Senior Capstone Design 1

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Green Ellipsis – Upcycling of Single Use Plastic Soft Drink Bottles

Final Design Proposal

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Acknowledgments

Words cannot express our gratitude to our project sponsors Brian Alano and Jane Kane. Their innovation and guidance have been essential to making the project what it is today.

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We would like to thank Steve Andrepont, who we have had the privilege of collaborating with. Steve is extremely knowledge in all things engineering and particularly, additive manufacturing.

Team Value Statement

- Respect – We will treat people, including the sponsor and group members, with dignity. We will thoroughly take all ideas and opinions into consideration.
- Sustainability – We will do our part to help eliminate waste and pollution through the design of our system.
- Integrity – We will uphold the academic principles of the University of North Florida and the professional standards of Green Ellipsis.
- Inclusivity – We will practice equal access to opportunities and resources during our design process.
- Responsibility – We will be responsible in our design process to ensure we create a safe and effective design.
- Diversity – We will allow individuality and creativity where people feel welcomed to voice their opinions and ideas.

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Antonio Mendoza

X Nicholas Wedyck

Nicholas Wedyck

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Christian Ventouras

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Tyler Johns

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Marc Caina

Executive Summary

Green Ellipsis is a local engineering service that was established in 2015. They pride themselves on influencing others to move away from the current reliance on plastics. Single-use polyethylene terephthalate (PET) bottles continue to pack landfills around the country. Green Ellipsis has a solution to this issue, the Recreator 3D, which converts two-liter PET plastic bottles into 3D printer filament. Currently, the setup for this process is intensely laborious. The user must manually cut off the bottom of the bottle, then cut a strip using scissors and pull it through the pultruder. To solve the problem, automation of this setup process is required.

The new design must reduce the duration of the reclamation process by 20 percent and decrease the human interaction required by 50 percent. It must accept washed two-liter Pepsi bottles and output an eight-millimeter-wide strip for the pultrusion setup. Since the end goal for this project is hobbyist use, the design must fit within a 75cm by 240cm by 80cm volume and run off standard wall power(120Vac/60hz). The safety of the user is also a concern, therefore, any blades and cutting mechanisms must clear of the user to minimize the risk of injury. Finally, the project is provided an overall budget of $1,000.

Multiple preliminary concepts were produced and analyzed to determine their effectiveness toward meeting the design requirements. The Analytical Hierarchy Process (AHP) and a down selection matrix were used to compare the concepts. Various ideas were considered for the design concepts including a stand-alone system that will cut the entire strip before the pultrusion step, a lathe style system that moves the bottle while a stationary blade cuts the bottle, and an adaptation of the current system.

Once the final design concept was determined, calculations were done to establish the mechanical and electrical requirements of the system. Specific components were sourced based on the results from the design calculations and the overall design was finalized. The overall design consists of four main subsystems: the linear actuating mechanism, the bottle mount and rotator, the bottom cutter, and the strip cutter. The user will input a clean two-liter bottle to the bottle mount and start the process using the existing PLC on the upcylcer. Then a linear solenoid will actuate a blade to puncture the bottle and a NEMA 23 motor will rotate the bottle to cut the bottom of the bottle off. The linear solenoid will retract, and the bottle will lower toward the strip cutter via the linear actuating mechanism. The NEMA 23 motor will rotate the bottle to begin the strip cutting and the process will run until the lower limit switch is triggered. The lower limit switch is positioned so the process will stop when the cylindrical section of the bottle is completely cut.

The next steps in the design process are to order components and begin manufacturing. After the assembly of the first prototype, testing will be conducted to evaluate the performance of the design and how effectively it meets the design requirements.

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Background

Green Ellipsis is a local engineering service that was established in 2015. The current mission statement, “Green Ellipsis dreams of and designs for a sustainable humanity,” is the driving force of the company. Green Ellipsis’ goal is to bring sustainable engineering to the local community and beyond whilst also mitigating waste. In addition, Green Ellipsis prides itself on influencing others to move away from the current reliance on plastics. This is done by using the well-known mantra of reduce, reuse, and recycle whenever possible. Moreover, The United States Environmental Protection Agency (EPA) cites the notion of reduce, reuse, and recycle as a way that individuals and groups can assist the community and environment in saving energy and natural resources [1]. This closely aligns with the goal Green Ellipsis is trying to accomplish about designing for a sustainable humanity.

The majority of Green Ellipsis’ work is centered around 3D printing. During the height of the Covid pandemic, Green Ellipsis helped with the design, manufacturing, and distribution of over 10,000 face shields to hospitals in North Florida and healthcare providers in Indiana and New York. Green Ellipsis has also designed parts ranging from a shower curtain hook to a power supply cover that could be 3D printed by anyone.

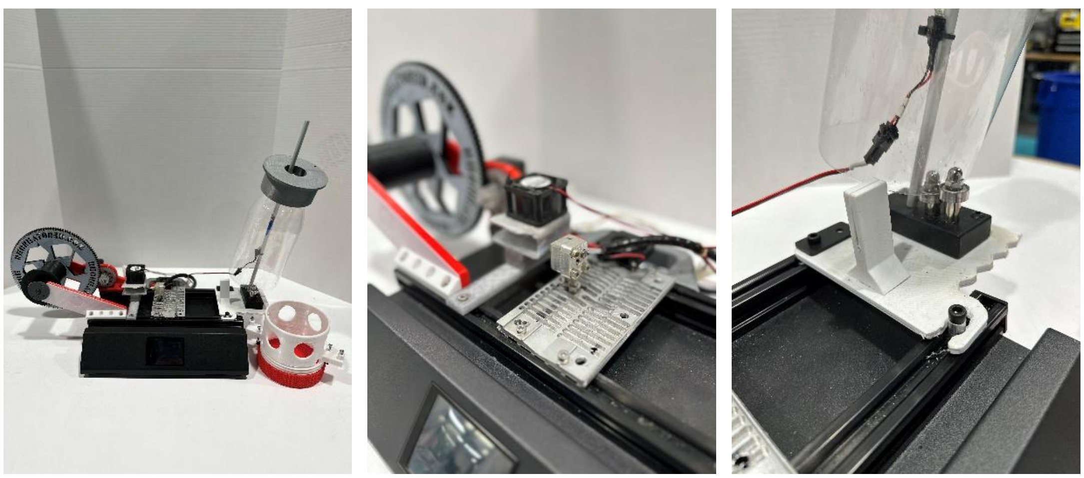
Recently, Green Ellipsis has become a part of the open source pultrusion community. Pultrusion is the process of manufacturing plastics via a pulling force. This shifted the design focus of Green Ellipsis toward the recycling of polyethylene terephthalate (PET) plastic bottles, specifically for hobbyists. These PET bottles are recycled by converting the usable portions into 3D printer filament. Once the plastic is recycled, it can then be reused to create useful 3D printed objects. The current device for converting PET plastic bottles into 3D filament is shown in Figure 1. Green Ellipsis hopes to publish the solutions found for the PET recycling process to the community as a kit for any hobbyist to recreate. This kit would include assembly instructions, parts, and hardware to properly assemble the device.

Figure 1: Current Apparatus for Converting PET Bottles into 3D Printer Filament

Problem Statement

Single-use polyethylene terephthalate (PET) bottles continue to accumulate in landfills around the country. Because of this, the need for recycling and upcycling of PET grows greater every day. 3D printers can uniquely contribute to this need by upcycling PET bottles into PET filament. Moreover, upcycled PET filament can then be used to 3D print useful items. Green Ellipsis uses a publicly available device that solves this issue as shown in Figure 2a. This device converts plastic bottles into 3D printer filament. Figure 3 details all steps in this upcycling process.

Currently, the setup for this process is laborious. Moreover, there are several manual processes that must be done before the machine can run. First, the label on the bottle needs to be removed with the adhesive scrubbed off and the inside cleaned. Then the bottom needs to get cut off. Next, the bottle gets turned through shearing bearings (Figure 2c) and a 30-degree angled point gets cut at the end of the strip. Finally, the strip gets pulled through the heated chamber (Figure 2b) and attached to the motorized spool. Therefore, it is not ideal for easy use, which is the current end goal for the device. Automation is required to solve the problem of a laborious setup process.



(a) (b) (c)

Figure 2: (a) The overall system (b) The hot end and pultrusion device (c) PET bottle cutter

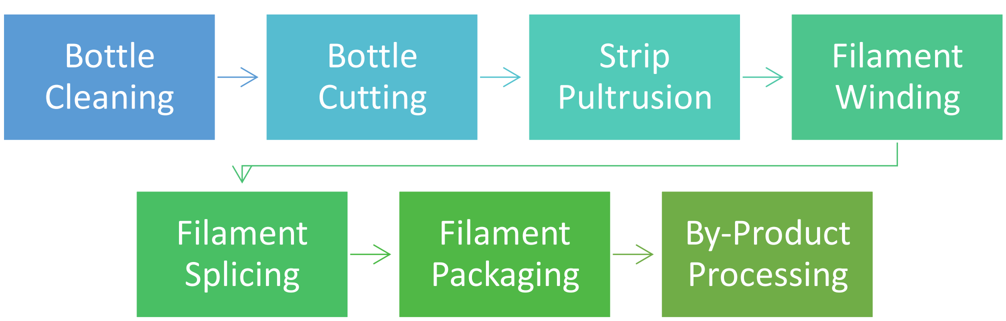


Figure 3: Process Overview for PET Upcycling

Automating one of these steps would reduce the labor required by the user to produce PET filament. More specifically, the laborious setup process benefits the most from automation, as mentioned previously. In a simpler form, the setup processes include Bottle Cleaning, Bottle Cutting, and Strip Pultrusion. Bottle Cutting was chosen as the optimal step to automate in the setup process. The method used to make this decision will be described in the Design Alternatives and Decision-Making Process section. The current Bottle Cutting step consists of cutting off the bottom of a two-liter bottle with a blade. Then, an angled starting strip is cut, which is necessary for the subsequent process. Ideally, this step would be completed using a single device with minimal human interaction.

The following are the design requirements and constraints that are specifically tailored based on the bottle cutting automation step. Design requirements are the desired demands of a design, such as desired performance and required materials. Each requirement and constraint were established based on the project description, as well as meetings with Green Ellipsis. All requirements and constraints are measurable to verify the success of the product.

Design Requirements

- Reduce duration of process by 20 percent
- Reduce amount of user touches by 50 percent
- Bottle cutting process must accept washed two-liter PET bottles
- Eight-millimeter-wide ribbon must be produced
- Strip must begin with a 30-degree angled cut to integrate with the upcycler
- Must integrate with current system

Design Constraints

- Machine needs to fit in a 75cm by 240cm by 80cm volume
- Must run off standard wall power (120Vac/60hz)
- Blades must be guarded or away from areas where the user interacts with the device
- Use two-liter Pepsi product PET bottles
- $1,000 budget

The five design constraints listed above are strict limitations of the bottle cutting process that were imposed by Green Ellipsis. First, the size constraint details the dimension constraint on the entire upcycler. So, the bottle cutting machine must be able to fit with the rest of the upcycler on a tabletop within the volume shown. Second, the power constraint limits the bottle cutter machine to a standard U.S. 120-volt wall outlet. Third, the safety constraint addresses the importance of creating a machine that does not easily harm the user. Moreover, the current bottle cutting process has open blades (scissors and X-ACTO knife) that can potentially cut users. Therefore, it is important to remove the user from having to be near the blades when using the machine. Fourth, a general constraint guides the overall design by restricting the types of bottles the bottle cutter machine allows. Two-liter Pepsi product bottles have a uniform mid-section and can therefore be used in the pultrusion process of the upcycler. Finally, a strict budget constraint rounds out the design constraints. A maximum of $1000 will be provided by Green Ellipsis to automate the bottle cutting process.

Theoretical Concepts:

Additive Manufacturing

Additive Manufacturing, also known as 3D printing, is the opposite of traditional manufacturing. Getting its start in the 1980s, additive manufacturing utilized computer aided design to generate objects by building them up layer by layer. Not until the early 2000s did technology allow a level of precision comparable to that of traditional manufacturing. After the expiration of patents in 2009, many affordable 3D printers popped up all around the world and led to a new community-driven interest in 3D printing [2].

3D printers are widely used today, and the most common one is fused filament fabrication (FFF), also known as fused deposition modeling (FDM). Figure 4a shows the FFF process. First, the material is fed via a spool of filament, the most common sizes being 1.75mm and 3mm. It is then extruded via a drive wheel through a heated nozzle more commonly known as the hot end. This brings the material to melting temperature where it is deposited onto the print bed layer by layer [2]. There are many types of material that FFF can use. The most common being polylactic acid (PLA), however, there are Acrylic Styrene-acrylonitrile (ASA), Acrylonitril-butadieen-styreen (ABS), High Impact Polystyrene (HIPS), nGen, Polyethylene coTrimethylene Terephthalate (PETT) and Polyethylene Terephthalate Glycol (PETG).

Figure 4b shows the entire 3D printing process. First, the object is created in Computer Aided Design (CAD) software. Afterwards, it is imported into a software known as slicing software. This converts a three-dimensional object into tool paths that the printer can understand. It also configures and includes other necessary items not in the CAD file required for printing such as supports, infill density, and color changes. Afterwards, the part is printed, and the printer has certain conditions set by the slicer such as fan speed, tool speed auto leveling, and minimum layer time. With other types of 3D printing, there is much more post processing required, but mostly for FFF it usually only consists of removal of support material [3].

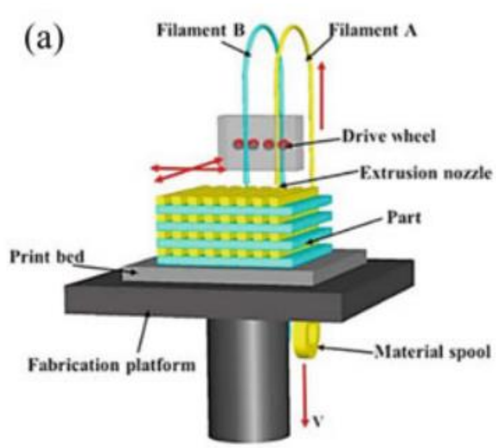


Figure 4: (a) FFF Process (b) Process of 3D Printing [3]

In addition to the software needed to print, it is also necessary to know which firmware the 3D printers run on. One of the most widely used open-source firmware is the Marlin firmware, derived from GRBL and Sprinter. Both of which are firmware utilized in machine control and CNC machining [4]. Marlin firmware is mainly used in rapid prototyping and can be easily configured to suit specific project needs. It can accommodate Delta, Cartesian, SCARA, and Core XY printing formats using G-code [4].

The Making of Polyethylene Terephthalate (PET)

Polyethylene terephthalate, also known as polyester, is made through an esterification process of combining the monomers, ethylene glycol and terephthalic acid. Under elevated temperatures and low vacuum pressure, water and polymer chains are created. During this step, the PET is in a viscous liquid stage, which is then extruded forming a glass-like amorphous matter. A second polymerization stage removes impurities that provide the PET its toughness, stiffness, and resistance to creep, as well as its flexibility [5]. A visual of this process is shown in Figure 5. This stable polymer is highly resistant to chemical and biological reactions to other materials, making it a viable option for packaging foods, beverages, and many other consumer products [6]. After the melted polymer has been made, it is either spun or drawn into fibers or solidified. Subsequently, PET films are made through extrusion; molten PET can be blow-molded into desired shapes and PET pellets can be cut from the solidified polymer [7].

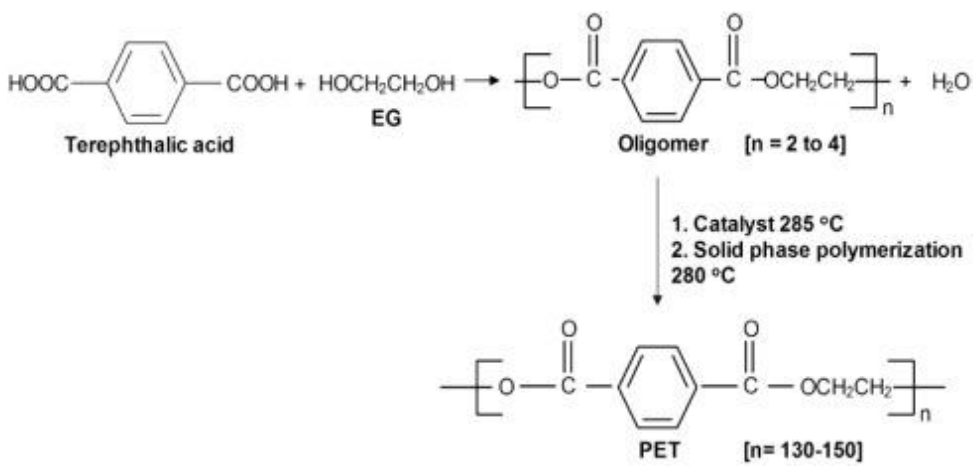


Figure 5: The Chemical Process of Producing Polyethylene Terephthalate [5]

Plastic Waste

Polyethylene terephthalate is one of the most widely available semicrystalline thermoplastics. It is used in many industries for its tear and tensile strength, food-safe uses, and gas barrier properties. Invented in the 1940s by J.T. Dickson, it was not commercially used until the 1960s [8]. Because of this, PET plastics have become ubiquitous with food and liquid packaging. Most PET bottles are intended for one-time use and are thrown out afterwards. Despite PET bottles being easily recyclable, it still has a low recycling rate [8]. Figure 6 shows the percentage of PET bottles recycled for various countries.

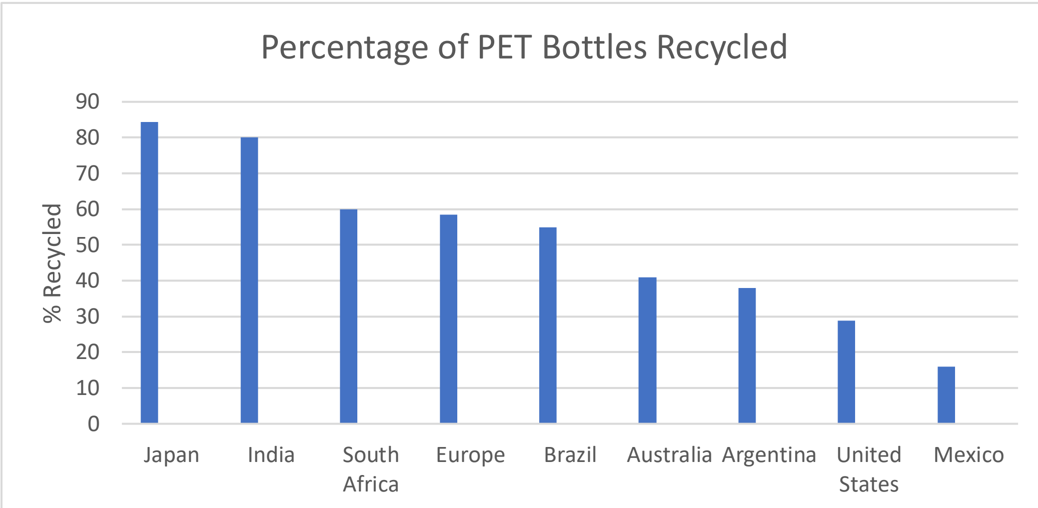


Figure 6: Shows Recycling Rate of Various Countries as of 2019 [8]

PET Upcycling

With the abundance of single-use PET bottles growing exponentially every day, upcycling has been a solution to help minimize this waste. Upcycling is the process of repurposing single-use items, such as plastic bottles, to create a product of higher quality or value [9]. The benefit of upcycling compared to recycling is that upcycling requires less energy input and removes the need for virgin materials to create a new product [9].

There are many ways to upcycle PET bottles. One of the main ways is to repurpose the bottles for everyday use, such as planters or containers. However, recent advancements in technology have made upcycling of these bottles feasible for the use of 3D filaments. Since the majority of 3D printing requires a plastic material feed, the upcycling of PET bottles is an innovative solution to the pollutant waste [10].

PET Upcycling Process

A community has emerged to promote the upcycling of PET bottles that were not recycled. The seven main processes can be seen in Figure 7. The first iteration was by Joshua Taylor of Recreator 3D [11] as seen in Figure 8.

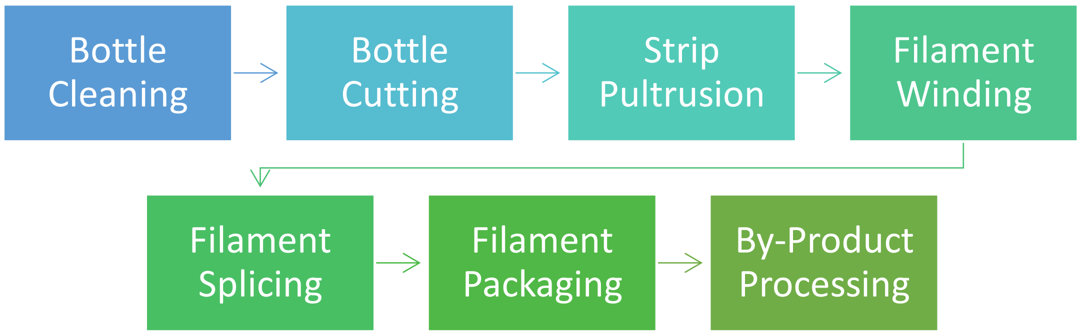


Figure 7: Process Overview for PET Upcycling

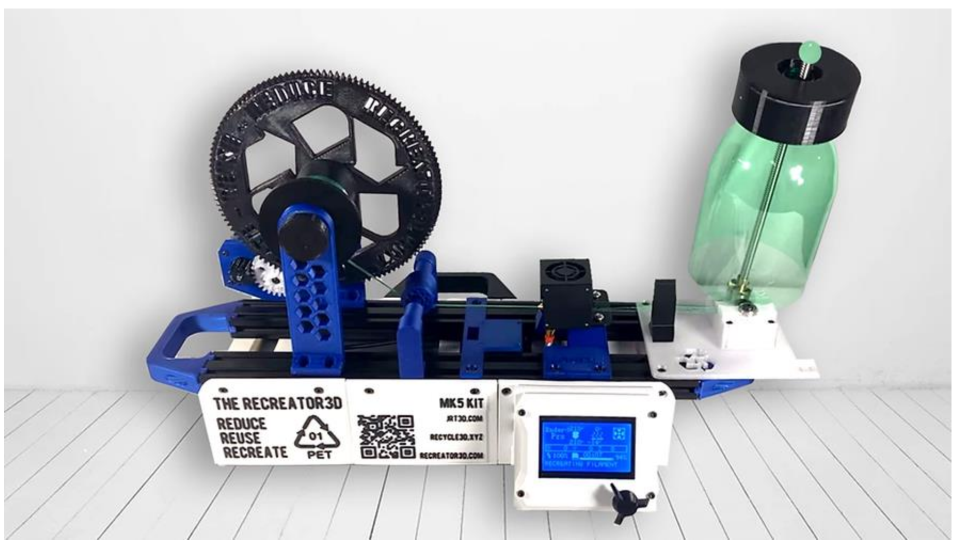


Figure 8: Joshua Taylor's Recreator 3D [11]

In this specific configuration, the bottle is prepared before being turned into filament. The bottle cleaning process is the first of seven steps to upcycling PET bottles. First, it is cleaned of debris with the heat-bonded adhesive and the label still attached. A quick rinse for the inside of the bottle removes enough debris for the process. Afterwards, the bottle's label is removed, and the label's adhesive is removed with a degreaser and abrasive scrub pad. The second step is the bottle cutting process, where the bottom of the bottle is cut off. Next, an eight-millimeter-wide strip is started and cut approximately 5.5mm in length.

A narrow strip must first be created to start the strip pultrusion. This strip starts out as a fine point and gradually widens to the appropriate width based on the bottle thickness. In the Strip Pultrusion step, the previously cut strip is pulled through the hot end and wound around the moving spool. To ensure proper operation of the pultrusion process the hot end must reach a proper temperature of 234℃. Due to the hot end temperature being below the melting temperature, a circular or "U" shape is formed with a void in the center of the filament from the pultrusion process [11]. The cross-section of the reclaimed filament is shown in Figure 9.

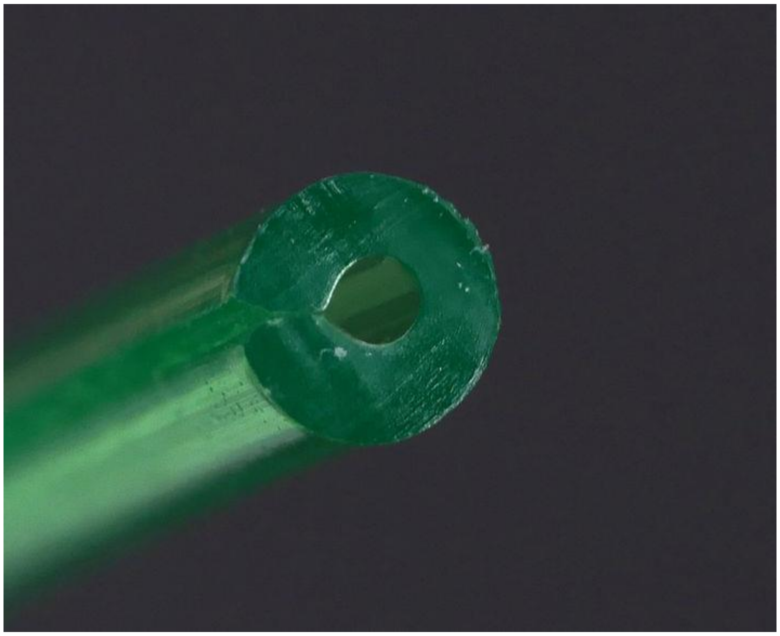


Figure 9: Reclaimed PET After Being Formed into 1.75mm Filament [11]

After winding the molded filament onto the spool, the stepper motor driving the spool continues to pull the newly formed filament. This completes the pultrusion process until the PET bottle runs out of usable material. When performing this process, around twenty-five grams of filament can be made from a single bottle.

Filament splicing would be the next process to occur after the bottle gets used up. However, splicing PET is tricky due to the crystallization of PETP from prolonged heat exposure without proper cooling [11]. In the Filament Packaging step, the filament must be dried before it can be used for 3D printing. This can range from commercial equipment to an oven set to 150℃. After being dried it must be stored in airtight packaging with desiccant to avoid moisture absorption. The last process is By-Product Processing. In this process, the top and bottom of the bottle can be recycled or upcycled. Currently, this has no definitive process, however, multiple options are available. The leftover bottle can be pressed into pucks or ground up into shredded PET for injection molding.

Division of Labor

Figure 10 shows the division of labor amongst the team with Antonio Mendoza being the point-of-contact directly to the Green Ellipsis team. Antonio made sure to clearly communicate ideas back and forth along with scheduling meetings with Mr. Brian Alano and his mechanical engineer, Jane Kang. Christian Ventouras, a natural leader, would set up internal group meetings outside of class to work collectively in-person and represent the team during professor meetings. Tyler Johns is the Lead Electrical designer taking on firmware coding and bringing 3D printing expertise. Marc Caina, the Lead Mechanical designer, applied mechanical calculations to spec out all components that best fit the design of the group project. Nicholas Wedyck took the role of modeling and designing the device in SolidWorks 3D CAD software. Not only was Antonio the point-of-contact, but he also assisted Tyler in designing the electrical control system for the Recreator and used SolidWorks Electrical to design the electrical system schematic. Table 1 shows the billable hours performed by each group member over the course of the project.

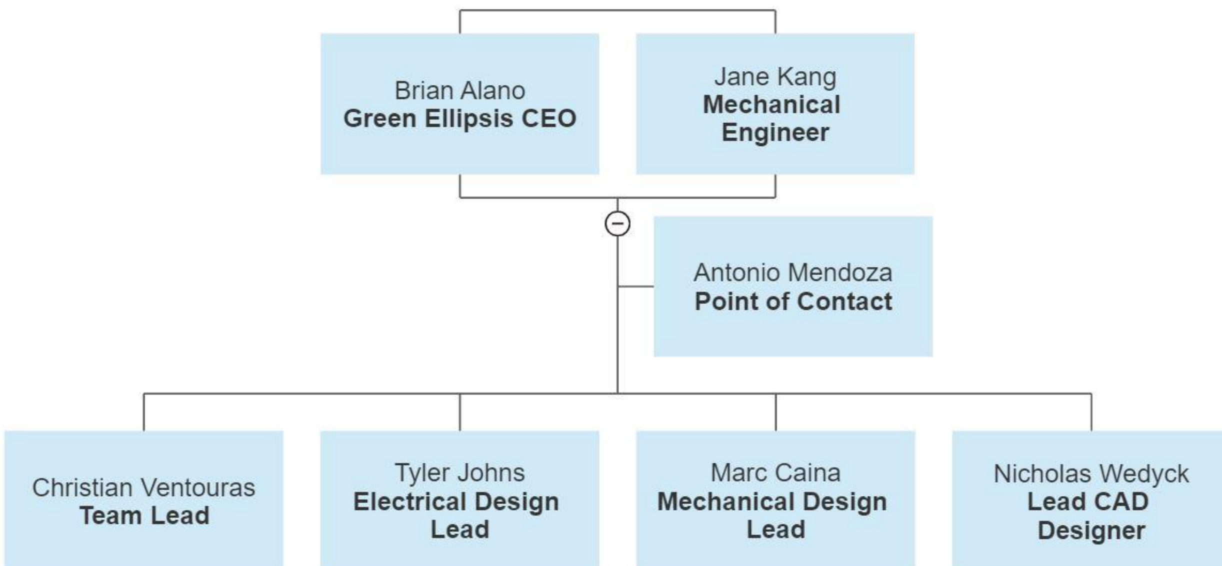


Figure 10: Division of Labor Org Chart

Billable Hours

Table 1: Billable Hours per Week

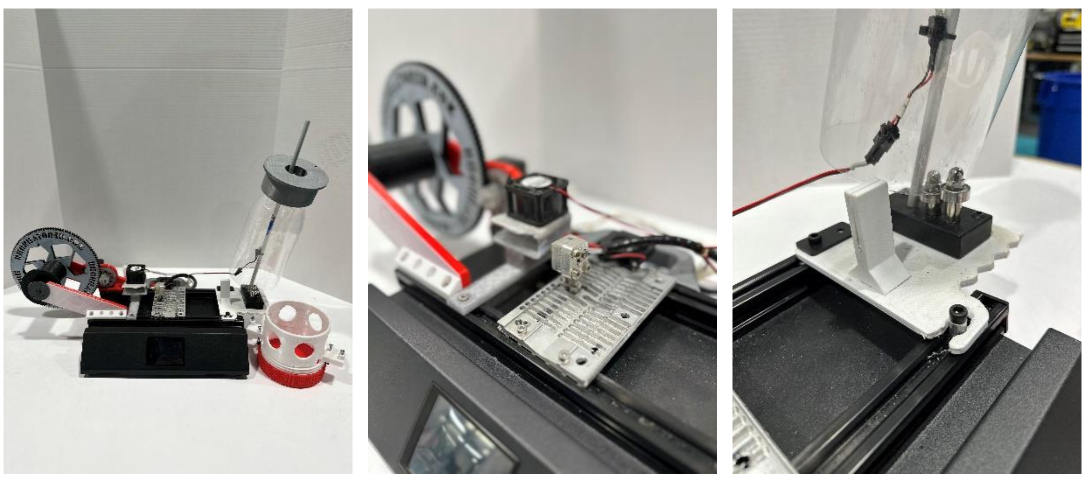
Personnel / Week	1	2	3	4	5	6	7	8	9	10	11	12	Total
Antonio Mendoza	5.5	10	7	6	3	6.5	3	3	8	17	7	13	89
Christian Ventouras	5	11	9	6.5	3	9	3	3	10	14	9	8	90.5
Marc Caina	5	9.5	7	6.5	3	8	3	3	10	13	7	8.5	83.5
Nicholas Wedyck	5	10	9.75	9.5	3	8.5	4	3	14	22	13	14	115.75
Tyler Johns	5.5	10	9	6	3	7	3	3	8	18	7	10	89.5
Total	26	50.5	41.75	34.5	15	39	16	15	50	84	43	53.5	468.25

Proposed Design

Problem Statement

Single-use polyethylene terephthalate (PET) bottles continue to accumulate in landfills around the country. Because of this, the need for recycling and upcycling of PET grows greater every day. 3D printers can uniquely contribute to this need by upcycling PET bottles into PET filament. Moreover, upcycled PET filament can then be used to 3D print useful items. Green Ellipsis uses a publicly available device that solves this issue as shown in Figure 11a. This device converts plastic bottles into 3D printer filament. Figure 12 details all steps in this upcycling process.

Currently, the setup for this process is laborious. Moreover, there are several manual processes that must be done before the machine can run. First, the label on the bottle needs to be removed with the adhesive scrubbed off and the inside cleaned. Then the bottom needs to get cut off. Next, the bottle gets turned through shearing bearings (Figure 11c) and a 30-degree angled point gets cut at the end of the strip. Finally, the strip gets pulled through the heated chamber (Figure 11b) and attached to the motorized spool. Therefore, it is not ideal for easy use, which is the current end goal for the device. Automation is needed to solve the problem of a laborious setup process.



(a) (b) (c)

Figure 11: (a) The overall system (b) The hot end and pultrusion device (c) PET bottle cutter

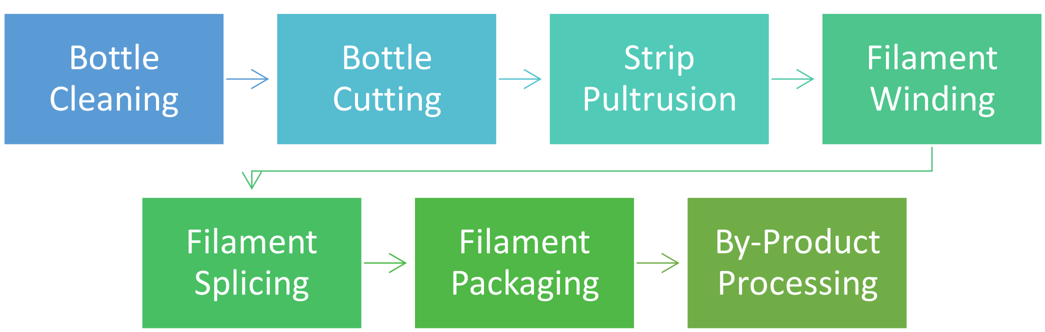


Figure 12: Process Overview for PET Upcycling

Automating one of these steps would reduce the labor required by the user to produce PET filament. More specifically, the laborious setup process benefits the most from automation, as mentioned previously. In a simpler form, the setup processes include Bottle Cleaning, Bottle Cutting, and Strip Pultrusion. Bottle Cutting was chosen as the optimal step to automate in the setup process. The method used to make this decision will be described in the Design Alternatives and Decision-Making Process section. The current Bottle Cutting step consists of cutting off the bottom of a two-liter bottle with a blade. Then, an angled starting strip is cut, which is necessary for the subsequent process. Ideally, this step would be completed using a single device with minimal human interaction.

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Design Requirements

- Reduce duration of process by 20 percent
- Reduce amount of user touches by 50 percent
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- Machine needs to fit in a 75cm by 240cm by 80cm volume
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- Use two-liter Pepsi product PET bottles
- $1,000 budget

The five design constraints listed above are strict limitations of the bottle cutting process that were imposed by Green Ellipsis. First, the size constraint details the dimension constraint on the entire upcycler. So, the bottle cutting machine must be able to fit with the rest of the upcycler on a tabletop within the volume shown. Second, the power constraint limits the bottle cutter machine to a standard U.S. 120-volt wall outlet. Third, the safety constraint addresses the importance of creating a machine that does not easily harm the user. Moreover, the current bottle cutting process has open blades (scissors and X-ACTO knife) that can potentially cut users. Therefore, it is important to remove the user from having to be near the blades when using the machine. Fourth, a general constraint guides the overall design by restricting the types of bottles the bottle cutter machine allows. Two-liter Pepsi product bottles have a uniform mid-section and can therefore be used in the pultrusion process of the upcycler. Finally, a strict budget constraint rounds out the design constraints. A maximum of $1000 will be provided by Green Ellipsis to automate the bottle cutting process.

Design Alternatives and Decision-Making Process

Three different concepts were considered for automation. Each concept focuses on a different step in the setup process. This is because there is a requirement to automate at least one process in the design. Furthermore, it is necessary to focus on the most important and feasible process to automate. The three concepts considered for automation included:

- Bottle cutting
- Bottle cleaning
- Strip pultrusion

Preliminary, hand-drawn sketches were generated based on these discussions to get an idea of potential automation solutions. A down selection process was then utilized to narrow the concepts down to one final concept. Once the final concept was selected, three more concepts were created based on that process step.

Bottle Cutting

Currently, the user must use a handheld tool (designed by Green Ellipsis) to cut the bottom of the bottle off. Then the user sets the bottle into the current device, pulls a small strip, and cuts the end at an angle with scissors. A couple of factors explain the benefits of automating this process. First, tool usage would benefit from this concept automation. The current device requires the user to use three different tools during this process. So, an automated solution would reduce the number of tools, which reduces user interaction and potential injury.

Another benefit to automating this process is the repeatability between angled strip cuts. The end of the strip must begin as a fine point, then increase to the eight-millimeter width at 30 degrees. This is so the strip can properly enter the heated chamber during the pultrusion process. Since the current setup requires the user to cut with scissors, repeatability is not precise. An automated solution would allow for a thickness and length that could be precisely replicated each time. Figure 13 shows a potential automated solution to the bottle cutting concept based on the described benefits of an automated solution.

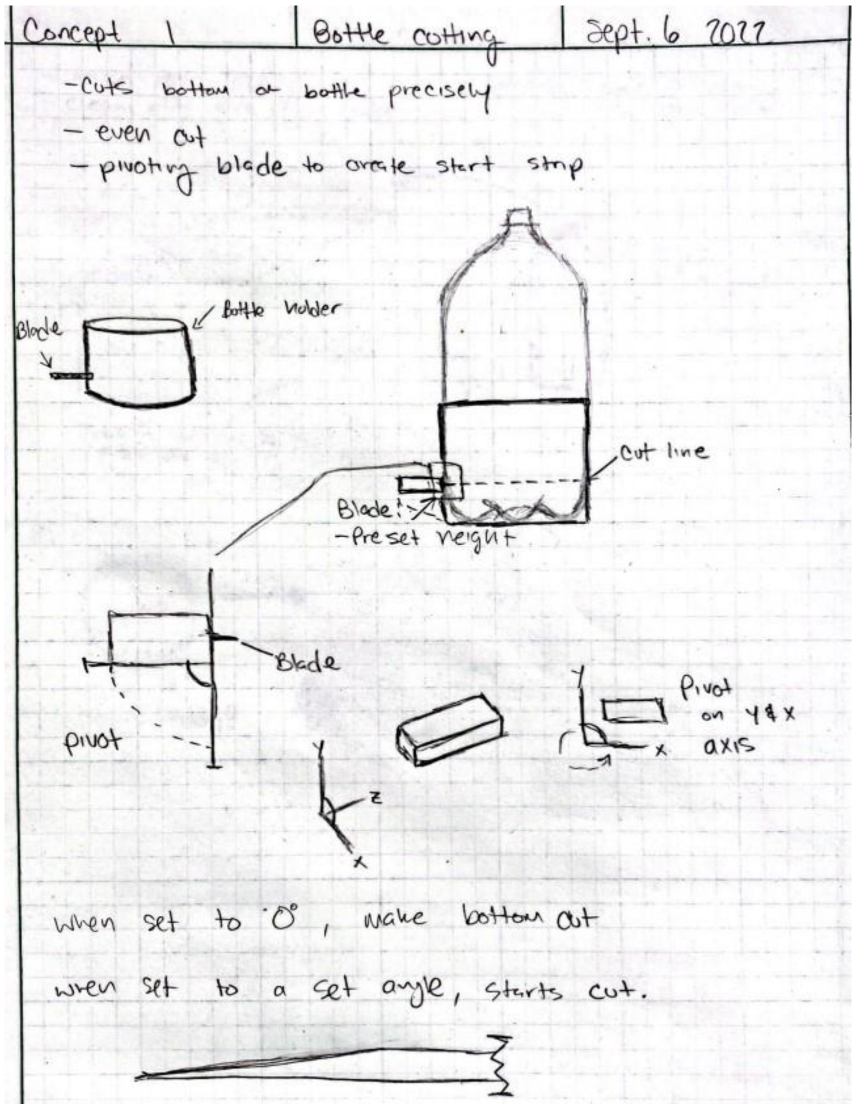

Figure 13: Bottle Cutting Concept Sketch

Bottle Cleaning

The current bottle cleaning stage requires the user to remove the label, remove the adhesive, and wash the inside and outside of the bottle. There are a couple of reasons why this concept would benefit from automation. The first benefit would potentially reduce the duration of the current process. Moreover, scrubbing off the adhesive and washing the bottle by hand is time consuming. An automated solution could do both processes at the same time, reducing the duration of the overall process.

Another benefit comes from the current process being labor intensive. Currently, the user must cut the bottle label with scissors and peel it off carefully. Then the user must use an abrasive material and cleaner solution to remove the adhesive from the bottle. Finally, the inside of the bottle must be washed. An automated solution would reduce human interaction, making it a less laborious process. A potential automated solution for the bottle cleaning concept is shown in Figure 14, which details the automation benefits previously described.

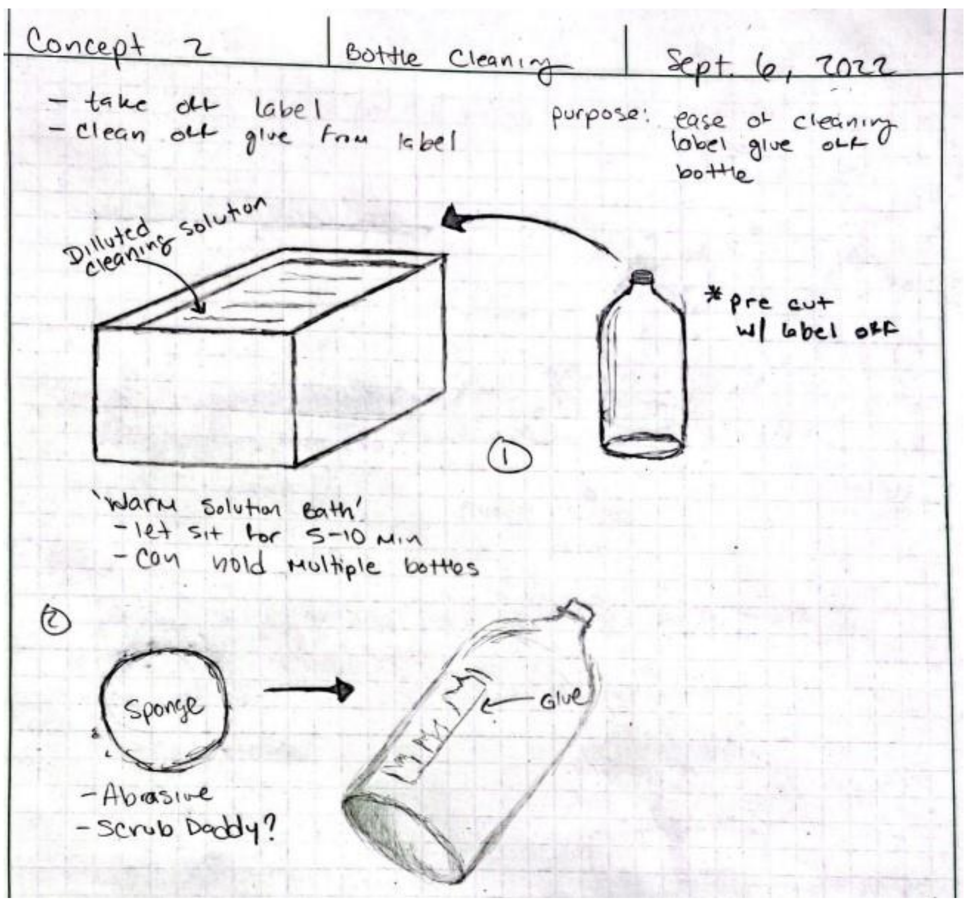

Figure 14: Bottle Cleaning Concept Sketch

Strip Pultrusion

The current strip pultrusion process requires the user to pull the strip to the heated chamber with pliers, feed the strip through the heated chamber, then pull the deformed PET filament and attach it to the rotating spool. There are two automation benefits to this process. The benefit first involves user interaction and safety. Furthermore, the entire process requires the user to touch the plastic at each point in the process, even when it enters the heated chamber. Automation would allow the user to stay away from the heated chamber, which would mitigate the chance of skin burns.

The second benefit of automation is cycle time. The pultrusion process takes quite a while to complete. This is made worse considering that the user must be present during the entire process. Automation would allow the user to prep the next bottle instead of having to interact with the device during the pultrusion process. Thus, decreasing the total cycle time of the entire upcycling process. Figure 15 shows an example of a potential automation solution, which highlights the detailed benefits explained.

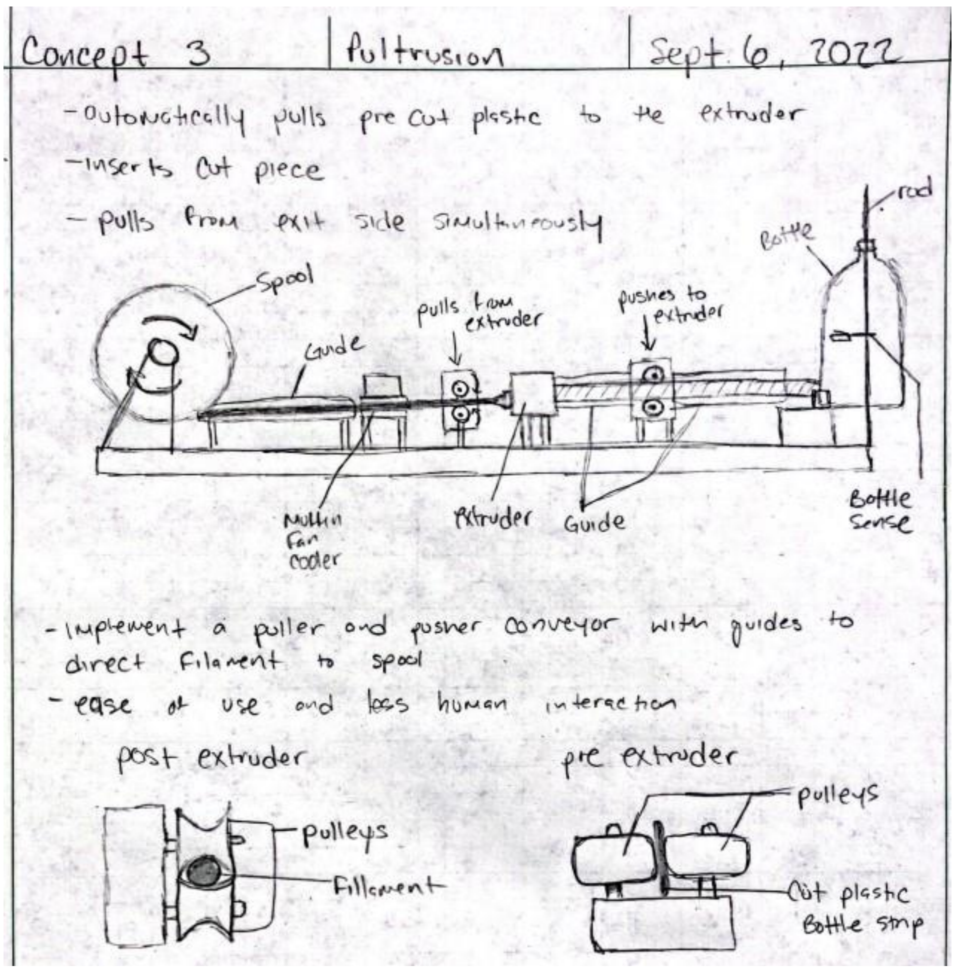

Figure 15: Strip Pultrusion Concept Sketch

Down Selection Process for Upcycler Automation Step

A weighted, down selection matrix was used to determine the most suitable concept for the upcycler automation. The Analytical Hierarchy Process (AHP), from *Engineering Design* [12], was employed to generate normalized weights for each criterion. The "AHP's Ratings for Pairwise Comparison of Selection Criteria" from *Engineering Design* [12] was used to generate the normalized criteria weights. The ratings are listed in Table 2 below. Table 3 shows the Normalized Criteria Comparison Matrix. This matrix was used to determine criterion weight by comparing their impact on design success. Table 4 below depicts the down selection matrix. The matrix uses the qualitative ranking system listed in Table 5 to obtain the most suitable concept. The table includes a value, correlated with a description, which represents how effectively the concept meets the design criterion.

Table 2: Engineering Design AHP Ratings [12]

AHP's Ratings for Pairwise Comparison of Selection Criteria

Rating Factor	Relative Rating of Importance of Two Selection Criteria A and B	Explanation of Rating
1	A and B have equal importance.	A and B both contribute equally to the product's overall success.
3	A is thought to be moderately more important than B.	A is slightly more important to product success than B.
5	A is thought to be strongly more important than B.	A is strongly more important to product success than B.
7	A is thought to be very much more important than B, or is demonstrated to be more important than B.	A's dominance over B has been demonstrated.
9	A is demonstrated to have much more importance than B.	There is the highest possible degree of evidence that proves A is more important to product success than B.

The ratings of even numbers 2, 4, 6, and 8 are used when the decision maker needs to compromise between two positions in the table.

Table 3: Normalized Criteria Comparison Matrix

Normalized Criteria Comparison Matrix										
	Impact on Duration of Process	Waste Minimization	Cost	Size	Power Requirement	Produces Hazardous Fumes	Manufacturability	Human Interaction Needed	Probability of Injury	Criteria Weights
Impact on Duration of Process	0.303	0.299	0.225	0.209	0.282	0.200	0.299	0.303	0.299	**0.269**
Waste Minimization	0.061	0.060	0.025	0.116	0.121	0.111	0.060	0.061	0.060	**0.075**
Cost	0.101	0.179	0.075	0.116	0.008	0.156	0.179	0.101	0.179	**0.122**
Size	0.034	0.012	0.015	0.023	0.013	0.022	0.012	0.034	0.012	**0.020**
Power Requirement	0.043	0.020	0.375	0.070	0.040	0.067	0.020	0.043	0.020	**0.078**
Produces Hazardous Fumes	0.034	0.012	0.011	0.023	0.013	0.022	0.012	0.034	0.012	**0.019**
Manufacturability	0.061	0.060	0.025	0.116	0.121	0.111	0.060	0.061	0.060	**0.075**
Human Interaction Needed	0.303	0.299	0.225	0.209	0.282	0.200	0.299	0.303	0.299	**0.269**
Probability of Injury	0.061	0.060	0.025	0.116	0.121	0.111	0.060	0.061	0.060	**0.075**

Table 4: Design Concept Down Selection Matrix

		Automation Concepts		
Selection Criteria	**Weights**	**Bottle Cleaning Concept**	**Bottle Cutting Concept**	**Strip Pultrusion Concept**
Impact on Duration of Process	0.269	5	4	3
Waste Minimization	0.075	1	3	4
Cost	0.122	3	5	1
Size	0.020	3	4	4
Power Requirement	0.078	3	4	2
Produces Hazardous Fumes	0.019	4	5	1
Manufacturability	0.075	3	4	2
Human Interaction Needed	0.269	5	4	5
Probability of Injury	0.075	3	5	4
NET SCORE		3.94	4.14	3.27
RANKED		2nd	1st	3rd

Table 5: Evaluation Scheme for Down Selection

Evaluation Scheme for Down Selection Matrix	
Five-Point Scale	Description
1	Weak
2	Fair
3	Good
4	Great
5	Excellent

The "Impact on Duration of Process" criteria ranks how much a concept affects the overall duration of upcycling the two-liter bottles into 3D printer filament. As the production time of the 3D printer filament decreases, its production cost also decreases. Since the major goal of this design is to automate this process to make the filament more economical, this criterion ranked highest alongside the "Human Interaction Needed" criterion. This is because the more a person needs to interact with a process, the less the process can run on its own. Therefore, increasing the labor costs of 3D printer filament production. Since the design is provided a budget of $1000, the "Cost" criterion is ranked second highest. For the scale of this project, $1000 is a sufficient budget, however, to maximize the effectiveness of the design, the cost of each concept is weighted heavier than other criteria.

The "Waste Minimization" criterion was given a moderate ranking as the main design goal of the original process was to minimize waste and pollution in the world. The "Manufacturability" criterion is ranked the same since this characteristic of the design affects the overall cost of the design. The "Probability of Injury" criteria was also given the same ranking. The ability of the design to reduce the risk of injury for a user can reduce the liability taken on by Green Ellipses.

The "Power Requirement" criterion was given a lower ranking. The design is constrained to run on standard wall power(120Vac/60hz). This is so hobbyists who are interested in creating their own 3D printer filament can run this machine in their own homes. Since the power requirements of the original design are well below what is supplied from standard wall power, the power requirement of the automation design concept is not a major element in the decision-making process. The "Size" criterion was ranked lowest. The size requirement given by the sponsor is that the design must fit in a 75cm by 240cm area. The current design takes up 60cm by 45cm, therefore, there is abundant room for the automation component.

Final Concept Selection

There are several key areas that attributed to the bottle cutting concept scoring highest. First, bottle cutting ranked highest on "Cost," which was weighted second of the twelve criteria. This is important because it means that automating bottle cutting will save the most in cost and will ensure that the budget will not be exceeded. Next, bottle cutting ranked high again for "Human Interaction Needed" and "Impact on Duration of Process," which were tied for the highest weighted criterion. This shows that the bottle cutting design will benefit most from automation, making that process less labor intensive. All of this leads to the fact that the bottle cutting concept is the design that will be focused on moving forward.

Bottle Cutting Design Concepts

After Bottle Cutting was determined to be the process to automate, three design concepts for this process were created. The first design concept is an iteration of the current bottle cutting mechanism. Figure 16 shows a simple CAD model of this design. The design includes a 3D printed housing with a hinged blade that is rotated by a motor. Furthermore, the bottle gets manually inserted into the housing and held by the user. Then the motor actuates while the blade is at a perpendicular angle to the bottle. Once a full rotation is completed, the user locks the blade into a thirty-degree angle. Finally, the motor actuates a final time to cut the initial angled strip. The benefits of this design are its simplicity and lack of failure points. Moreover, the design requires minimal moving parts. However, it requires abundant user input to operate. The flexibility of a bottle could also cause issues when initialing the angled cut, especially after the bottom gets cut off.

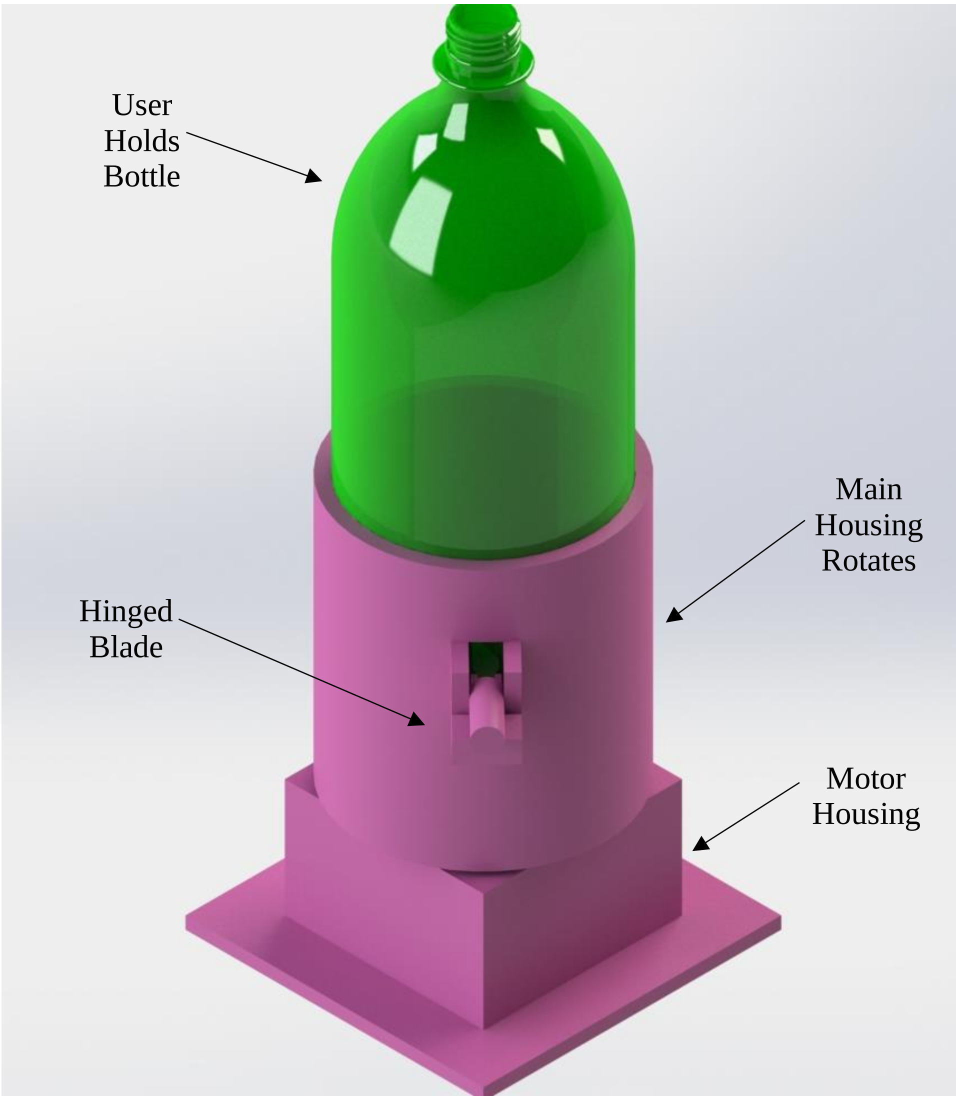

Figure 16: Bottle Cutting Design Concept One

Unlike the first design concept, the second design concept will be integrated with the rest of the upcycling process. Figure 17 shows the physical layout of design concept two. In this design, the user first attaches the bottle to the custom mount. Then a blade punctures the bottle, the bottle begins to rotate, and the bottom gets cut off. Next, the linear actuating mechanism lowers the rotating bottle onto the strip cutter blade. This cuts the initial angle on the strip, then continues to cut the eight-millimeter-wide strip. There is a possibility with this design to then feed the strip directly to the next step in the Green Ellipsis upcycler process.

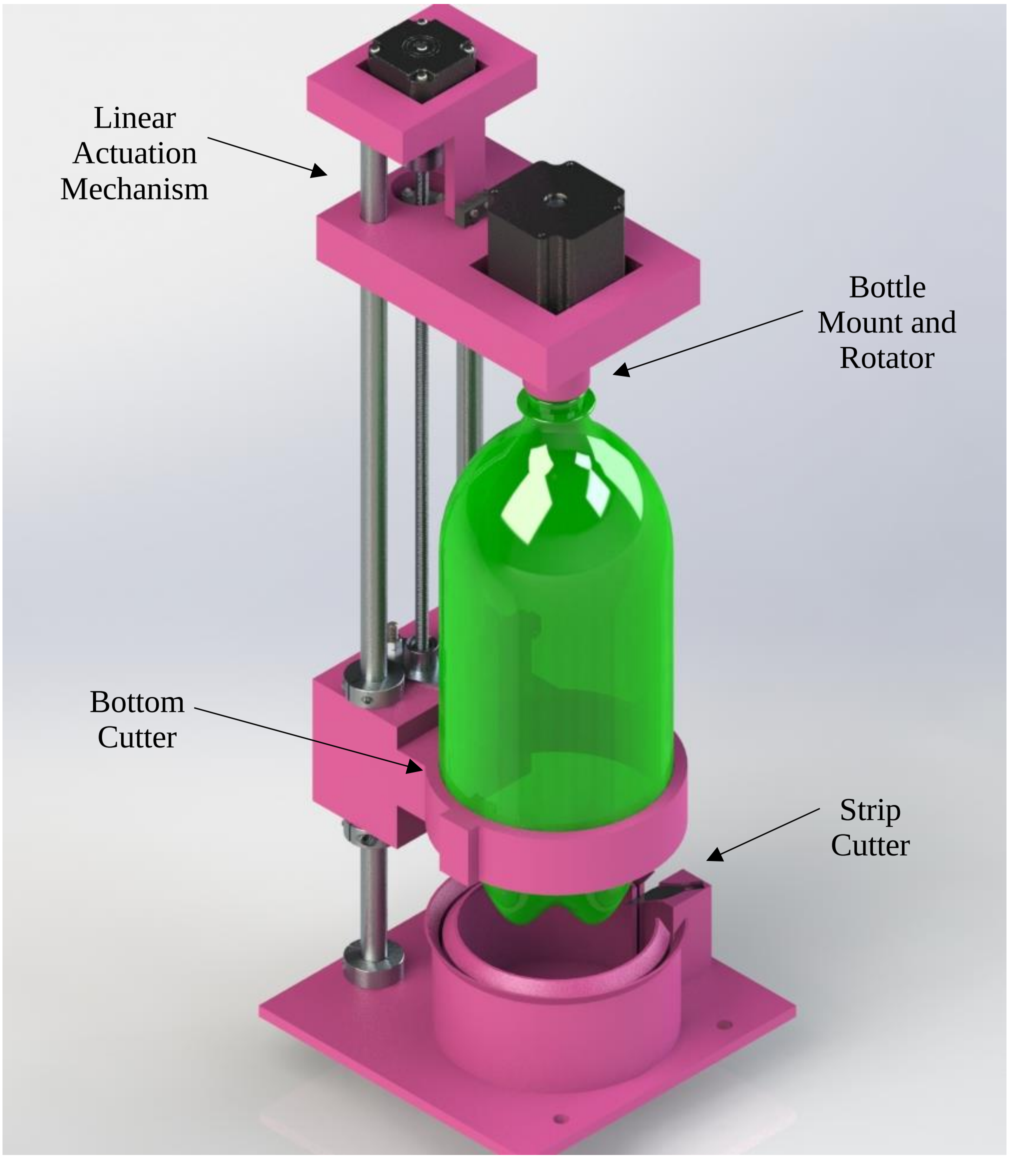

Figure 17: Bottle Cutting Design Concept Two

The third design consists of two stepper motors, one to actuate the bottle linearly along the Z-axis and one to rotate the bottle about the Z-axis. A preliminary CAD rendering of this design concept is shown in Figure 18. The bottle first gets inserted into the bottle holder. Then the motor rotates the bottle to cut the bottom off. After the bottom is off, the blade will begin to raise (using a lead screw design) as the bottle rotates. This will cut the initial pointed strip and the rest of the eight-millimeter-wide strip. This design is a bit more simplistic compared to design concept two.

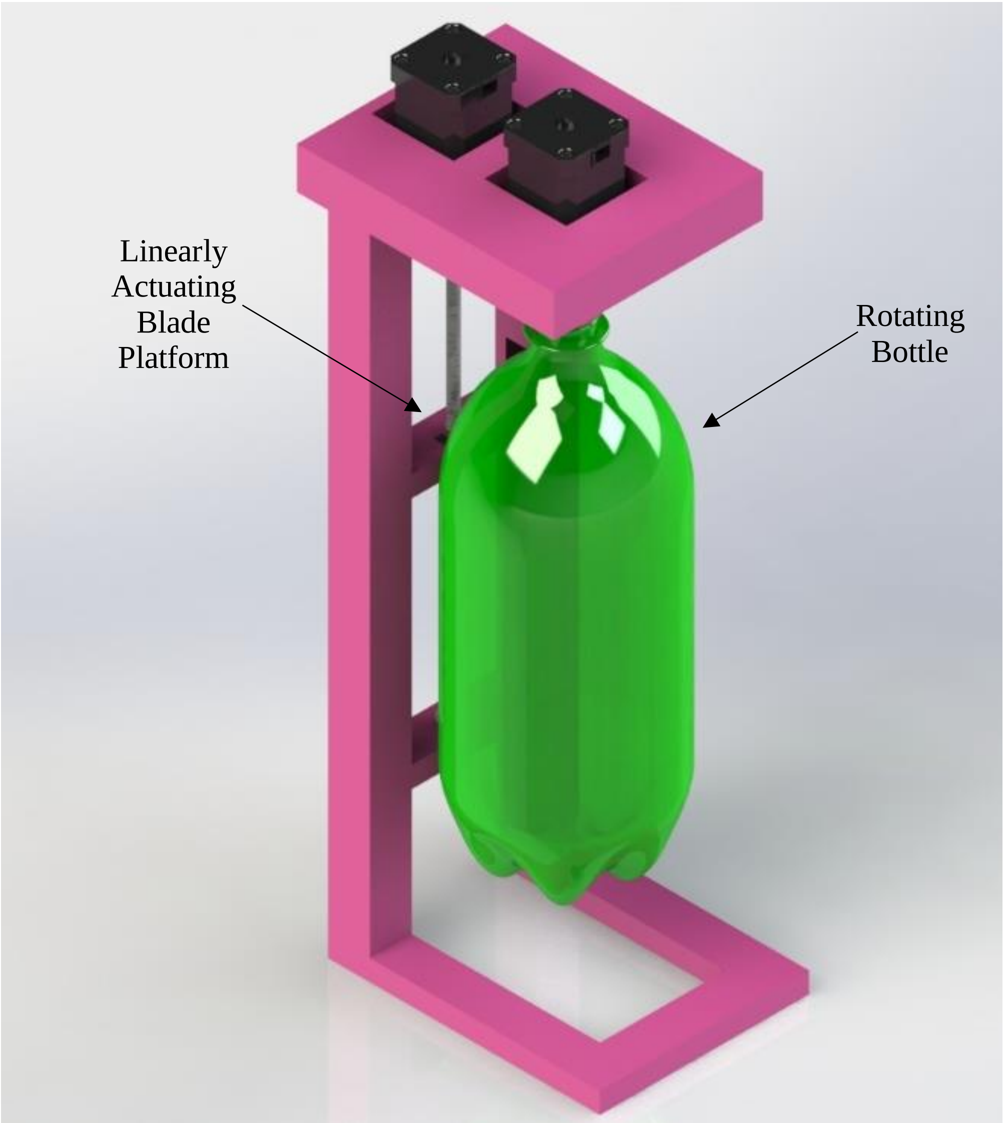

Figure 18: Bottle Cutting Design Concept Three

Down Selection Process of Bottle Cutting Design

The down selection process for the three design concepts was done using the same procedure as the automation step down selection process. The Analytical Hierarchy Process (AHP), from *Engineering Design* [12], was employed to generate normalized weights for each criterion. Then a weighted down selection matrix was created to compare the three concepts using the normalized weights. The down selection matrix is shown in Table 6. The criteria used in the AHP are similar to the ones used in the automation step down selection, however, criteria that were not relevant to the bottle cutting process were excluded.

Table 6: Down Selection Matrix for Three Design Concepts

		Design Concepts		
Selection Criteria	**Weights**	**Design Concept 1**	**Design Concept 2**	**Design Concept 3**
Impact on Duration of Process	0.262	4	3	3
Cost	0.147	4	4	4
Size	0.047	5	5	5
Power Requirement	0.091	5	5	5
Manufacturability	0.095	4	3	3
Human Interaction Needed	0.262	2	5	4
Probability of Injury	0.095	4	2	2
NET SCORE		3.61	3.85	3.59
RANKED		2nd	1st	3rd

The "Impact on Duration of Process" criteria ranks how much a concept affects the overall duration of upcycling the two-liter bottles into 3D printer filament. As the production time of the 3D printer filament decreases, its production cost also decreases. Since the major goal of this design is to automate this process to make the filament more economical, this criterion ranked highest alongside the "Human Interaction Needed" criterion. This is because the more a person needs to interact with a process, the less the process can run on its own. Therefore, increasing the labor costs of 3D printer filament production. Since the design is provided a budget of $1000, the "Cost" criterion is ranked second highest. For the scale of this project, $1000 is a sufficient budget, however, to maximize the effectiveness of the design, the cost of each concept is weighted heavier than other criteria.

The "Manufacturability" criterion is ranked the same since this characteristic of the design affects the overall cost of the design. The "Probability of Injury" criteria was also given the same ranking. The ability of the design to reduce the risk of injury for a user can reduce the liability taken on by Green Ellipses.

The “Power Requirement” criterion was given a lower ranking. The design is constrained to run on standard wall power(120Vac/60hz). This is so hobbyists who are interested in creating their own 3D printer filament can run this machine in their own homes. Since the power requirements of the original design are well below what is supplied from standard wall power, the power requirement of the automation design concept is not a major element in the decision-making process. The “Size” criterion was ranked lowest. The size requirement given by the sponsor is that the design must fit in a 75cm by 240cm area. The current design takes up 60cm by 45cm, therefore, there is abundant room for the automation component.

The second design concept was ranked the highest with a score of 3.85. The first design concept followed with a score of 3.61 and the third design concept ranked last with a score of 3.59. The main reason the second design concept scored the best is because it ranked highest in the “Human Interaction needed” and “Impact on the Duration of Process” criteria. These criteria are weighted the heaviest based on their impact on meeting the design requirements. Design calculations were then performed on a component level to determine the specifics of the design.

Design Calculations

Power Screw Torque to Raise and Lower the Bottle

A linear actuator, primarily consisting of an ACME thread lead screw, stepper motor, and a flange nut, were used to move the bottle along the Z-axis. The torque required from the stepper motor to raise and lower the bottle was calculated to determine the torque specifications for the motor. Equations 1 and 2 are used to perform this calculation (*Shigley's Mechanical Engineering Design*, [13]). The equations used are shown below, where F is the weight of the load lifted, $\boldsymbol{d_m}$ is the mean diameter of the M8x2 lead screw, *l* is the height change per revolution of the lead screw, *f* is the coefficient of static friction between the lead screw and the collar, and $\boldsymbol{\alpha}$ is the angle of taper for the ACME lead screw threads.

$$\boldsymbol{T_R = \frac{Fd_m}{2}\left(\frac{l+\pi f d_m \sec\alpha}{\pi d_m - f l \sec\alpha}\right)} \tag{1}$$

$$\boldsymbol{T_L = \frac{Fd_m}{2}\left(\frac{\pi f d_m \sec\alpha - l}{\pi d_m + f l \sec\alpha}\right)} \tag{2}$$

These equations were derived from the free-body diagram of an ACME lead screw raising and lowering a load. ACME threads are tapered threads that have superior strength and durability compared to square threads. In order to perform the calculations, it was assumed that the force from the load lifted is uniform across the threads. The results from the calculations are shown in Table 7, while complete calculations are shown in Appendix A.

Table 7: Torque to Raise and Lower Bottle

Result	**Torque(N-mm)**
Torque to Raise (T_R)	31.01
Torque to Lower (T_L)	20.06

Calculation for Self-Locking ACME Threads

Since ACME threads are used for the lead screw, a calculation to determine if the threads will self-lock when the stepper motor is not applying torque is required. The equation used to perform this calculation (*Shigley's Mechanical Engineering Design*, [13]) is shown below:

Threads are self-locking if:

$$\boldsymbol{f > \tan\lambda} \quad \textbf{(3)}$$

$$\boldsymbol{\tan\lambda = \frac{L}{\pi d_m}} \quad \textbf{(4)}$$

These equations compare the coefficient of dynamic friction (f) between the Stainless-Steel threads and the Brass collar to the height increased per revolution ($\tan\lambda$) [14]. The dynamic friction was used for this calculation since it is lower than static friction. Therefore, the calculation will give a more conservative result when determining if the friction is greater than the force pulling the lifted load down.

The values calculated for both f and $\tan\lambda$ are shown in Table 8. Since $\tan\lambda$ is less than the coefficient of dynamic friction, the ACME threads are self-locking. The complete calculations are shown in Appendix A.

Table 8: Results from ACME Thread Self-locking Calculation

Parameter	**Value**
Coefficient of dynamic friction (*f*)	0.44
Height increased per revolution ($\tan\lambda$)	0.09

Torque Required to Cut the Bottle

The torque to cut the bottle with a blade is required to determine the torque specification for the stepper motor. For this calculation, cutting the bottle was treated as a shear failure between the blade and the bottle. The shear area was assumed to be the thickness of the bottle times the blade tip and the blade shank. This area is shown in the complete calculation in Appendix A. The basic equations used for the calculation are:

$$\boldsymbol{F = A \times \sigma_{shear}} \quad \textbf{(5)}$$

$$\boldsymbol{Torque = F \times r_{bottle}} \quad \textbf{(6)}$$

Where σ_{shear} is the shear strength of PET plastic and r_{bottle} is the radius of the two-liter bottle. The shear strength of PET is 55.16 MPa [15]. The results from the calculations are shown in Table 9. Based on the torque required to cut the bottle, the NEMA 23 stepper motor was chosen. This decision is discussed further in the Proposed Design section.

Table 9: Torque to Cut a Two-Liter Bottle

Parameter	**Result**
Shear Force	16.2 N
Torque	888.9 N-mm

Moment Calculation for NEMA 23 Platform

A NEMA 23 was previously determined to be used to rotate the PET bottle around the Z-axis as the bottom of the bottle is cut off. Located 101.6 mm away from the lead screw and aluminum rods, the weight of the motor will exert a downward force creating a moment where the rods and platform connect. A schematic and a free-body diagram of this are shown in Figure 19 and Figure 20. The rod and platform are assumed to be rigid bodies. Furthermore, the platform is assumed to be a weightless beam. The equation used to calculate this moment is derived from Static Equilibrium [16] and is as follows:

$$\boldsymbol{M} = \boldsymbol{F} \times \boldsymbol{d} \quad \textbf{(7)}$$

where,

$$\boldsymbol{F} = \boldsymbol{m} \times \boldsymbol{g} \quad \textbf{(8)}$$

Here, M is the moment around where the rod and platform connect. F is the downward force created from the mass of the motor, which was found to be 680 grams [17], multiplied by gravity. And d is the distance from the rod to the center of the motor. The resulting moment was calculated to be 677.67 N-mm. in the clockwise direction. The handwritten calculation is in Appendix A.

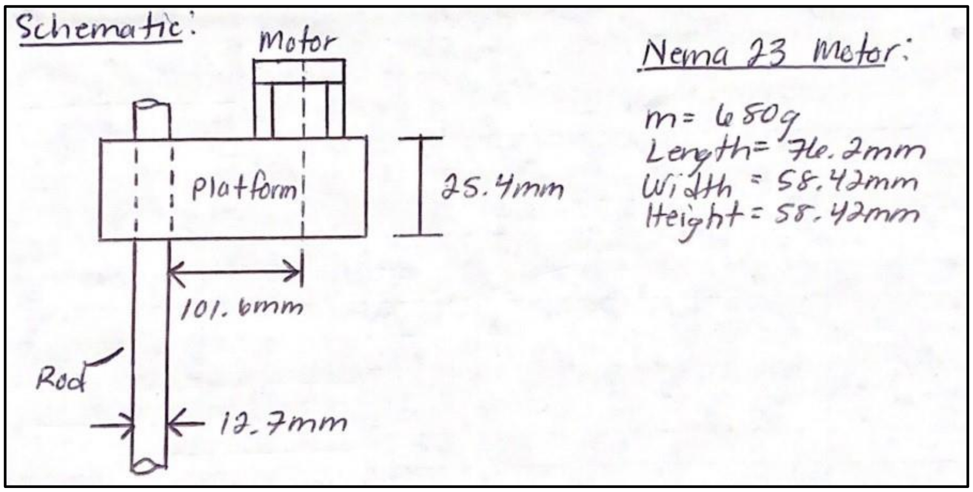

Figure 19: Schematic of NEMA 17 Motor Platform

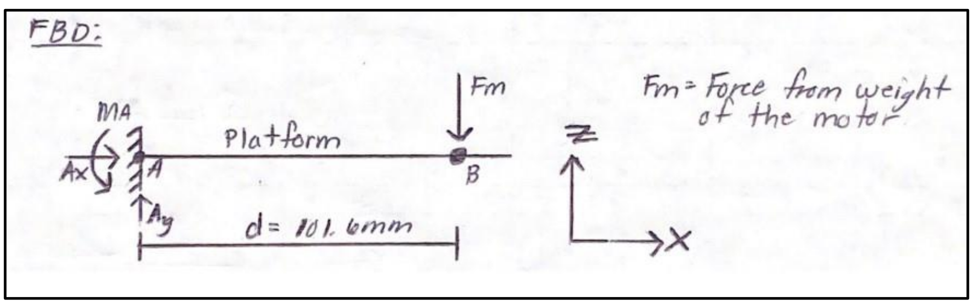

Figure 20: Free-Body Diagram for the Moment of Platform

Puncture Force

The cutting device shown in Figure 21, consisting of a linear solenoid and a blade, is used to puncture, and cut a two-liter bottle. The puncture force of this device is required to specify the necessary push force of the solenoid to ensure the bottle will be punctured. A free-body diagram of this is shown in Figure 22. Assuming 50 percent of the sharp edge of the blade punctures through the bottle and neglecting the friction between the blade and the bottle, while also neglecting the resistance force of the bottle wall, the following equation was derived [18]:

$$\boldsymbol{F} = \boldsymbol{P} \times \boldsymbol{t} \times \boldsymbol{\sigma_{shear}} \qquad \textbf{(9)}$$

Here, F is the puncture force required to pierce the bottle, P is the perimeter of the hole created from the dimensions of the blade [19], t is the wall thickness of the bottle [20], and σ_{shear} is the shear strength of the PET material [15]. The result from the calculations provided a puncture force of 9.83 N, therefore, the push force of the linear solenoid is required to be higher than 9.83 N. The handwritten calculation of this is in Appendix A.

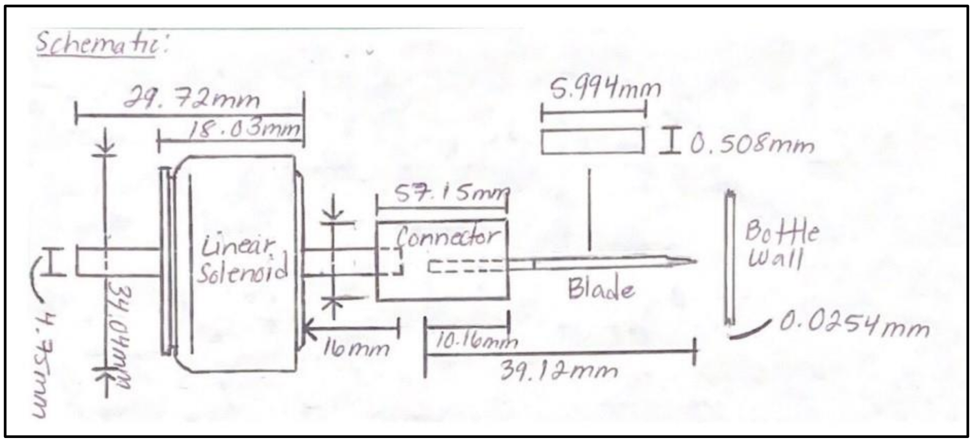

Figure 21: Schematic of Cutting Device

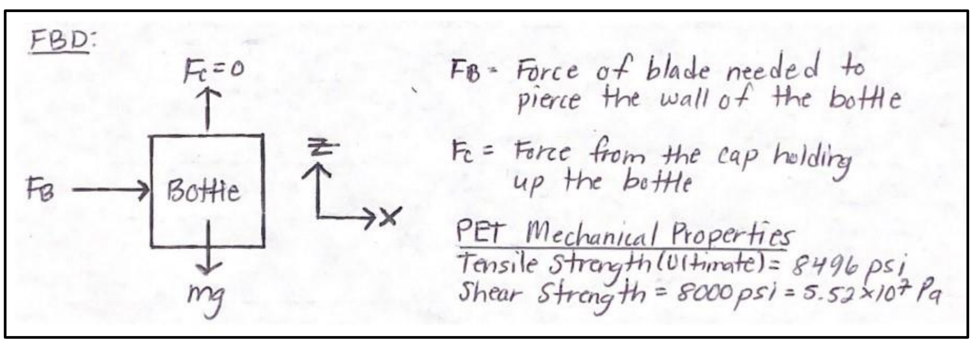

Figure 22: Free-Body Diagram for Puncture Force

Power Supply Calculations

The PET upcycler's motors based on the previous calculations are NEMA 17 and NEMA 23. Driving these stepper motors will be a Creality's Ender 3 mainboard. This Maximum Power Consumption of the mainboard is 277 Watts with an average draw of 125 Watts [21]. Using a 400-watt power supply will be more than enough to power the main board.

$$\boldsymbol{Power = Voltage \times Current} \quad \textbf{(10)}$$

All peripherals will be driven through the main board which is supplied by the 400-watt power supply and can deliver a maximum of 16.66 amps of peak current. Given a max power draw of 277 watts and an average draw of 125 watts, the provided power supply will provide adequate power to the device.

Another consideration is the linear solenoid which has a max power draw of twenty-one watts. As shown in Appendix B, the push-pull solenoid will be connected via the designated heated bed port. The heated bed normally draws power in two states, ramping up temperature and maintaining temperature. The maximum power draw when ramping up is 142 watts and is the most power intensive part of the printer. In the maintain temperature operation, it draws approximately 9 watts [22]. With this arrangement, the solenoid will have an adequate power supply from the heated bed port.

Final Proposed Design
Device Layout

A comprehensive CAD drawing that displays the final device, an exploded view, and a parts list is shown in Appendix C. Figure 23 shows an isometric view of the CAD model, which details the physical layout of the device. All components shown in pink represent 3D printed structures. Each of these 3D printed parts have detailed manufacturing drawings shown in Appendix C.

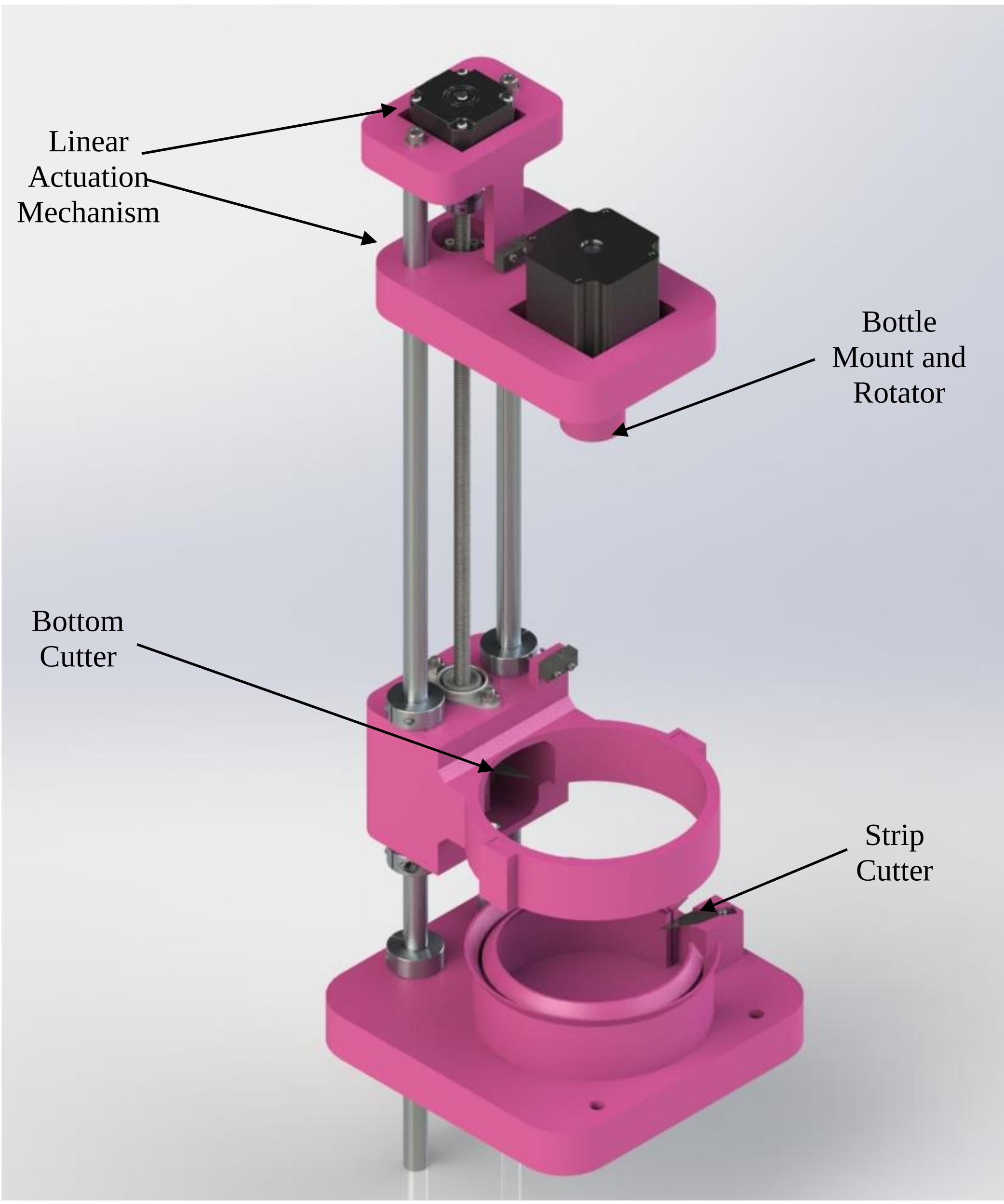

Figure 23: Rendering of the Final Design Layout

Device Operation

The final design will automate the bottle cutting process through a series of steps. There are four major steps to the final design: user setup, bottom cutting, linear actuation, and strip cutting. These steps are critical to the final design and will therefore be explained more in depth below.

User Setup

The first step in this process involves a small amount of user setup before automation can begin. Figure 24 shows the current iteration of the HMI for the upcycler. In this configuration a home button is not displayed. After powering on the device and before starting the PET upcycler, the device must return to the starting position. After pressing home on the LCD, the Z-axis motor relocates to the zero point as defined in the program. The platform will translate upwards until it actuates the Z-limit switch, indicating that that platform has successfully moved to the desired location.

Next, the user will need to remove the middle bottle clamp which is used to help keep the rigidity of the bottle as it is punctured and cut. The middle clamp is held together with a dovetail design, which can be seen in detail in Appendix C. Next, the user must twist the bottle into the custom cap. This custom cap allows for the connected NEMA 23 motor to turn the bottle while holding it in place. Once the user does this, the middle clamp can be placed back where it was removed to secure the middle of the bottle. This is the end of the required user interaction with the device.

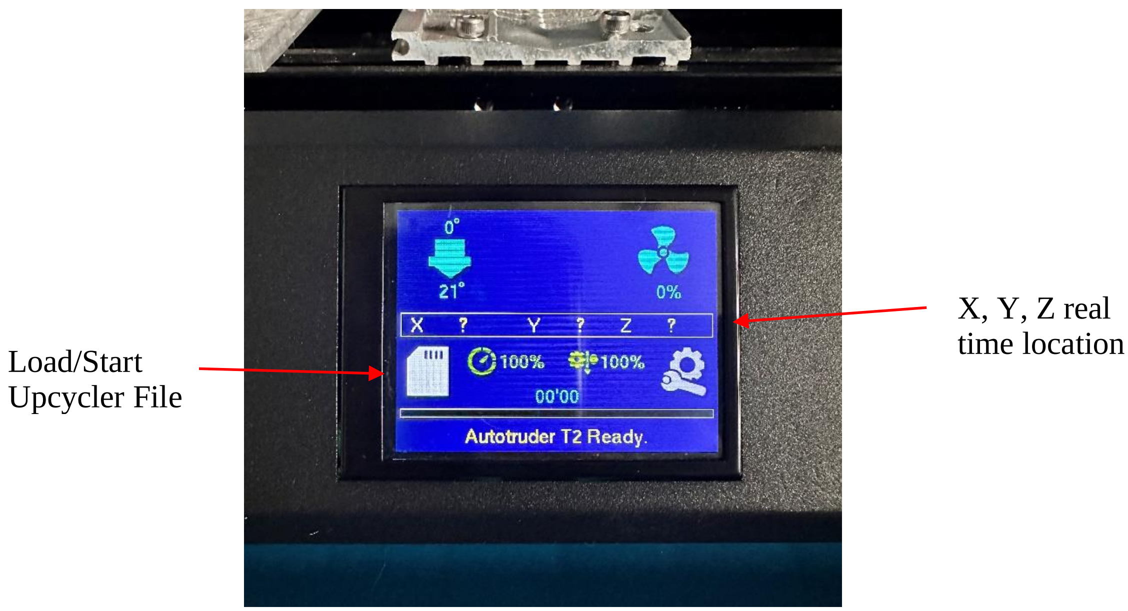

Figure 24: Current Human Machine Interface (Home Button not Displayed)

Bottom Cutting

The automation begins at this step once the user starts the device. First, the linear solenoid actuator becomes energized and pushes the blade into the side of the bottle near the bottom as shown in Figure 25. The linear solenoid was selected as the best way to puncture the bottle as the puncture force is relatively low at 9.83 N. Also, a linear solenoid was selected because the blade must be guarded for safety reasons when not in use. When the linear solenoid is not receiving power, the blade will be guarded from the user.

Once the bottle is punctured, the NEMA 23 motor begins to rotate the bottle counterclockwise. This rotation direction keeps the bottle tight on the custom cap while the bottle sees a reaction force from the blade. A NEMA 23 motor was found to be necessary, as the required torque to cut the bottle was calculated at 888.9 N-mm. The selected NEMA 23 motor is rated at 1220.24 N-mm, giving a safety factor of 1.37. Once the device is built, testing will be done to determine the number of bottles that can be cut before the blade becomes too dull. Depending on the outcome, a higher torque motor, or a small gear system may be required. Moving on, as the bottle does a full rotation, the blade cuts through the bottle and the bottom falls off. Finally, the solenoid gets de-energized, and the blade retracts back out of the way of the bottle.

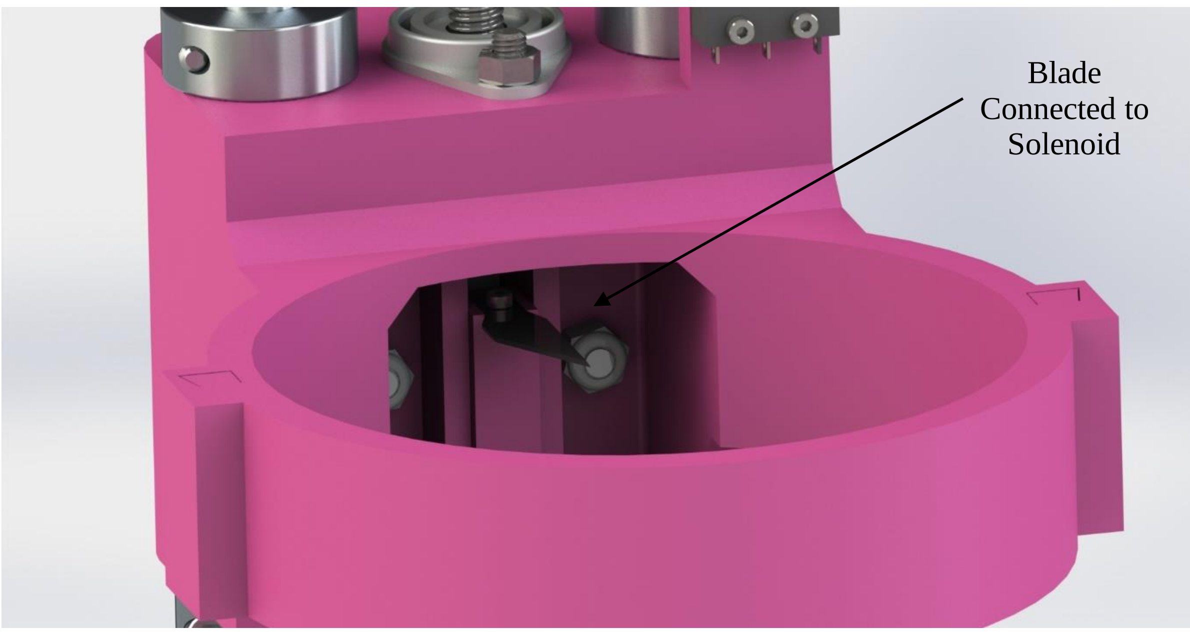

Figure 25: CAD Rendering of Bottom Cutting Assembly

Linear Actuation

After the bottom of the bottle is cut off, the bottle moves in the negative Z-direction toward the strip cutter. The system used to maneuver the bottle along the Z-axis consists of a lead screw linear actuating mechanism driven by a stepper motor. Based on the calculated torque required to raise and lower the bottle, a NEMA 17 stepper motor is sufficient. The NEMA 17 motor outputs a holding torque of 0.23 N-m. [23]. Figure 26 shows the stepper motor connected to the lead screw. The parts are connected using a size-down coupler between the stepper motor shaft and the lead screw. This was done because the stepper motor shaft has a diameter of five millimeters, and the lead screw has a diameter of eight millimeters.

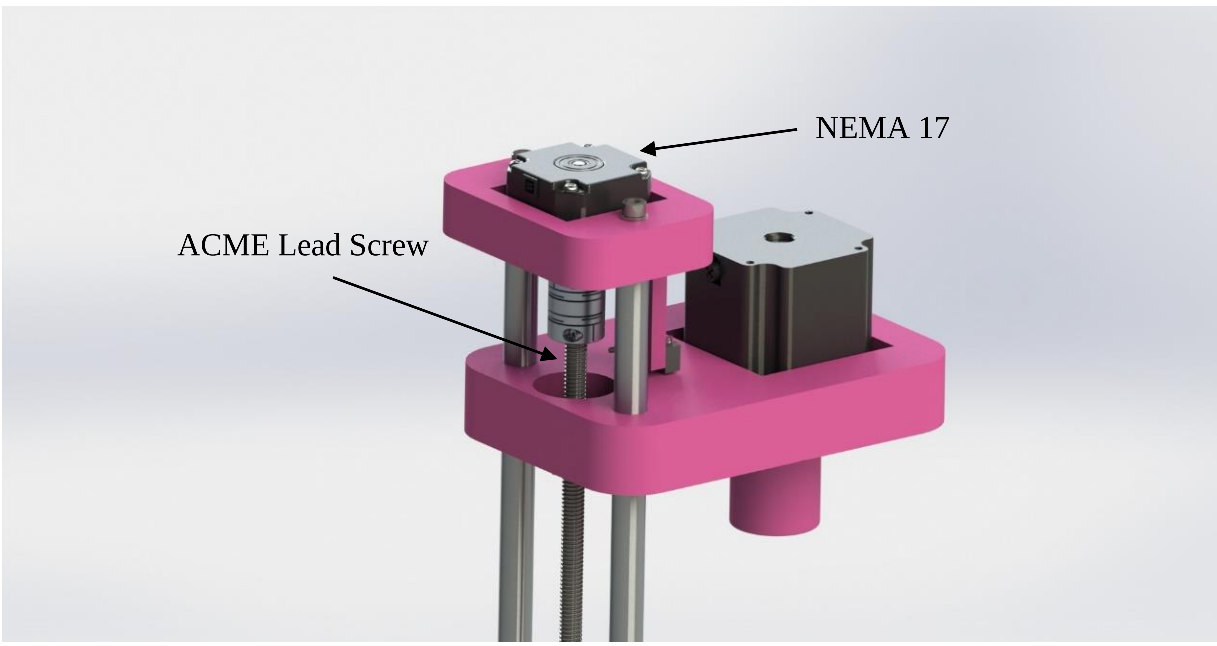

Figure 26: Rendering of Final Linear Actuator Design

ACME threads were chosen for the lead screw because of their self-locking ability at efficiencies lower than 35% [24]. The efficiency of a lead screw is how well the lead screw converts torque into linear motion [24]. It was calculated that, for the parameters of this design, the lead screw is self-locking. This is beneficial because a separate braking system is not needed for the actuating mechanism. This simplifies the design and reduces the overall cost as no additional parts are needed. A lead screw collar was used to transfer the motion from the lead screw to the bottle. Figure 26 shows the collar attached to the bracket holding the bottle.

Strip Cutting

The bottle becomes surrounded by 3D printed guide tracks as it is lowered. These guide tracks are shown in Figure 27. These guide tracks assist the bottle in keeping its form when the strip is cut. The bottle reaches a horizontal blade that is encased in the tracks as it lowers. Once the bottle reaches the blade, the bottle begins to rotate again. Testing will be required to figure out the exact combination of linear actuation and rotation speed in order to get a strip width of eight millimeters.

From here, there will be two different operations that will be programmed. The first lets the device run until the bottom limit switch is triggered, which the strip can then be fed into the subsequent processes. The second involves the device stopping halfway, where the user then feeds the strip into the subsequent process. From here, the device would restart, and it would cut the strip while the other end gets spooled on Green Ellipsis' current device.

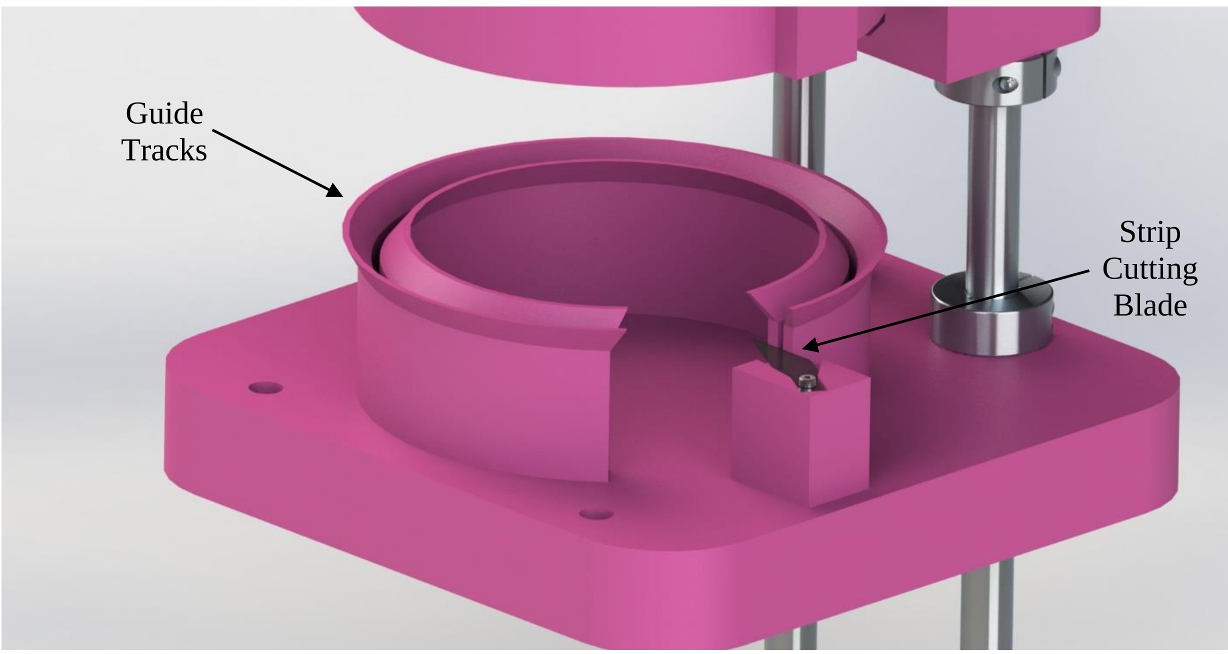

Figure 27: CAD Rendering of Strip Cutting Assembly

Operational Flow

The operational flow chart for this final design is shown in Figure 28 below. This flow chart details the interaction between the user and the device. Also detailed is the operation of the device after the user has initiated the bottle cutting automation process. Green blocks indicate operator interaction, while blue blocks indicate automated operation.

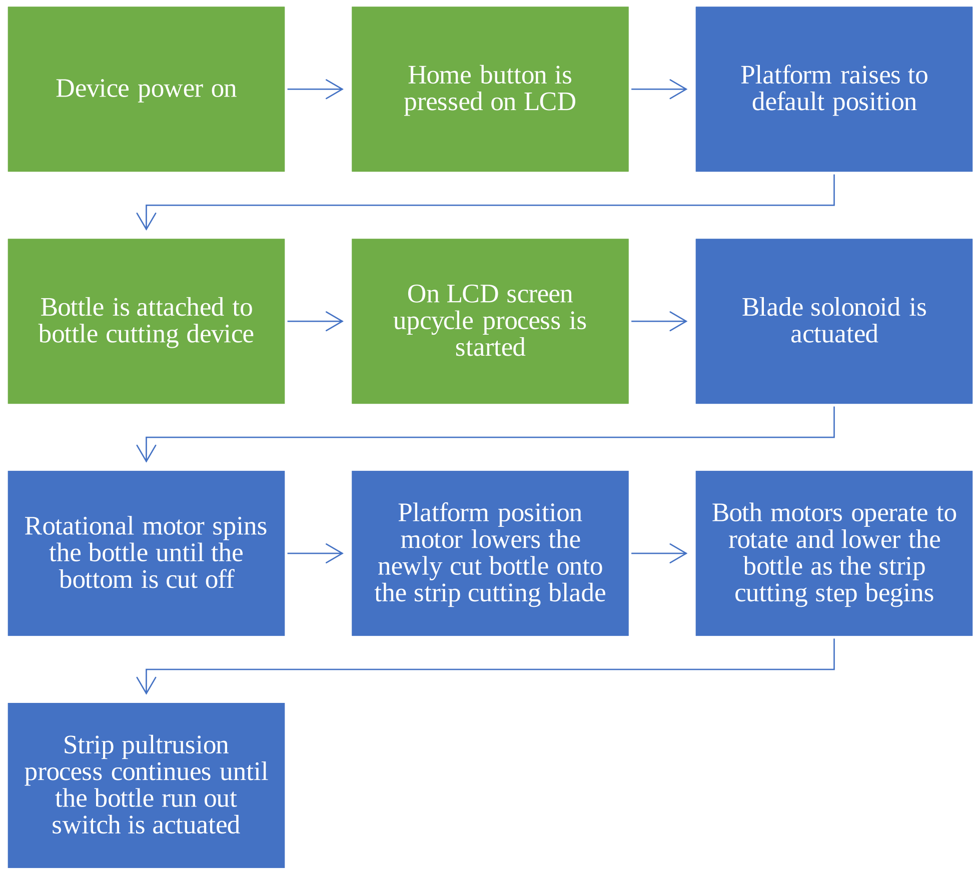

Figure 28: Operation Flow Chart for Typical User Input and Normal System Operation

Manufacturing

There are seven distinct parts that must be manufactured for this design. All these parts will be 3D printed using PLA filament that was supplied by Green Ellipsis. PLA was chosen to be the primary manufacturing material based on the following reasons. Unlike the pultrusion section which must be heat resistant, the bottle cutting section will not experience extreme temperatures. Therefore, PLA plastic can be used. In addition, PLA possesses a well-balanced mix of strength and affordability. As a renewable polymer, PLA is a practical choice for rapid prototyping [25]. Other materials have improved qualities in strength, heat resistance, or shear strength; however, this improved quality comes with additional costs. The CAD Manufacturing drawings for these parts are in Appendix C.

System Block Diagram

Figure 29 below shows the block system diagram for the PET upcycler. The schematic for this upcycler can be found in Appendix B. The main power is fed into an Ender 3 board. This board controls two main systems. The first system is the bottle cutting system. This takes one two-liter bottle and automatically cuts the bottom off, then cuts the plastic strip needed for the pultrusion process. In addition to software stops, the bottle cutting system utilizes two limit switches. First, the lead limit screw limit switch communicates to the device where it is in relation to the Z-axis to prevent damage to the machine. The second limit switch is the bottle runout switch, which signals the machine to stop the strip cutting step. This notifies the device that the usable portion of the bottle is depleted, and the process is to be terminated to prevent damage to the machine.

The other main system in the block diagram is the Recreator system. This system takes the already pultruded material, feeds it through a heated nozzle, and forms filament that gets rolled onto a spool. There are two operations for the bottle cutter operation. First, the bottle cutter can cut the entire bottle utilizing the pultruder. This ribboned bottle would then be fed into the pultruder at the discretion of the operator. The second method can run in conjunction with the pultrusion system. When fed into the pultruder, the bottle run-out switch would stop all operations including the pultrusion. This summarizes the current systems on the PET upcycler.

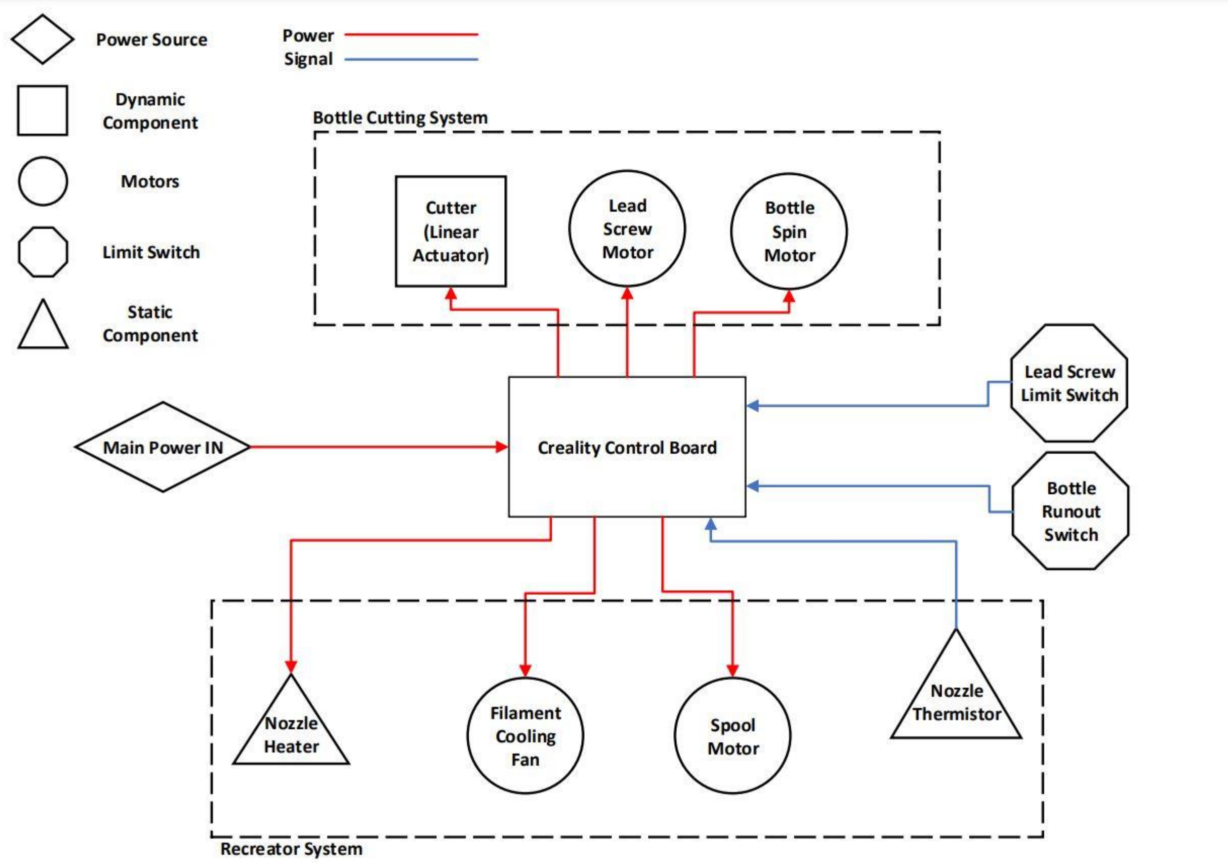

Figure 29: Block System Diagram with Grouped System Functionality

G-Code Software

The software used to code the movements of the motors will be Gcode. This utilizes a "G" or "M" prefix followed by an integer to operate the RepRap firmware [26]. Appendix B shows an example of the code utilized in the bottle cutter operation. G1 is linear movement on a specified axis. Three axes are utilized, with Z-axis corresponding to Z, Y-axis corresponding to the rotational axis of the bottle, and the E-axis being the rotation of the spool. Codes M190 actuates the linear solenoid to cut the bottle and M1 shuts off the solenoid. Commands M104, M105 and M109 set up the heating elements for the pultrusion process (which is already implemented for the entire Green Ellipsis upcycling system). M220 sets the speed for the pultrusion process. M8 and G92 starts the movement of the spool. The last command is M808, which is a for-loop-loop that will loop ten times. In practice, this tells the printer to extrude until the pultrusion process stops.

Scope of Work and Work Breakdown Structure
Fall 2022

Table 10 below shows the work breakdown structure for the development process of the upcycler automation. In addition, Figure 30 shows the Gantt chart, which better illustrates the exact timeline of the development process. There are eight overarching stages included in the development process, with each stage having sub tasks to be completed.

Team formation and problem definition scope is the preliminary process of defining the values, responsibilities, and problem statement of the project at hand. Concept selection follows the problem statement by brainstorming strong concepts to solving the problem and selecting the best ones according to the weighted down selectin chart and AHP chart. The report introduction is the start of the documented project proposal and includes the team formation, problem definition/scope, concept selections as well as any research done to understand the theoretical concepts proposed. Project planning defines the projected course of action for completing the needed tasks of the project by creating a work breakdown structure with Gantt charts and creating a preliminary budget.

The PET Upcycler Design phase is the process of performing initial calculations for the proposed design. This includes any calculations done to determine the material, power requirements, sizing, etc. From this, an initial prototype can be manufactured and tested. The Testing and Analysis phase goes over the iterative process of assessing the design, evaluating its performance, and implementing improvements until the design meets the requirements and constraints. Multiple tests are performed in this process including strength tests to ensure they can survive expected stresses, electrical testing to ensure all electrical components are operating correctly, and automation efficiency tests to evaluate how well the design automates the process. During the Final Design and Final Product phase, the final design and accompanying documentation is prepared for the final presentation.

Table 10: Work Breakdown Structure for Automation of PET Upcycler

Development Process	Time (Weeks)
1. Team Formation and Problem Definition/Scope	
1.1. Team Values Statement	1
1.2. Problem Statement Version 1	1
1.3. Weekly Planning Schedule	1
2. Concept Selection	
2.1. Brainstorming Session	1
2.2. Concept Research/Background Knowledge	1
2.3. Concept Down Selection	1
3. Report Introduction	
3.1. Brainstorming/Section Selection	1
3.2. Research of Background and Theoretical Concepts	1
3.3. Problem Statement Revision	1
3.4. Written Draft of Report Introduction	1
4. Project Planning	
4.1. Preliminary Work Breakdown Structure	1
4.2. Preliminary Budget	1
4.2.1. Cost Breakdown	1

5. PET Upcycler Design	
5.1. Design Review	2
5.2. Problem Statement Version 2	1
5.3. Configuration Requirements	1
5.4. Mid Semester Progress Presentation	2
5.5. Initial Material Selection	1
5.6. Initial 3D CAD Models	1
5.7. Initial Electrical Schematics	1
5.8. Critical Design Review Report with CAD, Schematics, Flowcharts, Final Work Breakdown Structure Report, Final Project Budget and Bill of Material	3
5.9. Version 3 of Problem Statement	1
5.10. Purchase Necessary Materials Required for Testing	1
6. Prototyping/Testing/Analysis of Mechanical/Electrical Components	
6.1. 3D-Print Components	1
6.2. Mechanical Testing	1
6.3. Electrical Testing	1
6.4. Automation Efficiency Testing	1
6.5. Brainstorming Improvements	1
6.6. Implementing Improvements	2
6.6.1. Update CAD Models	
6.6.2. Iterate Until Desired Outcomes Met	
7. Final Design	
7.1. Review Final Design	1
7.2. Final Design Proposals	16
7.3. Final Team Presentations	1
7.4. Reflective Writing Assignment	1
7.5. Final Team Presentations	2
7.6. Purchase Materials Required for Final Design	1
8. Final Product	
8.1. Plan the Construction of the Final Design	1
8.2. Manufacturing Necessary Parts	4
8.3. Assembling Mechanical Components	4
8.4. Assembling Electrical Components	4
8.5. Verify Final Design with Requirements and Constraints	1
8.6. Prepare and Showcase Final Product/Report	3

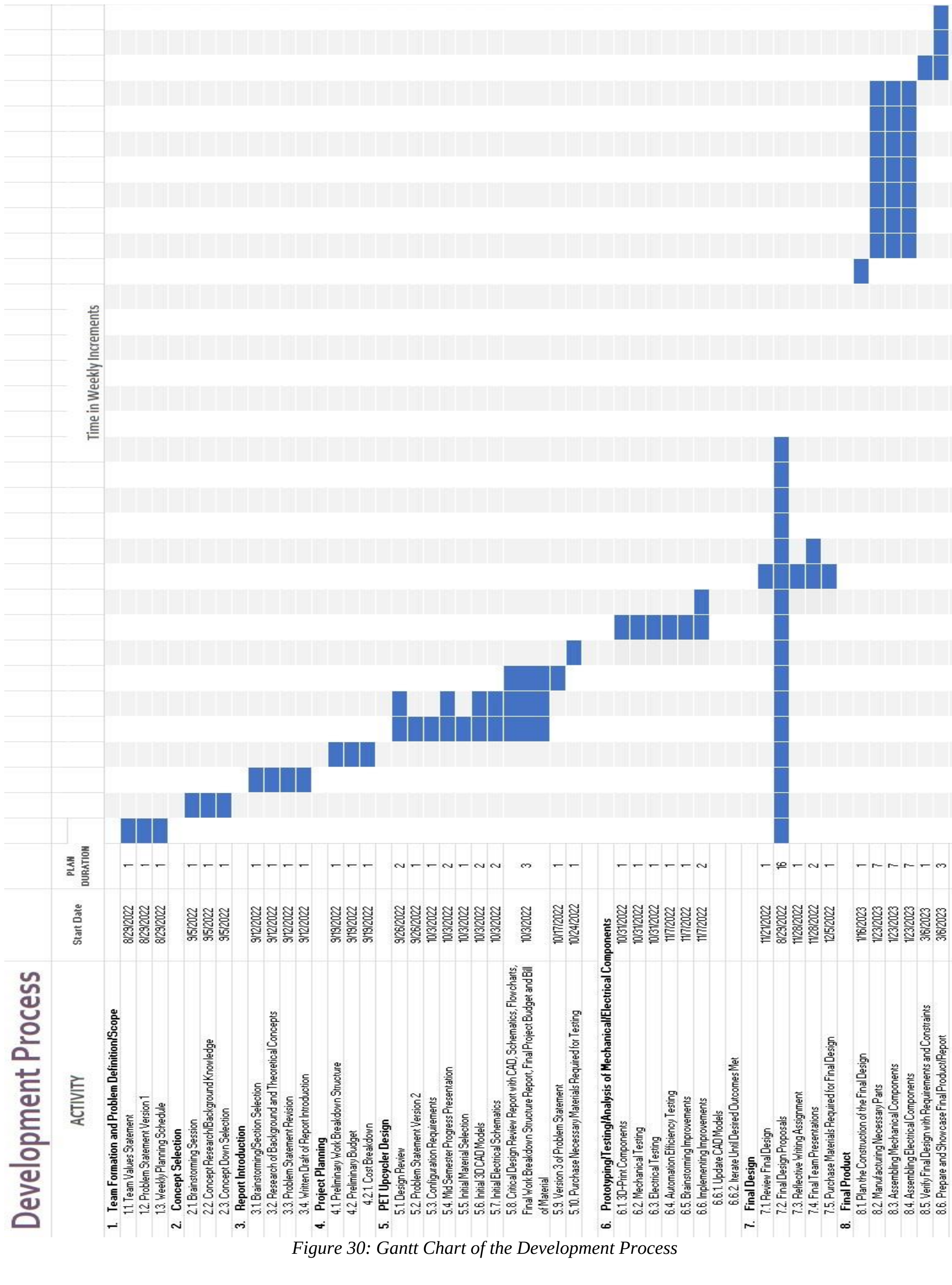

Figure 30: Gantt Chart of the Development Process

Project Budget and Bill of Materials

The overall budget constraint on the design project for Green Ellipsis is $1,000. The accumulated costs will come from the testing of initial designs and the construction of the final proposed design. The majority of the parts were sourced from Amazon based on guidance from Green Ellipsis. Current projections for the proposed design have an overall cost of $301.95. Table 11 shows the Bill of Materials below.

The PLA 3D printer filament provided by Green Ellipsis will be used to manufacture the seven components shown in Appendix C. Most of these components will be attached to the main structure of the bottle cutter device. Furthermore, the main structure includes aluminum rods and eight clamping shaft collars. Metric hardware is used to connect all the components together, as recommended by Green Ellipses. The hardware includes a kit of M2, M3, M4, and M5 screws, washers, and nuts.

The linear actuation system includes six components from the project budget. These components include the NEMA 17 motor, the lead screw, the flange nut, the mounted roller bearing, the shaft coupling, and the two plunger switches. The bottle cutting and stripping systems include the rest of the parts. These parts include the NEMA 23 motor, the two X-Acto blades, and the linear solenoid.

Table 11: Bill of Materials for Proposed Design

Item	Vendor	Part Number	UOM	Qty.	Price	Total Cost
Lead Screw with Flange Nut (8mm x 300mm) (2 Pack)	Amazon	B095MD8B9G	Pack	1	$10.99	$10.99
NEMA 23 Stepper Motor	Amazon	B00PNEPF5I	Unit	1	$25.99	$25.99
X-ACTO #11 (BladesX40)	Amazon	B00006ICJW	Pack	1	$16.99	$16.99
8mm Flange Bearing (4 Pack)	Amazon	B07C4Y7P2C	Pack	1	$8.99	$8.99
Linear Motion Rods (12mm x 600mm) (2 Pack)	Amazon	B08GS31NSB	Pack	1	$24.99	$24.99
Flexible Shaft Coupling (8mm to 5mm) (2 Pack)	Amazon	B07RMZCLZ3	Pack	1	$12.99	$12.99
Hex Socket Head Screw/Washer/Nut Set	Amazon	B07F75DMHF	Pack	1	$30.98	$30.98
3D Printer Filament	Green Ellipsis	N/A	Spool	2	$0	$0
NEMA 17 Stepper Motor	Green Ellipsis	N/A	Unit	1	$0	$0
12mm Clamping Collar	McMaster-Carr	6063K16	Unit	8	$9.90	$79.20
Plunger Switch	McMaster-Carr	7658K19	Unit	2	$4.88	$9.76
Linear Solenoid	Newark	20M1701	Unit	1	$81.07	$81.07
					Total Cost:	**$301.95**

Conclusion and Recommendations

The proposed design presents a solution to automate a laborious step in the pultrusion process. The current process has the user manually cut the bottom of the bottle off, start an initial strip via scissors, install the cut bottle into a shearing device, and pull it to the pultruder to cut the eight-millimeter width ribbon. With the proposed automation design for the bottle cutting process, user interaction, the number of tools used, and the time required for the process will be decreased. This design aims to reduce these parameters by creating a device that cuts off the bottom of the bottle, starts the strip, and cuts the eight-millimeter ribbon in one process.

The problem of how to cut the eight-millimeter ribbon surfaced during the design decision-making process. Two ideas were proposed. The first idea lowers the cut bottle onto the existing bearing shear device, which cuts the remainder of the bottle into the ribbon. The second idea lowers the cut bottle onto a blade that cuts the ribbon, as explained in the final design proposal. Both ideas have advantages and drawbacks that can only be confidentially explored and solved through testing. Therefore, this is a currently unsolved design issue.

The next steps in the design and manufacture processes have been established. Once the material ordering process is complete, the manufacturing of the 3D printed parts will begin. Each part will be printed using the PLA filament already provided by Green Ellipses. Construction and testing of the proposed design will begin after the 3D printed parts are manufactured and the materials have been delivered. Two forms of testing, functionality testing and effectiveness testing, will be completed. First, functionality testing will be completed to ensure the design works as intended. Then effectiveness testing will be done to assess how well the design meets the design requirements. Moreover, total duration, human interaction, and strip width will be evaluated during the effectiveness testing process. After the testing, design changes will be made and implemented into the final product.

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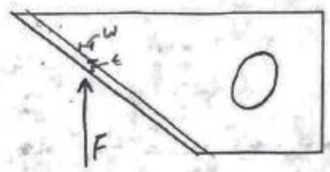
Appendices
Appendix A: Design Calculations
Torque to Cut Bottle

Torque to Cut Bottle | Christian Ventoures

Given: $\sigma_{shear} = 55.16\ MPa \Rightarrow$ (Poly-Tech Industrial) [2]
$w = 0.2mm,\ t = 1.465mm,\ r_{bottle} = 55mm$

Find: F_{shear} and T_{shear}



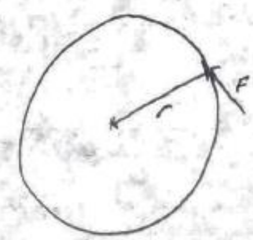
Solution:

$$F = \sigma_{shear} A$$

$$A = wt = (0.2mm)(1.465mm)$$
$$A = 0.293\ mm^2$$

$$F = (55.16\ MPa)(0.293\ mm^2)$$
$$\underline{F_{shear} = 16.162\ N}$$

Top-down of bottle



$$T_{shear} = F_{shear}(r_{bottle})$$

$$T_{shear} = (16.162\ N)(55mm)$$

$$\underline{T_{shear} = 888.9034\ Nmm}$$

Torque to Raise and Lower Lead Screw

Torque to raise/lower lead screw | Senior Design 1 | Christian Venturas

Given: M8 x 2 ACME lead Screw, $f = 0.51$ (static), $F = 13.5N$

[3]

Find: T_R, T_L

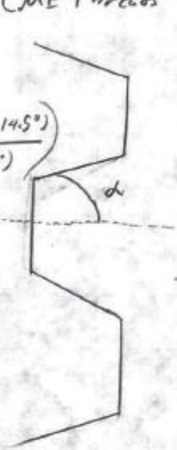
$\alpha = 14.5°$

$d_m = 7.101 mm$

$L = 2 mm$

Solution: Torque to raise

ACME threads



$$T_R = \frac{F d_m}{2}\left(\frac{L + \pi f d_m \sec(\alpha)}{\pi d_m - f L \sec(\alpha)}\right)$$

$$T_R = \frac{(13.5N)(7.101mm)}{2}\left(\frac{(2mm) + \pi(0.51)(7.101mm)\sec(14.5°)}{\pi(7.101mm) - (0.51)(2mm)\sec(14.5°)}\right)$$

$$T_R = 31.011\ Nmm$$

Torque to Lower

$$T_L = \frac{F d_m}{2}\left(\frac{\pi f d_m \sec(\alpha) - L}{\pi d_m + f L \sec(\alpha)}\right)$$

$$T_L = \frac{(13.5N)(7.101mm)}{2}\left(\frac{\pi(0.51)(7.101mm)\sec(14.5°) - (2mm)}{\pi(7.101mm) + (0.51)(2mm)\sec(14.5°)}\right)$$

$$T_L = 20.064\ Nmm$$

ACME Lead Screw Self-Locking Calculations

Selflocking Calculation | Senior Design 1 | Christian Ventouras

Given: $F = 0.44$ [1], M8 x 2 ACME leadscrew

$L = 2\,mm$
$d_m = 7.101\,mm$

Find: If leadscrew is self locking

Solution:

Lead screw is self locking if:

$$F > \tan(\lambda)$$

$$\tan(\lambda) = \frac{L}{\pi d_m}$$

$$\frac{L}{\pi d_m} = \frac{2\,mm}{\pi(7.101\,mm)} = 0.08965$$

Since,

$$0.44 > 0.08965$$

the ACME lead screw is self-locking.

Moment Calculation

Calculations:

$$\circlearrowleft^{+} M: M_A = (F_m)(d)$$

$$-F_m = mg = (680g)(9.81 m/s^2) = 6.67 N$$

$$\therefore M_A = (-6.67N)(101.6mm) \Rightarrow \boxed{M_A = -677.67 \ N \cdot mm}$$

- Since the moment calculated at A is negative, this means that the moment acts in the clockwise direction.

Puncture Force Calculation

Calculations:

$$F_B = (\text{Hole Perimeter})(\text{Material Thickness})(\text{Shear Strength})$$

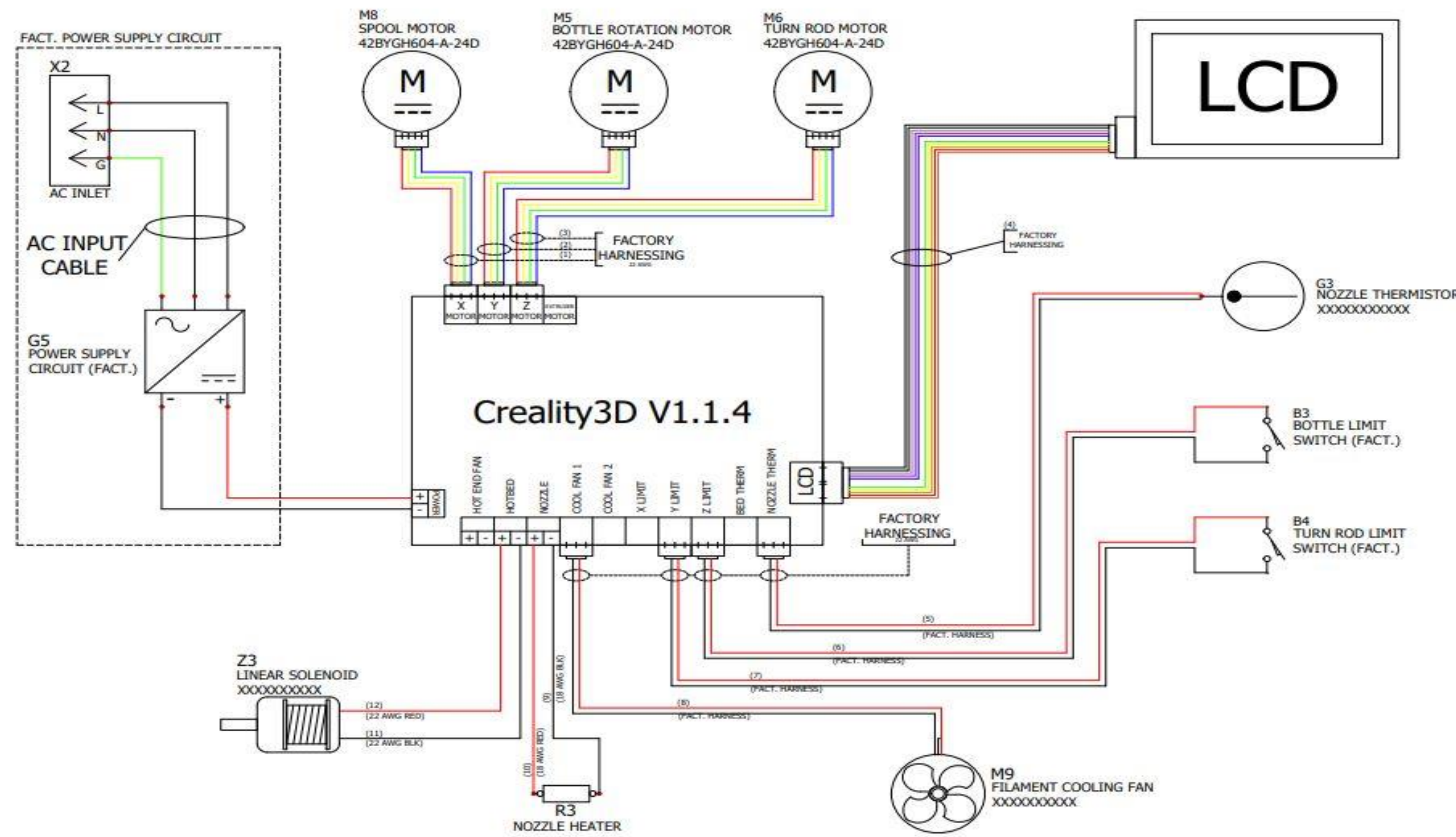
$$= [(0.508mm \times 2) + (2.997mm \times 2)](0.0254mm)(5.52 \times 10^7 Pa)$$

$$= (0.178 \cancel{mm^2})\left(\frac{1 \times 10^{-6} m^2}{1 \cancel{mm^2}}\right)(5.52 \times 10^7 Pa)$$

$$\longrightarrow \boxed{F_B = 9.826 \ N}$$

Appendix B: Electrical CAD and Code

Electrical System Schematic

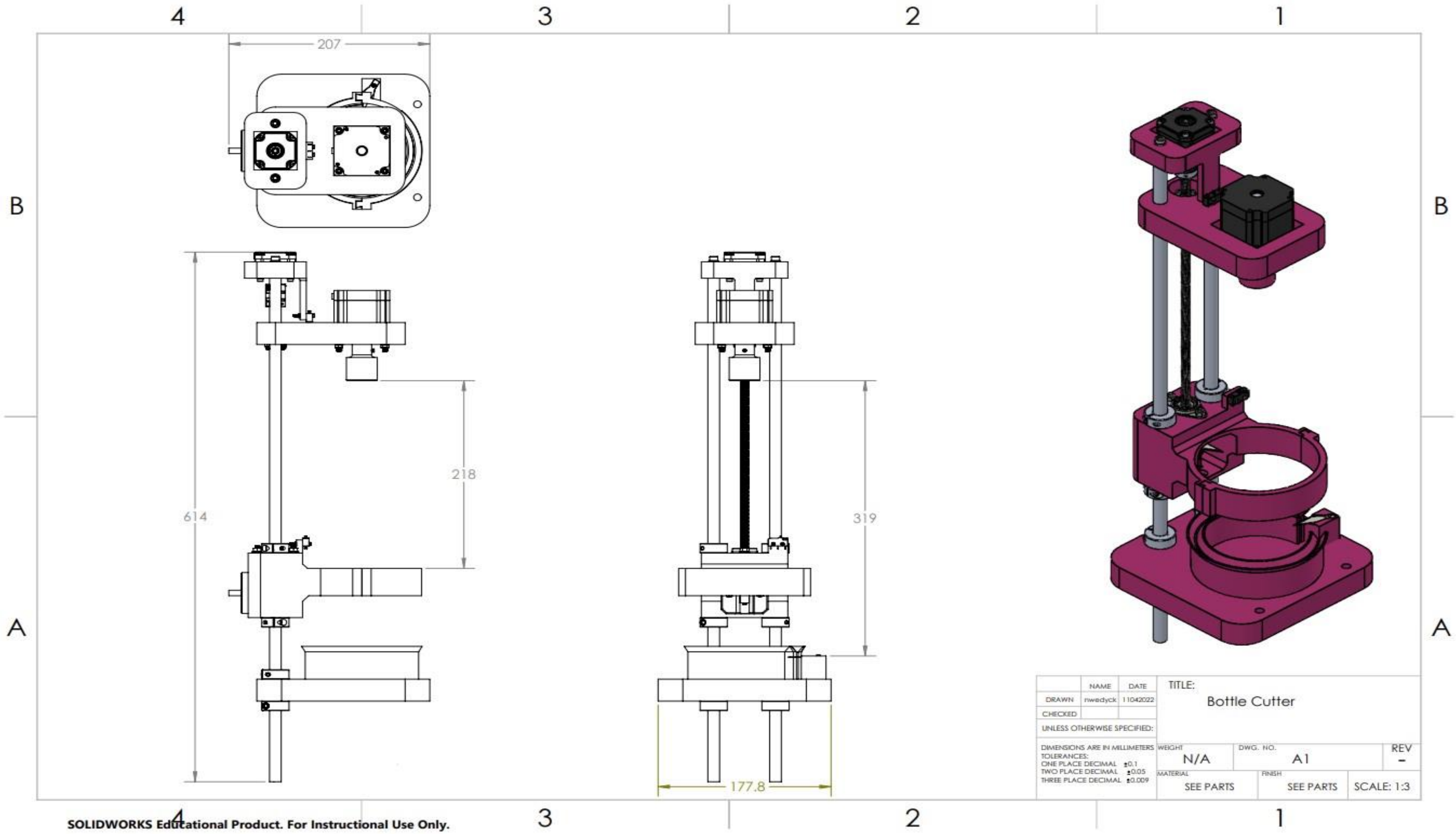


						REVISION
		0	11/1/2022	tony1		0
		REV.	DATE	NAME	CHANGES	SCHEME
CONTRACT:	LOCATION: L1 Main electrical closet	User data 1			User data 2	05

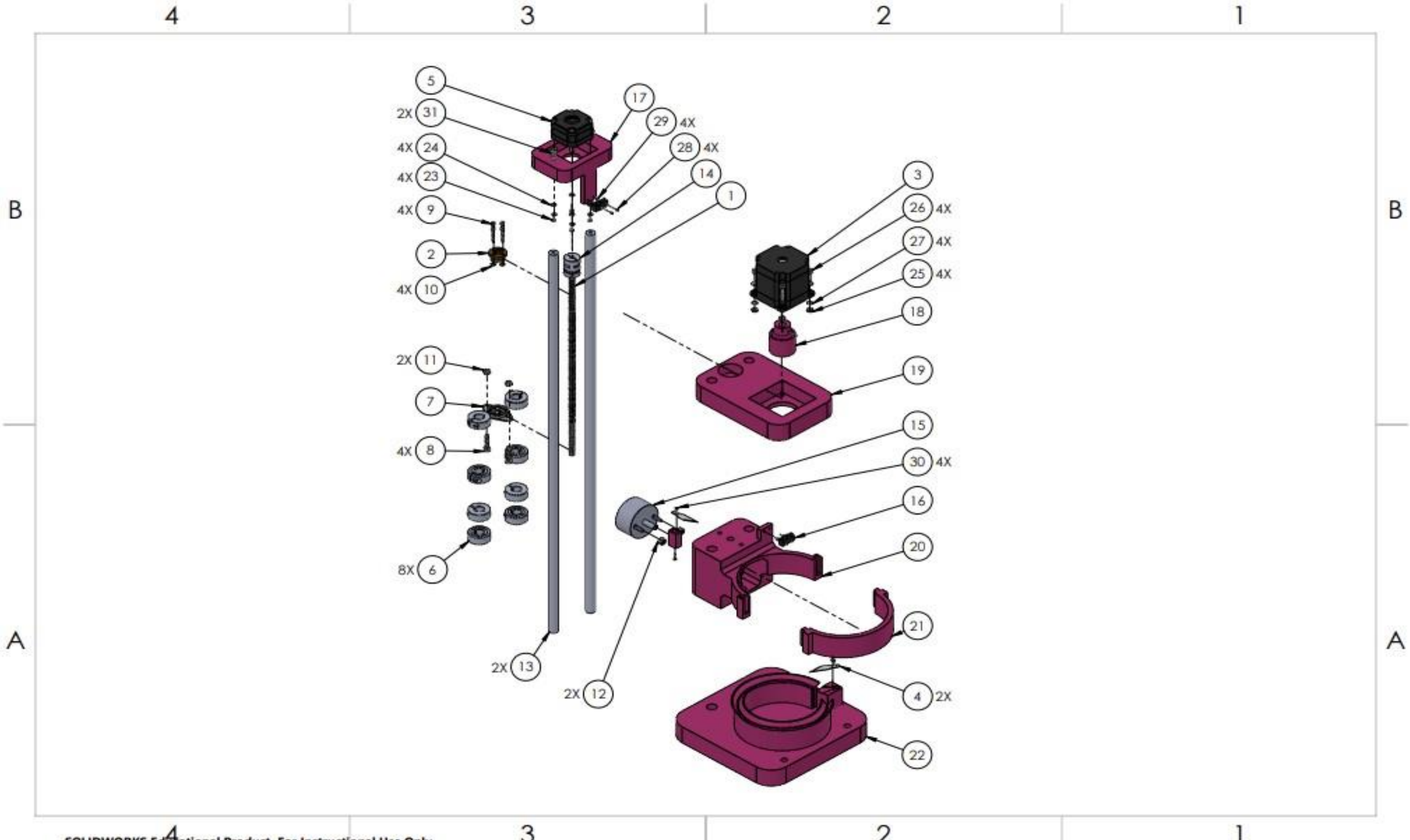
G-Code

```
;Print Profile for Recreator 3D
;Version 1


;home
G1 Z0
;Start bottle cutting process and strip cutting
M190
G1 Y200
M1 Bottle Cut complete, Press Okay to Continue
G1 Z150
G1 550

;Starting heating and pultrusion process
M104 S220 ; Set extruder temperature to 220 Celsuis
M105
M109 S220; Wait to get up to temp
M220

;Starting Pultrusion
M82
G92 E0
G1 F18000 E0
; loop to constantly extrude
M808 L10
G1 E500 F18000
M808
```

Appendix C: Mechanical CAD
Bottle Cutter



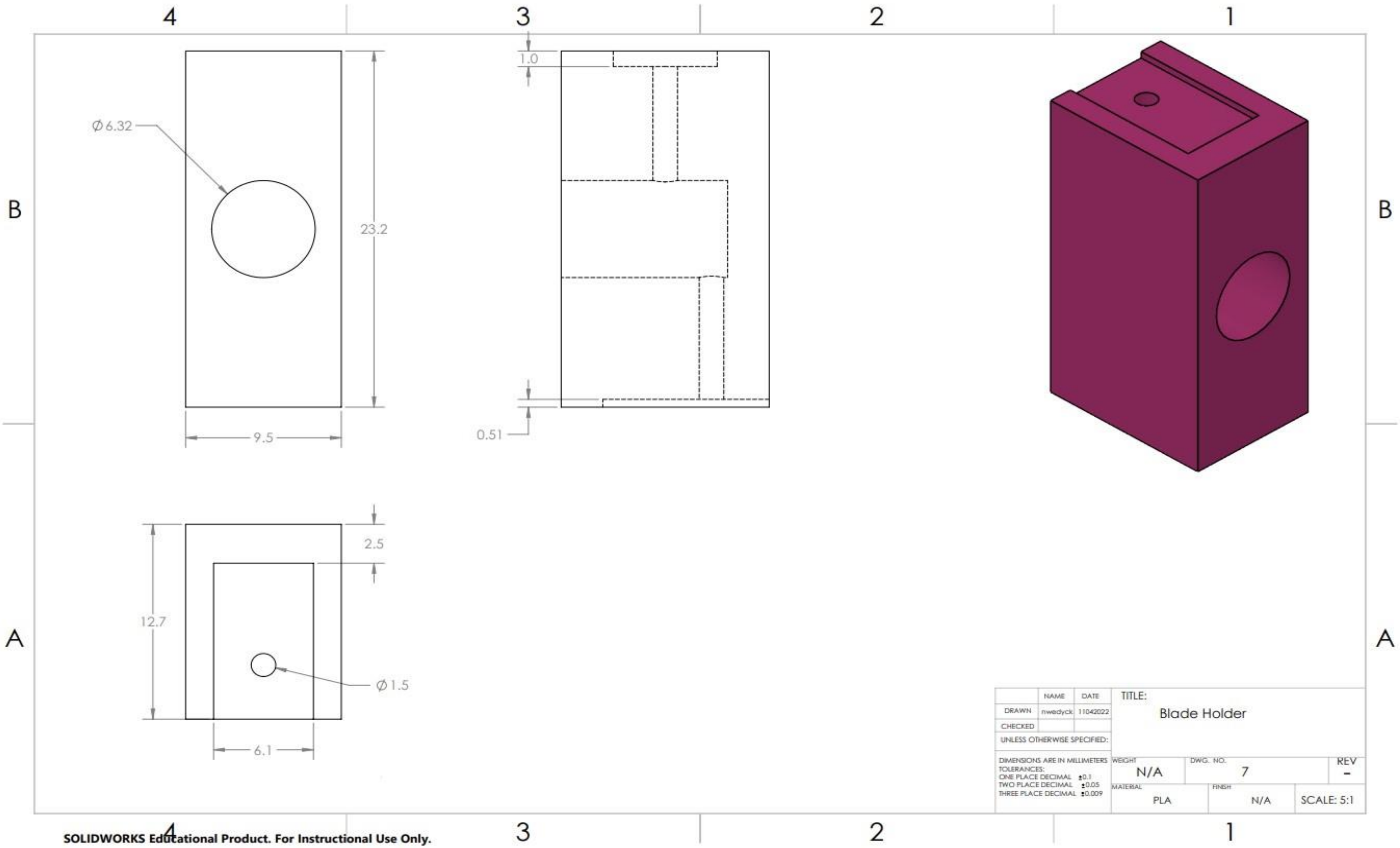
Exploded View



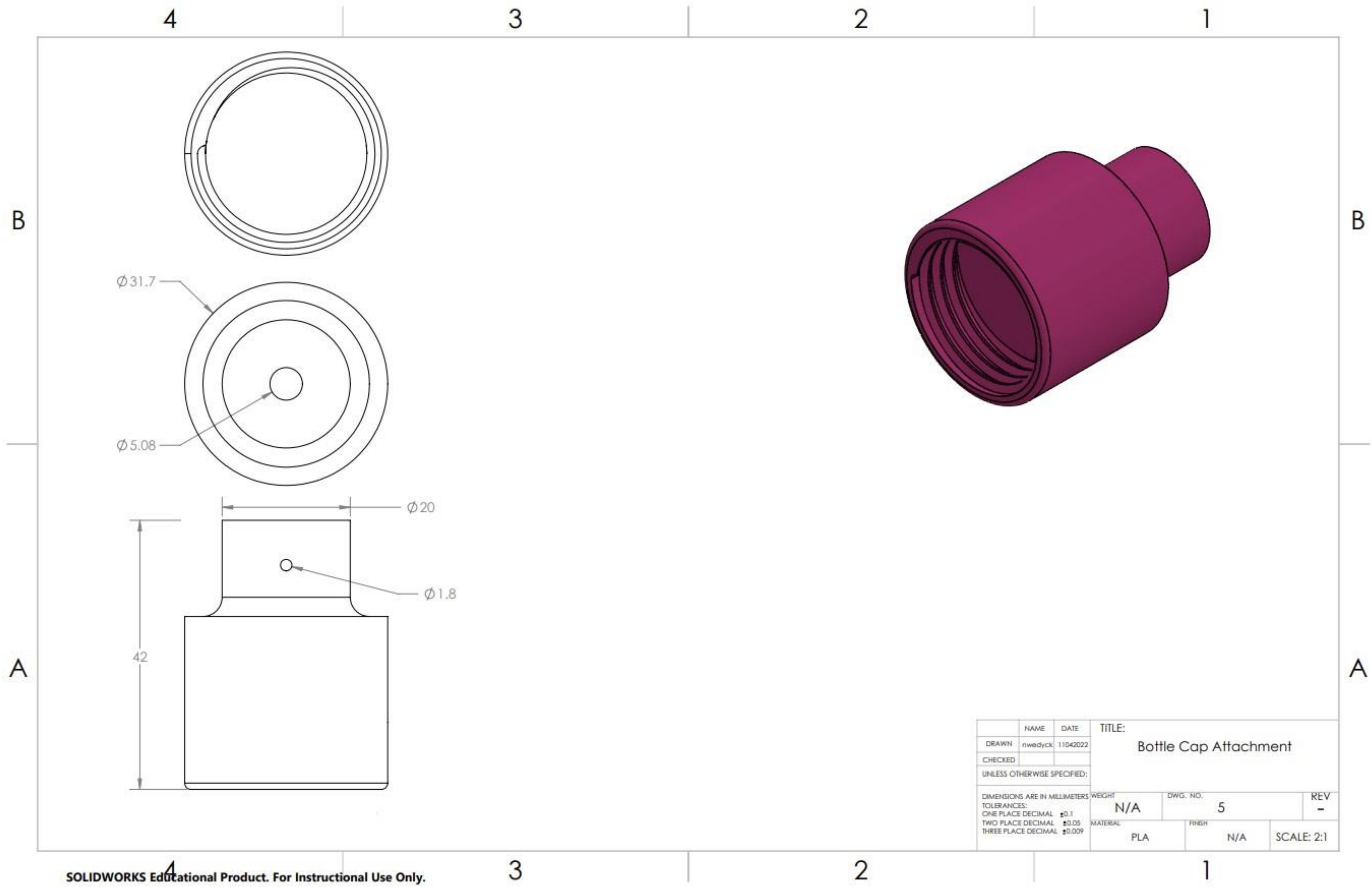
Parts List

#	Item	QTY
1	Lead Screw (8mm x 300mm)	1
2	Flange Nut for Lead Screw	1
3	NEMA 23 Stepper Motor	1
4	X-ACTO #11	2
5	NEMA 17 Stepper Motor	1
6	12mm Clamping Collar	8
7	8mm Flange Bearing	1
8	M5 SS Socket Screw 20mm Long	4
9	M3 SS Socket Screw 20mm Long	4
10	M3 Hex Nut	3
11	M5 Hex Nut	2
12	18-8 Stainless Steel Nylon-Insert Locknut 8-32 Thread Size	2
13	Linear Motion Rods (12mm x 600mm)	2
14	Flexible Shaft Coupling (8mm to 5mm)	1
15	Linear Solenoid, Push or Pull, Continuous, 28 VDC, 120.1 N, 38 ohm, 21 W	1
16	Subminiature Snap-Acting Switch Plunger Actuator, SPDT	2
17	Bottle Cutter Top (3D Printed)	1
18	Bottle Cap Attachment (3D Printed)	1
19	Bottle Cutter Mover (3D Printed)	1
20	Bottle Cutter Main Mid (3D Printed)	1
21	Bottle Cutter Secondary Mid (3D Printed)	1
22	Bottle Cutter Base (3D Printed)	1
23	M3 SS Socket Screw 8mm Long	4
24	M3 Washer	4
25	M4 Hex Nut	4
26	M4 SS Socket Screw 20mm Long	4
27	M4 Washer	4
28	M2 SS Socket Screw 20mm Long	2
29	M2 Hex Nut	2
30	M2 SS Socket Screw 8mm Long	4
31	M5 Washer	2

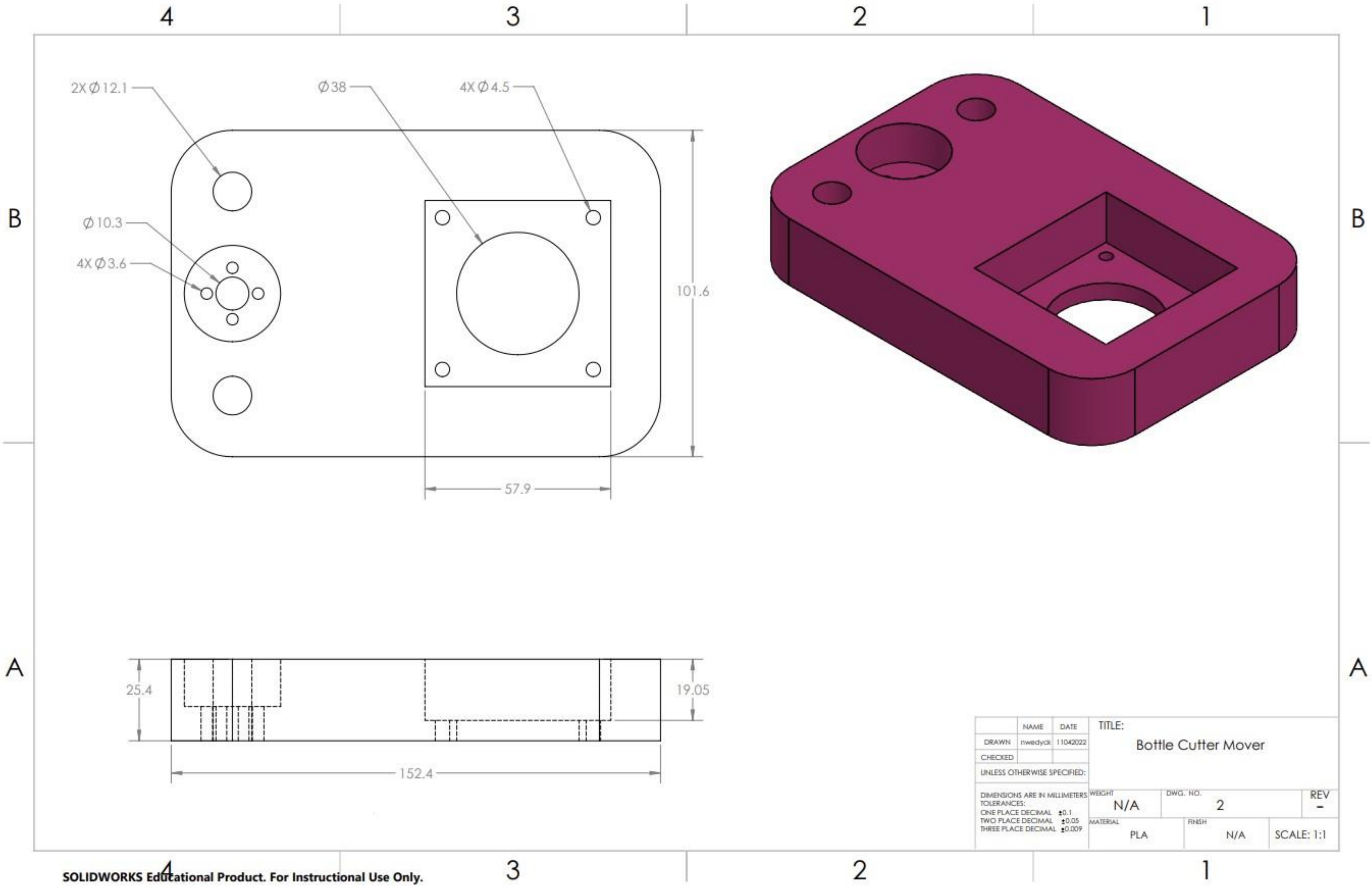
Blade Holder



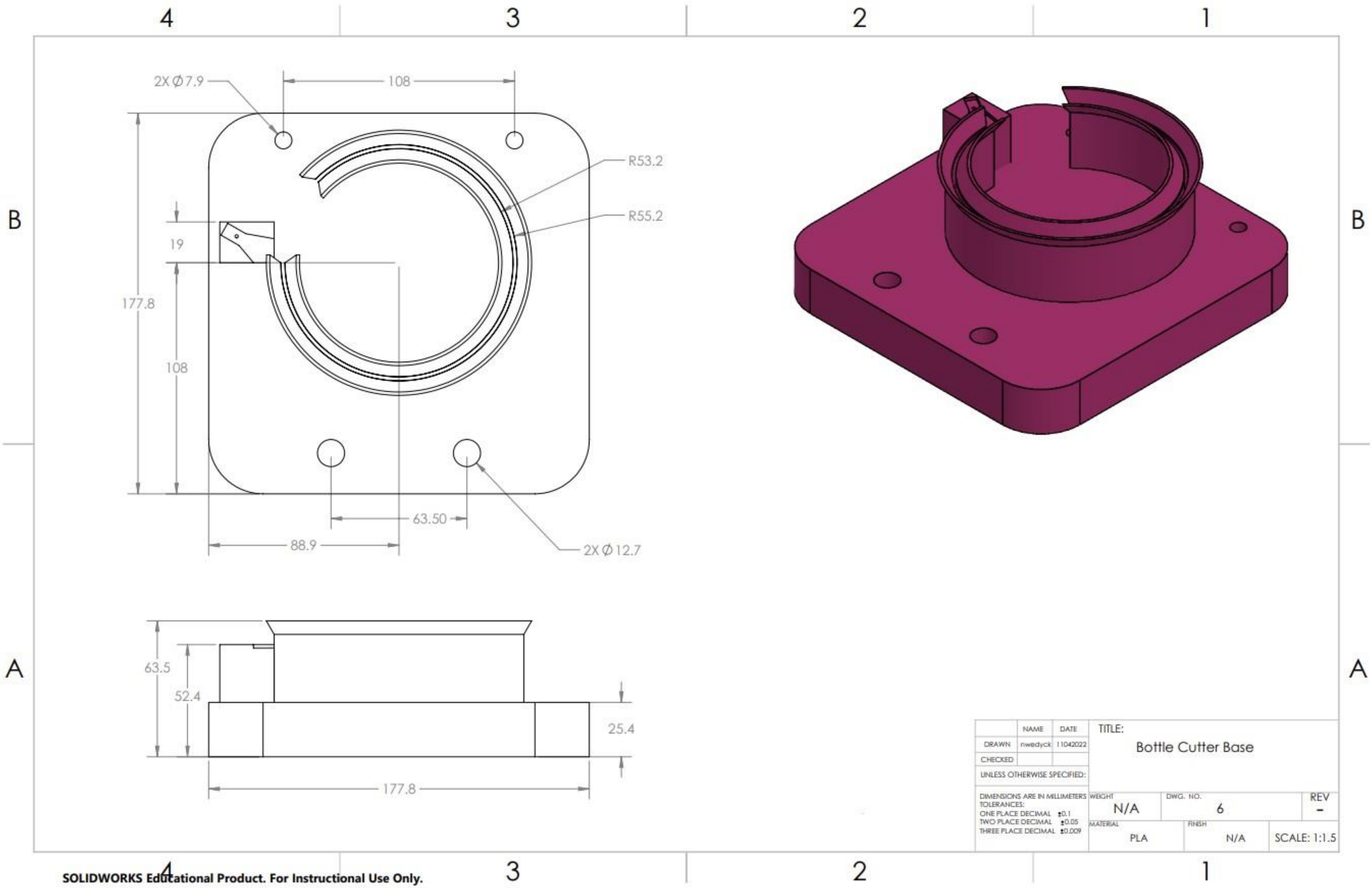
Bottle Cap Attachment



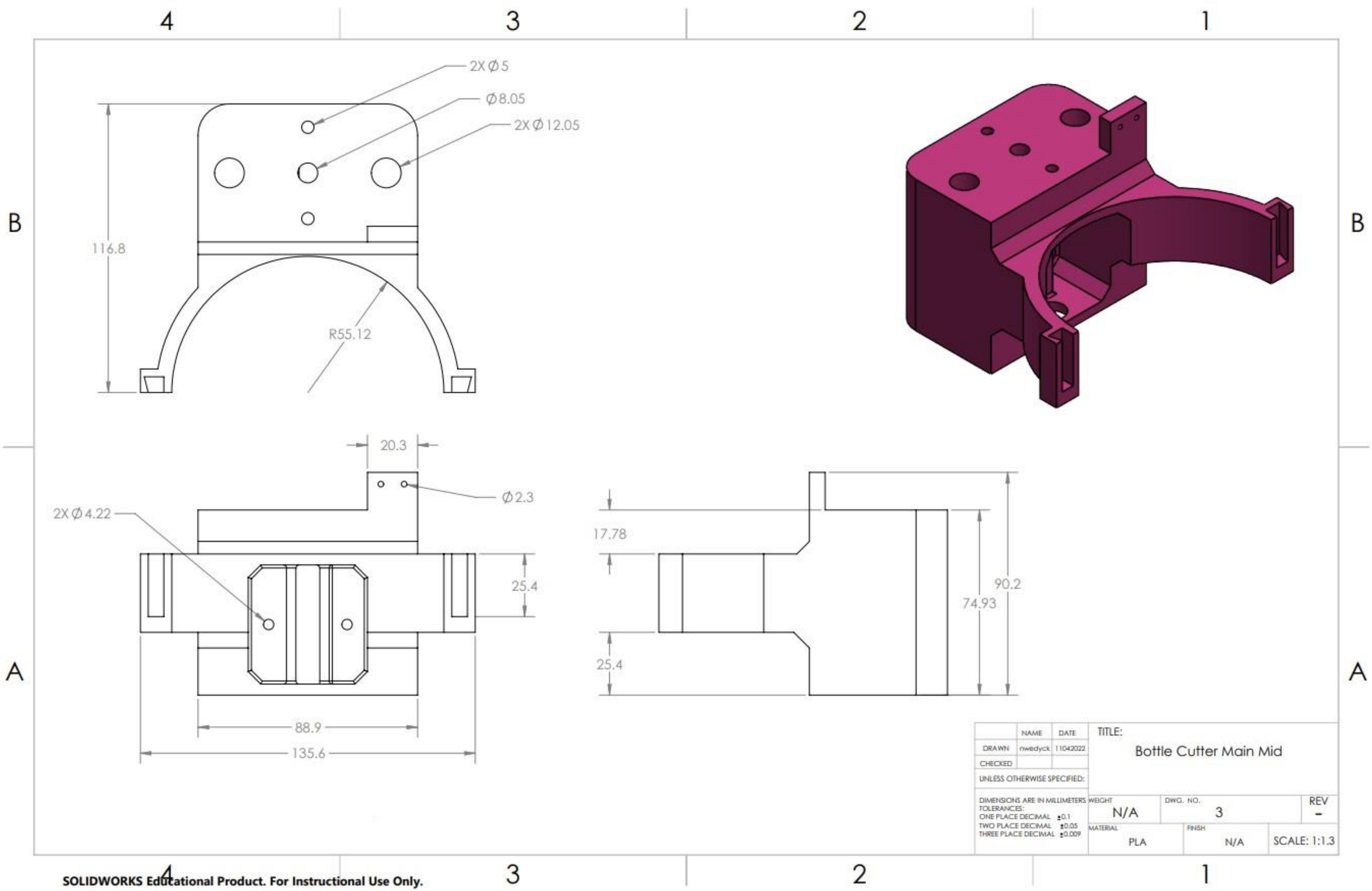
Bottle Cutter Mover



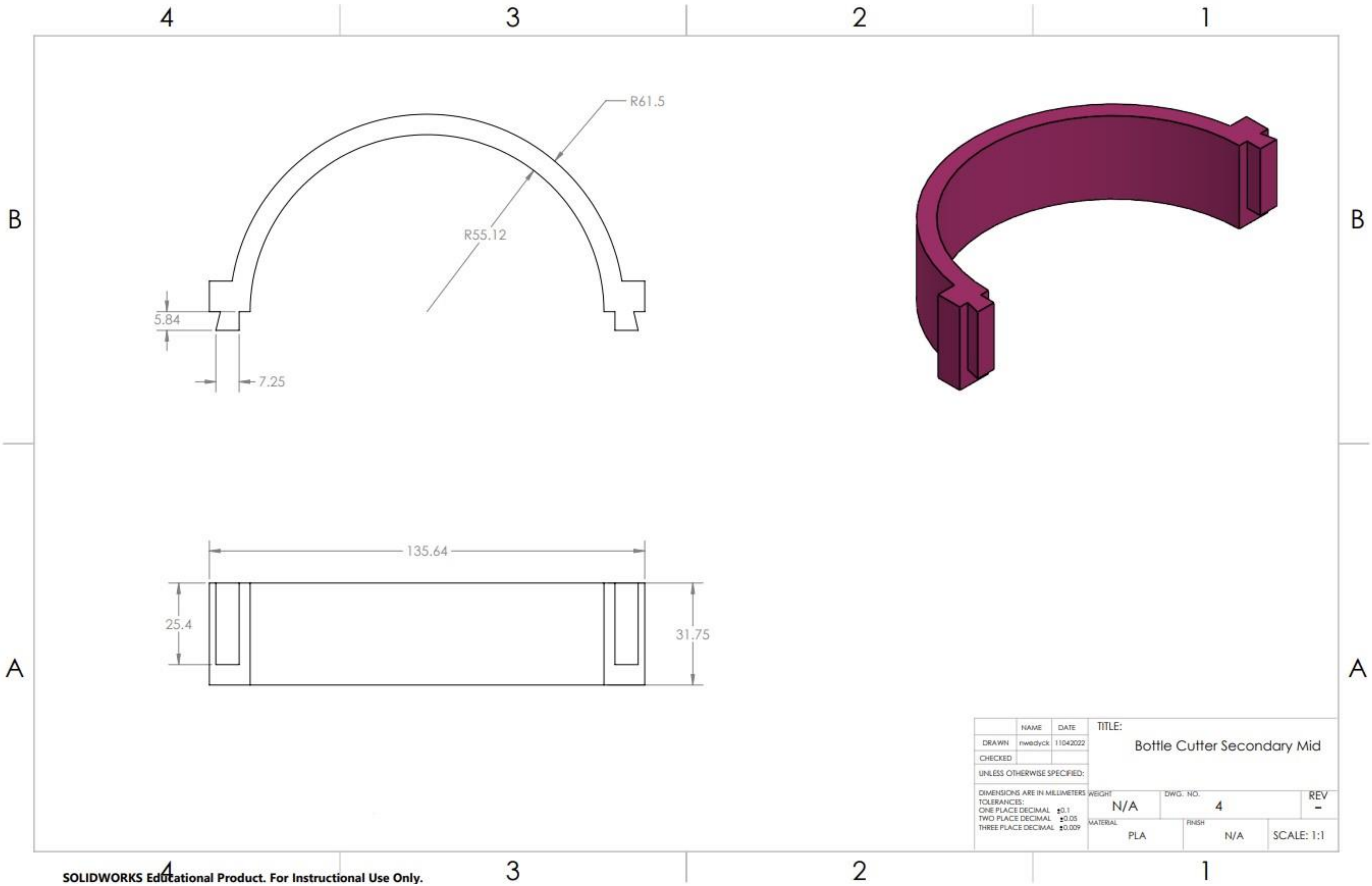
Bottle Cutter Base



Bottle Cutter Main Mid



Bottle Cutter Secondary Mid



Bottle Cutter Top