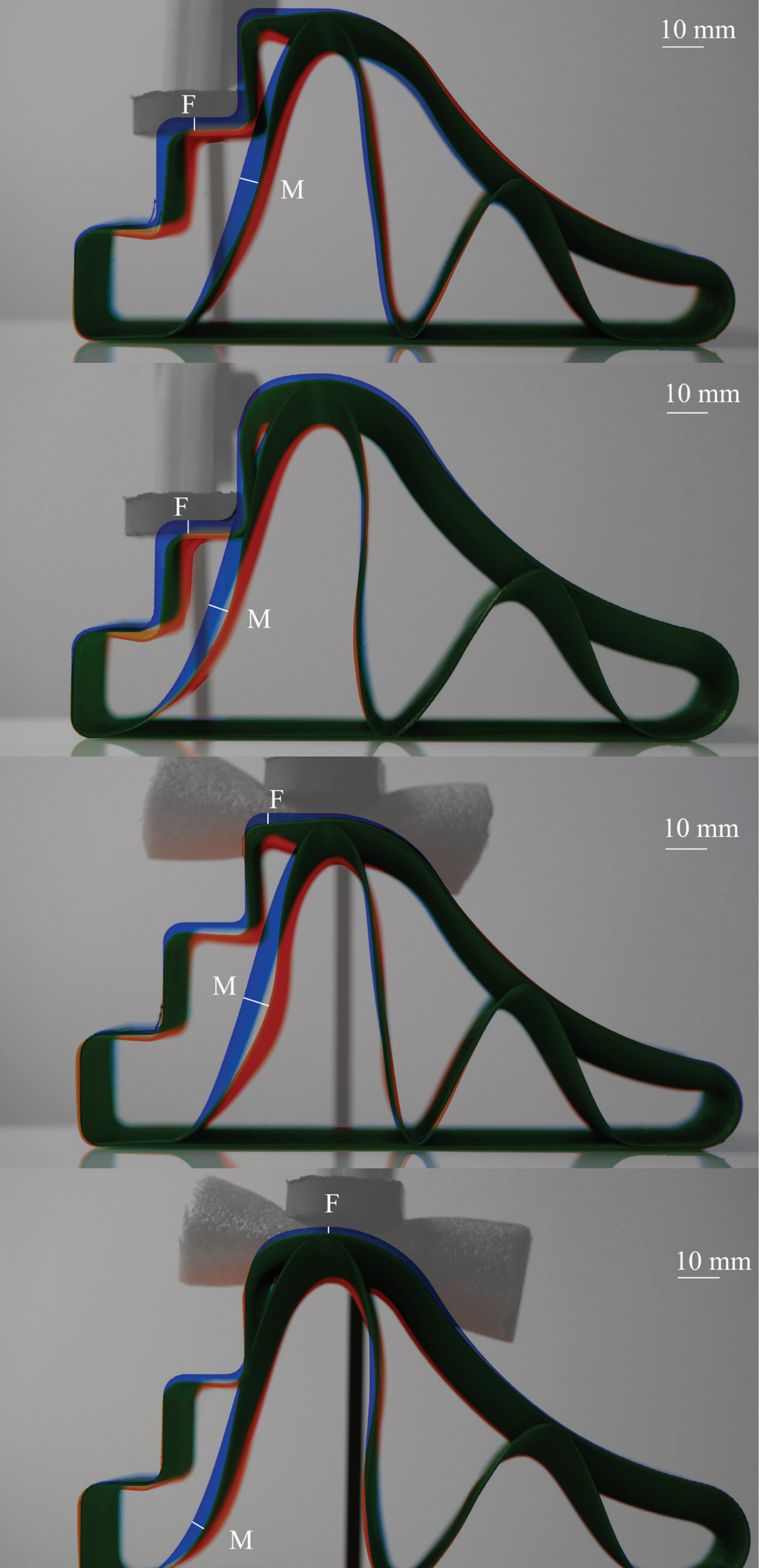


Figure 45: 1:10 Scale models under load.



Old geometry - 60 mm wide

Load: 21N on second step

Max (M): 4,6 mm

At force point (F): 3,0 mm

Final geometry - 60 mm wide

Load: 21N on second step

Max (M): 5,0 mm

At force point (F): 3,2 mm

Old geometry - 60 mm wide

Load: 44N on top surface

Max (M): 6,3 mm

At force point (F): 2,5 mm

Final geometry - 60 mm wide

Load: 43N on top surface

Max (M): 3,0 mm

At force point (F): 1,4 mm

Figure 46: 1:10 Scale models under load (continued).

5.5. The final slide design

The final design features a single loop with a double wall at the stairs and slide section. The internal wave structure connects the stairs and slide surface to the bottom plate to ensure enough strength while keeping the minimalistic infill aesthetic intact. The model prints without support and the gentle curves allow for high speed printing. The first layers are build perpendicular to the print bed to reduce the risk of failure in the first layers.

The bottom surface is slightly hollow to ensure the slide is always resting on its outer edges even if the ground is not perfectly flattened. This reduces the chance of the slide tipping over.

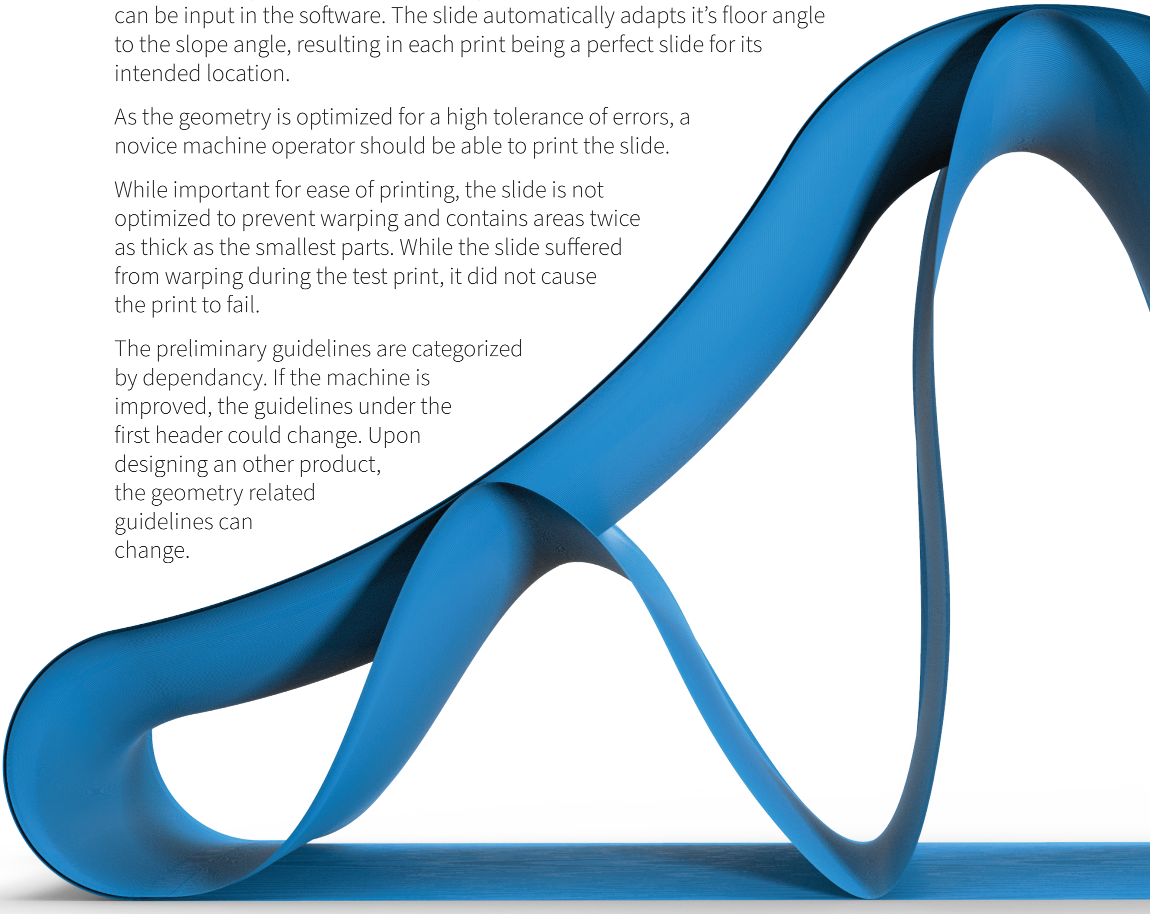
The layer lines resulting from the printing process run in the direction of the slide. Together with the smooth surface finish achieved by 3D printing with PET, it ensures a smooth sliding experience.

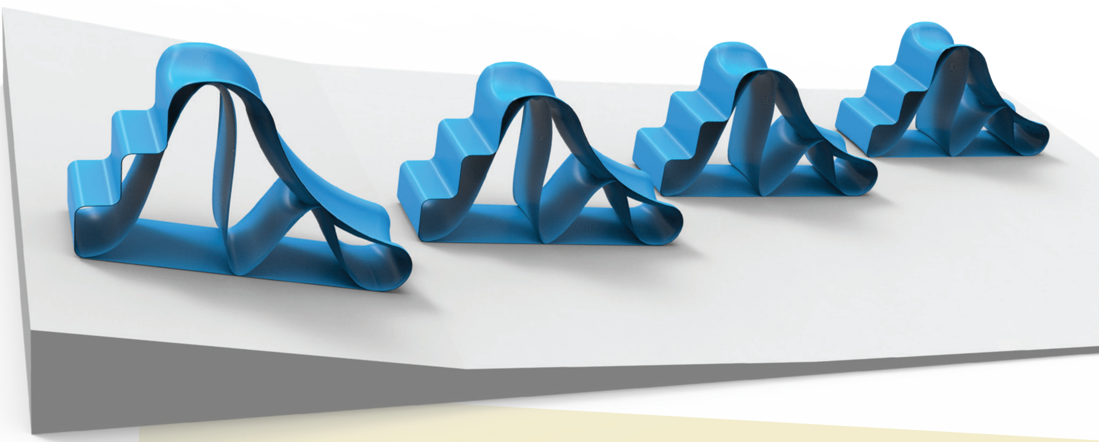
Before printing the slide, the slope angle of the intended location of placement can be input in the software. The slide automatically adapts it's floor angle to the slope angle, resulting in each print being a perfect slide for its intended location.

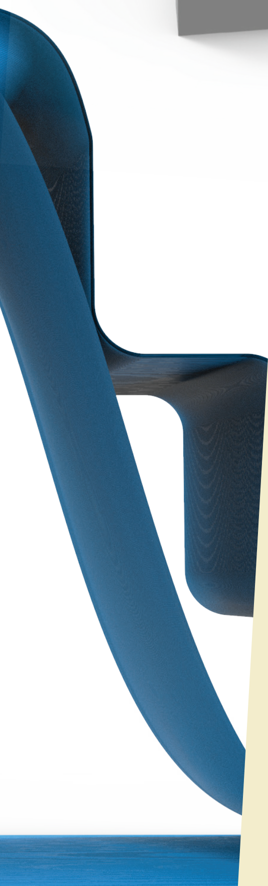
As the geometry is optimized for a high tolerance of errors, a novice machine operator should be able to print the slide.

While important for ease of printing, the slide is not optimized to prevent warping and contains areas twice as thick as the smallest parts. While the slide suffered from warping during the test print, it did not cause the print to fail.

The preliminary guidelines are categorized by dependancy. If the machine is improved, the guidelines under the first header could change. Upon designing an other product, the geometry related guidelines can change.







Preliminary Design Guidelines

(When changing the printing technique, these rules could change)

- ✓ No bridging
- ✓ Support not preferred
- ✓ No top and bottom surfaces
- ✓ Avoid tool head travel: create a single loop tool path
- ✓ Never let the digital path intersecting itself, keep (at least) 0.01 mm distance at connection points to ensure loop integrity
- ✓ Account for a buffer zone in the first ten layers to account for damage from bed adhesion techniques

(When changing geometry, these rules could change)

- ✓ Use at least 10mm fillets on corners for realistic representation in CAD (at 150 mm/s print speed)
- ✓ Increase corner fillets when printing at higher speeds
- ✓ Connect inner and outer loops using an overlapping connection for maximum contact area. Position away from plain view.
- o Connect inner and outer loops by shifting the connection point between layers for connections without a mark. Account for reduced strength.

(When changing material, these rules could change)

- o Only staple the print to the bed at low-strain points
- ✓ Maximum overhang 55 deg for PET
- o Strive for uniform material thickness

5.6. Printing the slide with the PET recycling unit

The client stated that 300 kg per day of PET waste was generated in an army base context. Assuming a 500 mL bottle weighs around 10 grams (PETRA PET Resin Association, n.d.), 300 kg equals 30.000 bottles daily. If people drink 6 bottles (3 L) per day, it would take 5000 people to produce 300 kg of bottle waste daily.

The Dutch military camp in Iraq housed maximum 1690 people ("Kamp Holland," 2021), a refugee settlement by UNCHR houses 20.000 people (UNHCR The UN Refugee Agency, 2018) and a most Tanzanian cities house 150.000 to 450.000 people (Faria, 2021). When using the printer parameters from the tests, a slide uses 40,5 kg of PET. In Figure 47, the expected bottle waste and number of slides printable with said waste can be seen.

The new extruder is expected to increase printer output between -2% to 23%. Extrusion speeds of up to 9,8 kg/h of 30% glass filled PP (nozzle size: 8mm) are measured in practice, which could, based on its volume, translate to 11,7 kg/h of PET. An increase of 23% would result in a maximum output of 14,4 kg/h (346 kg/day), which is slightly higher than requirement mentioned in chapter 2.

If the 3D printer is run 24/7 at maximum extrusion speed, the waste of around 6000 people could be processed daily. While technically possible, its feasibility in real life is unlikely. To reach the maximum material output, the printer should be run at a higher tool head speed, layer height or layer width. Increasing the layer height and layer width to accommodate extra output is deemed undesirable, as it encourages uneven cooling.

For optimal layer adhesion, each layer needs to be at a specific temperature when the next layer is added. The total time required for a print is dependent on the time it takes to cool to the proper temperature to add the next layer, multiplied by the number of layers. The time to print a layer is thus independent from the length of the path. To increase the material output, an increased tool head speed can only be achieved by increasing the model loop or reducing the cooling time for each layer.

The maximum achievable tool head speed is dependent on the output of the extruder, heated hose and nozzle assembly, as stated in section 3.7.

The ideal timing for applying another layer of PET is unknown, but in practice a workable cooling time has been around one minute per layer when using 5 mm layer width (3,8 mm nozzle) and 1,6 mm layer height (as observed in the virgin PET print test). When only printing slides, a maximum output of 160 kg/day would be achieved, as a slide print took around 6 hours to print with a layer height of 1,6 mm. In this case, non-stop slide production by 3D printing can be achieved in settlements occupied by 3000+ people.

Figure 47: Amount of PET waste generated by number of people (1690, 5000, 20.000 people) and slides that could be printed using this waste.

To increase cooling of the layers, the ambient temperature can be reduced, airflow over the model increased and the surface area of the layer increased. The recycling unit will be build inside an climate controlled container, offering control over the ambient temperature. In FDM printing, print head mounted cooler fans are common practice. By decreasing the layer height while increasing the layer width, the surface area in contact with the ambient air can be increased. Decreasing the layer height does increase the layer count, which might increase print time. As PET is a terrible heat conductor, a combination of these options might be interesting for future experiments.

Discussion, Advice & Conclusion

6.1. Discussion

The problems in 3D printing with PET flakes were identified and showed the importance of the extrusion machine and consistency in the material. Increasing the screw channel depth, the compression ratio and adding an industrial sifter should eliminate the issues found.

The increase of the screw channel depth, compression ratio and addition of a sifting machine to the machinery was not applied in practice. The predicted increase in consistency of the output could thus not be compared to test results. Following the theory on transport screws and polymer extruders, the suggested dimensions should be sufficient. While preliminary extrusion tests appeared to emphasize this, the performance of a polymer extrusion machine is influenced by a high number of parameters. Further development, involving practical tests, should be performed with a material sample produced the machinery to be used in the recycling unit to ensure the new extruder design is based on correct material properties. Particle distribution and maximum particle size might differ amongst different machines.

By designing and printing a children's slide, preliminary guidelines were drawn up for successful printing in the given context. As the design guidelines were set up with a high tolerance of error in mind, the presented children's slide is printable for novice machine operators.

If the printing technique is developed further, for example to control bed adhesion or stringing during tool head travel, the guidelines influenced by the printing technique could change. For example, the buffer zone could be reduced or removed or multiple tool paths would become applicable to designs.

The product was not printed in recycled PET flakes, but only in virgin PP and PET pellets. As discussed in section 2.6, recycled PET is expected to be more viscous and brittle. To what degree however, is unknown. The slide is made within the limits of the machine with significant margins, under normal circumstances. After ensuring proper material flow from the extruder, further research should reveal more detailed properties of the material during and after printing.

In case parameters of the material differ or the recycling unit is used to process a different polymer, geometry limits, such as the maximum overhang achievable, and warping behaviour can change. From tests appeared that the overhang angle for glass filled PP is different from PET, warping caused less issues and the bed adhesion staples caused less damage.

The material properties are also influenced by the quality of the collected material. To ensure consistent print results, the input material should be clean and pure. Future research should be done on the influence of contaminants on print properties, to decide on collection and cleaning methods .

In the print test with virgin PET, extensive warping due to shrinkage was observed. Increasing nozzle size, layer width or layer thickness increases the output, but also increases the sensitivity to warping. An analysis should be done on the influence of warping on the internal stresses and overall strength of the print. Solutions should be explored to prevent warping or internal stresses when printing with the 3D robot printer.

An indication was given on the number of slides that could be printed for each scenario and what parameters can influence the amount of material processed. Over time, additional products should be designed to fit the different use scenarios and their waste management needs. 3D printing a different model will yield a different print speed, as the print speed is dependent on the length of the loop. The corner fillets will increase at higher speeds and if multiple loops need to be connected, the ideal connection method can differ for different geometries.

6.2. Client advice

Finalize machinery design

The first steps towards the creation of a localized recycling unit have been taken. Next, a material sample should be sourced using the shredding/granulating equipment chosen for the recycling unit. The most important follow-up step is to further develop the design of the extrusion machine with a polymer extruder engineer or manufacturer, preferably with recycling experience, based on this material and test a prototype in practice. Material processing equipment manufacturers should be involved in the process of mapping out the desired material chain in detail, in particular experts on material sizing (shredders, granulators and sifters).

Envision the bigger picture

Before designing the container layout and machine process, a closer look must be taken to the context of where the machines will be placed. In this project, it was assumed that the climate control system is able to keep the recycling unit at a constant temperature. The ambient temperature has a significant influence on printing performance, but the temperature and humidity limits are unknown, as are the power requirements that come with it. The input material is assumed to be clean and pure for this project, which is unlikely in practice. Thought must be given to method of waste collection, separation and cleaning and the influence of contamination on processability of the material . The waste input was assumed at a constant 12,5 kg/h, but likely fluctuates in practice, which means that the machinery must be designed to be able to catch up from peak inputs. The purpose of this project was to increase sustainability and encourage waste clean-up. An environmental impact analysis should be done, incorporating increased energy consumption, material usage for production and transport of the recycling unit.

Develop new printer features

The print bed of the current machine consists of wood to which the first layer of the print is stapled. As concluded from chapter 5, this technique has a high chance of damaging a recycled PET print, as recycled PET is more brittle than for example PP. As the machine should be suitable for a novice operator, bed adhesion should be simplified and made fool-proof. When printing in PET, significant warping was observed. Further testing in a temperature- and humidity-controlled environment should point out its influence on print warping. A heated print bed could increase bed adhesion and reduce warping, and is commonly done in FFF/FDM printing. Research into an application to 3D Robotprinting's printer could be considered.

6.3. Conclusion

This project has shown what challenges post-consumer PET waste can pose when using it as a feedstock for 3D printing. The most important part of the manufacturing chain is the 3D printer's extruder. While it proved hard to design the complete polymer extrusion screw, the most important aspects were identified and preliminary dimensions for channel depth, compression ratio and screw diameter were drawn up, based on a material sample. These numbers provide a starting point for future development of a dedicated PET flake extruder and the machinery earlier in the processing chain. For further development, experts on material processing and polymer extrusion screws should be consulted, as the interaction between the extruder and material processing equipment is of major importance to the 3D printing properties.

Preliminary design guidelines for an effective, easy to print product were set up by iteratively developing and testing a children's slide using PP and virgin PET pellets. These preliminary design guidelines stem from desktop FDM/FFF printing and can be used to limit risk of failure and gain an understanding of the capabilities of this 3D printer. As the PET flake extruder was not build in this project, the guidelines should be tested using recycled PET flakes in a future project and the values corrected if necessary. In comparison to virgin PET, recycled PET is expected to be more brittle and viscous.

References

3D Insider. (n.d.). How to 3D Print Beginner's Guide To 3D Printing. https://3dinsider.com/3d-printing-guide/?amp

3Dprinting.com. (n.d.). What is 3D printing?. https://3dprinting.com/what-is-3d-printing/

3D Printing & Additive Manufacturing – A Complete Overview. (2021). HUBS A Protolabs Company. Retrieved from https://www.hubs.com/guides/3d-printing/

Arhant, M., Le Gall, M., Le Gac, P. Y., & Davies, P. (2019). Impact of hydrolytic degradation on mechanical properties of PET – Towards an understanding of microplastics formation. Polymer Degradation and Stability, 161, 175-182. doi:10.1016/j.polymdegradstab.2019.01.021

Assadi, R., Colin, X., & Verdu, J. (2004). Irreversible structural changes during PET recycling by extrusion. Polymer, 45(13), 4403-4412. doi:10.1016/j.polymer.2004.04.029

Ansys Granta EduPack (2020) [Computer software]. Canonsburg, USA: ANSYS, Inc.

Baird, D. G., & Collias, D. I. (2014). Polymer Processing Principles and Design (2nd ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

Blok, J., Eikelenboom, D., Van Der Schaaf, J., & Schouten, N. (2018). The Lumen Project. Unpublished manuscript, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands.

Brans, K., Gilhuis, J., Henssen, A., & Van Der Ven, O. (n.d.). MaliPET. Unpublished manuscript, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands.

Climate & Clean Air Coalition. (2015). Solid Waste Management City Profile. Retrieved from https://www.waste.ccacoalition.org/sites/default/files/files/dar_es_salam_city_profile_0.pdf

Dunmore, C. (2015, March 2). Syrian refugee starts pizza delivery service in Za'atari camp. UNHCR The UN Refugee Agency. Retrieved from https://www.unhcr.org/news/latest/2015/3/54f43af26/syrian-refugee-starts-pizza-delivery-service-zaatari-camp.html

Extrusion Guide Book. (2015). Plastics. Retrieved from https://www.plastics.gl/construction/extrusion-guide-book/

Faria, J. (2021, May 16). Population of Tanzania in 2021, by city. Statista. https://www.statista.com/statistics/1221854/largest-cities-in-tanzania/

Ferguson, S. (2018, November 13). A New, Fully Inclusive Playground for Syrian Refugee Children [Web log post]. Retrieved from https://www.unicefusa.org/stories/new-fully-inclusive-playground-syrian-refugee-children/35110

Franciszczak, P., Piesowicz, E., & Kalnins, K. (2018). Manufacturing and properties of r-PETG/PET fibre composite – Novel approach for recycling of PETG plastic scrap into engineering compound for injection moulding. Composites Part B: Engineering, 154, 430-438. doi:10.1016/j.compositesb.2018.09.023

Frankland, J. (2013, March 25). The Limits Of Compression Ratio [Web log post]. Retrieved from https://www.ptonline.com/articles/the-limits-of-compression-ratio

Flory, P. J. (1940). Viscosities of linear polyesters. An exact relationship between viscosity and chain length. Journal of the American Chemical Society, 62(5), 1057-1070. doi:10.1021/ja01862a020

Griff, A. (2016, August). Extrusion basics: Screw design essentials you learned a long time ago, but maybe forgot. Retrieved from http://www.plasticstoday.com/extrusion-pipe-profile/extrusion-basics-screw-design-essentials-you-learned-long-time-ago-maybe

Gu, F., Guo, J., Zhang, W., Summers, P. A., & Hall, P. (2017). From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Science of The Total Environment, 601-602, 1192-1207. doi:10.1016/j.scitotenv.2017.05.278

Guerrero-de-Mier, A., Espinosa, M. M., & Domínguez, M. (2015). Procedia Engineering, 132, 126-131. doi:10.1016/j.proeng.2015.12.488

Gupta, V. B., & Bashir, Z. (2002). PET Fibers, Films, and Bottles. In S. Fakirov (Ed.), Handbook of Thermoplastic Polyesters: Homopolymers, Copolymers, Blends, and Composites (pp. 317-388). doi:10.1002/3527601961

Haynie, M. (n.d.). PET Drying. Plastics Technology. https://www.ptonline.com/knowledgecenter/plastics-drying/drying-questions/pet-drying

How FDM/FFF 3D Printing Technology Works? (2018, January). Manufactur3D Magazine. Retrieved from https://manufactur3dmag.com/working-fdm-fff-3d-printing-technology/

Inhabitat. (2012, June 4). Dirk Vander Kooij's Repurposed Robot Prints "Endless" Furniture From Recycled E-Waste [Web log post]. Retrieved from https://inhabitat.com/dirk-vander-kooijs-repurposed-robot-prints-endless-furniture-from-recycled-e-waste/

Jambeck, J., Hardesty, B. D., Brooks, A. L., Friend, T., Teleki, K., Fabres, J., … Wilcox, C. (2018). Challenges and emerging solutions to the land-based plastic waste issue in Africa. Marine Policy, 96, 256-263. doi:10.1016/j.marpol.2017/10.041

Kamp Holland. (2021, Juli 19). In Wikipedia. https://nl.m.wikipedia.org/w/index.php?title=Kamp_Holland&oldid=55397917

Kelly, A. L., Brown, E. C., & Coates, P. D. (2006). The effect of screw geometry on melt temperature profile in single screw extrusion. Polymer Engineering & Science, 46(12), 1706-1714. doi:10.1002/pen.20657

Lau, J. (2017, September). Why the venting is so important for a plastic injection mold? Retrieved from https://www.moldchina.com/mold-venting-slot/

Little, H. A., Tanikella, N. G., Reich, M. J., Fiedler, M. J., Snabes, S. L., & Pearce, J. M. (2020). Towards Distributed Recycling with Additive Manufacturing of PET Flake Feedstocks. Materials, 13(19), 1-22. doi: 10.3390/ma13194273

Northern Container Sales. (n.d.). Shipping Container Dimensions Internal and External Intermodal Container Dimensions. https://northerncontainersales.ca/more-info/container-dimensions/

Mora, J. P. (2021, February 12). Nicaraguans strive to support themselves in exile in Costa Rica. UNHCR The UN Refugee Agency. Retrieved from https://www.unhcr.org/news/stories/2021/2/60258ae24/nicaraguans-strive-support-themselves-exile-costa-rica.html

Oxfam Novib. (n.d.). Unieke hulp voor vluchtelingen: van afval naar banen. https://www.oxfamnovib.nl/blogs/dilemmas-en-oplossingen/unieke-hulp-voor-vluchtelingen-van-afval-naar-banen

Paci, M., La Mantia, F.P.. (1998). Competition between degradation and chain extension during processing of reclaimed poly(ethylene terephthalate). Polymer Degradation and Stability, Volume 61 (Issue 3), page 417-420. Retrieved from https://www.sciencedirect.com/science/article/pii/S0141391097002279?via%3Dihub

PETRA PET Resin Association. (n.d.). DID YOU KNOW? Little-known facts about PET plastic. http://petresin.org/news_didyouknow.asp

Polyethylene terephthalate. (2020, November). in Wikipedia. https://en.m.wikipedia.org/w/index.php?title=Polyethylene_terephthalate&oldid=987465216

Reifenhäuser Reiloy. (2021). Compression Ratio. Retrieved from http://www.reiloyusa.com/processing-tips/screw-design/compression-ratio/

Ritchie, H., & Roser, M. (2018, September). Plastic pollution. Our World in Data. Retrieved from https://ourworldindata.org/plastic-pollution#mismanaged-plastic-waste

Singh, K. (2018). Experimental study to prevent the warping of 3D models in fused deposition modeling. International Journal of Plastics Technology, 22, 177-184. doi:10.1007/s12588-018-9206-y

Singh, R. K., Biswaji Ruj, Sadhukhan, A. K., & Gupta, P. (2019). Thermal degradation of waste plastics under non-sweeping atmosphere: Part 1: Effect of temperature, product optimization, and degradation mechanism. Journal of Environmental Management, 239, 395-406. doi:10.1016/j.jenvman.2019.03.067

Syntron Material Handling. (2019, April). Designing a Hopper – Material Properties and Size. Retrieved from http://www.syntronmh.com/en/news-events/designing-a-hopper-material-properties-and-size

Tadmor, Z., & Gogos, C.G. (2006). Principles of Polymer Processing (2nd ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

Tomita, A., Cuadros, D. F., Burns, J. K., Tanser, F., & Slotow, R. (2020). Exposure to waste sites and their impact on health: a panel and geospatial analysis of nationally representative data from South Africa, 2008-2015. The Lancet Planetary Health, 4(6), 223-234. doi:10.1016/S2542-5196(20)30101-7

UNHCR The UN Refugee Agency. (2018). Camp planning standards (planned settlements). Retrieved from https://emergency.unhcr.org/entry/248797/camp-planning-standards-planned-settlements

UNHCR The UN Refugee Agency. (n.d.). Water Sanitation and Hygiene. https://www.unhcr.org/water-sanitation-and-hygiene.html

Ulin, K. (2013, May 13). Field Diary from Domiz Refugee Camp [Web log post]. Retrieved from https://www.unicefusa.org/stories/field-diary-domiz-refugee-camp/7383

Upmold. (2017, November). Injection Mold Venting Standards and Design. Retrieved from https://upmold.com/injection-mold-venting-design/

Van Plestik. (2020). About. Retrieved from https://vanplestik.nl/nl/about/

Wu, H., Lv, S., He, Y., & Qu, J. P. (2019). The study of the thermomechanical degradation and mechanical properties of PET recycled by industrial-scale elongational processing. Polymer Testing, 77, 105882. doi:10.1016/j.polymertesting.2019.04.029

Xu, L., Ling, M., & Wu, Y. (2018). Economic incentive and social influence to overcome household waste separation dilemma: A field intervention study. Waste Management, 77, 522-531. doi:10.1016/j.wasman.2018.04.048

Zander, N. E., Gillan, M., & Lambeth, R. H. (2018). Recycled polyethylene terephthalate as a new FFF feedstock material. Additive Manufacturing, 21, 174-182. doi:10.1016/j.addma.2018.03.007

Appendices

Appendix A: Determining Material Properties

Introduction

To determine the requirements for processing equipment to recycle PET bottles, the size of the material particles is important. In this experiment the PET bottles are shredded in a desktop shredder-granulator machine (3D EVO Shred-It) with a 3 mm sieve, by an external party. In processing equipment, it is advised that the smallest hole size is at least twice the particle size (Syntron Material Handling, 2019). That means it is important to know what the largest particles are when using a granulator with a 3 mm sieve. Observations show that the largest particles are more than 3 mm, which could jam processing equipment designed for particles of 3 mm in diameter.

Research question

What is the size distribution of the particles in a PET material sample sourced from bottles?
What is the density of the PET flake material sample?
Is the sample compactable and if so, what is the density increase?

Method

Apparatus

The material is sorted using five 3D printed sieves sized from 1 to 5 mm in hole size, increasing with increments of 1 mm. The sieves were sourced from Thingiverse and available for download here: https://www.thingiverse.com/thing:1145938

A camera was used to photograph the results.

A kitchen scale was used to calculate the density.

For future experiments, it is recommended to use a high precision scale (accuracy in tenths of a gram) to measure the material residue in each sieve.

Procedure

The sieves were stacked and the top sieve was filled with approximate 57 cm^3 material from the sample (filled to the top, but not with material above the sieve's edge). The sieve stack was shaken mildly to allow the particles to arrange themselves through the sieve levels. Close attention was paid to not lose any particles from the top. When there were no more particles coming from the bottom of the sieve stack, the sieves were unstacked and their contents compared. A photograph was taken from the front and top to document the results.

To determine the density of the flake material, a jug was filled with a set volume of the material sample. The jug was then weighed on a kitchen scale. The sample was shaken and weighed again.

Measures

The contents of the sieves were photographed from the top and from a side angle. The weight and volume of the material was noted on a notepad.

Results

From the 117 gram of sifted flakes, 6 grams were caught in the 5 mm sieve, and 10 grams was caught in the 4 mm sieve. This is 86% yield (and 14% waste).

The largest measured particle was sized 16x15x4 mm and was a crumpled irregular shaped piece.

1,050 L = 277g
1,450 L = 365g
1,500 L = 388g

Average density (n=3) : 0,2581 g/cm3

1.450L becomes 1.050L = 27,6%   d = 0,3476 g/cm3
1.500L becomes 1.200L = 20,0%   d = 0,3233 g/cm3

Average density (n=3, compacted): 0,3355 g/cm3

After shaking the volume is reduced by 23,8%.

(For comparison: density of solid (amorphous) PET: 1,29 - 1,39 g/cm3)

Discussion

Even though the machine used to create the material sample uses a 3mm sieve, the material produced contains a reasonable amount of particles sized larger than 5 mm. This is almost twice the size of the sieve and can be very problematic for processing equipment. As can be seen in the images in section 'Results', within 57 cm^3 of material, there is already a notable amount of flakes sized larger than 4 mm and a very high amount of flakes stuck in the 3 mm sieve. A possible explanation for this can be that the material has to be smaller than the sieve size in only two out of three dimensions. Since PET flakes are usually less than a millimetre thick, this means that once they are less than 3 mm wide, they can reach lengths longer than that. Because of their low thickness and high toughness, it is also possible for flakes to fold and pass through the filter, which causes the final material to have a big range in particle size.

Another explanation can be that while cleaning the machine and sieve, particles who were left behind in the sieve fell through and in the material sample. Because of the amount of particles sized larger than 5 mm, this explanation is less likely, as the machine would have to have had a rather high amount of unprocessed chunks in it.

The sieves were, due to time constraints, printed very small. The provided Thingiverse link also offers sieves with a higher diameter. By increasing the material processing speed, a larger sample can be and thus the accuracy of the results of the experiment.

Conclusion

This experiment provides valuable insights on the material sourced from a shredder-granulator combination. By knowing the density of the flake material, calculations can be made to make sure the feeding part of an extrusion screw is transporting enough volume.

An interesting direction to explore a little further in could be to contact experts in the field of shredding and granulating plastic with larger machines.

Appendix B: Exploring the extrusion machine

Introduction

After talking to the experts from 3D Robotprinting and hearing the problems occurring in the machine, some of the initial problems were mapped. However, their exact causes were not inherently visible. The expert thought to know what it was caused by, but it was never properly researched.

Since previous experiments caused expensive parts of the 3D printer to break, this experiment was set up to gain first-hand experience in extruding with recycled PET flakes. By using a small extruder, the problems mentioned by the expert were tried to reproduce. This test served to experiment with the temperature required to melt PET consistently, as this is important when choosing a certain extruder orientation: direct or using a heated tube.

Research question

What problems arise during the extrusion of recycled PET flakes and what is important in the extruder geometry and its settings?

Method

Apparatus

For this experiment, a Noztek Touch desktop filament extruder was used, available at the Applied Labs of the faculty of IDE. The machine has two temperature zones and controllable motor speeds.

Procedure

The machine was pre-heated to 240 degrees. The material sample used was created from PET bottles shredded and granulated by a 3DEVO Shred-it desktop machine with a 3 mm sieve by a third party. The material was fed in the machine. While watching and analysing the output of the machine, the temperature and RPM were gradually increased to a point where the material would flow easily and show a properly melted, glasslike output.

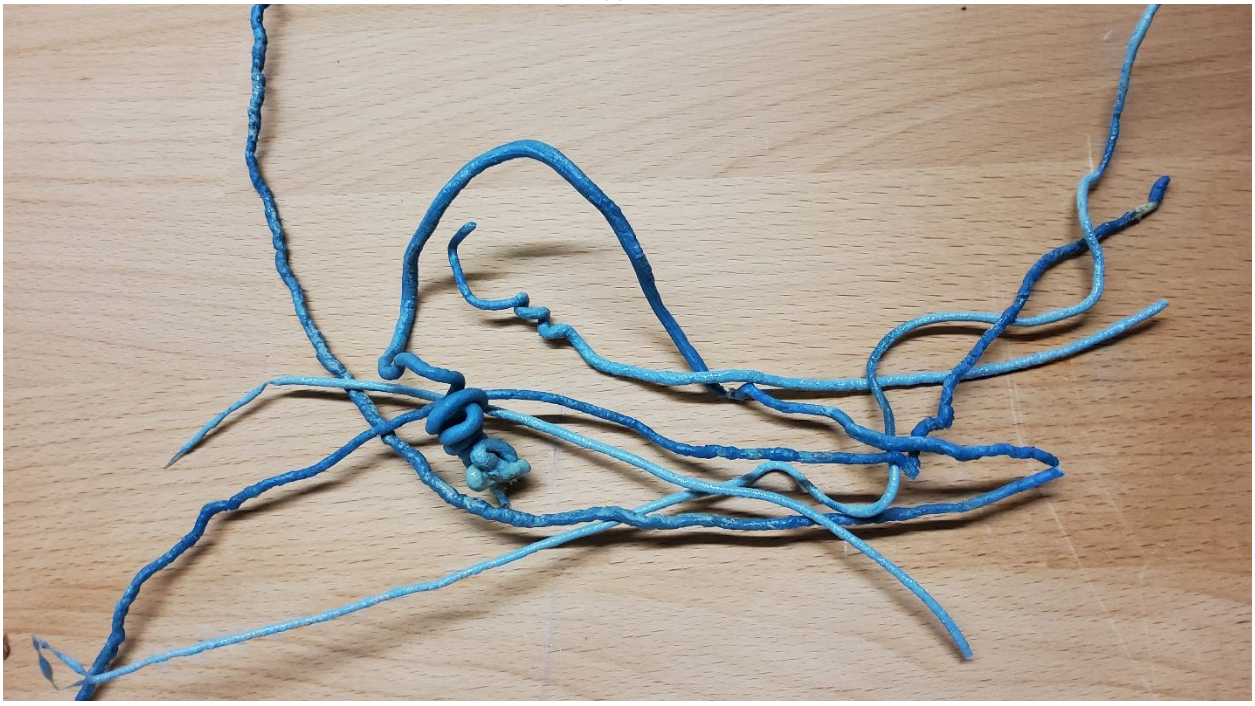
Measures

The material extruded within each step of changed extruder settings were laid out on the floor and photographed. During the experiment the characteristics of the material extruded was noted using a notepad. Other note-worthy events were also noted, for example feeding problems into the extruder.

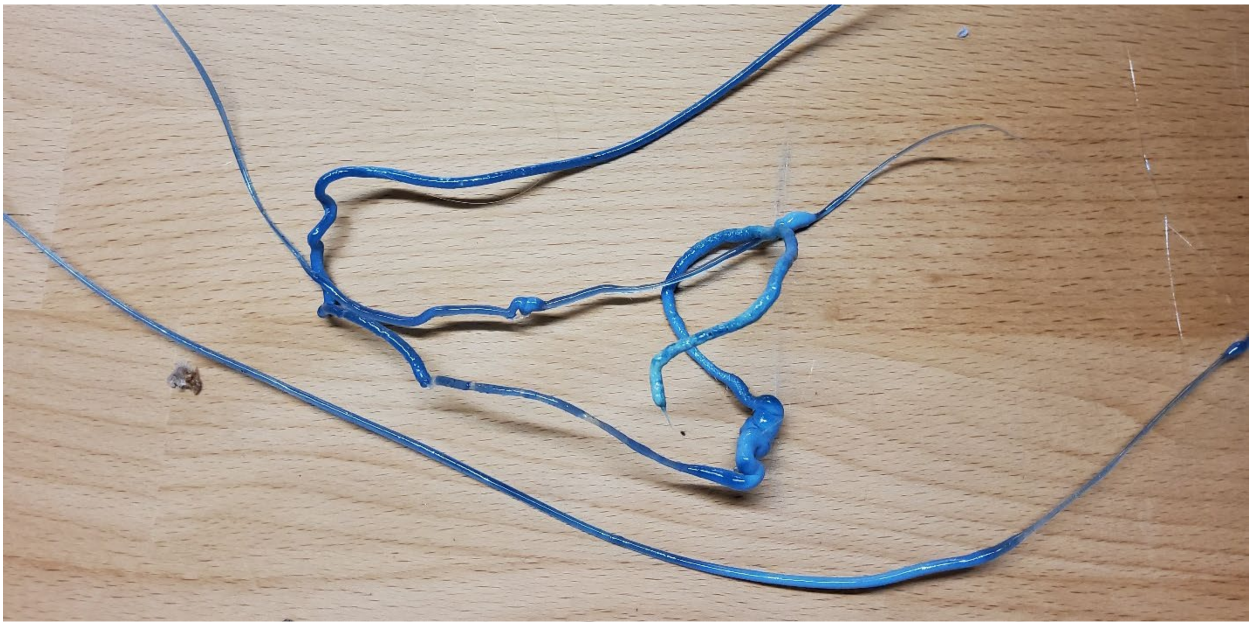
Results

Before the experiment started, rat-holing occurred in the hopper.

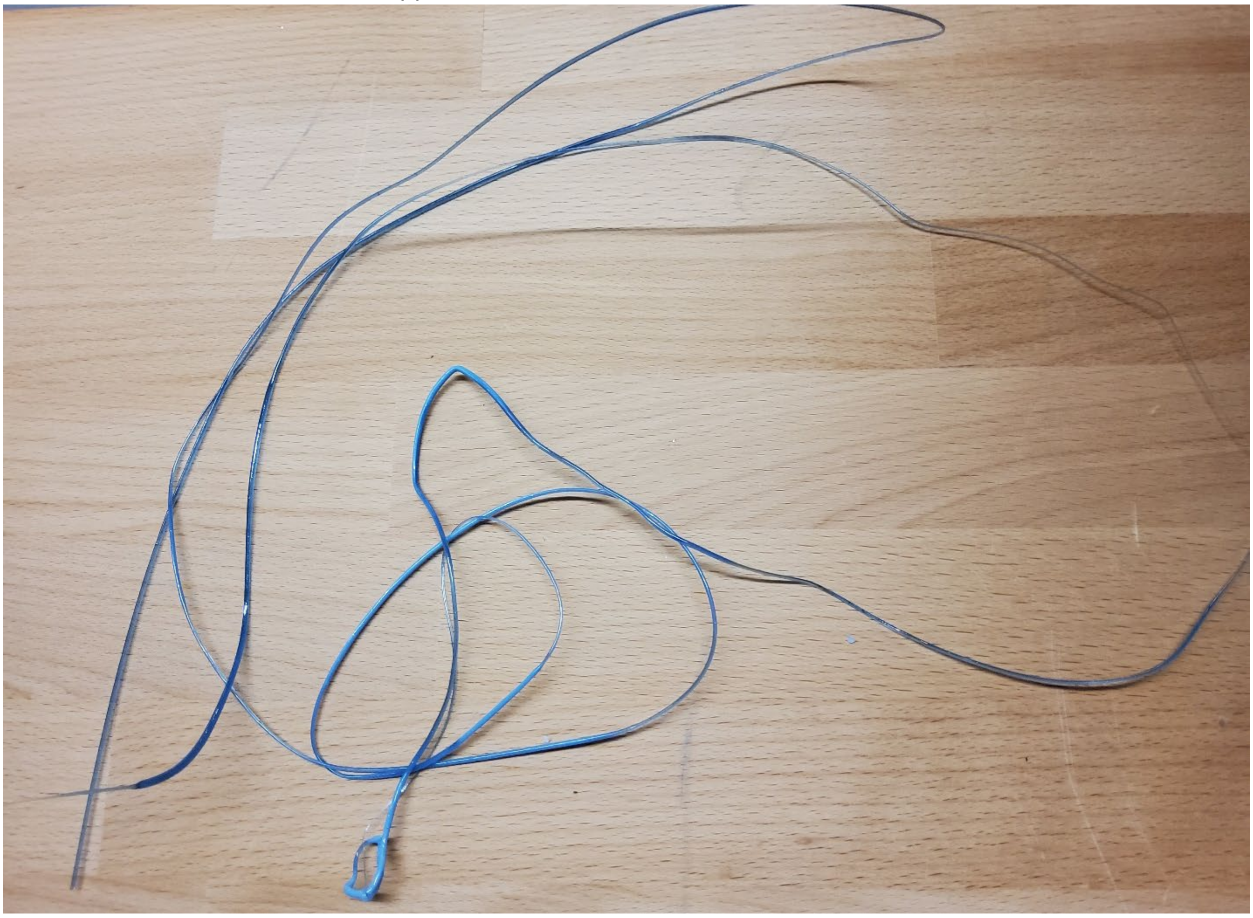
Batch 1. Extrusion happens in bursts: There is no extrusion for a while, after which a small eruption happens at the end of the extruder. Material looks extremely rugged and opaque.



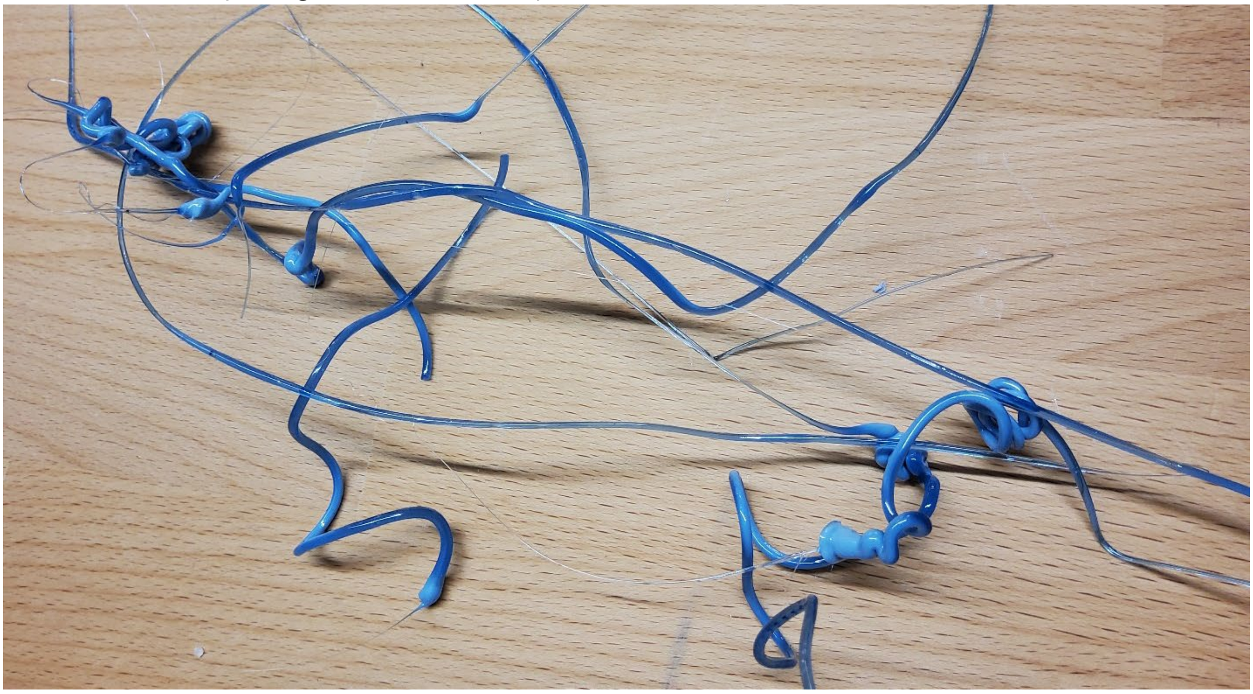
Batch 2: Material is partially transparent mostly upon stretching, revealing solid pieces inside. Solid particles can also be felt on the outside of the strands.



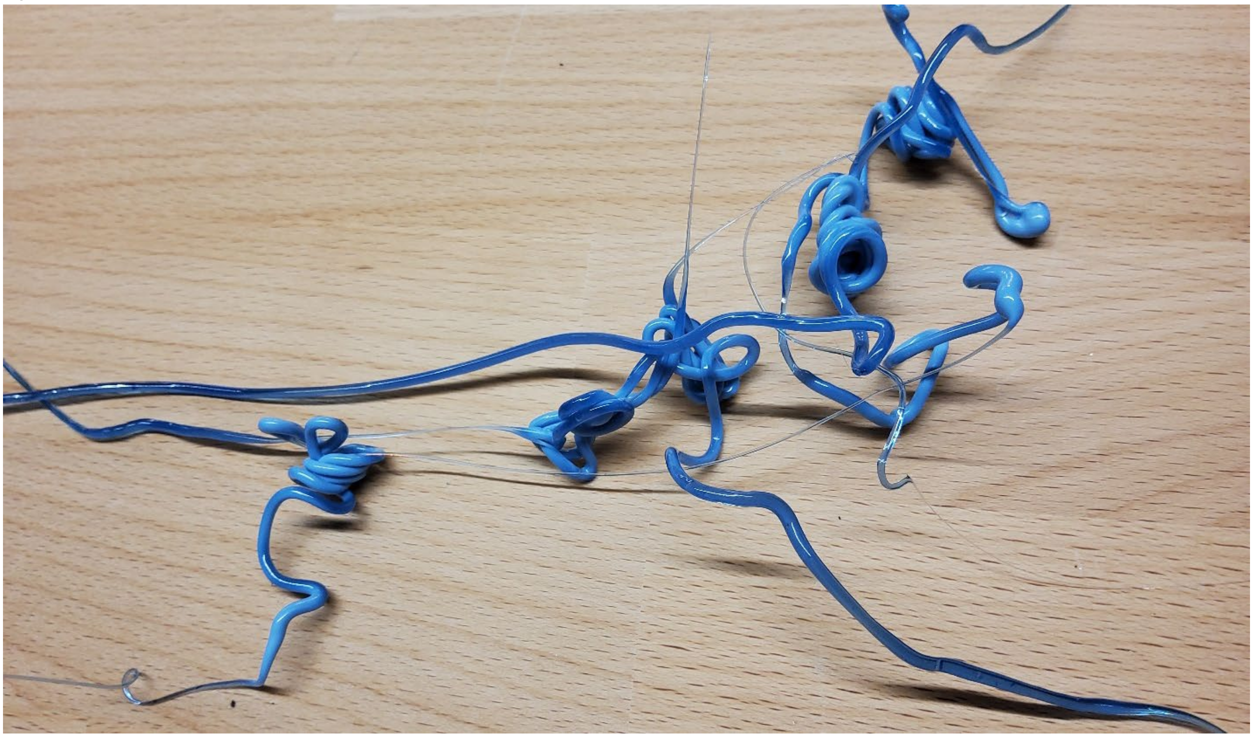
Batch 3: By stretching the material slightly when it is warm, it turns transparant darker blue. Solid particles are still visible and extrusion still happens in bursts.



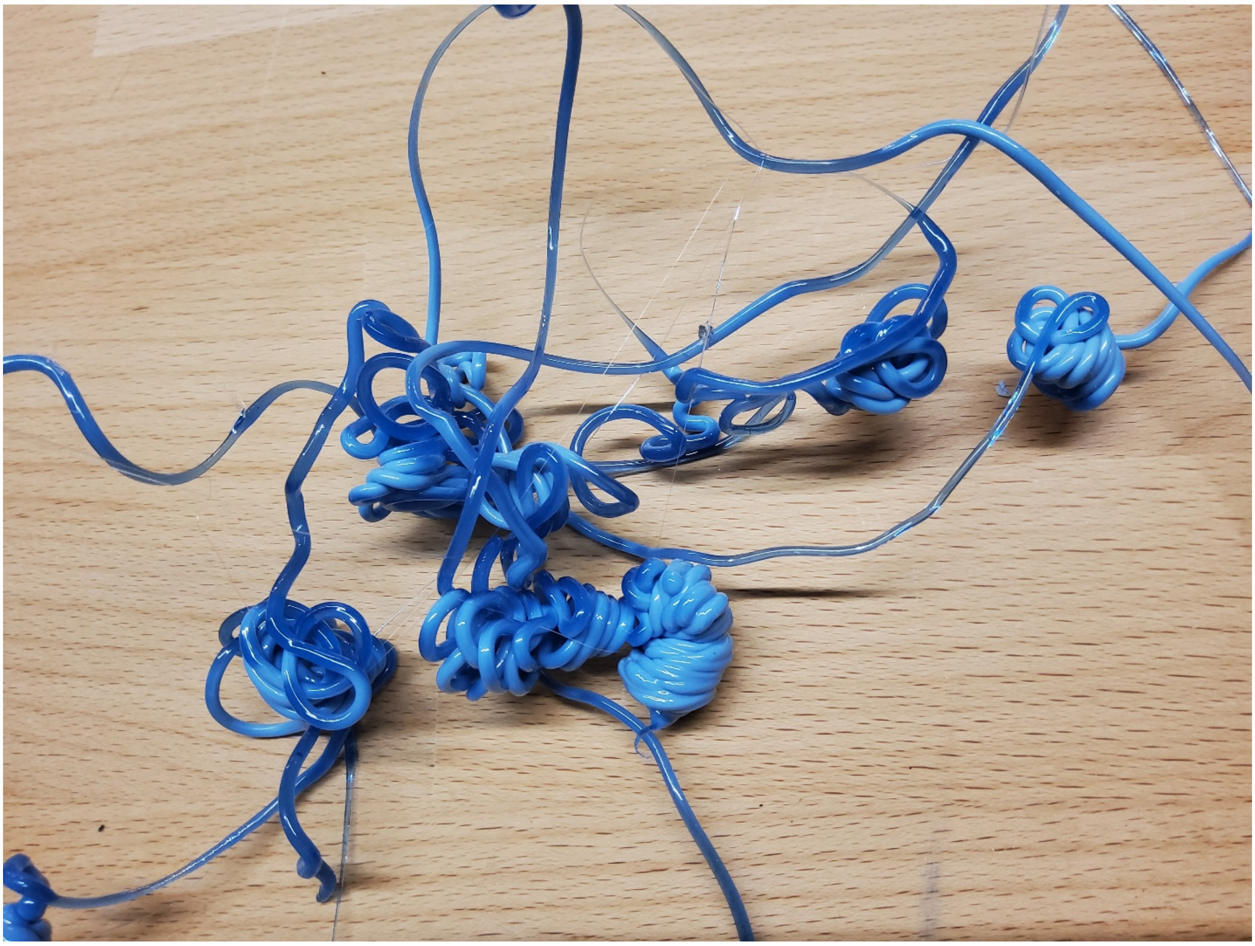
Batch 4: Material improving, but still show solid particles and a little air bubbles.



Batch 5: Solid particles are no longer visible. Air bubbles are. Material output is more consistent, but not optimal.



Batch 6: Material output is more consistent, not perfect, but the material is molten. Ideal temperature seems T1: 260, T2: 245 with 20 RPM.



40 RPM is too much. Extrusion happens more in bursts. Colour ranges from milky light blue to clear dark blue, this appears to depend on how much the material is pulled when hot.

At T1: 260, T2: 252 at 30 RPM, material flow is not consistent. Massaging/pressing on the flakes appears to help a little bit, but real consistency is not achieved. Small air bubbles are visible in the material.

In the hopper, large particles form bridges, preventing small pieces from entering the machine. Flakes push themselves out of the rotating screw and have trouble entering the screw openings. When a large particle eventually is stuck in the screw, it takes a lot of smaller particles with it and disturbs existing bridges.

Upon flushing the machine using PE granulate, the output increased a lot and was consistent.

Discussion

In this system, the flakes were very large compared to the screw size. While the material did get extruded, it is likely that the inconsistency issues are related to this. The most interesting observation was when the PE granulate was used to clean the barrel. This led to the following hypothesis of what is happening: The PET flakes are not able to create enough pressure inside the barrel, possibly due to too little material entering the screw. The pulsating pattern in the extrusion can be caused by this, as the material is building up enough pressure to overcome the extrusion through the small outlet hole. This phenomenon might be increased by the short barrel length of this machine. Since PET has a relatively high melting point which it has to reach in a short amount of time, the material could not be heated enough, thus increasing viscosity. Upon reaching the desired temperature (possibly also caused by the increased pressure), the material is able to flow out. Increasing the temperature of the machine should decrease this phenomenon, which matches the results seen in the experiment.

Due to incomplete notes and late processing of the data, the precise temperatures at some steps are incomplete.

Conclusion

Problems during the extrusion of recycled PET flakes include, minor rat-holing, inconsistent output flow, feeding problems and minor air bubbles. These problems are possibly caused by short barrel length, small feeder screw size and inconsistent material size.

This experiment showed a clear distinction between flakes and granulate, as well as provided first-hand experience and a close-up look at what happens in the extruder at screw level. It has provided a better understanding of material behaviour at the hopper-screw connection.

Appendix C: Observation of 3D Printing test bars

Introduction

Some problems occurring when 3D printing with PET flakes were listed by the client, like starve feeding, inconsistent output and clogging hoppers. In an initial observation research, the process of printing with the 3D printer by 3D Robotprinting and a mixture of virgin and recycled PET was analysed.

Research question: What problems surface when 3D printing with 50-50 virgin-recycled PET material feedstock?

Method

Participants

The client expert J. Menger operated the 3D printer.

Stimuli

The expert was observed during the execution of a printing assignment.

Apparatus

The machine as depicted below was used to print the test bars. A CEAD 3D printing extruder was used. A camera was used to photograph and a notepad was used for notes of the results.

Procedure

The expert was observed during the execution of a printing assignment. During the assignment, questions were asked on the performed actions. The printed model is a long solid box (sized approximately 5x5x30 cm) and is printed in a 50-50 mixture of recycled PET flakes and virgin PET granulate.

Measures

The observations and answers to questions were noted and issues photographed.

Results

The extruder's hopper failed due to static PET dust sticking to the walls and sensors. The refill mechanism therefor was not activated.

The printed test bars are susceptible to sagging and required cooling between each layer (by hand). The printed test bars were hard to remove and damaged the wooden print bed upon removal.

Discussion

From this observation multiple problems surface: Because of the transport of flakes through the tube, the flakes become statically charged. Especially the smaller particles stick to the walls of the plastic hopper on the extruder and on the sensors, crippling the system's refill process. The build-in vibration motor was not capable of removing the static dust from the hopper walls. To continue the experiment, the system had to be rebuilt in the heated tube configuration.

Conclusion

The experiment served as a continuation of the exploration of the 3D printer and its capabilities and weaknesses. The issues mentioned by the expert beforehand were confirmed and first hand 3D printing experience was gained. Also the result of improper cooling of the model was visible. The printer is best used for large items.

Appendix D: Funnel shapes, Flow aids & ‘cold extrusion’

Introduction

PET Flake material is a particulate solid. Particulate solids have some interesting properties, as they behave neither as a fluid nor a solid. It behaves like a fluid, as it flows through openings, takes the shape of its container and exerts pressure on the container walls. However, shearing stress in the material is proportional to the normal load (not to rate of deformation), it may have cohesive strength and shows non-isotropic stress distribution upon application of a unidirectional load, behaviour usually only seen in solids (Tadmor & Gogos, 2006). This yields for interesting behaviour in hoppers and funnels. According to Syntron Material Handling (2019), a hopper should have an angle of 60 degrees and the smallest hole should not be smaller than twice the largest particle size. If clogging of the system still happens, several methods of getting the material to flow again exist: (pneumatic) hammering or air cannons and more preventive measures include fluidization systems or vibration motors. To test whether these systems are applicable and/or necessary for use with PET flakes, this experiment was set up.

Research question

How do PET Flakes behave in different hoppers, what are effective flow aids and what parameters are important when feeding the machine screw?

Method

Apparatus

Using a 3D printer and CAD software, several prototypes of funnels were created: a funnel with a wide opening, a small opening, suitable for a vertical screw, a horizontal screw and an angled screw. An iteration using air as a flow aid was also printed. The height of the hoppers was increased by adding a cardboard edge to increase material hold by the hopper while not increasing the print time. For the cold extrusion part of the experiment, a 18 mm concrete drill was used and a 20 mm (assumed) wood/metal drill was used. Additionally, a ruler, a potato masher, steel wire and an air compressor were used to prototype flow aids.

Procedure

For different hopper shapes a bag of flakes was poured in and the flow of the material was observed. Next, the outlet was blocked after which the hopper was filled with flakes. Upon removal of the blockage, behaviour of the material in the hopper was observed. From this point, if the hopper did not properly empty on its own, a flow aid was used to try to force the material out. This was repeated with multiple times using different flow aids.

Measures

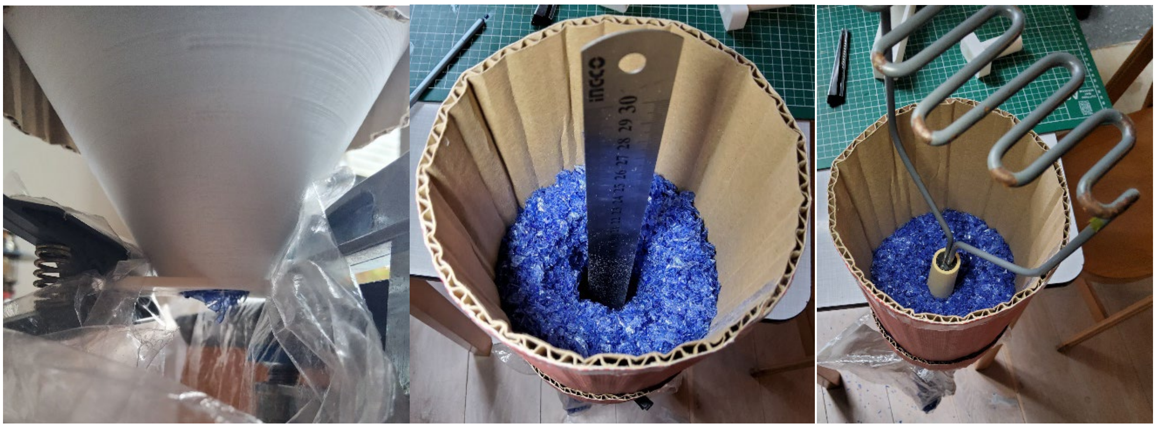
Results

Test 1: Slotted opening: Flakes pass through the hopper quicker than it is possible to pour them in.

Test 2: Slotted opening, filled 100%, stationary: A little less fluent than test 1, but empties completely without issues.

Test 3: Slotted opening, filled 50%, stationary: Even less fluent, chunks stay behind. Upon repetition, this did not happen again. Empties completely.

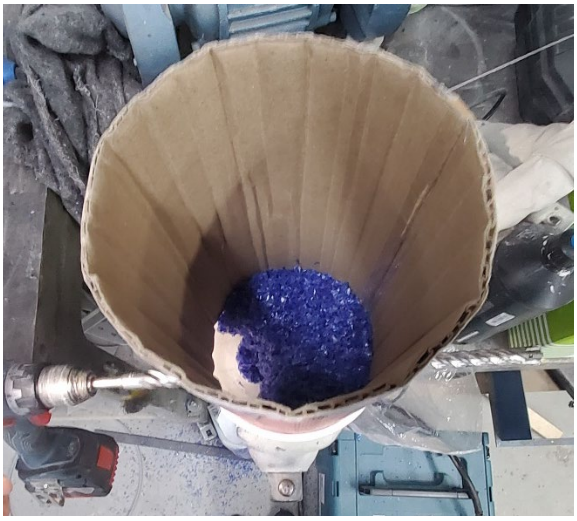
Test 4: Round opening 20mm: Instant clog blocks the output. A rotating ruler in the centre of the hopper lets the material flow out evenly, but shows a lot of tunnelling/rat-holing. Increasing pressure with a potato masher does not work, pressing with both the flat side and handle does not work.



Test 5: Round opening 20mm, vertical, with 18mm concrete drill: When turning the screw flakes are extruded consistently. Very noticeable tunnelling is occurring. Blowing air from below does not help. Rotating some curved steel wire does.

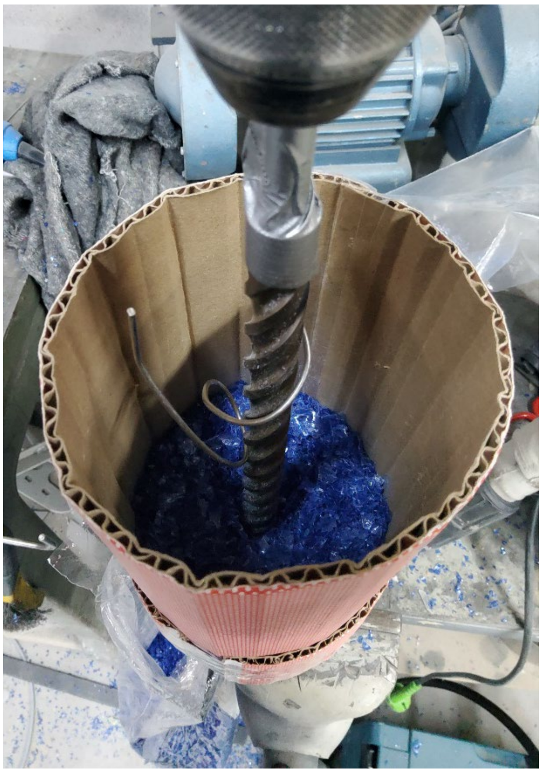
Test 6: Round opening, vertical, with air channels: Blowing air through the hopper does not work. Possibly due to the air channels being too small or to little pressure.

Test 7: Slotted opening, horizontal, with concrete drill: Extruding an optical consistent stream of material. Light tunnelling visible at the back side of the hopper, but it does not cause issues. The hopper is emptied completely without any issues.



Test 8: Round opening, vertical, with concrete drill: Extreme tunnelling, but hopper is emptied entirely. Stream is less consistent compared to horizontal setup.

Test 9: Round opening, vertical, with concrete drill with steel wire flow aid: Steel wire stirs nicely, but in a filled hopper it is too weak. The wire winds itself around the drill.



Test 10: Round opening, tilted 30 deg, with metal drill 20 mm: Very promising, a lot of output per revolution. Tolerances are less tight compared to other hoppers.

Test 11: Round opening, tilted 30 deg, with concrete drill 18mm: Biggest output, but possibly because of opening being bigger compared to the other systems.

Discussion

The tilted funnel with the shallow concrete drill showed best results. This model also showed less tight tolerances between the drill and the barrel. Fluidization of the flakes proved ineffective, possibly due to the different in weight of the particles. A steel wire shows most promising results in tearing down flow disruptions if used by hand.

While the experiment was set up to quickly test different models, the results lack measurements. Upon repetition of the experiment, the number of revolutions and material extruded should be recorded to show a clearer difference between the funnels and screws.

Conclusion

From these tests a better understanding in the flow behaviour of flakes was gained. The tilted hopper could be a promising direction to pursue in future concepts. The deep channel depth of the wood screw is useful for a controllable amount of flakes extruded, while the shallow concrete screw combined with an oversized channel displayed increased output at higher rotational speeds.

Appendix E: Extruder disassembly

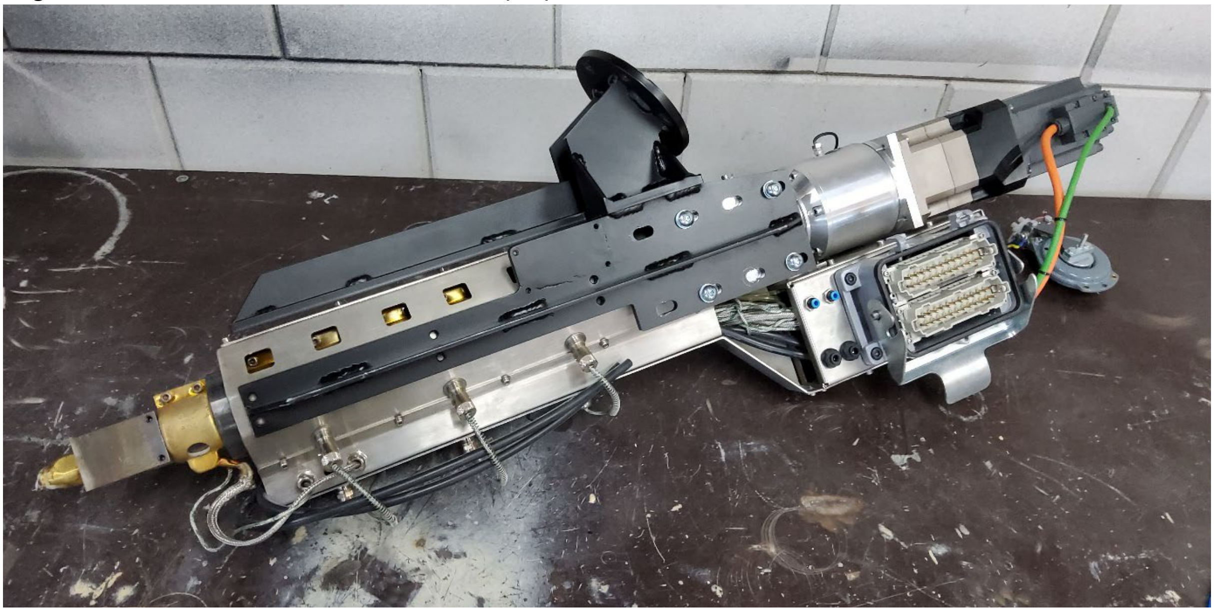
Introduction

Research question: What are the dimensions of the extruder used in the experiments?

Method

Apparatus

For this experiment a CEAD pellet extruder for 3D printing will be used. A ruler, callipers and a protractor angle finder were used to measure the screw properties.

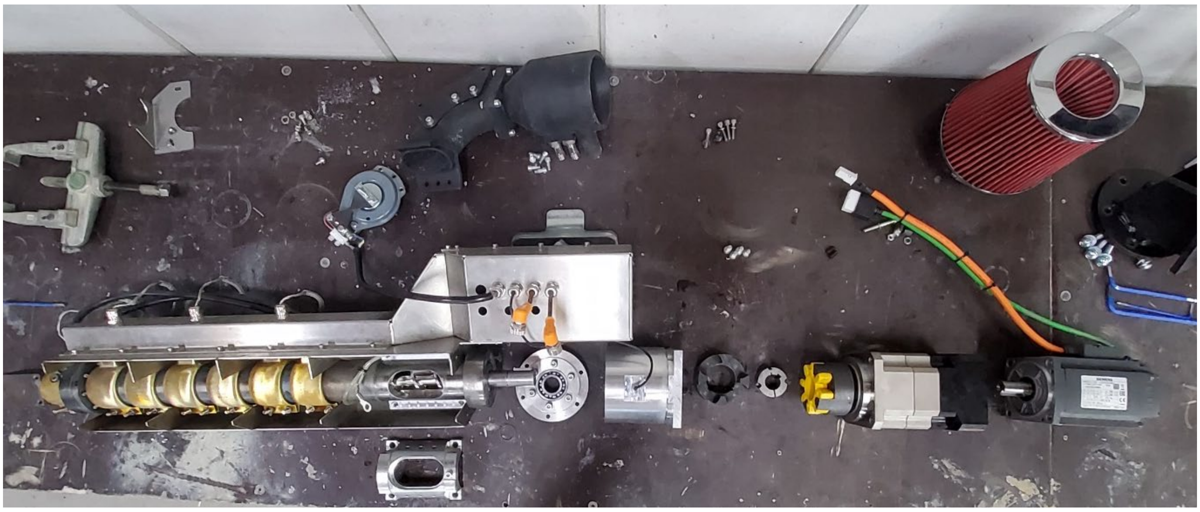


Procedure

The extrusion screw was dismantled step by step. Photos were taken from the process and the parts were measured using callipers and an angle measurer. The length of the screw and the screw zones, the diameter, flight angle and channel depths were measured.

Results

"Exploded view" of the machine



Extruder screw

From the image above the different zones can be seen in the extrusion screw. Length of the feed zone is 245 mm, length of the compression zone is 112 mm, length of the metering zone is 111 mm and the complete screw is 470 mm. The flight angle approximately 20 degrees. The channel depth at the feeding zone is 5,3 mm. Lead is 24,4 mm. Flight thickness is 3 mm. Screw diameter is 25 mm.

Maximum particle size for this machine: 5,3/2 = 2,7 mm (currently used print extruder: 4,3/2 = 2,2)

Limitations

It can be noted that the total of previously mentioned measurements is not equal to the total screw length by 2 mm, due to hand measurements.

Appendix F: Testing the Concepts

Introduction

Goal: make a choice between concepts.

Does a large screw depth & pitch improve feeding?

To what extend is it possible to force flakes in the system? Particular solids resist shearing forces, which theoretically means they are unable to be transported (through a funnel/compacted) by force. Can this be overcome by high amounts of force? How much of a surface decrease allows flakes to be pushed through? Does the extruders output increase in consistency if flakes are forced?

If cold forcing is not possible, is it possible to inject a semi-molten substance in the extruder?

Because the flakes are rather thin, they can fold. Without pressure a big flake can easily form a bridge. With pressure, it can be forced to fold and end up in the extruder. It is expected that a bigger funnel surface area change will require more force to push the flakes trough. It is thus expected that a bigger end hole in the funnel will improve the output. To be tested is if the material can be forced through a hole sized to the extruder inlet.

Method

Participants

The participant was selected based on his expertise in the field of plastic production techniques and polymers in general.

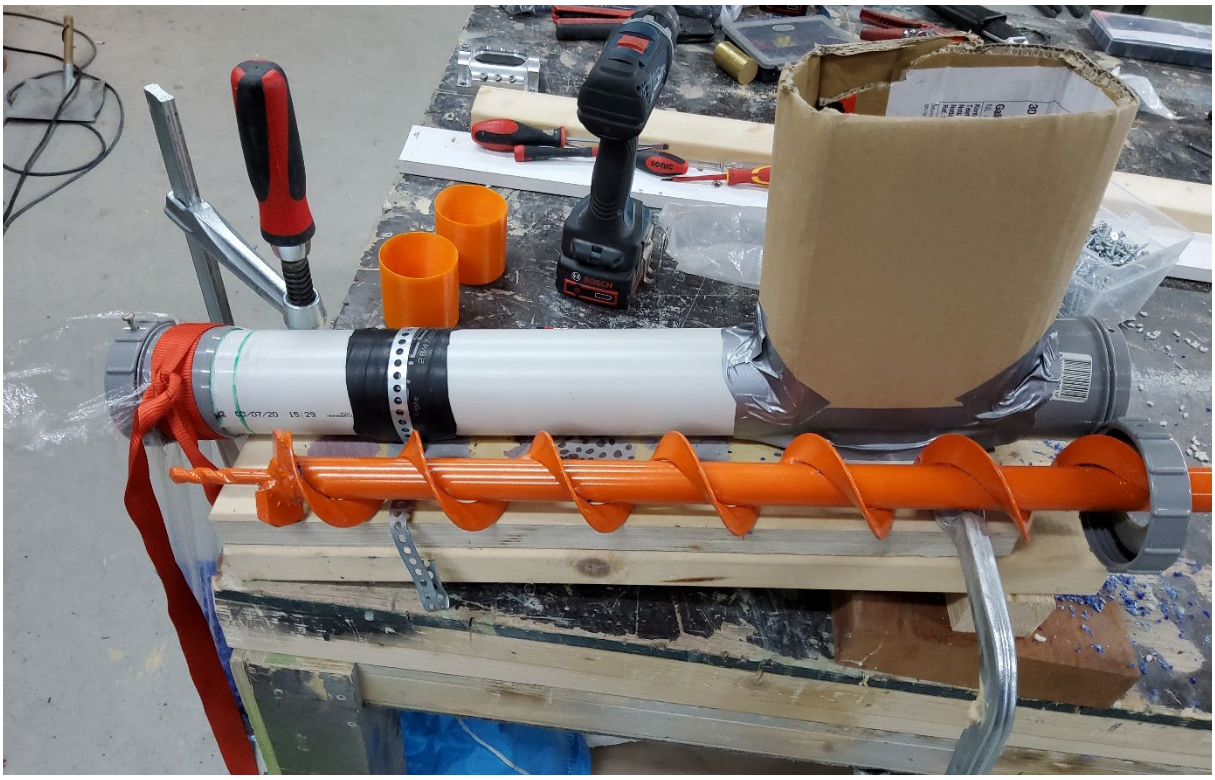
Stimuli

The participant was presented to the working principle communicated through the phone & email.

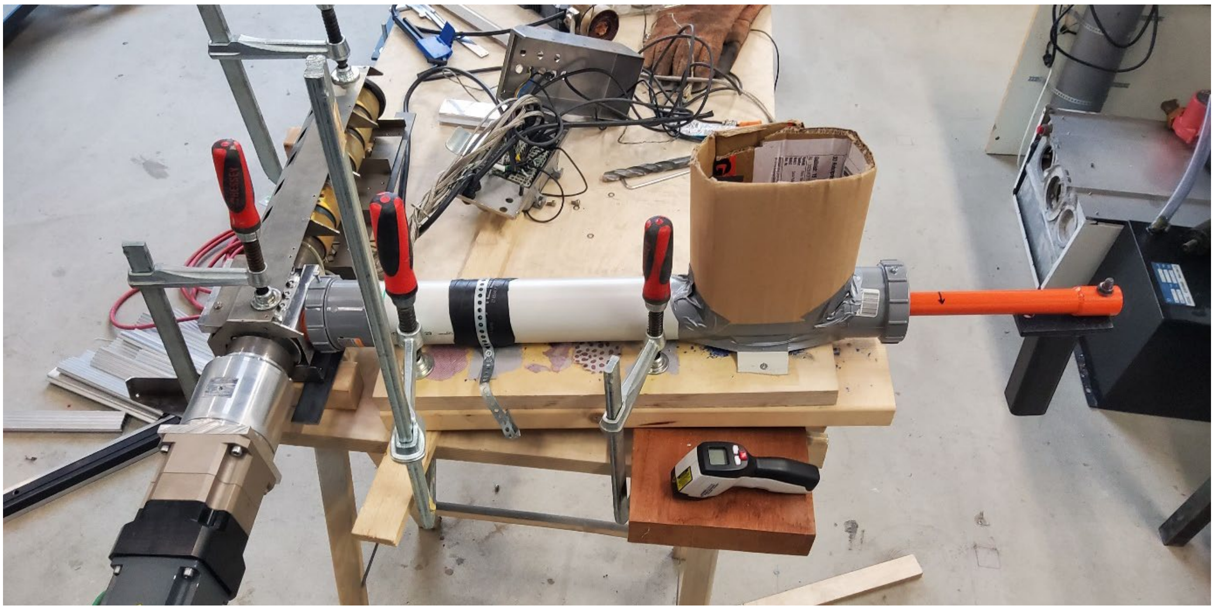
Apparatus

A prototype was built to test the principle behind the third concept. The prototype consists of a 'ground drill' of 60mm, an 70 mm PVC plumbing pipe (inside diameter: 67 mm) with threaded end caps over the outside. The caps have holes in the centre. On the back for the end of the drill to be put through, at the front sized to be slightly bigger than the holes in the 3D printed funnels. These funnels were printed with different hole sizes, angles and shapes: a round hole with 12 mm diameter, a round hole of twice the area and a slotted hole sized the same as the extruder inlet.

The ‘ground drill’ has a large channel depth and a constant pitch. The end of the drill has a metal drill bit welded to the end, accompanied by two thick steel plates. These plates were larger than the inner diameter of the tube and were thus grinded down to fit in the PVC tube. The end of the screw was bolted to a square metal tube on a 90 degree angle to be able to put pressure on the drill.



The tube with the connected end caps was fitted with a cardboard hopper on top of a cut out to feed the tube with flakes. The hopper walls were vertical compared to the tube. The tube was screwed to a piece of wood and clamped to it with a metal strip with a rubber layer to prevent rotation of the tube. This construction was clamped to a heavy table. The end caps were fitted with a short 4 mm screw to prevent unscrewing during use.



The prototype was connected to the extruder from appendix E using a 3D printed bracket and clamps.

Procedure

<u>Prototype tests:</u>

For each test, the prototype was emptied beforehand. The hopper was filled to the top with the material sample. The extruder end was fitted with a plastic bag to catch the extruded flakes. The screw was turned by hand until the flakes were all extruded, until the extruder was clogged or until the screw was not turn able anymore.

Test 1: The prototype is mounted horizontally, fitted with the small funnel and fed with PET flakes.

Test 2: The prototype is mounted horizontally, fitted with the large funnel and fed with PET flakes.

Test 3: The prototype is mounted at an angle with the table, fitted with the large funnel and fed with PET flakes.

Test 4: The prototype is mounted at an angle, without end caps and fed with PET flakes.

Test 5: The prototype is mounted at an angle, fitted with the small funnel and fed with PP granulate.

Test 6: The prototype is mounted at an angle, fitted with the large funnel and fed with PP granulate.

Test 7: The prototype is mounted at an angle, fitted with the slotted funnel vertically and fed with PET flakes.

Test 8: The prototype is mounted at an angle, fitted with the slotted funnel horizontally and fed with PET flakes.

Test 9: The prototype is mounted at an angle with the slotted funnel to the CEAD extruder and fed with PET flakes. CEAD extruder barrel temperatures: 220, 240, 250, 250 (degrees Celsius). CEAD extruder screw speed: 100 RPM.

Test 10: The flakes were fed directly into the CEAD extruder by hand. CEAD extruder barrel temperatures: 220, 240, 250, 250 (degrees Celsius). CEAD extruder screw speed: 150 RPM

Test 11: The flakes were fed directly into the CEAD extruder by a metal hopper with vibration motor. CEAD extruder barrel temperatures: 220, 240, 250, 250 (degrees Celsius). CEAD extruder screw speed: 150 RPM.

Expert interview:

The interview was taken through a call. Drawings of the three concepts were send to the participant beforehand. First a general introduction about the project was given, then the three concepts were discussed.

Results

Prototype tests:

Test 1: The screw requires a lot of force to turn. No output is achieved. The material is only stirred by the screw. The funnel is clogged with tightly packed flakes.

Test 2: The screw requires less force to turn than in test 1. A small amount of flakes are output. Flakes are pushed up at the front and drop down at the back of the hopper.

Test 3: No significant difference was observed.

Test 4: Screw requires little force and output is high and consistent. The barrel filled halfway, up to the screw core.

Test 5: The PP is extruded successfully.

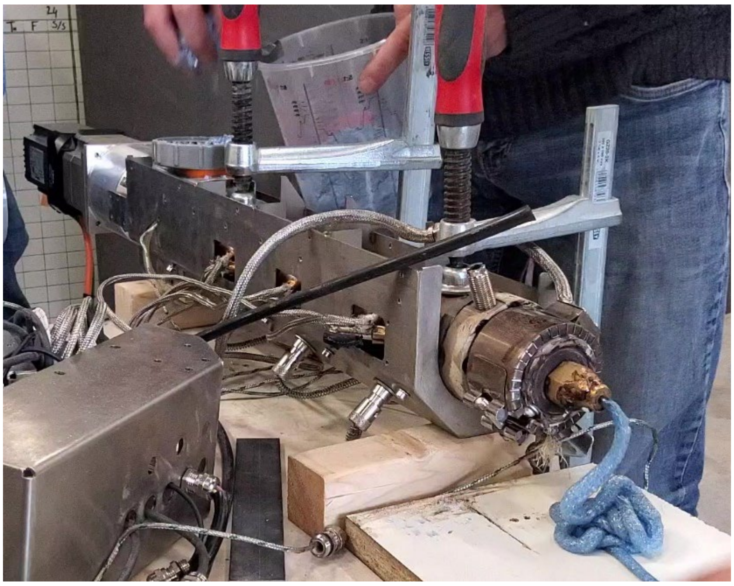
Test 6: The PP is not extruded and clogs the funnel.

Test 7: Screw requires force to turn but remains turn able. Output at the prototype end puts light but distinguishable pressure when the output opening is blocked by a hand. Drill feels warm, as is the end of the tube.

Test 8: Output is better than in test 7.


Test 9: Only little output from the extruder. By the sound of the electric motor a lack of material in the barrel was noticed. By wiggling the screw back and forth the best result is achieved, but it is only marginally better.

Test 10: Feeding the flakes by hand yields a significantly better result. The PET appears foamy upon extrusion. Air bubbles are visible in the extrudate. The output is constant. Upon cooling, the material is hard and brittle.



Test 11: Extruding with a metal hopper instead of hand feeding yields results equal to test 10. Light bridging was observed, but no flow obstructions persisted.

Expert interview

The participant considers the concepts viable. He thinks the force feeding concept could work. Sealing the vertical extruder is not a problem, as it is comparable to injection moulding air vent channels: The viscosity of plastic is high, even when fluid, so it will not penetrate small holes.

The participant mentionned that as plastics require a lot of energy to heat up, the start-up time of a larger extruder could increase. Plastics are terrible heat conductors.

At temperatures of 100+ °C aluminium can become brittle. For these machines, the use of steel is thus adviced, according to the participant.

During the granulating and shredding of the bottles, static electricity can also be induced in the material.

Discussion

Prototype tests

The tests showed that the force feeding concept is likely to fail. The concept could be further developed by adding a heated funnel instead of the 3D printed funnel currently used. However, the behaviour of the extruder when receiving a partially molten material as input is unknown. Therefore, this concept is regarded non-viable. The experiments showed that by increasing the channel depth, the particles are easily grabbed by the screw and moved down the barrel. Even the slightly larger CEAD extruder showed improved results over a previously tested 18 mm diameter extruder. The large extruder concept is thus deemed viable.

In the experiments, a single material sample is used. By reusing the material sample, small particles could get lost, shifting the particle distribution. The material was extruded without drying beforehand. This is likely the cause of the foamy PET output.

Conclusion

While the concepts were tested in a simplified form, the results convinced the client to pursue the development of a large extruder. It also ruled out the force feeding concept. The vertical extruder is considered interesting for future research, as it appears feasible, but requires additional research before it can be compared to the other concepts.

Appendix G: Product printing tests

Introduction

When designing the slide geometry, several issues showed. To find the best way to operate the machine through proper digital model design, tests were set up.

Research question: How to connect surfaces without disturbing the single tool path loop? How to connect multiple loops to form a single tool path loop?

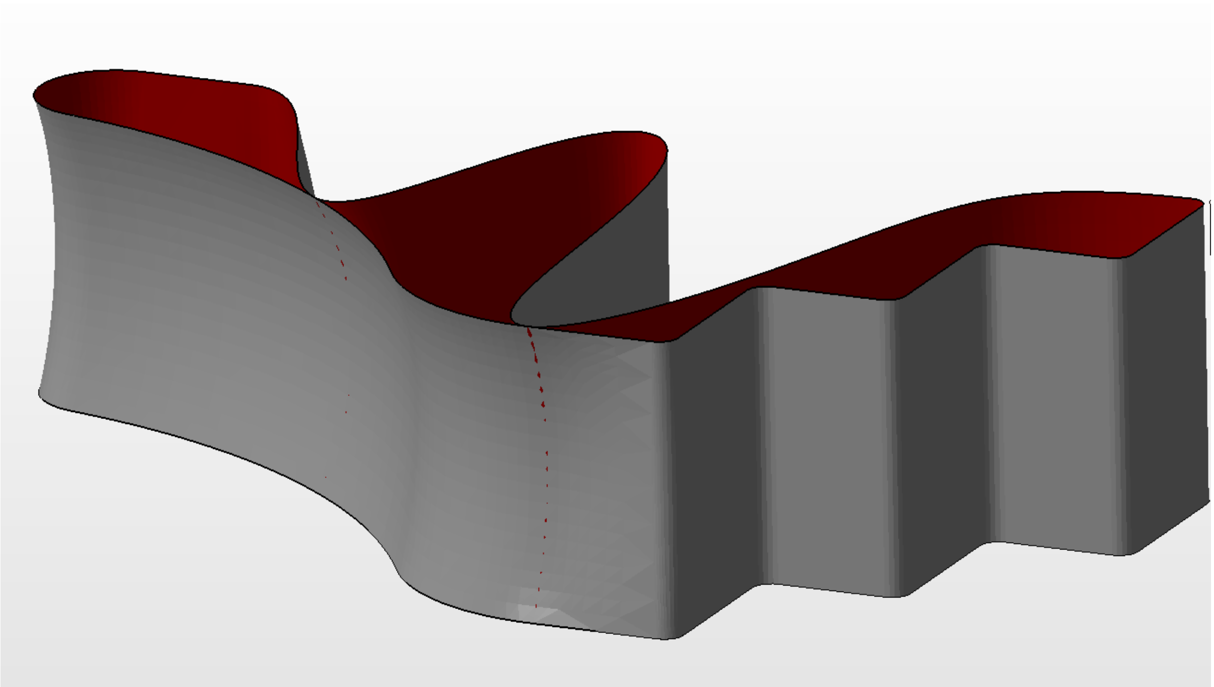
Method

Apparatus

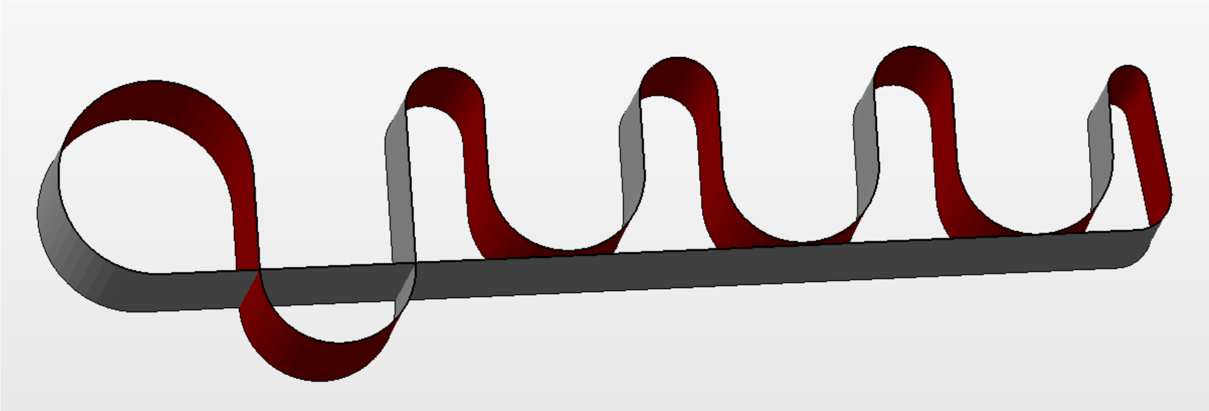
The printer used features a 18 mm standard polymer extrusion screw. Nozzle size: 3,6 mm. The prints were sliced using Cura 3.6.0. with settings: Surface mode; layer height 1,6 mm; layer width 5 mm. Most of the prints were done using PP (30% glass fill) pellets. The final print uses virgin PET granulate.

Procedure

Print 1: Single loop slide model, connections intersecting mathematically, using the ‘spiralize outer contour’ setting in Cura.

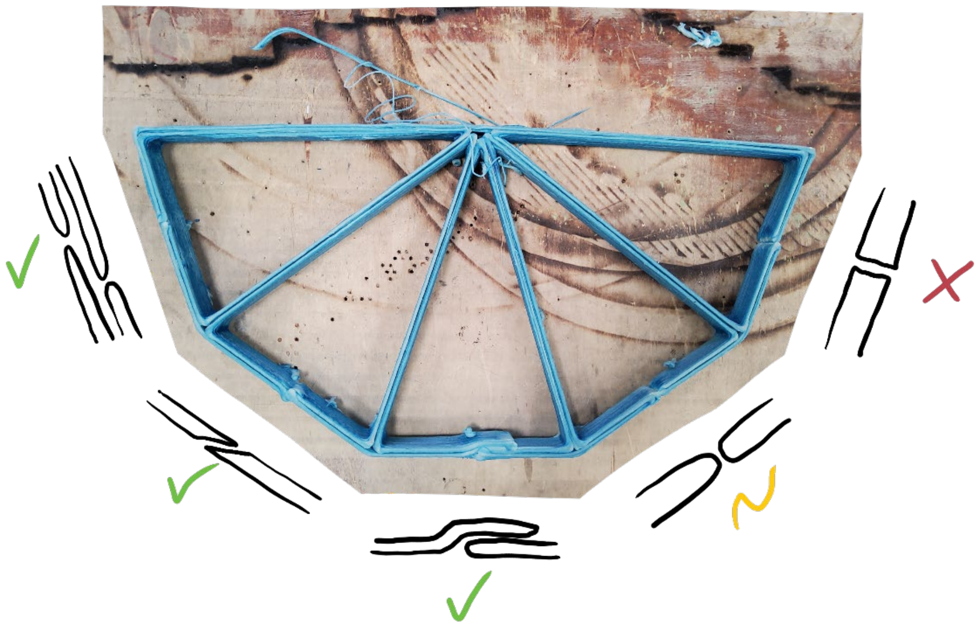


Print 2: Test model testing intersection connections. Using the ‘spiralize outer contour’ setting in Cura. The connections from left to right: a cross-over; no overlap (line distance = layer width); 50% overlap (line distance = 0,5 * layer width); full overlap (line distance = 0,01 mm).



Print 3: Single loop slide, connections do not intersect mathematically, using the ‘spiralize outer contour’ setting in Cura. The single loop slide was then put under a strain of approximately 80 kg, consecutively on each step.

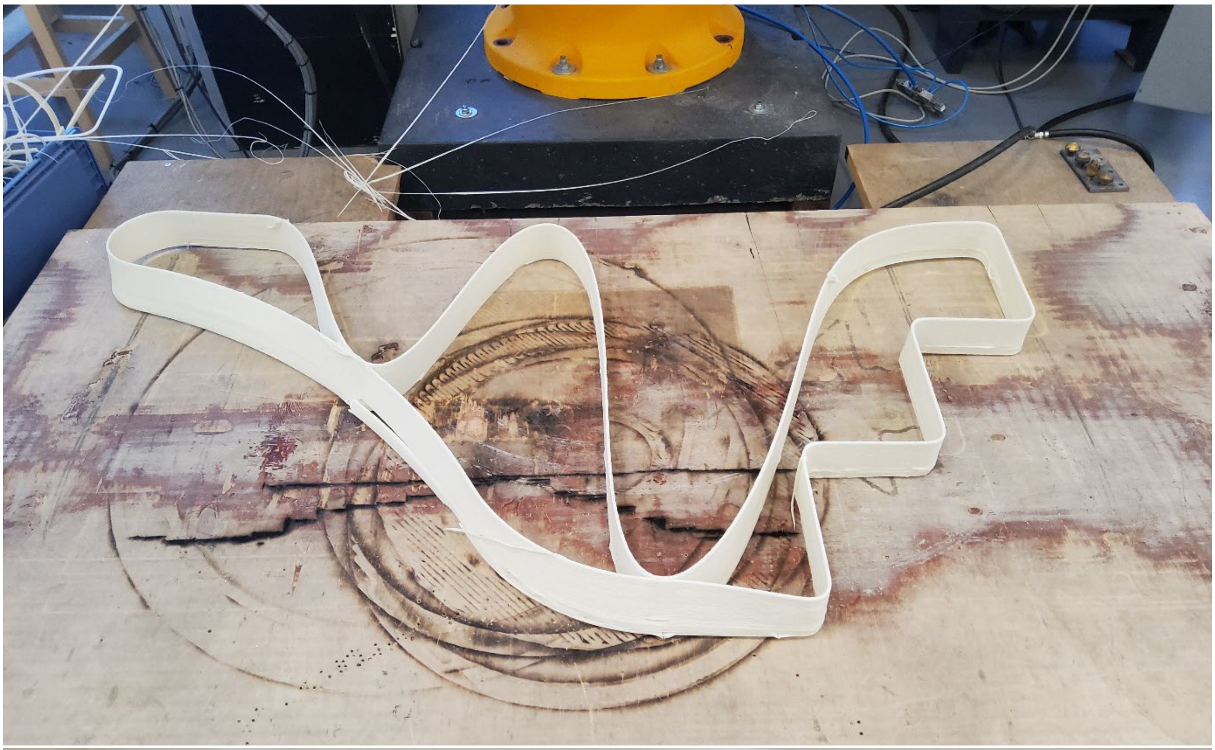
Print 4: Connection test, with 5 different connection points. The first connection shifts the weak point each layer. The second uses a weakness of the printer to force a small overlap in layers. By creating two sharp corners opposing each other, the tool path overlaps and fuses the layers together. The third connection increases the surface contact area of the connection. The fourth connection is just a turning point of the tool head at a small distance (0,01 mm). The fifth is equal to the fourth connection, only without rounded corners.



Print 5: The double-loop slide in virgin PET pellets. The print was cancelled around 50% completion. The print was put under strain equal to print 3.

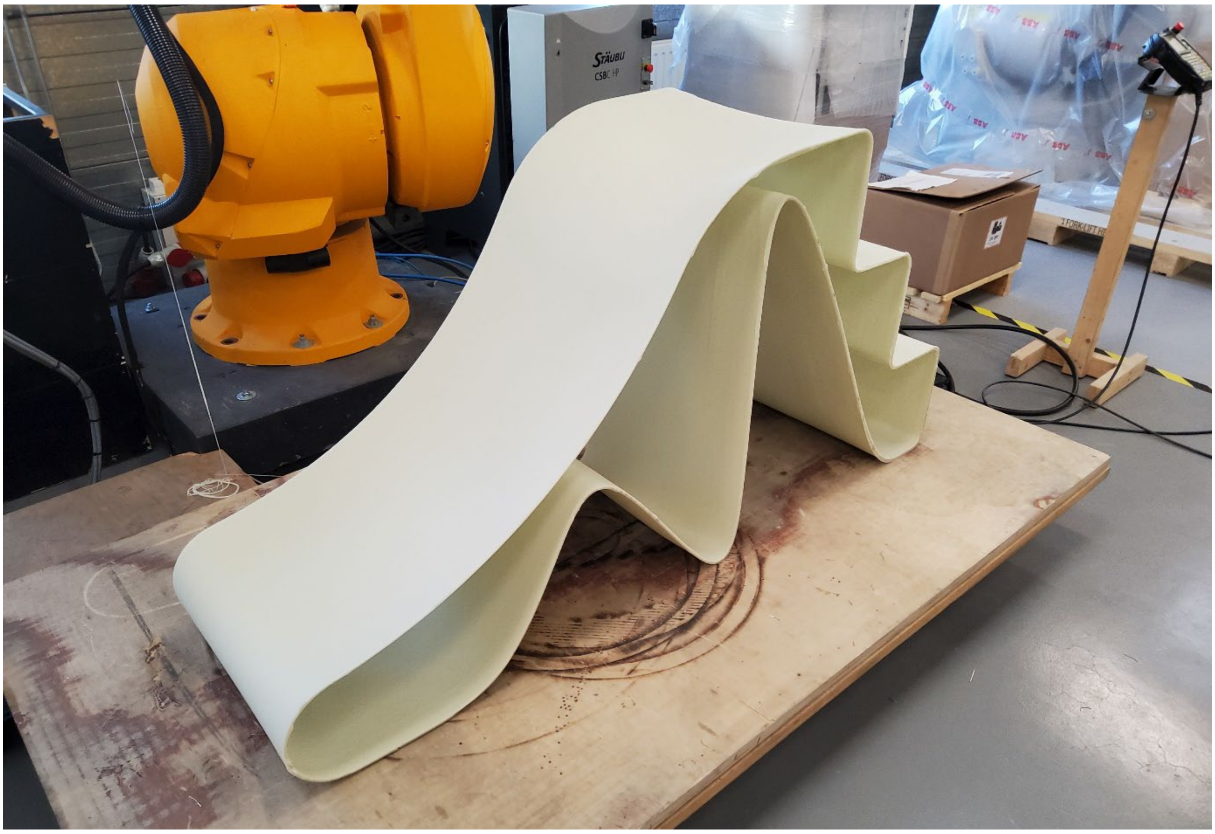
Results

Print 1: The print has trouble in sticking to the build plate at certain spots. The first cm printed is often damaged a bit by the staples used to make sure the print sticks to the bed. They sometimes cut it off, if good surface quality is desired. The speed of the robot is controlled during the first layers by hand. It can be increased/decreased if necessary. The paths connecting parts of the print by overlap likely caused errors at the surfaces that touch (see image at ‘Procedure’).



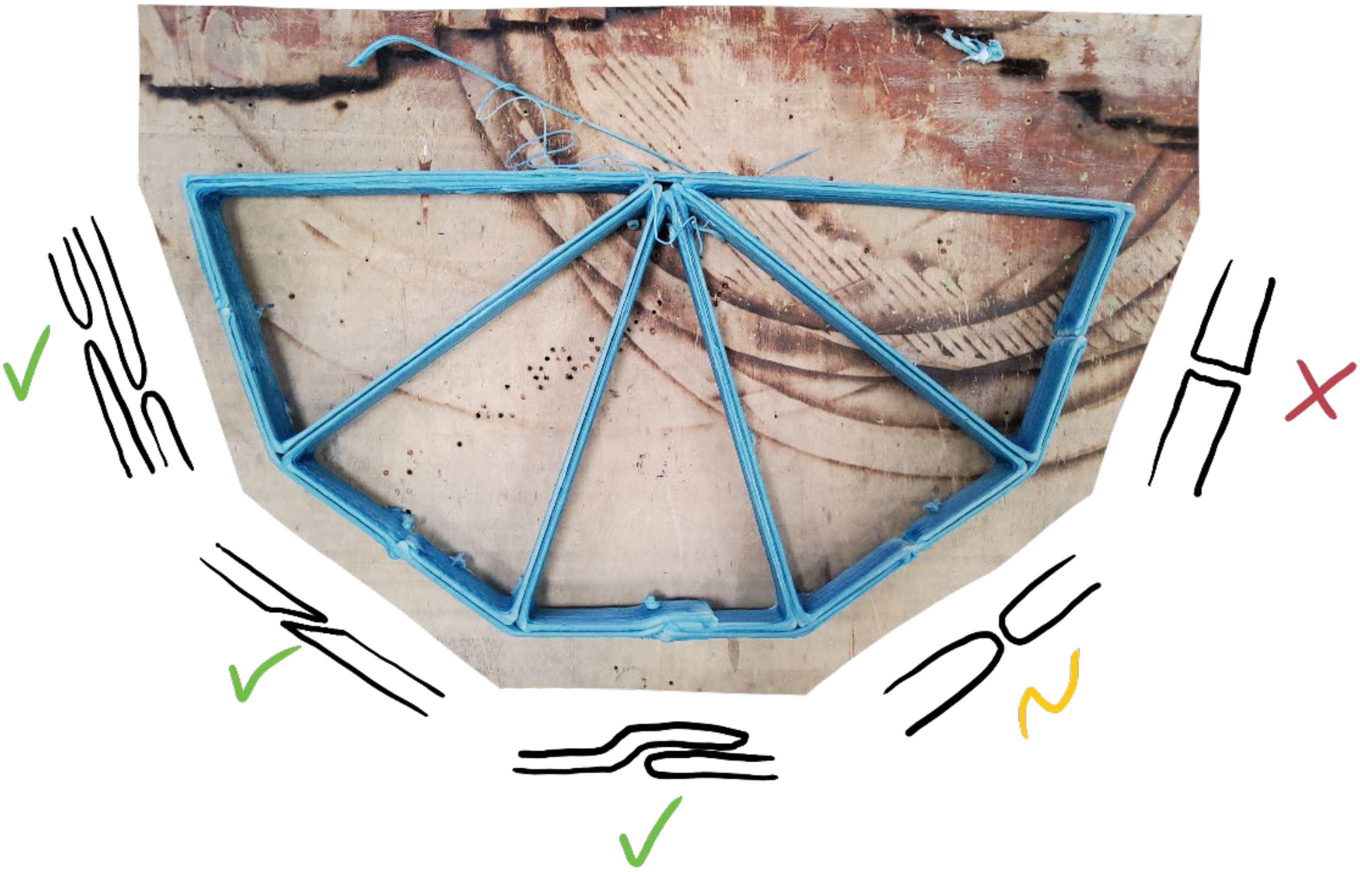
Print 2: Test geometry. When slicing, paths crossing each other result in the robot making two 90-degree corners instead of crossing over its previous path. Both the 90-degree corners in practice are filleted by 1 or 2 cm, thus leaving a gap where a connection should be. The material is quite flexible at 5 mm wall thickness (1,6 mm layer height).

Print 3: The slide prints first go. The connection point is slightly visible through the outside slide surface, as can be seen in the picture below. The contact area is around 100 mm (70 layers). Under strain, it is strong enough for children. If the bottom surface is prevented from moving, adults can be supported as well. Wall thickness in practice varies between 5 mm on the straight parts, to 8 mm in corners.

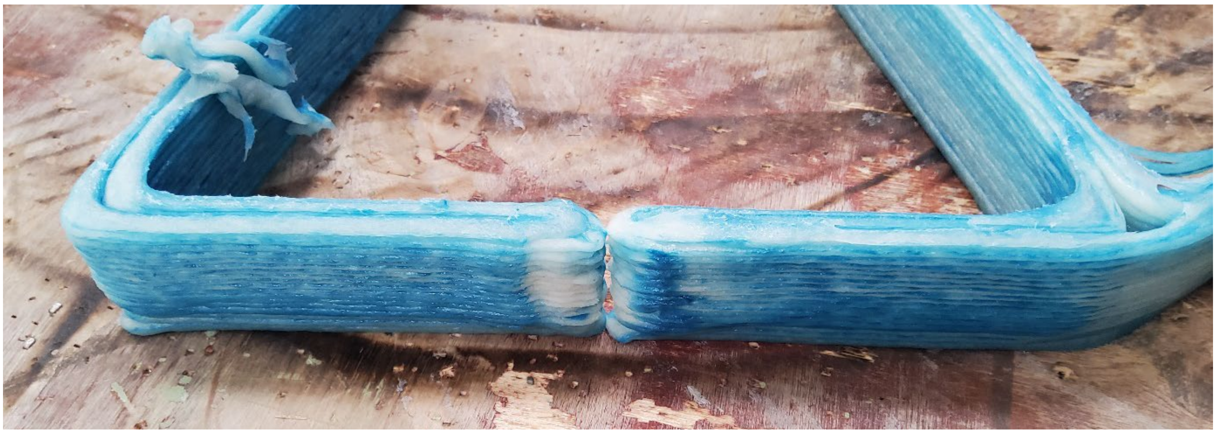


Tolerances are (currently) no set value; it is tweaked during the printing. If tight tolerances are necessary, the wall thickness is measured and the flow adjusted if necessary. In the future, this will be set in the software.

Print 4: Of the five connection methods tested, two failed to connect or were very easily separated. Three connections were solid.

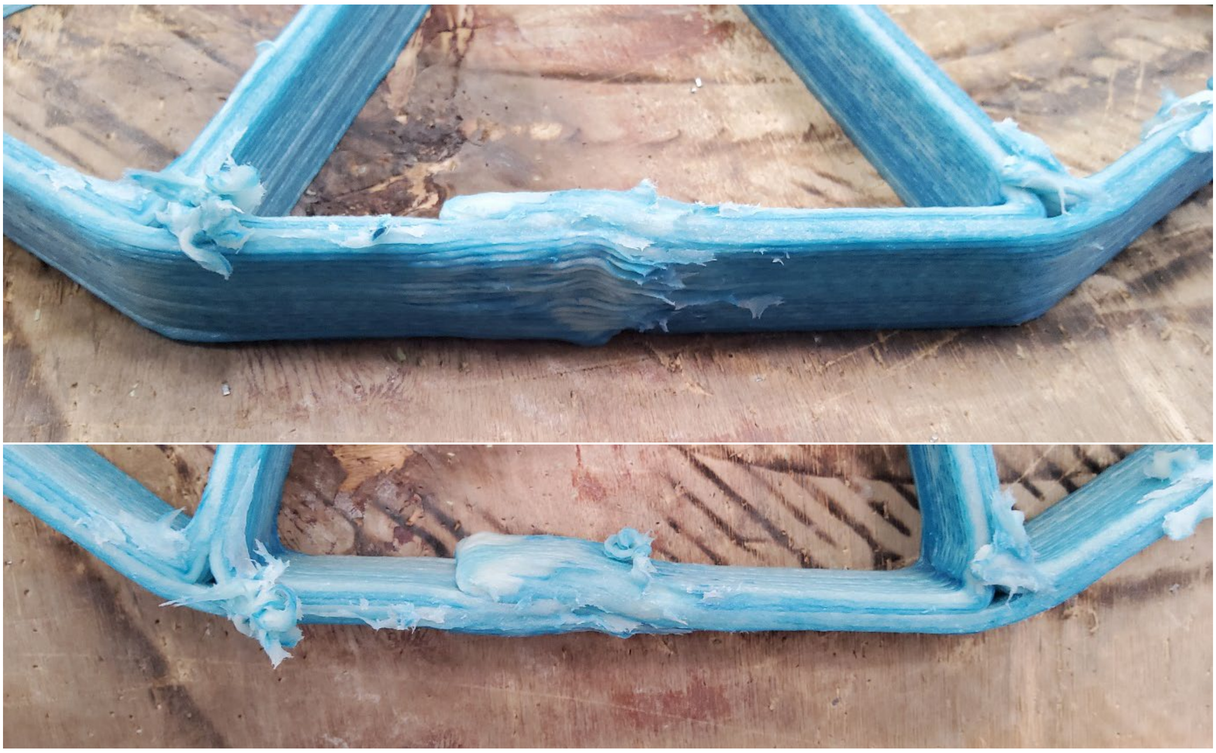


The most right connection did not connect at all, as can be seen:



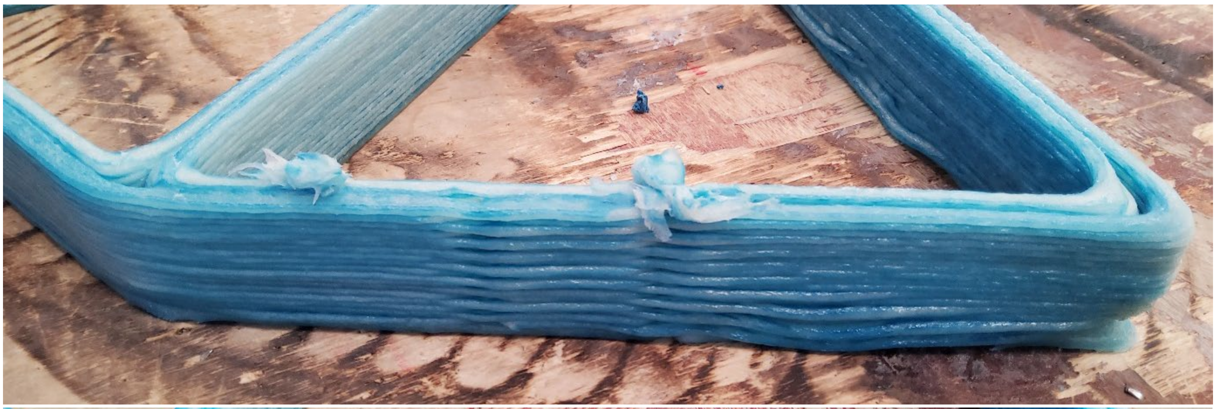
The second connection from the right connected, but was easily pulled apart. Could be interesting for removable parts.

The middle connection method showed cooling issues. The layers were saggy, which was also visible on the outside of the model. The layers did connect properly and were inseparable.



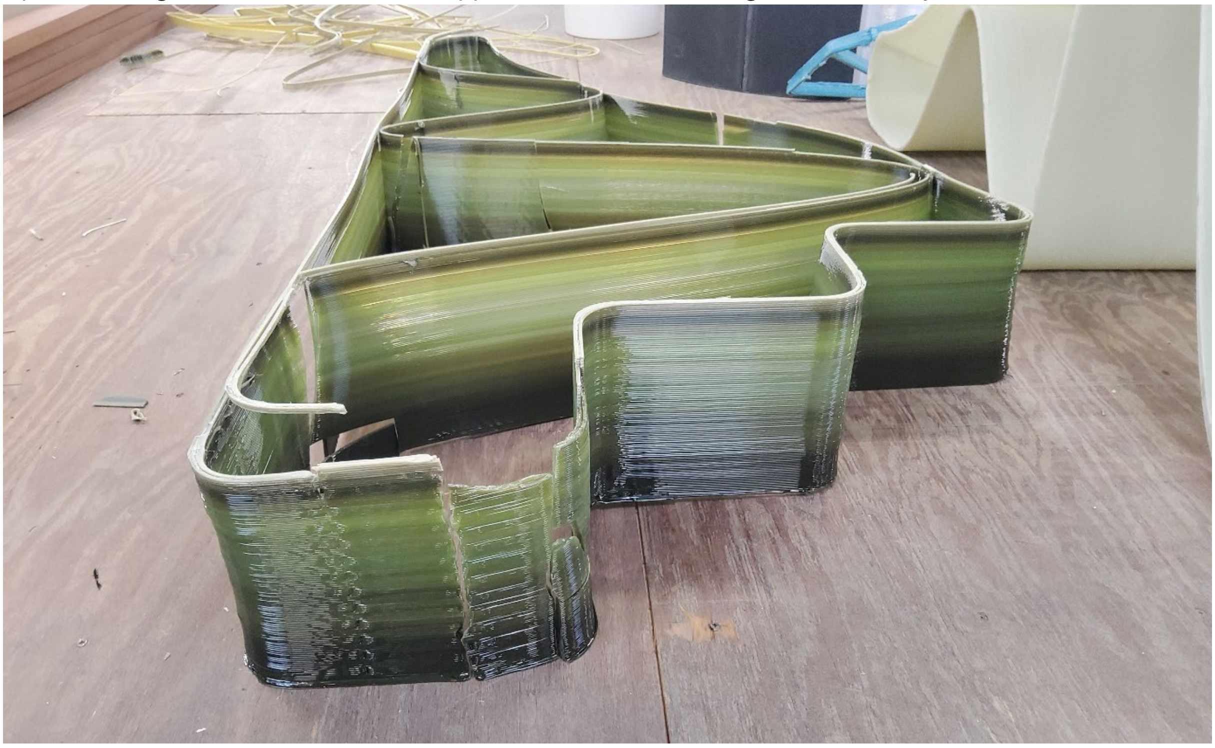
The second connection method from the left was also visible on the outside of the model, but suffered less of cooling issues. An increase of thickness around the connection point was observed. The parts were connected properly.

The most left connection showed no increase in material thickness. The connection was the most clean of the five. However, it is also took the most time to draw in the CAD software.



Print 5: The final print was cancelled at 50% and showed that PET is much more brittle than the previously used glass filled PP. By straining the model, it became clear that the stairs required more support. The overlapping connection point method was used, but for ease of CAD modelling, the layer shifted every 5 layers instead of every layer. This caused the strength to be reduced. The model in PET showed more warping than the previous PP models. The staples also chipped parts of and caused cracks in the model. During printing, occasional tool head travel showed. In hindsight, these travels were also visible in the slicer. The sliding surface of the slide is suitable for sliding when printed in PET, as it is very smooth.

Upon straining the model, the model snapped at the stairs, cracking the whole body.



Discussion

The experiments showed practical solutions to problems encountered in the design of the slide iterations. Using the knowledge found, further experiments were set up. Even though the final model in PET was not printed successfully, the guidelines can be set up from the findings. However, the experiments were set up specifically for the slide. For different geometries, different solutions can be applicable. For different materials and settings, different results can be expected.

The strength analysis was not accurate enough to result in solid conclusions, due to incomplete prints. Further experimenting is necessary to analyse force distribution through the model. As PET is brittle, it snaps like glass. It creates sharp edges and shards. Therefore it is important to ensure the model cannot be broken by kids (also when abused).

Conclusion

The proper way to connect features without intersecting the single tool path were found. Layer overlaps of 0,5 * layer width are sufficient in most cases. For extra safety can be chosen for a line distance of 0,01 mm. This does leave marks on the outside surfaces.

When using multiple loops in the slide, the loops can be connected in three ways when using the current settings. Each method showed distinct advantages and disadvantages:

Connection	Disadvantages	Advantages
Increase horizontal path overlap area	Large lump of material and sagging layers around connection	Fool-proof, high surface contact
Use a sharp cornered connection (without fillet)	Small lump of material around connection, quality influenced by tool head speed	Easy to generate in CAD-software, simple connection
Consecutively overlapping the connection point by the next layer, by shifting the connection point between layers	Reduced strength at connection, hard to generate in CAD-software, can induce errors in slicing software	Aesthetically interesting, uniform wall thickness

As the PET model appeared to be weaker than the PP model, additional testing should be performed, eventually strengthening the slide geometry.

Appendix H: Deflection tests

Introduction

From the print tests in appendix G was seen that the PET print was more brittle than the PP print. The slide snapped under strain at the stairs. The geometry's strength therefore should be increased. This was done by redesigning the slide with improved curvature, extra print optimalisations, by connecting the infill wave structure to the stairs and by increasing the width. To test the influence of these additions without printing four full-scale slides, 1:10 scale models were put under strain.

Research question: What is the influence of the width on the strength of the model? Is the final geometry stronger than the old geometry?

Method

Apparatus

The 1:10 slides were printed on a modded Wanhao Duplicator i3 V2.1 in MTB3D basic PLA (0,4 mm nozzle). The models were sliced in Cura 4.9.1. with following settings: Surface mode; Print speed: 75 mm/s; Flow: 110%; Printing temp.: 215 °C, Bed temp.: 60 °C; layer height: 0,16 mm.

A clamp was used to strain the models. A piece of foam tube was used to apply the pressure evenly over the curved top surface.

A scale was used to measure the force put on the models.

A camera was used to record the deflection.

Procedure

The slide was placed on the table edge. The position of the scale model was marked on the scale. The model was placed on the scale and gradually strained to the desired value. The weight on the scale was recorded and the deflection photographed. The unstrained model was photographed. The photos were imported in Adobe Photoshop. The unstrained layer's hue shifted (-152) and layer mode set to multiply. The length of the slide was measured and applied to the Photoshop document using the "set measurement scale" feature. Using the measurement function in Photoshop, the maximum deflection and the deflection at the point of the force application was measured.

This process was repeated for: final and the old geometry in 50 mm width and 60 mm width, for around 21N strain on the second step and around 42N strain on the top of the slide.

Results

Old geometry - 50 mm wide
Load: 21N on second step
Max (M): 7,6 mm
At force point (F): 4,7 mm

Final geometry - 50 mm wide
Load: 21N on second step
Max (M): 4,8 mm
At force point (F): 3,5 mm

Old geometry - 50 mm wide
Load: 42N on top surface
Max (M): 11,5 mm
At force point (F): 5,6 mm

Final geometry - 50 mm wide
Load: 43N on top surface
Max (M): 4,4 mm
At force point (F): 2,2 mm

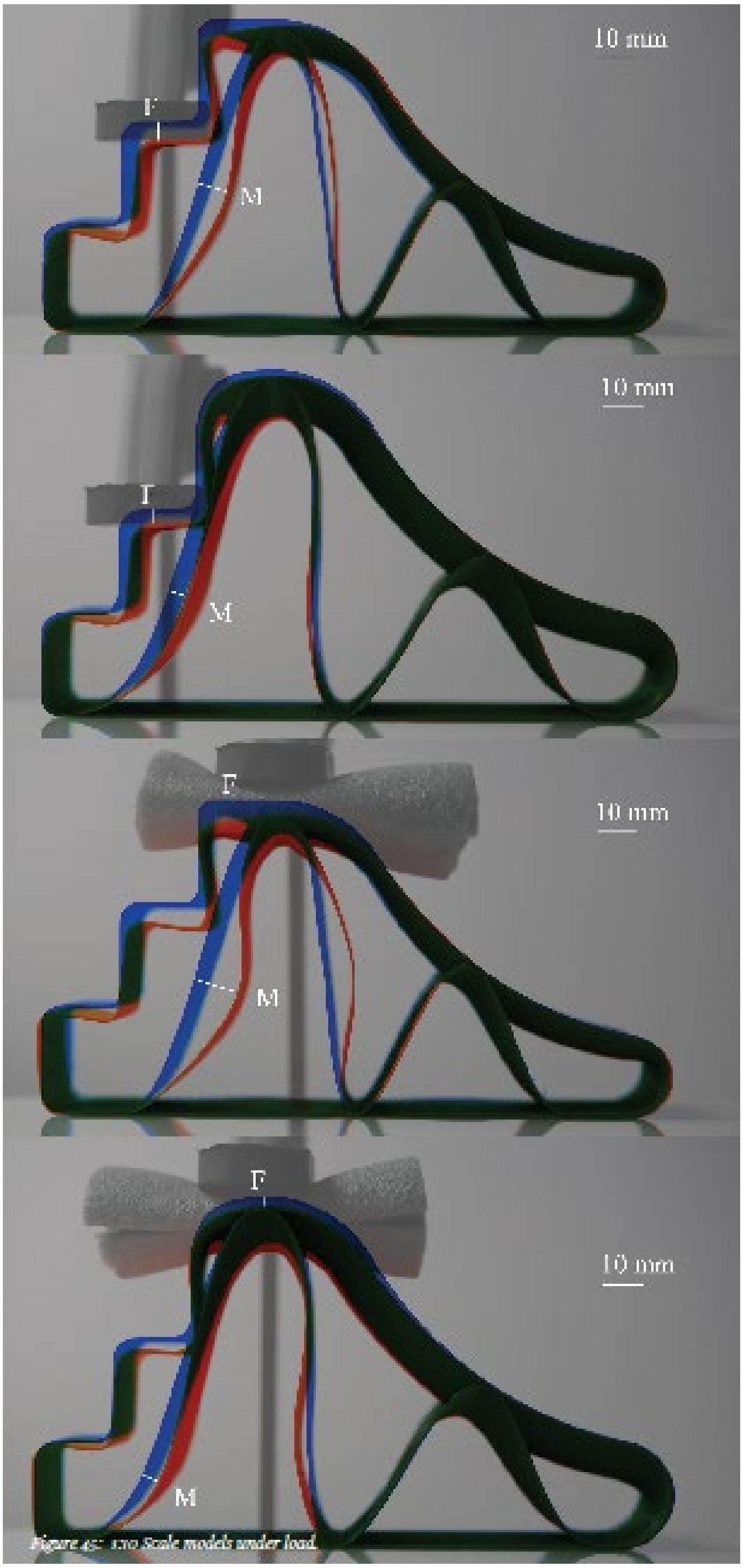


Figure 45: 1:10 Scale models under load.

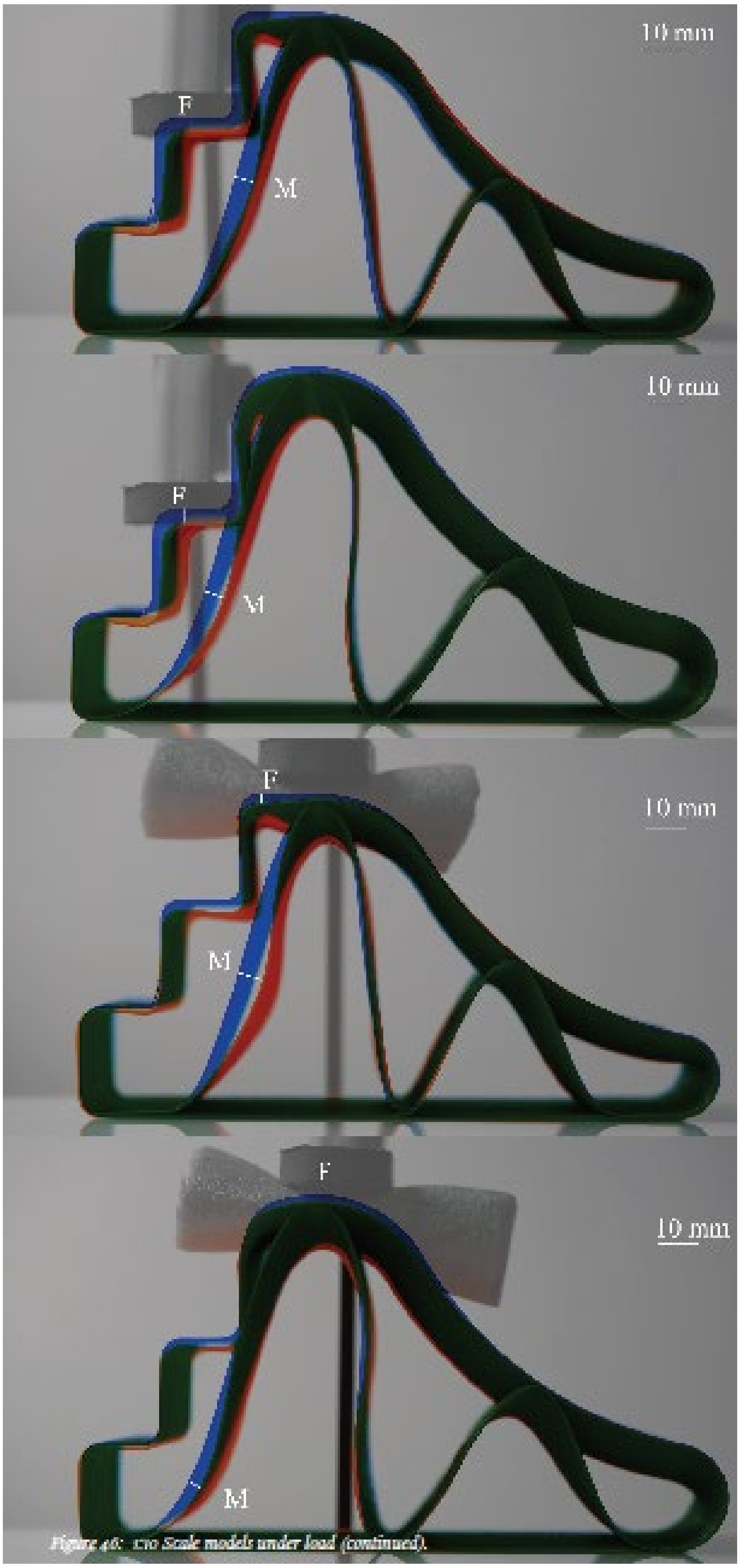


Figure 46: 1:10 Scale models under load (continued).

Discussion

The results show a clear distinction between the final geometry and the previous geometry. The final geometry does deflect less. Increasing the width is also effective to decrease the deflection in both geometries.

While the models were printed in 1:10 scale, it is uncertain how the forces should scale. PLA has also different material properties from PET, making a translation to the full-scale models difficult. The results do however show that the final geometry of 60 mm wide is the stiffest model.

Conclusion

The results showed increasing the width is an effective measure to increase strength and stiffness of the slide. The updated geometry is also effective in reducing the deflection under strain. The new full-scale model is thus likely to be stronger than the previous iteration. Due to a different material and different load, the results cannot be translated to full scale.

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: Eikelenboom 4288
initials: given name: Daniël
student number: 4216695
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: Zjenja Doubrovski — dept. / section: MD

** mentor: Ruud Balkenende — dept. / section: CPD

2nd mentor:

organisation: 3D Robotprinting

city: Rotterdam — country: The Netherlands

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.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair ______________ date 17 - 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: 35 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 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 Colinda van der Bunt date 27 - 07 - 2020 signature ______________

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

comments

name Monique von Morgen date 28 - 07 - 2020 signature ______________

Big 3D prints from recycled plastics

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 01 - 06 - 2020

30 - 10 - 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, ...).

3D Robotprinting builds 3D printers from an industrial robot arm and a granulate extruder. These devices can 3D print big objects, for a variety of industrial and decorative purposes. Past projects include parts for a wind tunnel for research at the TU Delft, connectors for off-shore pipes, customizable sewage pipe connectors, the shell of a submersible, a train simulator and multiple art and decorative items (figure 2). Materials used include TPE, PMMA and PLA, but mostly glass fiber reinforced PP with optional additives for color or fire retardant. To achieve a circular material loop, they have experimented with printing with flakes from post-consumer PET waste, however this is not comparable with virgin material as the flakes are shaped differently and are lighter. The machine has trouble pulling the flakes into the extruder which results in the machine clogging up. What precisely causes these jams and how to solve these problems, is unknown. As a current work-around, they add virgin PET granulate to the recycled flakes.

The printer comes in two variations: A version with a stationary extruder, which is connected to the print head with a heated tube while the second version has the entire extruder mounted to the robotic arm (figure 1). Their future vision with the printer, is to create a container sized machine, where on the one end PET bottles are fed in and on the other end a product emerges (Figure 1). This product would be especially useful in a remote areas where bottles are frequently used for clean drinking water. For this project, this is a military base in Mali. Everyday, the residents produce 300 kg of PET waste from water bottles, which is currently burned. If this waste stream could be used as a resource, it could provide unique opportunities to sustainably (re)build the base and local communities. It could contribute to the local economy by providing replacement parts, construction materials or other products that are otherwise inaccessible or have to be flown in.

One of the disadvantages of re-using waste plastic, is that the quality decreases when it is remelted. Therefor it is crucial to have as little heat processing steps in the recycling cycle as possible. An extruder suited for printing with flakes (instead of granulate from these flakes) takes away a step in the cycle and is essential to make sure material quality stays high as long as possible in a circular ecosystem.

space available for images / figures on next page

introduction (continued): space for images

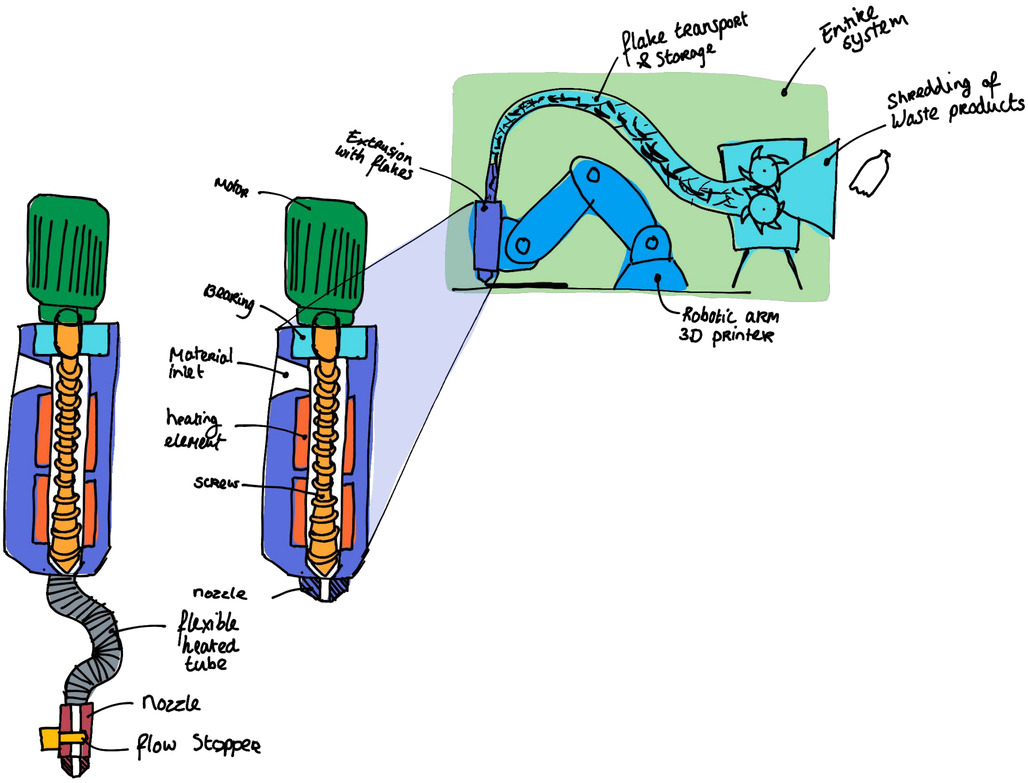


image / figure 1: Sketch of a future circular PET re-cycle system

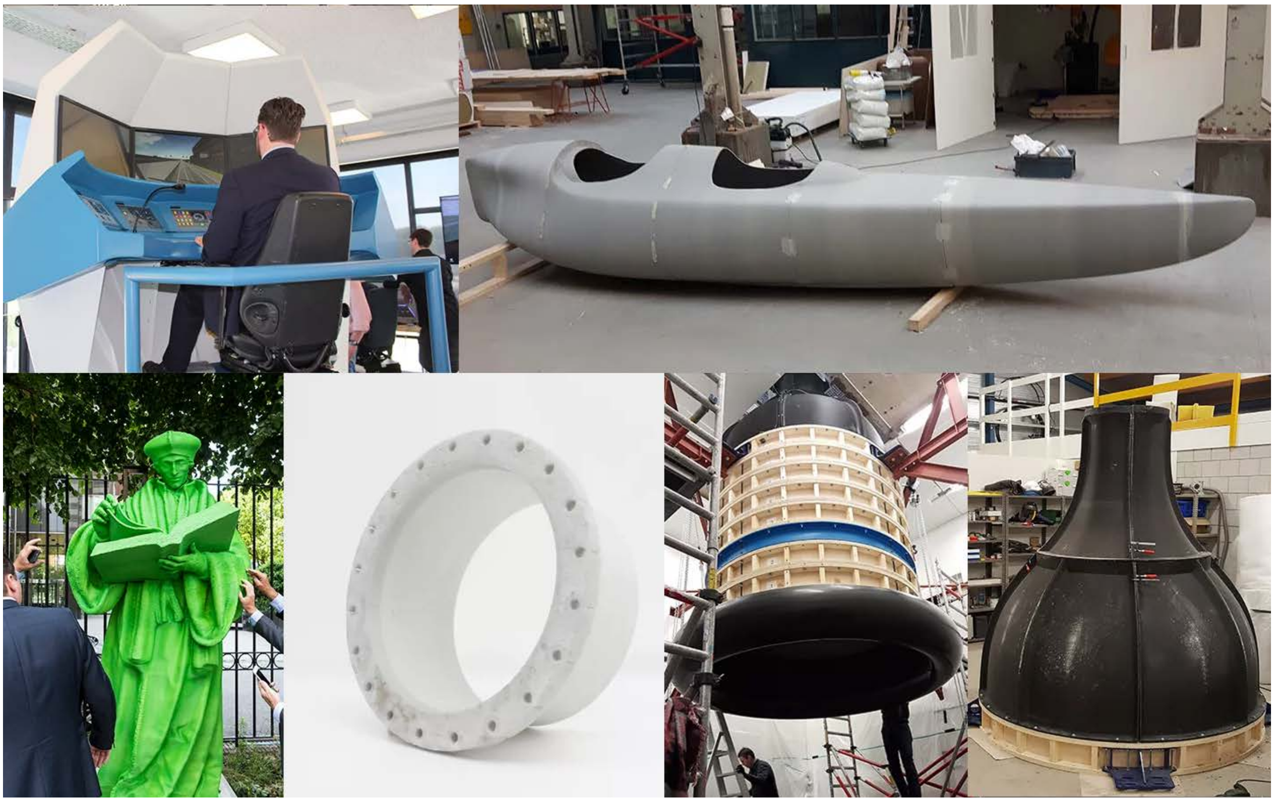


image / figure 2: 3D printed examples: Train simulator, submersible shell, Erasmus statue, 800mm flange, wind tunnel

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.

When shredding material for recycling, the resulting granulate is often in vastly different shapes and sizes due to the nature of the shredding process. These non-uniform shapes are then used in an extruder designed for pellets, which are heavier and more uniform in shape. Currently observed problems are flakes clogging up the extruding system and refusing to enter the extrusion screw. The solution should be found within this production chain without compromising on material quality.

Re-heating PET plastic and contaminants from other waste has an influence on the viscosity of the molten plastic, as well as polymer links breaking during the shredding process. Currently, it is observed that recycled PET has to be extruded at a higher temperature than virgin PET, but specific parameters of the recycling process --such as flake size, temperature, etcetera-- on the ability to be extruded by the machine, are unknown and thus need to be researched.

Because the extrusion of recycled plastic is not similar to virgin plastics, the material properties of the end product are different from products using virgin plastic. For industrial application of recycled plastics, it is thus important to discover the material properties.

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.

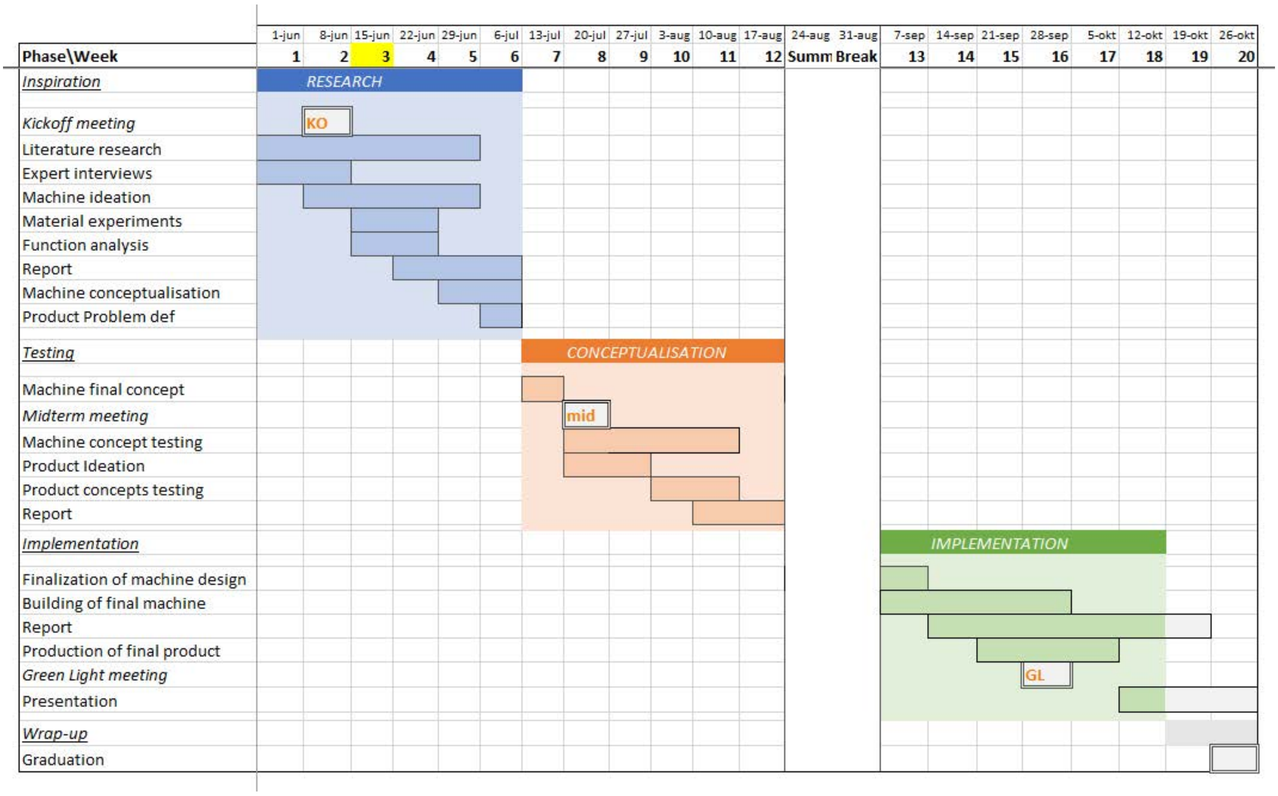
Design an extruder and/or process for extruding recycled PET, and demonstrate effectivity with a product that can be 3D printed with recycled PET and reprocessed at its end of life. Context: a (Dutch) military base in Mali.

The solution will consist of a redesign of a part of the production chain of recycled PET products. This can be a physical machine or machine part which processes PET flakes in a way that enables them to be fed trough the current extruder or a enhanced/new extruder which is capable of working with PET flakes. A combination of both is also possible. This part of the design will be referred to as 'the machine' in the planning.
The product developed to prove that the system is effective, can be anything ranging from building blocks to customized furniture to mounting brackets for specific technology like a solar panel. This will be called 'the product' in the planning. The primary goal for this product to show the capabilities of the technology and can have a secondary goal of reducing logistic efforts to get a certain specific item to a remote location or to contribute to local communities. The product will thus likely be more of a physical display of a vision, rather than a complete end-product, thereby proving the use of the complete waste-to-product machine as envisioned by 3D Robotprinting. To achieve full circularity, the (3D printed parts of the) product can be processed by the machine again after it has served its duty.

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 1 - 6 - 2020   30 - 10 - 2020 end date



The project is divided in three main parts. The first part focuses on gaining knowledge on the material and the machine, by performing literature research combined with experiments and interviews with experts from the company and university. From this knowledge machine ideas will come forth which will be developed into machine concepts. In the second phase, these concepts will be prototyped and tested with the product concepts developed in parallel. Before the summer break, a week is left to catch up in report writing. In the last phase the design is finalized and a final prototype is made of both the product and machine.

TU Delft

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.

Ever since I was a kid I have been fascinated with robotics. I almost went to study Artificial intelligence, but I decided to do something more creative: IDE. During my time at IDE, this interest for robots and automation surfaced with 3D printing. The more I learned about the technique and materials involved, the more I also wondered: Why do we recycle so little plastic? When I learned about circular economy during a course, I knew 3Dprinting was very well suited for a circular material stream. However, it is not happening yet. With this project I hope to gain a better understanding about (recycled) PET as a material and about the challenges and opportunities of using 3D printing to create a circular material stream and to lie a foundation to build upon in my professional career. I hope to put my technical knowledge gained on the machine and material into use in the next phase of my career.

FINAL COMMENTS

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