Processing WPI's Plastic Waste Into 3D Printing Filament

A Major Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
degree of Bachelor of Science

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Date: April 12th, 2020
Report Submitted to:

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Abstract

Single use water bottles are a prime example of a plastic that is not always recycled leading to environmental concerns. At WPI, students are constantly 3D printing plastic parts for different projects, frequently these parts add to the environmental problems since most prototypes are thrown away to be recycled. There is a need to repurpose this plastic waste which is where this project comes in. This project consists of a recycling system composed of a mechanical shredder, a filament extrusion machine and a filament winder in order to repurpose plastic waste into 3D printing filament. This is a system that has been prototyped at a small scale. It can be applied to larger scale applications.

Acknowledgments

We would like to thank our wonderful advisor John M. Sullivan for his valuable guidance, constant support, and incredible kindness throughout this project.

We also would like to thank Peter Hefti, Professor Mahul Bhatia, and Professor Joseph Stabile for providing key insights and general support to our team.

Finally, we are grateful for WPI and the Mechanical Engineering Department for giving us the opportunity to work on such an important project.

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1. Introduction

Paper food boxes from take-out foods, single-use beverage bottles, or a glass bottle after having a delicious beer are some of the everyday objects that could be recycled. Blue or green recycle bins contain items that Waste Management trucks pick up curbside. Other than putting items into the recycling bin, not many are aware of the lifecycle these objects follow in order to be recycled. The sad truth is that many objects that are believed to be recycled end up in landfills due to shortages of recycling facilities. Figure 1 demonstrates the global plastic waste disposal over the past few decades. The figure shows there has been an increase in recycled materials, but the discarded and incinerated portion of plastics are still dominate the percentage. The process of recycling is often tedious and energy intensive[1].

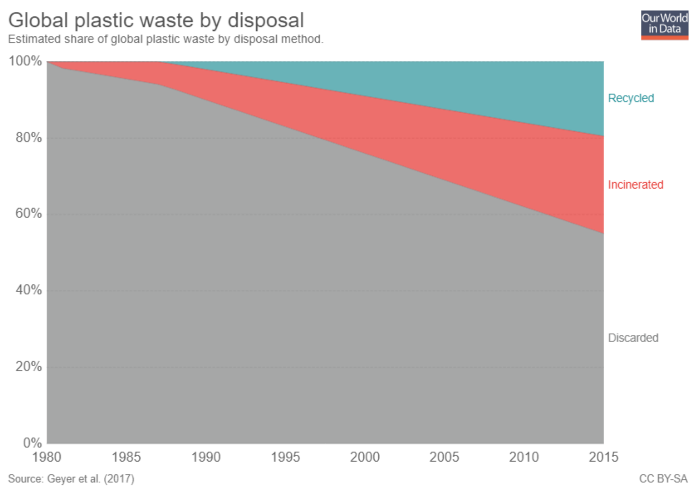


Figure 1: Global plastic waste by methods of disposal[2]

At WPI, every residence hall has multiple areas with a trash bin and a recycling bin. Black bags are for trash and clear plastic bags contain items to be recycled. At the Foisie Innovation Studio, trash cans are labeled as "Landfill" so that students are more aware of where their trash goes. WPI as an institution motivates students to be aware of recycling, but students are not aware of the process behind recycling and whether the plastics discarded on campus are even recycled.

Figure 2: WPI Recycling Diagram[3]

Given the school's project-based curriculum, students are encouraged to use readily available 3D printers to create prototypes because of its ease of use and abilities compared to other manufacturing methods. One of the downsides of 3D printing is that a part can be discarded as the dimensions or scope of the project changes, or failed printing attempts. However, there is currently no method of recycling this waste on campus. Therefore, the goal of this project was to recycle plastics such as PLA, PET and ABS to produce 3D printing filament at WPI to reduce the overall consumption of plastic filaments. To accomplish this goal, the team developed a prototype mechanism that was able to shred plastic bottles or 3D printed waste material into small pellets, heat up and extrude filament using an extruder and wind the extruded filament onto a spool.

Due to the COVID-19 pandemic, the project had to be stopped impromptu. As a consequence, many results and data were not attained. Despite this difficulty, the team had made significant progress with prototype models and has made decisions upon the results received so far. This project can be continued with the help of future MQP teams in order to achieve the goal of improving recycling efforts at WPI and beyond.

2. Background

2.1 Plastic Waste as a Problem

Due to the rapidly growing population in the world, the overall carbon footprint has increased dramatically causing alarming environmental damage. The future demands advanced recycling processes in order to process single use PET bottles. Currently, around 50% of plastic is used for single-use applications in packaging or consumer products, 20-25% is used for infrastructure and the rest is used in electronics, furniture, etc[1]. In the past few decades, only 10 to 20% of PET bottles were collected and sent to China to be recycled. As of 2017, China has stopped importing recyclables; raising the question of what comes next for recycling in the US (npr.gov).

Figure 3: China at Heart of Recycling

Just in the US, more than 60 million plastic bottles per day either end up in an incinerator or landfills, some ending up in waterways or as litter in streets[4]. Plastic waste poses a threat not just to wildlife but also to the environment since the recycling process of bottles includes the release of harmful chemicals such as bisphenol A (BPA)[5] and polystyrene-based (PS) oligomer[6]. These toxins can impact human health with complications such as heart disease, Type 2

Diabetes, and reproductive disorders. In order to address these challenges for a better environment, it is important to recycle plastics in an environmentally sustainable process. Each ton of plastic that is recycled can save 88% of the energy required for virgin plastic to be created[7].

Plastic can be repurposed and recycled, offering thousands of possibilities of new products ranging from new bottles to furniture, ropes, shopping bags or even shirts[8]. The plethora of possibilities allows to imagine recycled plastics in pretty much any application. With the rise of rapid prototyping and 3D printers, there is a whole new field to explore with recycled plastic.

2.2 Plastic Use in 3D Printing

Over the past few years, 3D printing has gained massive popularity and is being used in schools, offices, and hospitals for teaching and prototyping. 3D printing is an additive manufacturing technique that requires a Computer Aided Design model to print a shape or structure through a process of laying out filament layer by layer. This type of printing is considered a rapid prototyping technique as it eases the fabrication stage and allows for faster iterations. Moreover, 3D printing offers a solution for very complex structures that Computer Numerical Control (CNC) machines sometimes would not be able to achieve[9]. Eliminating the need for big machinery or molds, 3D printing is quickly taking over the prototyping industry. In a few hours, a CAD model will become a fully testable prototype which makes manufacturing prototypes cheaper and more flexible than CNC machining.

As there are several advantages to 3D printing, there are also some limitations. The process of manufacturing can be slow when dealing with larger quantities. Print failures decrease 3D printing reliability, since they can happen at any time for numerous reasons with no warning. Some additional limitations include parts' strength, its constrained working space, and temperature settings.

Due to 3D printing's ability for rapid prototyping, the user is able to develop prototypes faster causing previous iterations to become obsolete, ultimately producing a lot of waste. Waste also occurs whenever prints fail, which is caused by a variety of factors such as: lack of bed adhesion, wrong temperature settings, layer separation, poor design and geometry, lack of supporting structures, etc. These frequent problems, which are not always preventable, result in a lot of wasted material that could be recycled.

2.3 3D Printing Process

The 3D printing process involves melting a filament, usually plastics such as PLA, ABS, and PET, and extruding it through a nozzle onto the printer's bed. Each printer's mechanism is configured to receive a constant diameter of filament, usually 1.75mm or 2.85mm in commercially available printers. 3D printers function by reading a G-Code created by a slicing software, and following three basic steps: feeding, melting and extruding. The feeding stage pushes the filament using a stepper motor with drive gears into a hose that leads to the heating block as seen in the figure below. The heater element reaches a temperature range of 160 to 260ºC depending on the material that is being used. It is then melted and goes through a heated funnel onto the extruder bit, where the filament is pushed onto the bed.

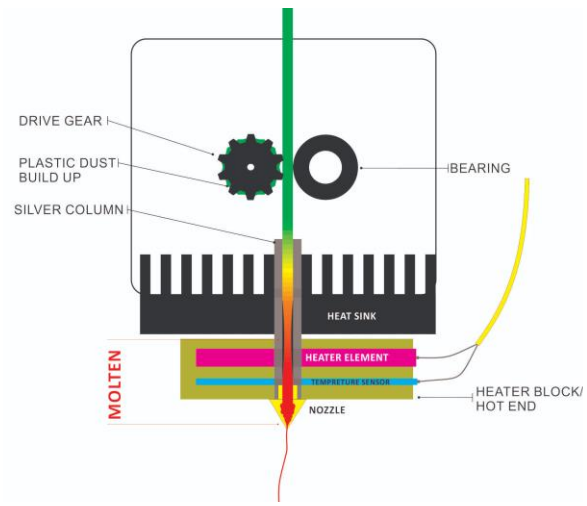


Figure 4: How a 3D printer heating unit works[10]

2.4 Properties of Plastics

3D printing and recycling require certain characteristics from plastics. Common plastics used for 3D printing filaments such as PET, PLA, and ABS have distinct chemical and physical properties, which results in different uses and applications.

2.4.1 PET

Polyethylene Terephthalate (PET) is the material used for beverage bottles because of its lightweight and elastic features compared to glass bottles, making it a favorable choice for single use packaging. PET is known to have high strength with a low crystallization velocity and poor processing property[11]. PET as a material can also be recycled multiple times for closed loop recycling of mixed food packaging, making it a good candidate for creating plastic bottles[12]. The way these bottles are made is by using an injection stretch-blow molding method[13].

The current process of recycling PET plastics has several steps. First, the plastic is collected from homes, businesses, or any other waste producing facility. Then, it is sorted, depending on the type of plastic, properties, and manufacturing process. Following that, the material needs to be clean, free of any adhesives, sugar residue, or any impurities that will interfere with the material's quality[14]. Additionally, for the recycling of PET bottles, the top and the bottom of the bottle are removed (Figure 5), as these are usually made of a stronger plastic, Polyethylene or variations of it. The cleaning process is long and requires a lot of energy and resources. After cleaning, the plastic is broken down into smaller pieces and melted so it can be used to make new products. This process requires a significant amount of energy and it releases a large amount of CO_2 in the environment. If this current process of transporting, separation and molding could be shortened or altered, there will be less energy consumption and less amount of CO_2 being released into the air.

Figure 5: Usable part of bottle for recycling

2.4.2 PLA

Polylactic Acid or PLA is a plastic commonly used for applications requiring ease of modification, stiffness, and clarity. Unlike most plastics, PLA is made of renewable resources like cornstarch or sugar cane, and it is fully compostable. This characteristic makes PLA a great alternative for a sustainable future. Additionally, PLA is a thermoplastic which means it can be heated to its melting point, cooled and reheated without any major degradation[15]. PLA can be easily melted making it very suitable for 3D printing and in rapid prototyping techniques. However, this low melting point doesn't allow PLA to be mixed with other common plastic in the recycling process[16].

2.4.3 ABS

Acrylonitrile Butadiene Styrene (ABS) is another commonly used plastic for 3D printing. Similar to PLA, ABS is a thermoplastic that has a low melting point. ABS is very useful in applications that require resistance to corrosive chemicals and physical impacts. Some of the most famous usages include computer keyboard, power-tool housings, and LEGOs. It is important to remember that ABS derives from petroleum like most plastics, and can cause a threat to the environment when it is not properly discarded or recycled[17].

2.5 Decomposition of Plastic for Recycling Purposes

Breaking down plastic into smaller pieces is done to reduce stockpiling volume as well as to increase the surface area of the material, decreasing the amount of energy needed to melt it. There are several methods to decrease the sizes of plastics that have been explored in the past such as shredding, hot wiring or melting.

2.5.1 Shredding Mechanisms

Mechanical shredders are a piece of hardware that is driven by a motor. This machine consists of an array of blades made out of a steel where with each rotation, it cuts through the material that it comes in contact with. Commonly used shredders are woodchippers where the blade cuts small pieces of a branch at a time with a blade rotating at very high speeds. Smaller versions of typical mechanical shredders are office paper shredders. These machines use the same base mechanism, with more blades and a less powerful motor, to ensure compatibility and quietness.

2.5.2 Hot Wiring Cutting

Hot wires offer a different approach for breaking down plastic into smaller pieces. Hot-wires are typically used to break down Styrofoam due to its precision and clear cut. The material is pushed into the wire that instantly melts as if there was a thin blade going through. This cutting method may offer an option that requires less electricity than mechanical shredders and has been explored in depth.

A hot-wire system works by passing an electric current through a resistive metal wire. The wire's resistance causes the electric current to be converted to heat in a process called the Joule heating effect[18]. This phenomenon is described by the formula $Q = I^2 * R$, where Q is the heat produced in Watts, I is the current in Ampere, and R is the resistance of the wire in Ohms. This resistance is directly related to the wire's gauge or diameter, and values for each gauge are tabulated. In order to estimate the heat over the length of a wire, we can consider the heat generated to be a linear volumetric heat flux. The following equation can be applied, $Q_L = \frac{Q}{L}$ where L is the length of the wire[19]. This way, the most important factors of a hot wire are its length and resistance. The voltage and current delivered to the wire can be adjusted depending on the desired temperature. The possible achieved heat in hot-wires is enough to reach very high temperatures that usually exceed any plastic melting point.

2.6 Melting Plastics

There are several methods of melting the plastic that has been researched by the team. Melting the plastic materials is an important aspect of the final mechanism since it can then be repurposed into new filament. The two main methods deemed viable for testing melting the plastic was extrusion and having a furnace mechanism.

2.6.1 Extrusion of Plastic into 3D Printing Filament

Extrusion methods are a common way of processing plastic pellets into 3D printing filament. For that, the mechanism needs an input of plastic pellets where it is then melted and extruded through a hole which is dimensioned based on the desired filament diameter. This process requires a constant input of material that is pushed onto the heating element where the plastic is melted and extruded by the incoming pellets that are being pushed by a screw. Figure 6 shows how an extrusion screw works: the input is fed through the hopper, and the rotation of the screws brings it forward to the compression and metering section, where there is usually a heating element that melts the material. Further pressure force from the material causes the melted material to exit through the hole.

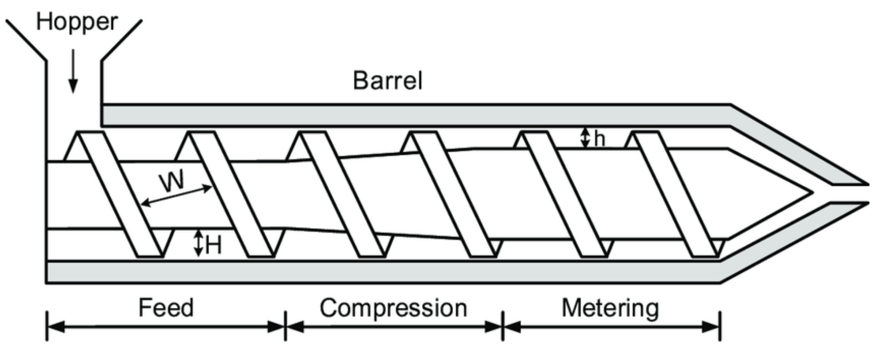


Figure 6: Extrusion Screw Diagram[20]

2.6.2 Furnace

Industrial furnaces are used for heating up metals or glass and plastics. Therefore, this method seemed a viable process for this project. An industrial electric furnace utilizes resistance or induction heating. A furnace that heats its contents to about 700C, more than enough to heat and melt PLA, or PET, is usually an electric forced recirculation furnace that delivers uniform temperature and better fuel economy[21]. A furnace is surrounded by side walls, hearth which will be very hot and a roof consisting of a heat-resisting refractory lining that would keep the heat inside, and a gas-tight steel casing, it is recommended that all of this is supported by a steel structure. For an electric furnace, the furnace will aid in the reshaping process of the plastics pellets or pieces once they have gone through it.

It is important to figure out the energy that would be put into the furnace. This can be calculated by:

$$Energy\ input\ to\ a\ furnace$$
$$= (\text{"}Heat\ needs\text{"}\ for\ load\ and\ furnace) \div (\%available\ heat/100\%)$$

In this project, PET water bottles need to be broken down, for which it is important to look at the physical properties of PET. The equation for this would be Weight * Specific heat * change in temperature = change in heat content

$$Q = w \times c \times \Delta T = change\ in\ heat\ content\ w$$

These equations help with understanding the heat transfer process. Industrial furnaces are mostly used for melting metals. If plastics are being melted, the required energy would be much lower than for melting metals and this could be cost efficient.

3. Design Process

3.1 Extrusion options in the market

Due to tight tolerances involved in a screw extruder, the possibility of outsourcing an extrusion machine became very high. Through extensive market research, it became evident the limited range of options for filament extruders, with prices ranging from $300 to over $4000. Considering the scope of this project, the only affordable options were the Filastruder ($300) or Felfil Evo ($650). Both of these machines take small pellets of plastic, melt them and extrude 3D printing filament. This way, outsourcing one of them would mean that there would be no need for a furnace in the final design.

Table 1: Extruder Comparisons

	Filastruder	**Felfil Evo**
Price	$300	$650
Maximum Temperature	260ºC	250ºC
Output Speed	Constant	Adjustable
Maximum Output Speed (m/min)	0.90	1.15
Available Output Nozzle (mm)	1.75 and 3	1.75 and 2.85
Hopper Volume	Adjustable	1liter
Compatible Materials	PLA, ABS, Nylon, Polycarbonate, PET - recycled T-glase, Acrylic, Polypropylene	PLA, ABS, HIPS, PETG, PA(6,12), PMMA, HDPE, LDPE, TPU, TPE, PVA
Additional Features		Sensor for adjusting output diameter

When comparing both of these extruders, as expected from the price, the Felfil kit has more advanced features such as the adjustable output speed and the output diameter adjustment sensor for more constant and better filament[22]. However, the Filastruder kit offers reasonable features at an economical price[23]. It claims to produce good filament and works well with PLA, ABS and PET recycled T-glase material.

3.1.1 Spooling Filament Extrusions

There are some readily available options for spooling being manufactured such as: the Filabot, the Filafab, and the Filawinder. All of these options have a system that prevents the Filament from being stretched or deformed. Both the Filawinder and the Filafab use a laser with sensors to change the speed of the motor. On the other hand, the Filabot uses a potentiometer to ensure the filament is not stretched.

Figure 7: Filabot[24]

Figure 8: Filafab[25]

Figure 9: Filawinder[26]

To ensure successful spooling, all systems have a mechanism that oscillates the filament to ensure evenly distributed filament in the spool. The Filawinder uses a stepper motor and a slot. After a full revolution, the stepper motor moves the slot slowly. The Filabot and the Filafab both have a traverse filament system to avoid the filament from stretching. The last thing that is needed for the spool to work effectively is cooling off the filament, so it hardens and does not get stretched. Both the Filabot and the Filafab come with cooling fans. However, the Filawinder does not as the fan is part of the Filastruder assembly.

The three researched filament spoolers (Filawinder, Filabot, and Filafab) are reliable and complete the task of spooling filament but at different prices. The Filawinder is able to complete the task for under $169. On the other hand, the other two options are more expensive. The Filabot costs $2200 and the Filafab costs $700 dollars. Without budget constraints, the best option would be the Filabot as it provides the best filament winding consistency.

3.2 Strategies for Reducing Plastic's Size

There are several ways of breaking down plastic into smaller pellets and for the purposes of this project, a length of 5mm sized pellets were needed for successful processing in the future stages. Hot wire cutting was the primary focus of the initial research since they presented an interesting alternative to mechanical shredders. However, mechanical shredders were also tested as an alternative to break down plastic.

3.2.1 Hot Wire Cutting

Initially, hot wiring was considered a viable way for cutting plastic because it usually provides a clean cut through materials when the wire is heated to the materials melting point. The first experiment conducted involved stretching a nichrome wire and heating it up to roughly 240ºC with a power supply that provides 10 Amps and 30 volts. Then, sheets of PLA plastic were pushed through the wire. The 2, 3 and 4mm sheets were successfully split by the single wire. This result prompted further testing on hot wire cutting.

In the initial single wire setup, different ranges of temperature were tested, and the most promising results happened with temperatures from 240 to 260ºC. When a single 26-gauge wire 2 feet was used, the wire maintained the desired temperature using 4.84 amps and 15 volts of power. Longer wire lengths exceeded the available power supplies to achieve the desired temperatures. However, the available power supply did accommodate a sufficient wire length for adequate testing.

In order to create a better setting for further testing, a laser-cut plywood box with multiple holes was produced. This setup was tested with a series of parallel 26-gauge wire as the first layer and a second layer with a series of wire perpendicular to those of the first layer as seen in the following graphic.

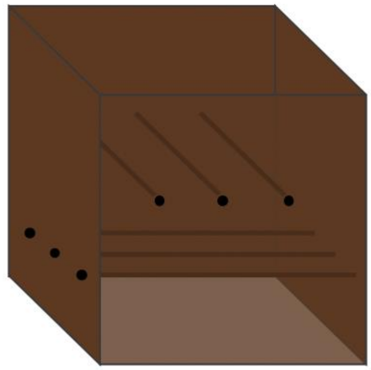


Figure 10: Box setup for hot wire testing

From the box setup experiments, it was discovered that hot wiring could have worked well if the process of feeding plastic could be more efficient. Plastic pieces needed to be pushed onto the wires, and when the plastic pieces were not pushed in fast enough, the cut surfaces would stick back together. This way, no significant separation actually happened. Another prominent issue in this trial was that after most of the piece went through the first layer, the piece would stop coming down with gravity, and actually melt around the wire. This amount of plastic around the wire causes a decrease of temperature in the wire because it offers a higher resistivity. Therefore, the wire loses the ability to melt the plastic at the right temperature, and the piece gets stuck as seen in the figure below. As a conclusion, hot wire requires a pushing force higher than gravity to successfully cut plastic.

Figure 11: PLA pieces stuck during the box setup testing

Further experimentation was conducted using the setup seen in figure XX. In that setup, different gauges, or wire thickness were tested. The 20-, 26-, and 30-gauge nichrome wires were placed parallelly to each other and heated to the same temperature. Then, a PLA sheet was fed through the wires. Again, the behavior of the pieces melting back together was experienced. However, the different gauges or thicknesses influenced how much the piece actually melted back together. The lower thickness (higher gauge) wire provided the best cut with a smaller surface melting back together, and that showed proportional behavior considering the other gauges' results.

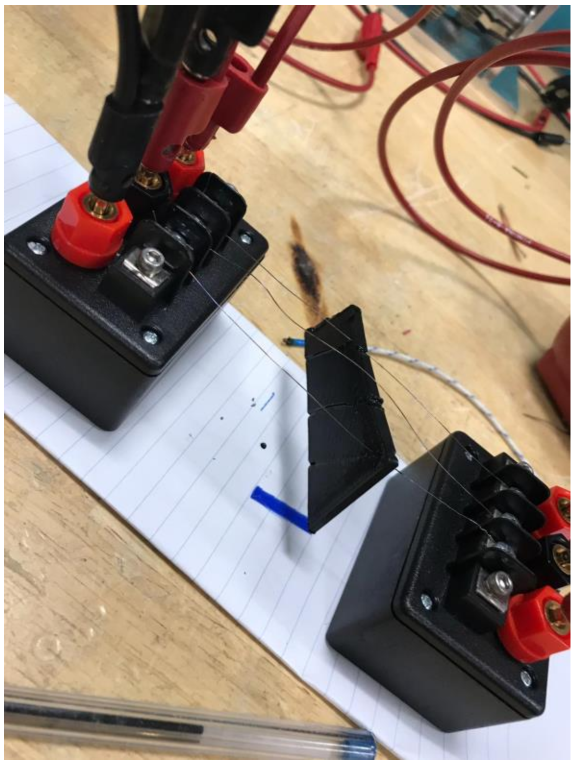


Figure 12: Parallel wires setup with lower gauge

Additional testing with the setup seen above involved pushing the pieces of plastic pieces through one layer of wires, collecting the cut outcome and refeeding it into the system. When pushed, the plastic piece goes through the layer and gets cut well. After feeding it two or three times, the plastic becomes considerably warmer through its volume, which should be expected because of heat transfer principles. This way, after multiple passes through the wire, the piece would start to melt as whole instead of actually cutting as desired.

After extensive experimentation with hot wiring, the main takeaways were that there needs to be a force pushing the plastic piece through the wire, that the higher gauges produce cleaner and better cuts, that longer contacts with the wire decrease its ability to cut well, and that heat transfer will cause the piece to melt if the wires are too close or if there is not enough time to cool down the material after a layer of wires. With these findings, especially regarding heat transfer, hot wiring was discarded as it could potentially lead to more problems while breaking down plastic.

3.2.2 Shredding

Moving back to a more traditional process in recycling facilities, mechanical shredders were researched and tested to break down plastic into small pellets. Considering the scope of the project, the main consulted options included affordable shredders and some build-your-own ideas found on the internet. In the following section, the specifications and limitations of four different types of shredders are analyzed.

3.2.2.1 Woodchippers

Woodchippers are usually used to keep gardens tidy, processing all the garden waste line leaves, twigs, and branches into mulch. These machines use a powerful motor that is able to process branches of a given size. The Sun Joe CJ603E Woodchipper, shown below, is one of the most affordable options in the market, costing about $170. The safety hopper and the powerful motor are designed to take branches of up to 1.7in (43.2mm) diameter, multiple garden waste and to break them down to be used for compost. Considering that plastic has a lower hardness and density than wood, a woodchipper would easily shred plastic as seen in several homemade tests[27]. However, the woodchipper has a small input size, which could provide limitations to tests with bigger plastic bottles or 3D printed waste.

Figure 13: Sun Joe CJ603E Woodchipper/Shredder[28]

3.2.2.2 Planer Low Cost Shredder

Another option to successfully reduce plastic into smaller pieces can be seen in Figure 14. This "Do It Yourself" shredder is extremely affordable, costing less than $50 and was specifically designed to break down 3D printed parts. The wood surface planer is placed upside down (considering how it is normally used), and the material is fed on an angle through a fixed-size hopper. A manually operated pressure stick is used to push the plastic onto the blades. The shavings are collected by the usual planer output collector sack[29]. Similar to the wood chipper, this shredder also has a small input size, considering it would only shred pieces as wide as the planer's blade. This limitation can present a future problem with the 3D printing waste.

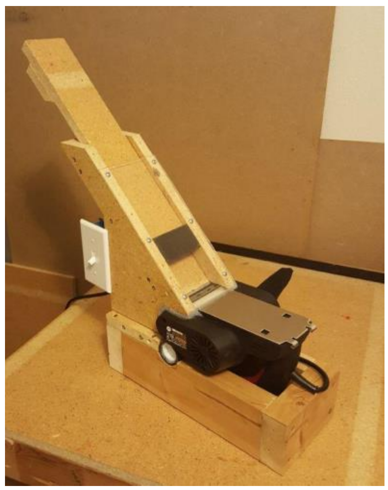


Figure 14: Low Cost Plastic Shredder from instructables.com

3.2.2.3 Office Paper Shredder

Paper shredders are widely used in offices to dispose of paper with sensitive information, or to just decrease the volume of paper waste. There are many options to choose from when looking at a paper shredder. From the number of sheets that can be added, to having cross shredding. The common sizes of paper shredders range from 6 inches to 24 inches, reflecting on a price range of $40 to $160.

Figure 15: Example of an Office Paper Shredder[30]

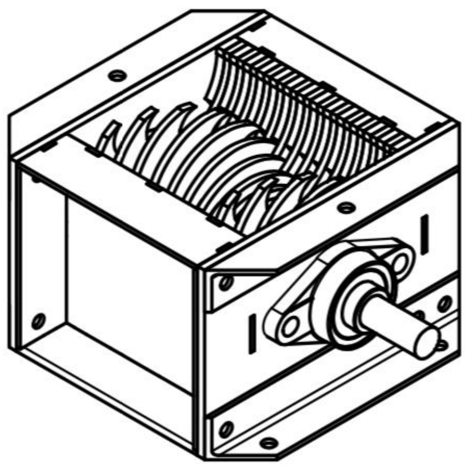
For the purpose of shredding plastic, the input part would be limited to a sheet with a limited thickness. This limitation provides a problem when processing 3D printed waste, but plastic water bottles can be easily cut into sheets and fed through such a shredder.

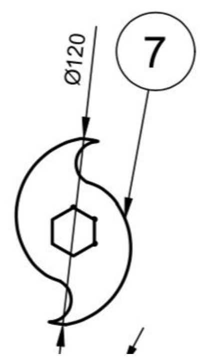
Tests were conducted using an office paper shredder. The first test was conducted with 3D printed sheets of PLA with multiple thicknesses (2, 3, and 4mm). Surprisingly, all thicknesses went through the machine without any struggles. The results were very promising since the output showed good pellet size. However, some pieces came out too big, and would need to be reprocessed. The issue is that after the first run in the paper shredder, the material deforms permanently and cannot be reprocessed in a paper shredder. Further testing was conducted with PET sheets from plastic water bottles, and similar results were attained. Both the testing results and the input limitation proved that the paper shredder did not provide the right specifications for this project.

3.2.2.4 Precious Plastic Mechanical Shredder

Precious Plastic is an organization that seeks to build a community with the goal of recycling plastic. The organization connects people that are enthusiastic about recycling and provides them with a platform of resources to find recycling facilities or collection points. For those who have an ability with advanced hand tools, Precious Plastic offers machine ideas to help them build their own recycling project at home. One of these machines is a high-torque, low-speed shredder commonly used to break down plastic bottles from packaging into smaller pieces[31].

As seen in the figure below, the shredder is a rectangular box that houses fourteen blades that are free to rotate into fixed blades. Figure 17 shows one the fourteen blades. It is important to notice that they are actually a double blade, meaning that they perform the cutting action twice in a full rotation. Another important feature to observe is the placement of the blades offset from each other by about 36º, allowing the object to be caught by the blades rather than bouncing on them.





Figures 16 and 17: Precious Plastic Shredder and Shredder Blade

The Precious Plastic shredder has been widely used around the world. Test results show how the device is capable of receiving plastic input, and outputting any of the results shown below. In order to achieve the small results shown on the right. The user may pass the plastic through several runs in the shredder, or he may attach a sieve (design by the same company) to the bottom of their shredder.

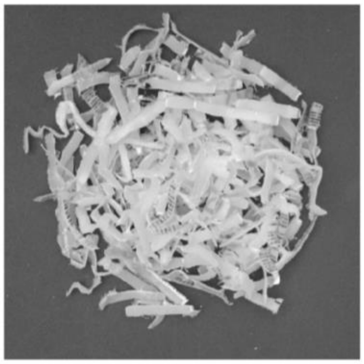
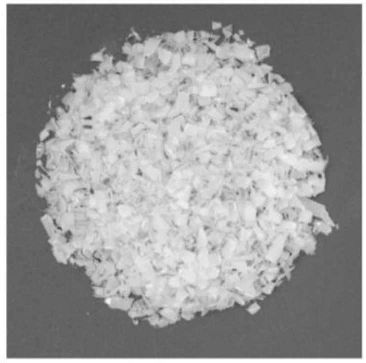
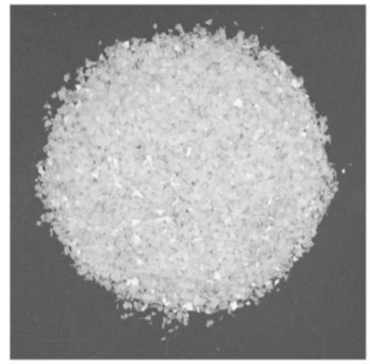
Name:	Large	Medium	Small
Visual:			
Size:	0-30 MM	0-10 MM	0-7 MM
Works with:	Sheetpress	Sheetpress Injection Compression	Sheetpress Injection Compression Extrusion

Table 2: Output of Precious Plastic Shredder[32]

The referred shredder can be built with very detailed instructions from the Precious Plastic company. However, it does require a good amount of machining, laser cutting metal, and welding. Another option is to source it from third party sellers that follow the Precious Plastic design and sell the machine through the company's website. Most of the options available are from European sellers and cost around $350. This price only goes for the mechanical shredder, the driving motor is not included. The sieve attachment may also be bought online for about $50 or manufactured with the Precious Plastic instructions.

4.0 Methodology

The goal of this project was to design a system that recycles plastic such as water bottles and 3D printed parts into recycled usable 3D printable filament. This goal will be achieved by the following objectives:

- Shred plastic water bottles and 3D printed parts into beads of about 5 x 5mm
- Extrude the shredded plastic into 1.75mm diameter 3D printing filament
- Feed the extruded filament into a winding system onto reusable spools

4.1 Shredding Plastic into 5mm Pellets

When shedders process plastics, it results in arbitrarily sized pieces of material. For the purposes of this project, it is necessary to have pellets of 5 mm or less in order to work with the extruder mechanism. While working with the shredder obtained for this project, the team has kept the goal of the shredded plastics in mind.

4.1.1 Shredder

The precious plastics shredder was chosen for this application due to its robustness and design. The mouth of this shredder is 15cm square allowing the team to deal with bigger amounts of plastics at once. Other than this plastic shredder, the others that were considered had the same limitation. The input for these machines were minimal and could barely fit anything thicker than 5mm. As mentioned in section 3.2.1.3, the tests showed the weakness of the paper shredder when dealing with plastic as it cannot shred anything thicker than 5mm. Given that all the other options considered had the same issue, the team decided that the $350 price tag was justified.

Figure 18: Assembled shredder

The shredder was delivered disassembled from Precious Plastics which was preferred as the team had control on how to arrange the blades for this specific scenario. The layout of the blades was very important as if they were all lined up on the same level, it would increase the chances of jamming and destroying the powertrain. This machine required at least a 1-HP motor to power it. The shredder specifications recommended a 5 rpm blade rotation speed, which corresponded to a 30:1 gear ratio for the drive motor[33]. This ensured that the shredder would be able to shred plastics such as PLA, ABS, PET reliability. The calculations below show a motor with the recommended specifications and the torque output that it produced (142Nm). This torque value is similar to tightening the lug nuts on your car or the torque produced by an impact drill.

```
Voltage = 230            % Volts
Amps = 4.2               % Amps
Watts = Voltage*Amps     % Watts
Gearbox = 30/1           % Ratio
RPM = 1750               % RPM
hp = Watts/746           % hp

ft_to_in = 12            % in/foot
lbin_Nm = 0.11298;
Gearboxeff = 0.9         %


Torque_Motor = (hp*5252)/RPM % lbm*ft
Total_Torque_Lbf = Torque_Motor*Gearboxeff*Gear
Total_Torque_lbin =Total_Torque_Lb*ft_to_in
Total_Torque_Nm = Total_Torque_lbin*lbin_Nm


fprintf('%f Nm',Total_Torque_Nm)
```

```
Voltage = 230
Amps = 4.2000
Watts = 966
Gearbox = 30
RPM = 1750
hp = 1.2949

ft_to_in = 12

Gearboxeff = 0.9000


Torque_Motor = 3.8862
Total_Torque_Lbf = 104.9274
Total_Torque_lbin = 1.2591e+03
Total_Torque_Nm = 142.2563
  142.2563


142.256313 Nm
```

Figure 19: Torque calculations

Testing by other users was done with different thickness plastics and the torque never exceeded 60 Nm on the shaft[34]. This rating was calculated with plastics much harder than the ones the team was going to be dealing with. Therefore, the team used this value as the baseline of the coupling performance rating. The coupling used in order to join the 1-inch shaft coming from the motor and the shaft from the shredder, a LoveJoy L-jaw type coupling had the required torque ratings for this project. Figure shows the exact coupling that was purchased for this project. The torque rating for this coupling is 63.4 Nm exceeding our needs as shown in Figure 20. As the team knew that the ratings would never get close to the 60 Nm value, it was evident that the L-095 coupling was going to suffice for this project.

	Max Bore		Spider Material							
			SOX (NBR) Torque		Urethane Torque		Hytrel Torque		Bronze Torque	
Size	in	mm	in-lbs	Nm	in-lbs	Nm	in-lbs	Nm	in-lbs	Nm
L035	0.375	9	3.5	0.4	—	—	—	—	—	—
L/AL050	0.625	16	26.3	3.0	39	4.5	50	5.60	50	5.60
L/AL070	0.750	19	43.2	4.9	65	7.3	114	12.90	114	12.90
L/AL075	0.875	22	90.0	10.2	135	15.3	227	25.60	227	25.60
L/AL090	1.000	25	144.0	16.3	216	24.4	401	45.30	401	45.30
L/AL095	1.125	28	194.0	21.9	291	32.9	561	63.40	561	63.40
L/AL099	1.188	30	318.0	35.9	477	53.9	792	89.50	792	89.50
L/AL100	1.375	35	417.0	47.1	626	70.7	1,134	128.00	1,134	128.00
L/AL110	1.625	42	792.0	89.5	1,188	134.0	2,268	256.00	2,268	256.00
L150	1.875	48	1,240.0	140.0	1,860	210.0	3,708	419.00	3,706	419.00
AL150	1.875	48	1,450.0	163.8	—	—	—	—	—	—
L190	2.125	55	1,728.0	195.0	2,592	293.0	4,680	529.00	4,680	529.00
L225	2.625	65	2,340.0	264.0	3,510	397.0	6,228	704.00	6,228	704.00
L276	2.875	73	4,716.0	533.0	—	—	—	—	12,500	1 412.00
C226	2.500	64	2,988.0	338.0	—	—	5,940	671.00	5,940	671.00
C276	2.875	73	4,716.0	533.0	—	—	9,432	1 066.00	—	—
C280	3.000	76	7,560.0	854.0	—	—	13,866	1 567.00	—	—
C285	4.000	102	9,182.0	1 038.0	—	—	16,680	1 882.00	—	—
C295	3.500	89	11,340.0	1 281.0	—	—	22,680	2 563.00	22,680	2 563.00
C2955	4.000	102	18,900.0	2 136.0	—	—	37,800	4 271.00	37,800	4 271.00
H3067	4.500	114	33,395.0	3 774.0	—	—	47,196	5 333.00	47,196	5 333.00
H3567	5.000	127	46,632.0	5 269.0	—	—	63,000	7 119.00	63,000	7 119.00
H3667	5.629	143	64,812.0	7 323.0	—	—	88,200	9 966.00	88,200	9 966.00
H4067	6.250	159	88,224.0	9 969.0	—	—	126,000	14 237.00	126,000	14 237.00
H4567	7.000	178	119,700.0	13 525.0	—	—	170,000	19 209.00	170,000	19 209.00

Figure 20: Performance data for the couplings

4.1.2 Motor

The driving force of the shredder is a 3-phase electric motor. At 1750 rpm it is rated on 230 volts, 4.2 amps, producing 1.295 horsepower. This translates to 142Nm of torque through a simple calculation shown in the figure below. The torque value in the motor calculation is a comparable force to that of tightening a lug nut in a vehicle.

```
Voltage = 230               % Volts
Amps = 4.2                  % Amps
Watts = Voltage*Amps        % Watts
Gearbox = 30/1              % Ratio
RPM = 1750                  % RPM
hp = Watts/746              % hp

ft_to_in = 12               % in/foot
lbin_Nm = 0.11298;
Gearboxeff = 0.9            %


Torque_Motor = (hp*5252)/RPM % lbm*ft
Total_Torque_Lbf = Torque_Motor*Gearboxeff*Gear
Total_Torque_lbin =Total_Torque_Lb*ft_to_in
Total_Torque_Nm = Total_Torque_lbin*lbin_Nm


fprintf('%f Nm',Total_Torque_Nm)
```

```
Voltage = 230
Amps = 4.2000
Watts = 966
Gearbox = 30
RPM = 1750
hp = 1.2949

ft_to_in = 12

Gearboxeff = 0.9000


Torque_Motor = 3.8862
Total_Torque_Lbf = 104.9274
Total_Torque_lbin = 1.2591e+03
Total_Torque_Nm = 142.2563
  142.2563


142.256313 Nm
```

Figure 23: Torque calculations for motor configuration

The last thing that had to be thought about was the sieve for the shaft. Given the size of the blades that are in the shredder, when the shredder processes plastic, sometimes it leaves larger chunks that cannot be added to the extruder. Therefore, a sieve needs to be inserted under the shredder to ensure pieces are small enough. Instead of buying a pre-machined shaft, the team decided to manufacture it to be able to control the size of the holes and adjust accordingly.

Below are flow charts of how the shredding process goes with and without a sieve given that the shredder can be used interchangeably. With a sieve there is no need to sort the material after it is being processed. However, without a sieve, it is necessary to sort the material to ensure 5mm pellets.

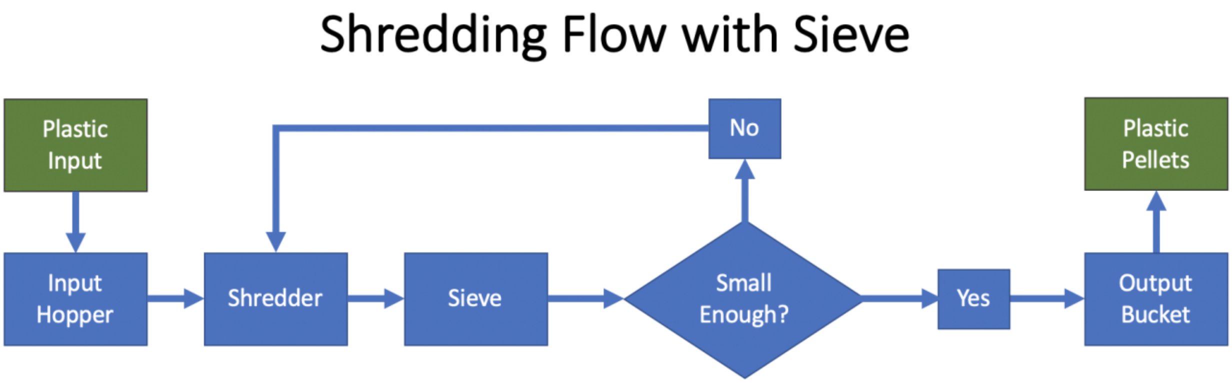


Figure 21: Plastic flow of mechanical shredder with the manufactured sieve

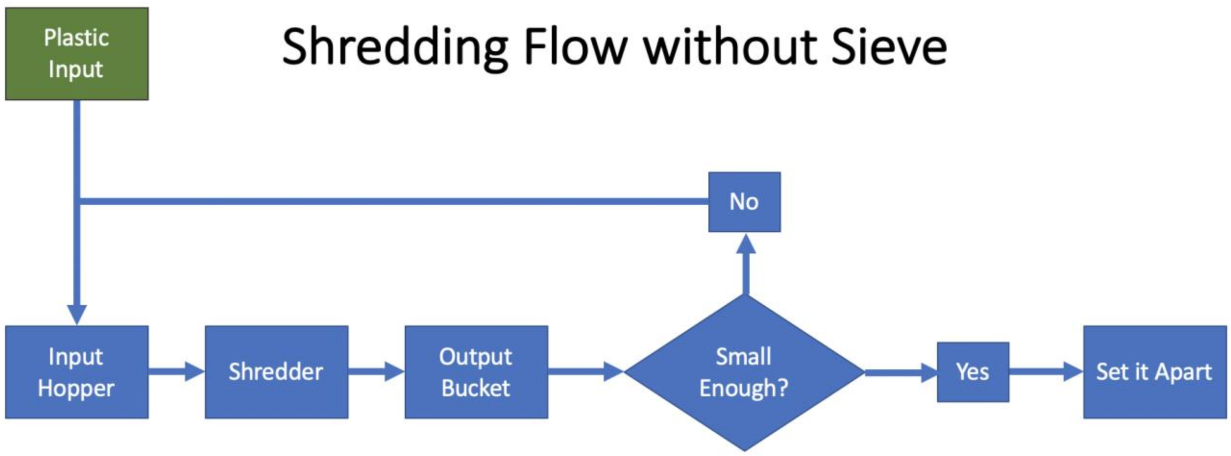


Figure 22: Plastic flow of mechanical shredder without the manufactured sieve

4.2 Filament Extrusion

In order to achieve the extrusion of 3D printing filament, the team sourced an extruder screw to ensure good quality of the filament being extruded. Additionally, 3D printing extrusion techniques require very specific tolerances that could prove to be an issue for the project. Some of the complications from filaments imperfections are the gear failure to push filament into the heating block when the filament is too small, and the filament being too big to go through the input hose. These discrepancies would result in a failed print and could ruin the mechanism of the printer. Considering budget limitations, our only option was the Filastruder, a product geared towards making your own filament at home. The specific extruder had great customer reviews and is backed up by solid customer support.

The Filastruder melts pellets of about 5 mm on each side during the continuous process of extrusion as shown in Figure 24. In one continuous run, plastic pellets are input and pushed forward by the screw. They are then melted and pushed through a 1.75mm-diameter hole out of the system. Typical extrusion rate is about one kilogram every 5 to 8 hours, and that translates to about 10 to 36 in/min, depending on adjusted factors such as diameter, material and thickness. The extruder temperature can be adjusted from room temperature up to 260 degree Celsius, while not creating a hazard as the hot surfaces are enclosed. It works on 110 Volts and consumes about 50 Watts per hour.[23]

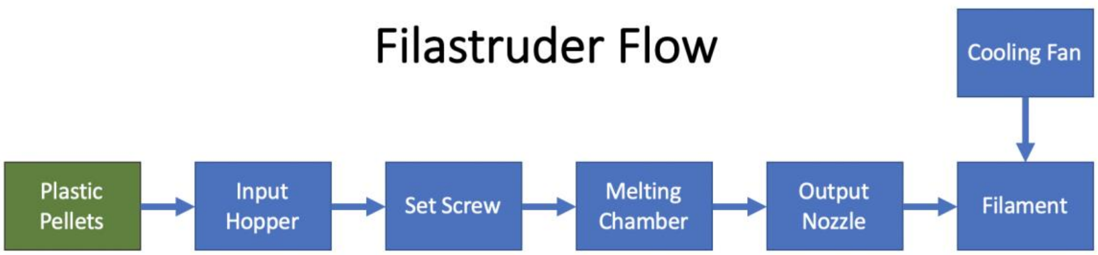
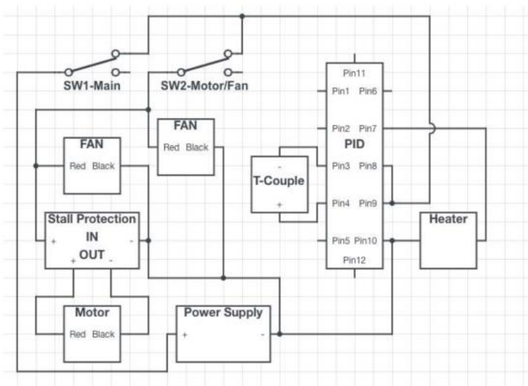


Figure 24: Flow of plastic in the extrusion process

The Filastruder assembly was done by following the detailed attached instructions. The assembly began with all the mechanical parts attached to a main machined metal square box. Then, a simple electric circuit (seen in the Figure below) was put together connecting the heating element, the screw motor and the fans to a power supply. The circuit is designed in a way that allows powering of the heating element without automatically turning on the screw motor. When achieving a desired temperature, the motor can then be turned on, and the process of pushing the material to create filament starts. To complete the assembly, a hopper was 3D printed to hold the input pallets. At first, the hopper design proposed by the manufacturer was used, but its rectangular opening didn't have a good way to feed plastic in. A new hopper with a circular input and a bigger opening was then designed and 3D printed.



Figures 25 and 26: Filastruder Electric Diagram and Filastruder[23]

4.3 Spooling mechanism

The extruder was able to produce filament rapidly, which unfortunately means that if not spooled right away, the filament can easily deform if it encounters an obstruction in its path. Therefore, instead of letting the filament extrude onto the floor, it is preferable to have it go straight into a spooling mechanism. Considering the available options, the Filawinder was the machine chosen to spool the extruded filament. Overall, given that the Filawinder was manufactured by the same company as the Filastruder, it proved to be a very good fit for this project. We were about to acquire this winder from a previous MQP team.

The Filawinder guides the filament from the extruder to a spool in the process seen in Figure 27. The winding mechanism's first part consists of the brushless motor that drives the two gears in order to rotate the spool. The spool is restricted to circular motion due to the 3D printed part with the bearing insert shown in figure 29. The bigger gear has a magnet on it in order to communicate the servo that the spool has completed a full revolution. The second part consists of a guide connected to a stepper motor as seen in Figure 28. When a full revolution has been completed in the first mechanism, the stepper motor moves the guide accordingly to prevent the filament from spooling in the same spot. The third part consists of a laser that is mounted parallel to a set of 4 sensors. The laser is used to measure the speed at which the Filastruder is extruding filament and changing the speed of the DC motor accordingly. The DC motor's speed is controlled by increasing or lowering the voltage accordingly.

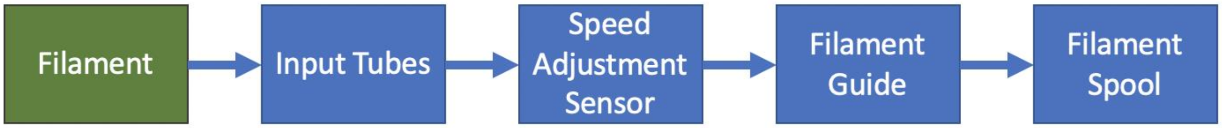


Figure 27: Winding flow

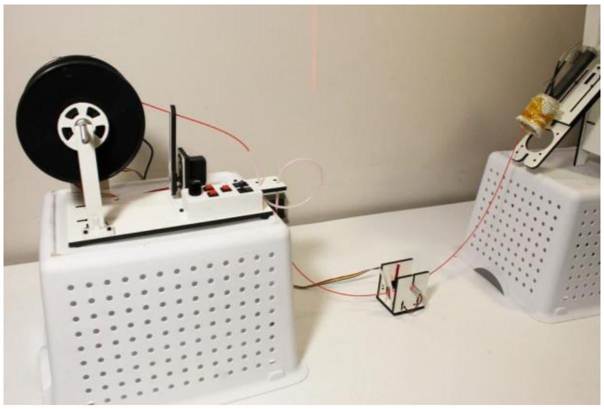


Figure 28: Extruding and winding set up[26]

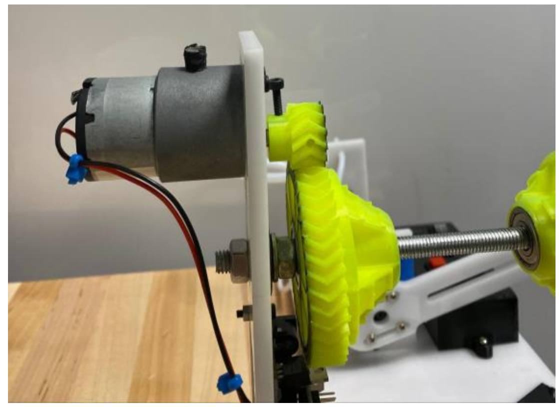


Figure 29: Motor and gear assembly

The winding mechanism has a control box that has three red buttons, one dial and two on/off switches. The top two buttons are in charge of adjusting the beginning and end boundaries which spans the width of the spool. The middle button is used for calibrating the laser and for setting the starting boundary. When pressing the middle button and the dial this sets the starting position of the guide. When the button is just pressed it goes into calibration mode for five seconds. At this point filament is put in front of the laser and moved up and down to calibrate the sensor. The laser assembly is necessary to ensure that the filament is not stretched when pulled throughout the process. When the extruder is producing less filament, the filament tightens which creates a shadow in the upper two sensors, this sends a signal to the Arduino to slow down the DC motor. The uppermost sensor is responsible for lowering the speed faster if the shadow gets to this sensor. Similarly, if the Filastruder extrudes more filament, the bottom sensors see the shadow as the filament sags sending a signal to the Arduino speeding up the DC motor. The lowermost sensor is responsible for speeding up the spool in case the filament sags too much.

5.0 Machining and Fabrication

5.1 Frame

The design shown in Figure 31 shows the frame and the placement of the motor, shredder, coupling, top cover within the frame. Due to the torques involved, it was necessary to have a frame that was low to the ground to lower the center of mass. Figure 30 shows the initial design idea for the frame. The idea was to have the whole system function together without the intervention of a person apart from adding the material to be recycled. But due to its high center of mass, this option was changed to the one below. This design would also allow for better control over the extruder input.

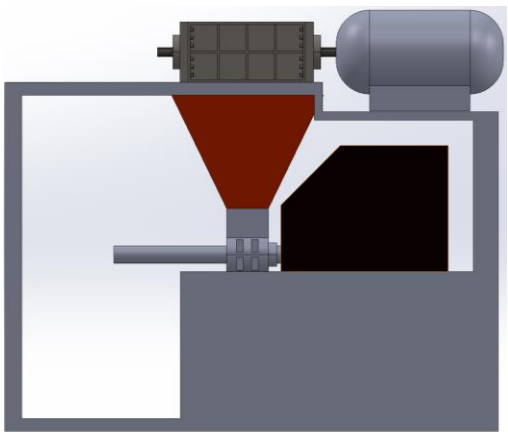


Figure 30: Initial set-up idea

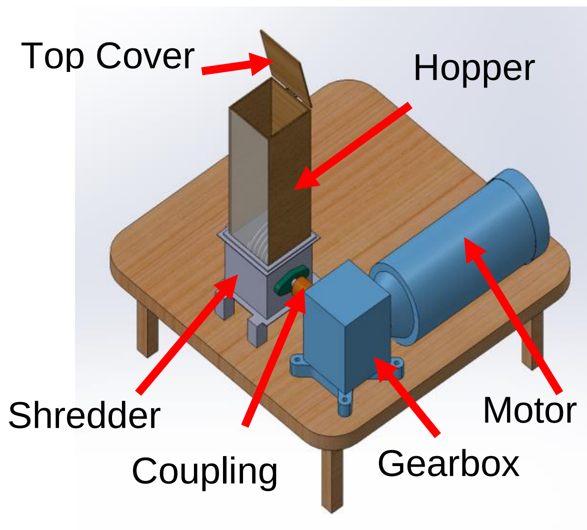


Figure 31: Final set-up

The frame was made out of a 1.2-meter square table and fitted with 5 cm T-slotted framing. This allowed choosing the height of the table to be able to have a bucket underneath to collect the PLA shredded parts. Figure 32 shows the hole made to the table to allow the plastic parts to go onto the basket underneath. Lastly, there was a 2-inch misalignment between the shaft of the motor and that of the shredder. Four T-slots beams, bolted onto the shredder, provided the adjustment capability needed to have a properly aligned system. Four T-slot beams were attached to the shredder giving it play to lift and lower the shredder to align it properly.

Figure 32: Shredder Output Hole

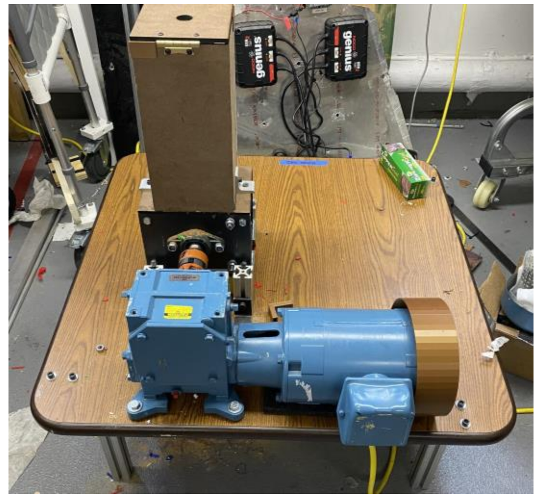


Figure 33: Final set up

5.2 Power Transmission

The shredder used in this project had a 20 mm smooth shaft made out of structural steel S235. This was coupled with a Lovejoy L-095. The hub that connects to the 20mm shaft has two set screws given that it is a smooth shaft. The set screws were not able to withstand the 60 Nm torque that the coupling is rated for. The result of this is shown in Figure 34, it is evident that the set screws created a groove around the shaft which was created due to the extreme forces involved when adding 3D printed parts. Therefore, in order to withstand this high torque, it was necessary to create a keyway in the shaft.

The size of the keyway was designed to match that of the new Lovejoy L-095 20 mm hub with a keyway[35]. This coupling had a 5mm by 2.3 mm keyway to ensure the best fit, tolerancing of 0.254 mm to ensure the best fit. Figure 35 shows the key inserted in the shaft. This setup was deemed successful as it was tested with 80% infill prints and showed no issues.

Figures 34 and 35: Damaged shaft and Machined shaft with key

5.3 Hoppers

Two different hoppers were designed in order to guide the material through the system. Figure 36 shows the shredder hopper which has been made as a safety precaution to prevent users from putting their hands in the shredder as well as being able to load the shredder with more stuff in at once. This hopper was then fitted with a cover and a hinge on top to further prevent injuries when using the machine. To further improve the design of the hopper with more time and budgeting, the team would have added a circuit breaker to the engine wiring assembly to have the engine only function when the cover is closed closing the open loop system.

Figure 36: Shredder Hopper

5.4 3D Printed Components

3D printing was used to manufacture parts for the extruder and motor. The extruder has a 4cm by 2cm wide mouth that leads to the screw that pushes the material to the heating element. To allow for more material to be added at once, the funnel design increases the mouth area from 8 cm^2 to 53 cm^2. The CAD model for the bottom piece that attaches to the hopper was provided by the manufacturer and was 3D printed as well. Lastly, the motor used to power the shredder has a fan in the back that rotates at 1725RPM. The cover equipped was damaged and needed to be replaced. Therefore, the team designed a new one and 3D printed as shown in Figure 39.

Figure 37: 3D Printed hopper

Figure 38: Filastruder hopper[23]

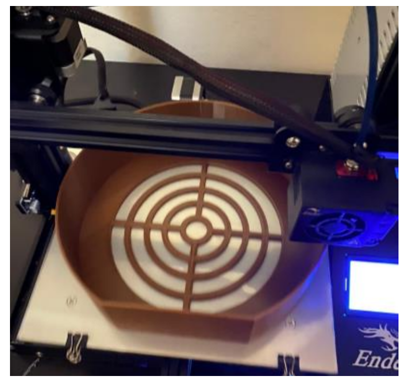


Figure 39: Fan cover

5.5 Rebuilding the Spool

The winding mechanism the team acquired was in need of repair. The teeth on the 3D printed gears were worn, some of them were skipping steps. These gears were reprinted with a higher infill and a smaller layer height to make them more durable. The pick-up magnet that goes in the larger gear for counting the rotations needed to be replaced. Without this pick-up magnet the filament guide would not move as there was no signal saying the gear made a full revolution.

Figure 40 shows the control box being replaced and re-soldered as the previous box and some of the wiring were damaged.

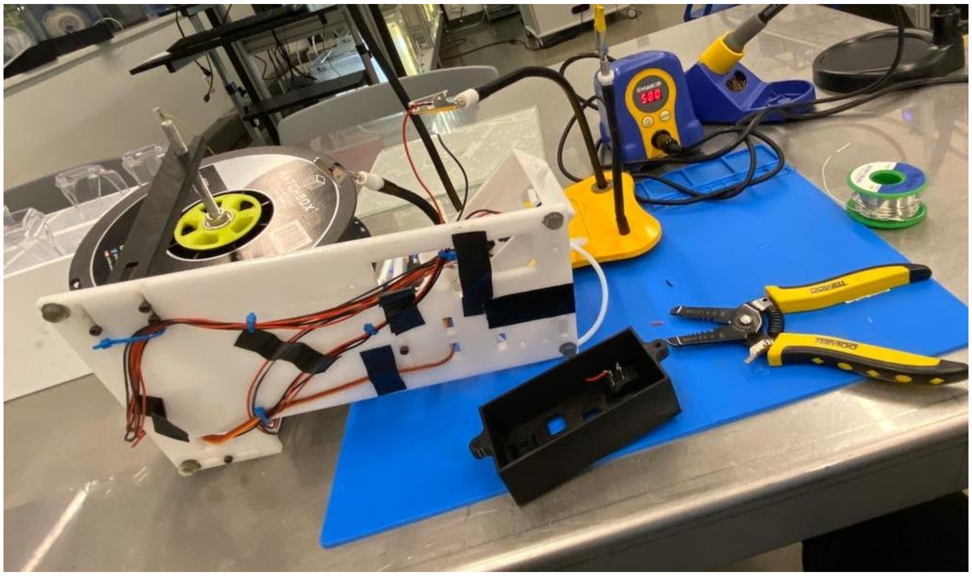


Figure 40: Filawinder with visible cables and framing after the team fixed broken parts.

5.6 Sieve

The sieve is a sheet of perforated metal with holes that are 5 mm wide. As seen in figure 41, the team 3D printed some versions of the sieve in order to see the best fit for our bracket that bolts to the shredder. The team also played with the density of holes and decided on a 1 to 2 holes to surface ratio. In order to manufacture this sieve out of metal, the team acquired a 1/16 inch aluminum sheet, pressed it between two pieces of plywood, and drilled with a hand drill. There are 150 5mm holes in the aluminum sheet. The manufactured sieve, seen in Figure 41, has a curvature that allows for the blades to have a 2.5 mm clearance when attached to the shredder.

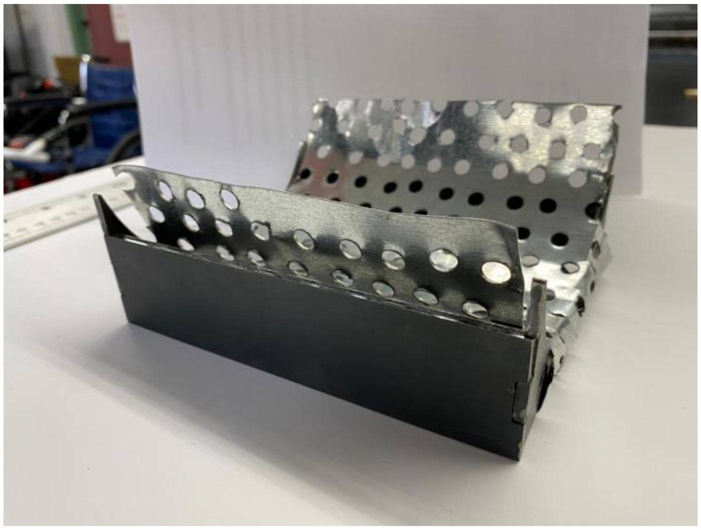


Figure 41: Sieve inserted in the shredder bracket

6.0 Results

6.1 Plastic Testing

While conducting tests for the Filastruder, a sample of different kinds of recycled plastic was extruded, where the material was PET but from various one-use bottle vendors. The expectation was for plastic to melt at about 260℃ in order for PET filament to be extruded smoothly. Unfortunately, the results were less promising. No filament was coming out of the Filastruder, instead a green liquid was coming out. After this finding, we questioned whether different bottle manufacturers add different substances to their PET bottles, that could make them melt at different temperatures.

In order to understand the melting points of different types of plastics, an experiment was carried out in the oven by putting cut up plastic pieces into a pan and heating them in a standard kitchen oven. Experiment was carried out by measuring temperatures and plastic state from 218℃ to 260℃. In the figure shown below, different types of plastics are cut up and put in individual areas in a pan to be melted. From left to right and top to bottom, the plastics are:

1. Dasani water bottle pieces
2. Aquafina water bottle pieces
3. SmartWater bottle pieces
4. Wellsley Farms water bottle pieces
5. Poland Spring water bottle pieces
6. PICS Price Chopper brand water bottle pieces
7. PETG filament

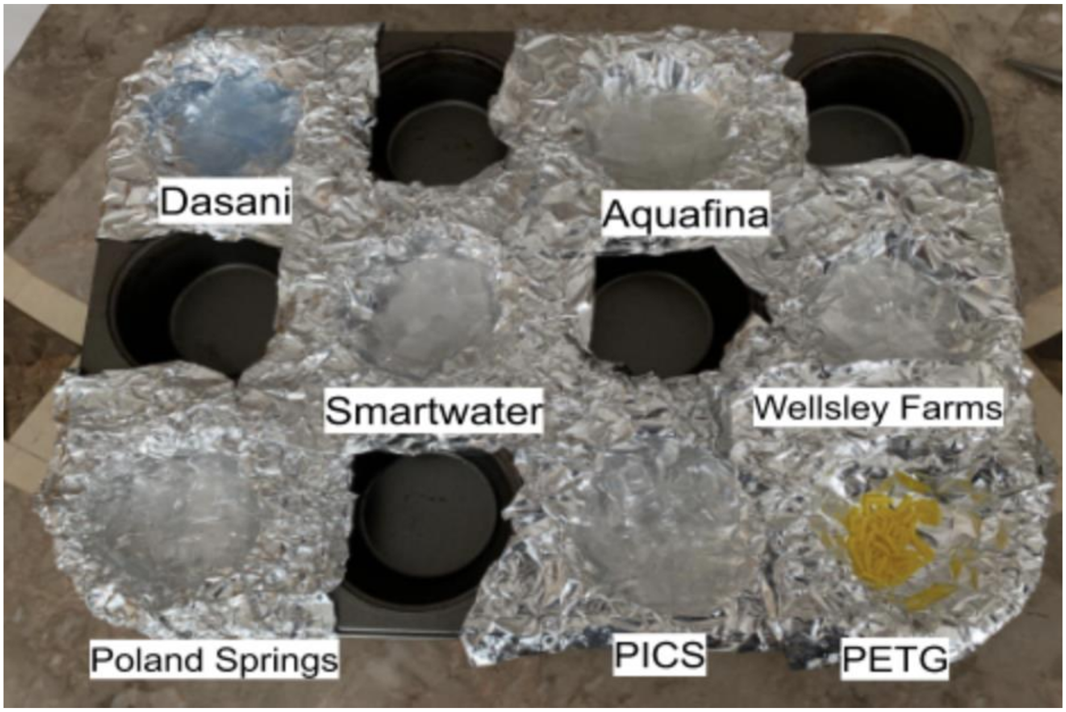


Figure 42: Experimental baking tray with different PET sources. Labels for reference

The oven was initially preheated up to 218C and the pan of plastics was put inside the oven. The small pieces were checked at various times to increase the temperature. During 15 minutes at 218C, the plastics were checked, and it was noted that there was no change in the melting process of the pieces besides for the PETG that started melting.

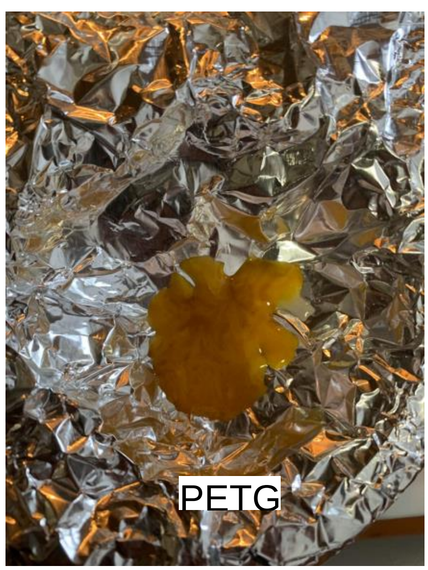


Figure 43: Melt PETG material

At 30 minutes, the temperature was raised to 232C to continue melting more of the plastics. After 15 additional minutes, the temperature was raised to 246C and finally after an hour, it was raised to 260C, at which point most of the plastic pieces started melting.

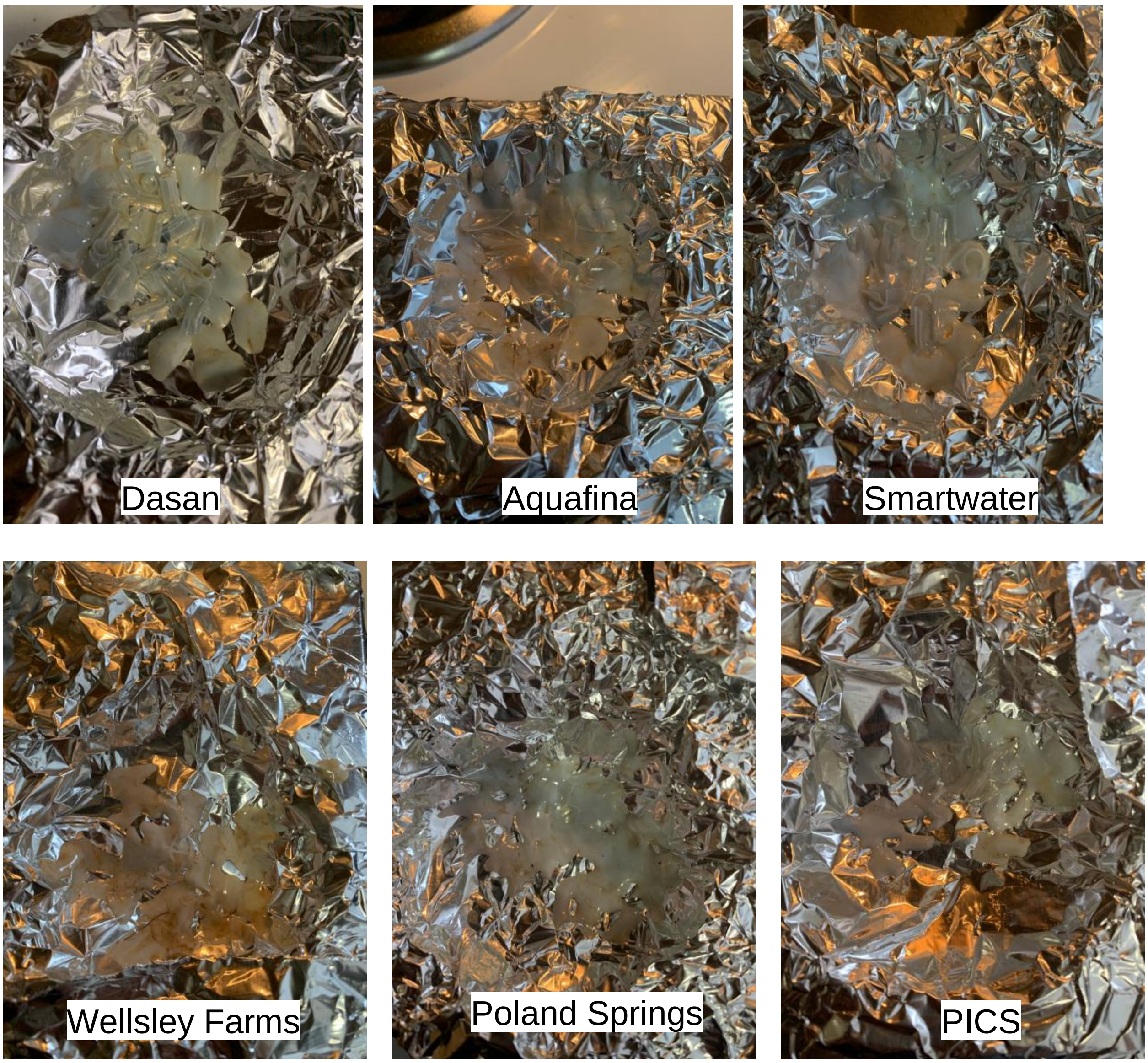


Figure 44: Melt water bottle plastics

The experiment in melting the plastic water bottles showed that Dasani, Smartwater and Aquafina had to be melted at a much higher temperature than the rest of the water bottles. These three water bottles were also much thicker material than the rest of the types of water bottles and the filament. In order to fully melt the Dasani, Aquafina and Smartwater bottles, the samples were put inside the oven and the temperature was raised to 285C, and after checking the plastics 5 minutes after putting them in, it was recorded that the plastics were fully melted and it also slowly started to vaporize.

6.2 Shredding Results

The shredder tests started with shredding PLA material. PLA with any percentage of infill was put through the machine and the machine was able to take harder stock. Parts previously discarded due to geometry or wrong infill, were now entirely shredded by the machine. Although the sieve was not yet in place for these tests, results were already very encouraging. One observation from these tests was that the shredder had a hard time catching the input material sometime since the material would bounce against the shredder teeth. The walls of the hopper aided to keep parts inside the shredder.

Figure 45 shows plastic that was run once through the shredder, to the left is material larger than 5mm and to the right is 5mm desired dimensions. Figure 46 shows plastic that was run through the shredder twice. To the left is plastic larger than 5mm, to the right is plastic within the 5mm diameter.

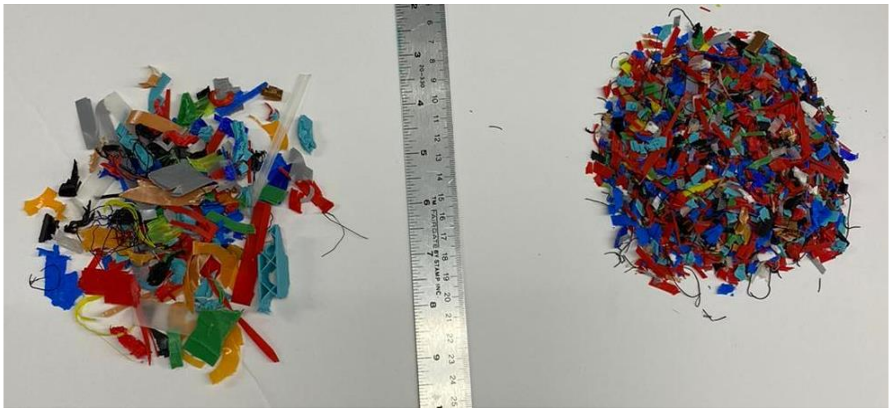


Figure 45: Plastic pieces after one pass on the shredder

Figure 46: Plastic pieces after two passes on the shredder

6.3 Extruding results

The table below shows the data collected for various testing of ABS, PLA and PET.

ABS testing add insulation

Temperature	160	165	180
Fan position	Below, direct	Below, direct	Below, direct
Extruding speed	Fast	Fast	Fast
Filament diameter	1.6mm	1.55mm	1.5mm

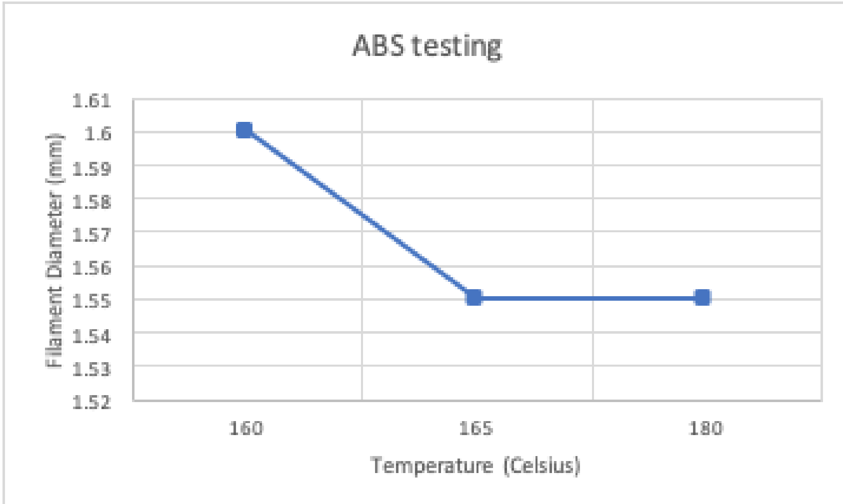


Figure 47: ABS testing temperature vs diameter

PLA testing add insulation

Temperature	200	180	147
Fan position	Below, direct	Below, direct	Below, direct
Extruding speed	fast	fast	slow
Filament diameter	Liquid, undetermined	1.56mm	1.75mm

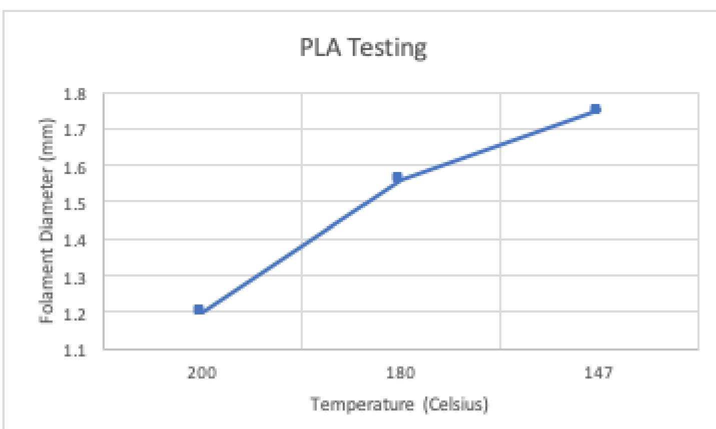


Figure 48: PLA testing temperature vs diameter

PET testing add insulation

Temperature	276	250	220
Fan position	disconnected	disconnected	disconnected
Extruding speed	No good extrusion	No good extrusion	No good extrusion
Filament diameter	Liquid, undetermined	Liquid, undetermined	Liquid, undetermined

PLA testing at 160ºC gave some promising results while extruding but further testing is to be conducted with varying temperatures for future work. The following figure shows that the extruded PLA had a diameter of 1.75mm and the extruded PLA contained a few unmelted pieces within it, which is why testing at a temperature of 180ºC was conducted. At 180ºC, the PLA started melting properly and there was a continuous flow of melted PLA.

Figure 50: Extruded PLA being extruded at a diameter of XXX mm (I can't read it, so list it here)

6.4 Spooling Results

The extruded PLA led the team to experiment with the Filawinder. In figure 51 below some of the PLA filament has been wrapped around the spool.

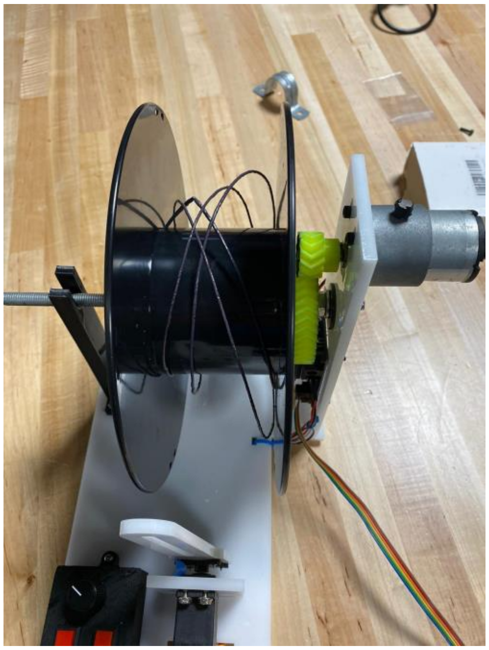


Figure 51: Filawinder with spooled PLA filament

7. Conclusion

This project's goal was to repurpose wasted filament scraps and one-time use water bottles to advance WPI's efforts towards a sustainable campus. Different vendors of one-time use water bottles showed substantial variation in the melting temperatures that could foil the desired ubiquitous nature of the repurposing filament maker. The shredder machine was capable of handling a wide variety in input raw material and delivered appropriate shredded plastic pieces. The output plastic pieces were 5mm in length which was the initial goal to achieve. The plastic was also extruded with a filament diameter of 1.75mm, which was the target for repurposed 3D printing. The final stage of the whole mechanism was the spooler and from initial testing, the filament was being spooled through the spooling mechanism. The whole mechanism worked. Future work can be done to improve each aspect of the mechanism for better filament output.

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