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MEMS 411: 3D Clay Printer

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3D Clay Printer

The Washington University School of Architecture has a class called Digital Ceramics, that utilizes a 3D Printer that prints clay instead of plastic filament. Students use this device to make art projects. As interesting as this device is, it isn't without problems. Our team decided to tackle some of the problems involved which we recognized to be: long set-up and tear-down times, and unsuccessful prints due to nozzle falling out.

We addressed these two problems with a two-fold solution. First, we created a new nozzle adapter (the piece that connects the tube that holds the clay to the nozzle, where the clay comes out) that does not allow the nozzle to fall out as it used to. Second, we created a new method of attaching the pieces together, as opposed to the old method of individually screwing in 16 screws. The new method involves one piece, where the screws/pins are secured in an elastic band using rubber grommets. The strap can then be stuck into each hole, going around the tube. This reduced the time from three minutes for 8 screws to 10 seconds.

Overall, our project was well received by the customer and greatly decreased the amount of time it takes to set up and disassemble a print, as well as increased the number of successful prints.

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1 Introduction

This report contains our research, process, and design for a new method of loading clay into a 3D ceramics printer. The previous loading process was very messy, time consuming, and inconsistent due to air bubbles. That method of loading and assembling the printer took around the same amount of time as it took to print a small piece of pottery, meaning a lot of time was being wasted on set-up. Often times even after completing set-up, the art would have to be thrown out because the printer had an air bubble and printed inconsistently. We sought to design a better method, tool, or mechanism for loading the clay into the tube used to eject it on the 3D printer.

Existing solutions on the market were effective at helping make clay-loading easier, but didn't fit our customer's other needs perfectly. The customer wanted a device that was easy to use, didn't waste a lot of clay, and was fairly inexpensive. These were important considerations for us as we created our design.

2 Problem Understanding

2.1 Existing Devices

This section includes our research of existing devices that would make clay loading easier. Each of them help with different parts of our problem, and we can consider them as we begin designing our own solution.

2.1.1 Existing Device #1: Pug Mill

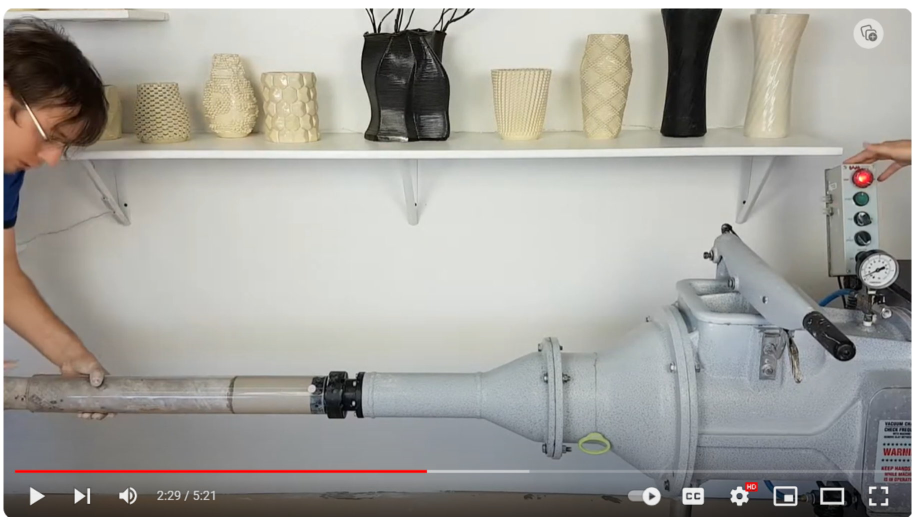

Figure 1: Loading a tube using a pug mill (Source: 3D Potter)[1]

Link: https://www.youtube.com/watch?v=YtHcdhgxBe8
Description: The easiest way to load extruder tubes is with a pug mill. The pug mill mixes the clay to remove air bubbles before shooting it into the tube. The right consistency of clay is needed to ensure the device works, and if this is not achieved, the pug mill won't load the tube correctly. This could make the learning curve difficult for new users, such as new students that join the class

each semester. The device is also very large, heavy, and would need to be installed. Our customer valued mobility and the ability for his/her students to be able to work on their own. This device could complicate that.

2.1.2 Existing Device #2: Standard Wall Mount Clay Extruder

Figure 2: 9" Standard Wall Mount Clay Extruder (Source: Sheffield Pottery)[2]

Link: https://www.sheffield-pottery.com/Bailey-Pottery-9-Standard-Wall-Mount-Clay-Extrude-p/bpm500003.htm
Description: The wall-mount extruder uses purely mechanical force to extrude the clay into the tube. It is mounted to the wall, and then can't be easily moved. This option is much cheaper than the pug mill, but is also something that would have to be purchased as opposed to built. There is an optional upgrade that uses an air compressor to extrude the clay as opposed to the physical force of the user.

2.1.3 Existing Device #3: Super-Duper Clay Gun XL Extruder

Figure 3: Scott Creek Super-Duper Clay Gun XL Extruder (Source: Sheffield Pottery)[3]

Link: https://www.sheffield-pottery.com/Scott-Creek-Super-Duper-Clay-Gun-XL-Extruder-p/sccgxl.htm?msclkid=b92056b61ef8182b0c5032497eee1c6b&utm_term=4583382943277220&utm_medium=cpc&_vsrefdom=adwords&utm_content=SCCGXL%20%20Scott%20Creek%20SuperDuper%20Clay%20Gun%20XL%20Extruder%20%206999&utm_campaign=**LP%20Shop%20-%20Tools&utm_source=bing
Description: The handheld clay extruder is the cheapest and simplest option by far. Clay is inserted into the tube of the "gun" and then a handle is squeezed to push it out, similar to a caulk gun. It holds around 5-6 pounds of clay, and claims that it can be cleaned easily. This option would allow for mobility and flexibility in where it is used. It would also be easy for new students to learn to use.

2.2 Patents

2.2.1 Clay Extruder (US8070350B2)[4]

This patent covers a clay extruder which makes use of a drum as a supply port for clay in which it is extruded through a port in a column-esque shape. The clay is fed through a spiral rotary blade wrapped around a rotary shaft that simultaneously kneads it as well. Often is mounted to a wall.

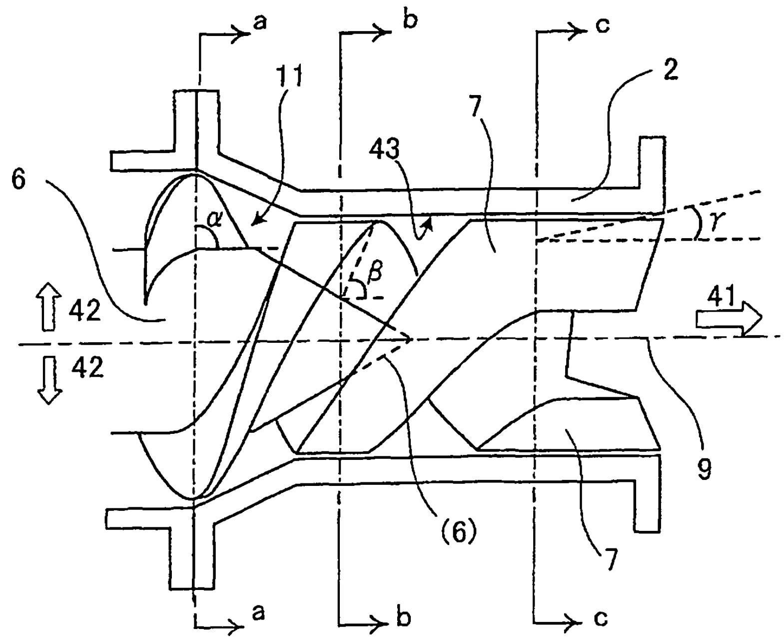

Figure 4: Patent Images for rotary shaft

2.2.2 Pugmill (US2297646A)[5]

This patent relates largely to a method of handling clay and the use of an apparatus for pugging clay, or throwing clay in a spiral motion to remove air bubbles. Often this is a spiral shaft that feeds clay from a rotating mill of wet clay.

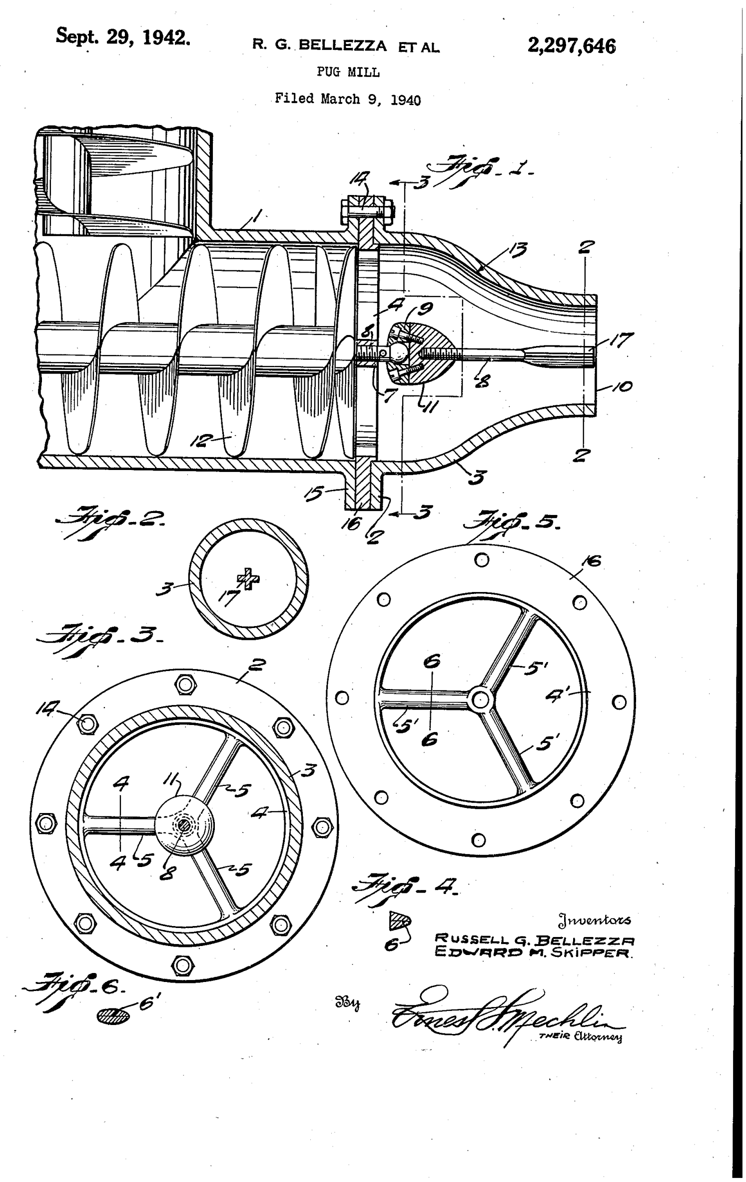

Figure 5: Patent Images for pugmill nozzle

2.3 Codes & Standards

2.3.1 Pressure Vessels (ASME BPVC Section VIII)[6]

This section concerns the design, construction, and testing of pressure vessels with an internal or external pressure that is over 15 psig. As well as the specific requirements for the materials used, this could pertain to our project depending on how we decide to pack the clay. If we use any kind of pressure system to tightly pack the clay and try to ensure there are no air pockets we would have to be aware of the specifications when using pressure and pressure vessels.

2.3.2 Pipe Flanges & Flanged Fittings (ASME B16.5)[7]

This covers pipe flanges and flanged fittings especially concerning pressure-temperature ratings, materials, tolerances, testing, as well as methods of designating openings for pipe flanges and flanged fittings. For our project as previously stated if we use a pressure system the safe use of valves within the pressure system is vital.

2.4 User Needs

Our customer is Kelley Van Dyck Murphy, an architecture professor at Washington University in St. Louis. Her and her students are looking for a more efficient way to load their clay extruder for their 3D clay printer. The clay extruder loader should be able to easily load clay into the extruder tube. It should make the process of loading a new clay printing tube faster, easier, cleaner, and more efficient.

2.4.1 Customer Interview

Interviewee: Kelley Van Dyck Murphy
Location: Givens Hall lower level, Washington University in St. Louis, Danforth Campus
Date: September 8^{th}, 2023
Setting: Kelley showed us the 3D clay printers, some printed pieces, and the current clay loading device and system. We asked questions about the process for clarification when needed.

Interview Notes:
What are the parts of the clay extruder?

- Nozzle holder, nozzle, tube (filled with clay), large screw pushes clay down through tube, stopper at top, small screws to hold top in place.

How do you currently load the clay into the extruder?

- Cut clay in chunks, wrap in towels to soften, make into a clay log and shove in, use plunger to push down into tube, clean up sides, and then screw on top.

What specifications does the clay need to have before and while being loaded into the tube?

- You need a pretty large batch of clay as you lose fair amount in machine during printing. That being said, you want to maximize the amount of clay in the tube without going past where the top screws onto the tube.
- You want to be aware for loading that you can't make tube exact diameter, but you do want to try to load the clay in one solid tube in order to eliminate air bubbles.
- The clay should be at the right consistency at the moisture level needed for printing. It can't be too hard as it won't be able to be pushed through the extruder. Also, keep in mind that the clay shrinks when it dries. You can use harder clay for the printers with stronger motors.
- The loaded tube is really heavy, and there is maybe about 6lb of clay in one print load.
- You want to try to eliminate air bubbles in the clay before and during loading the tube as air bubbles can ruin pieces because it causes the printer to skip a layer or it can make a piece collapse.

What are some alternative options you have heard of?

- A wall mounted extruder or pug mill.

Are there any other problems with loading the clay?

- The screws often cause problems. It is time consuming to screw in all the screws into the top lid as you have to use an alan wrench to screw each in. Using a drill strips the screws, and most of them have become stripped from the clay and frequency of use. Some screws just slide in and you have to tape over them to keep the lid in place.

What about the current design do you like/dislike?

- The tube lid closure could be better as the screws are difficult and time consuming. The clear tube is nice to have as you can see how much clay is left during or after printing. The dimensions should stay the same, but you could redesign the cap of the tube to something that would work better such as some type of latch.

- It is hard to eliminate all air bubbles, and air bubbles causes problems during printing.

What kind of 3D printer does the extruder work with?

- We use Potter bot by 3d potters, and they have lots of information on their website. The one that we want to load easier is the micro, but we also have larger one. There are helpful videos on the 3d potters website about how to load the extruder and they are very responsive to emails.

How long does it currently take to load a clay tube?

- It takes about 30 minutes to freshly reload the printer tube, but we want to lessen this time. Screwing and unscrewing is the most time consuming. We also want the learning curve to be easier. Keeping the clay extruder clean and efficient is a priority as it is hard to use when coated in clay or the holes are filled with clay. Right now we use bottle cleaners to clean it. We want to make the loading process clean and efficient.

Anything else?

- Givens lower level is open if you need to come take measurements, or they are also on the web. You are welcome to come watch the process during a class period also.

2.4.2 Interpreted User Needs

From the interview with Kelley, a list of user needs were complied below. Each user need was also labeled with the importance on a scale of 1-5 with 1 being least important, and 5 being most important.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The loader is easy to use and assemble.	5
2	The loader keeps the clay tube clean.	4
3	The loader is time efficient.	5
4	The loader has a fast learning curve.	4
5	The loader is durable and compact.	4
6	The loader is compatible with current 3D printing parts.	5
7	The loader uses the correct amount of clay at the right consistency.	5
8	The loader is aesthetically pleasing.	2
9	The loader minimizes air bubbles during printing.	4

From these user needs, the design metrics and target specifications of the device can be decided and specified.

2.5 Design Metrics

Below are the design needs based on our customer interview. After meeting with the customer, we created categories of certain metric requirements we would like to meet and their importance.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	2,3	Time it takes to clean	min	< 10	< 5
2	1,3	Time it takes to assemble	min	< 30	< 15
3	9	Minimal air bubbles		90% of prints succeed	95% of prints succeed
4	7	Amount of clay wasted is minimal	grams	< 100	< 50
5	5	Total weight	kilograms	< 2.5	< 1
6	4	Tries to learn how to load correctly	Tries	< 5	< 3
7	4	Time to teach someone how to use	min	< 30	< 10

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

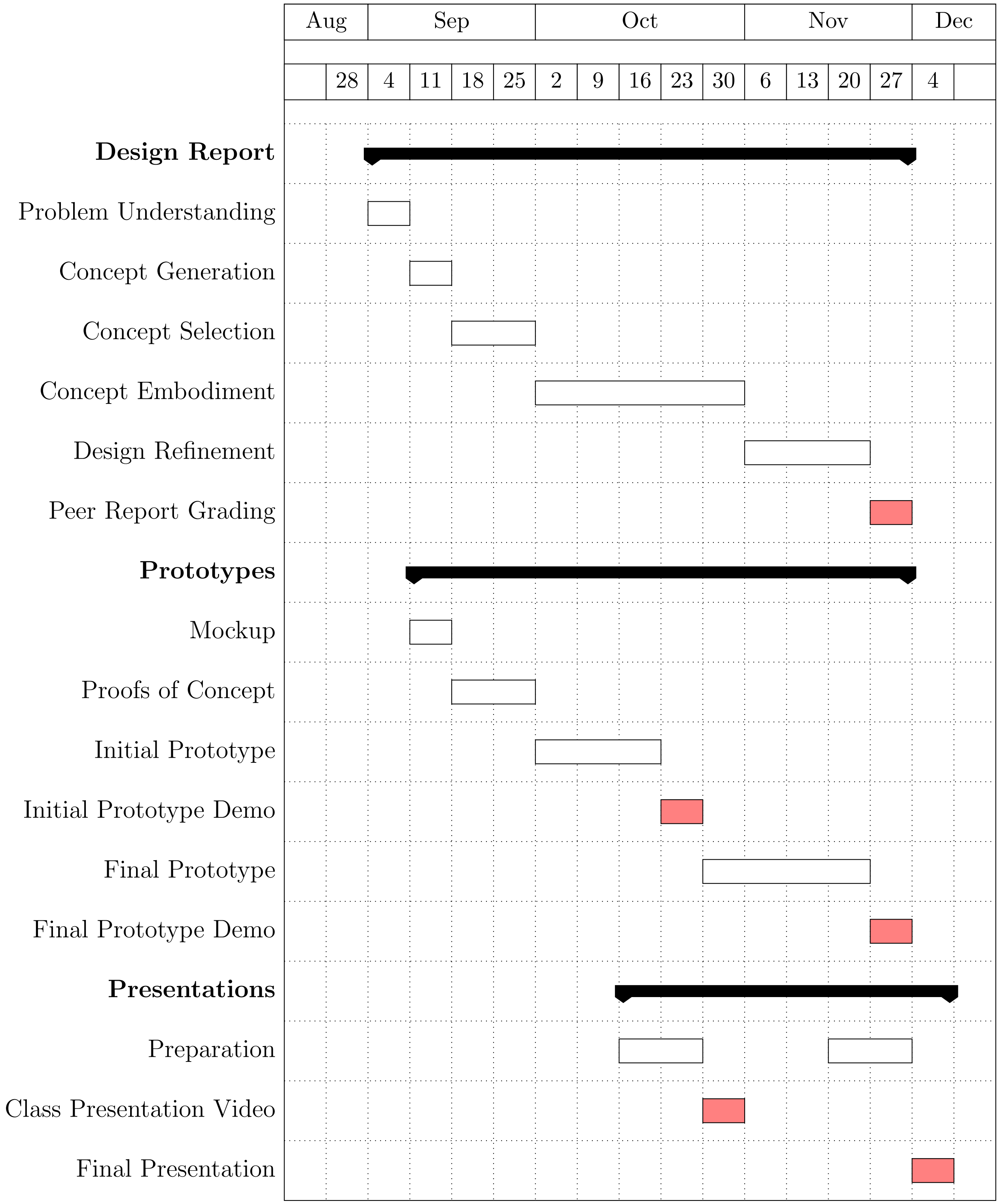

Figure 6: Gantt chart for design project

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3 Concept Generation

3.1 Mock-up Prototype

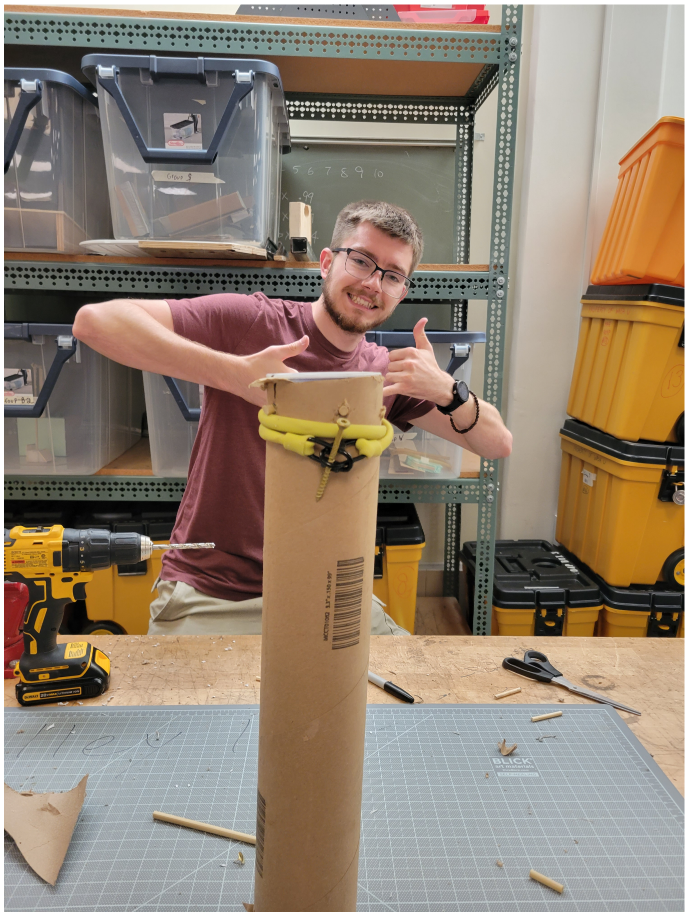

Figure 7: A side view of our mock-up prototype.

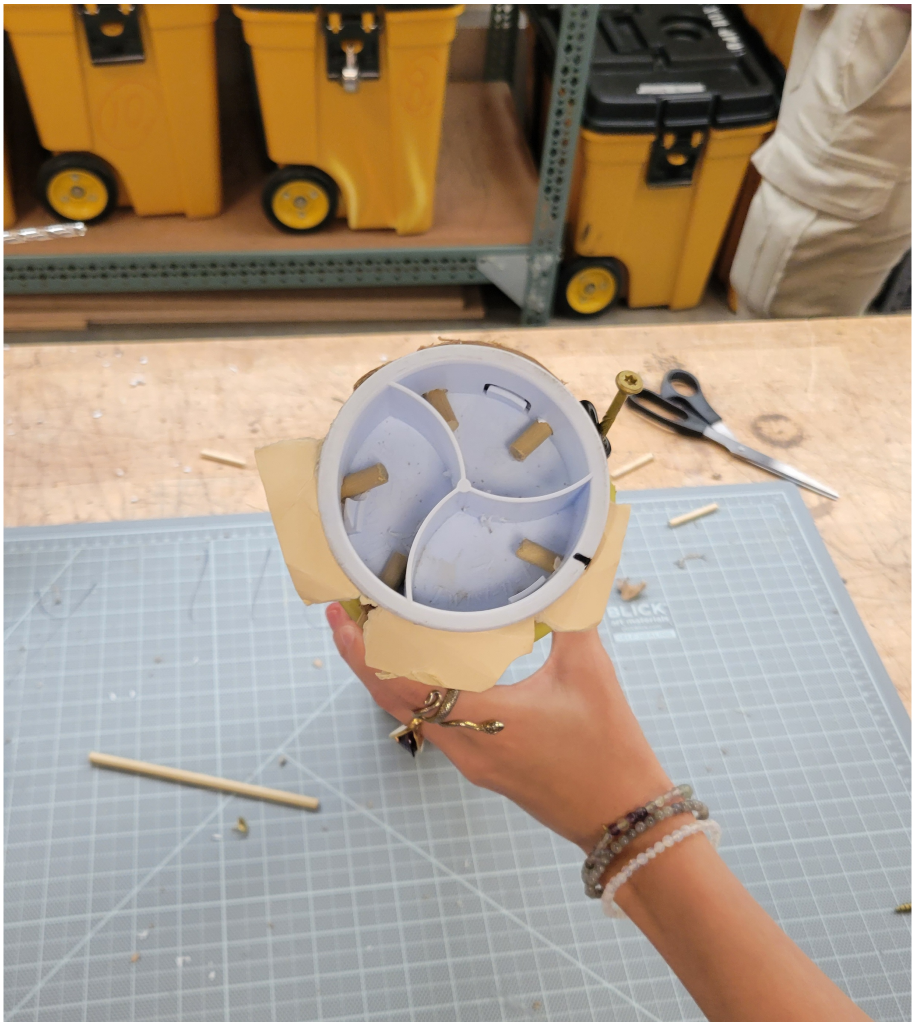

Figure 8: A top view of our mock-up prototype.

Figure 9: Mock-up of sushi rolling process of the clay.

Our mock-up depicts the redesigned clay extruder loading method and closure. The lid to the clay extruder will remain the same, but we decided to redesign the screws and use pins in the existing holes along with a hose clamp. The pins and clamp method to close the top off seemed to work well, but we are unsure if it will be able to withstand the force of the clay and plunger once the 3D printer is running. We realized that the "sushi method" of loading the clay might not work as there might still be air bubbles and the cap might be hard to put on top. Furthermore, it would be hard to ensure the user knows the right diameter to roll the clay to, have consistency between users/each loading. This method allows for a lot of human error and would still be very messy and hands-on.

3.2 Functional Decomposition

Our function tree is shown in Figure 10. Based on the project description and the customer interview, we came up with five subfunctions that are important for our 3D printed clay loader design.

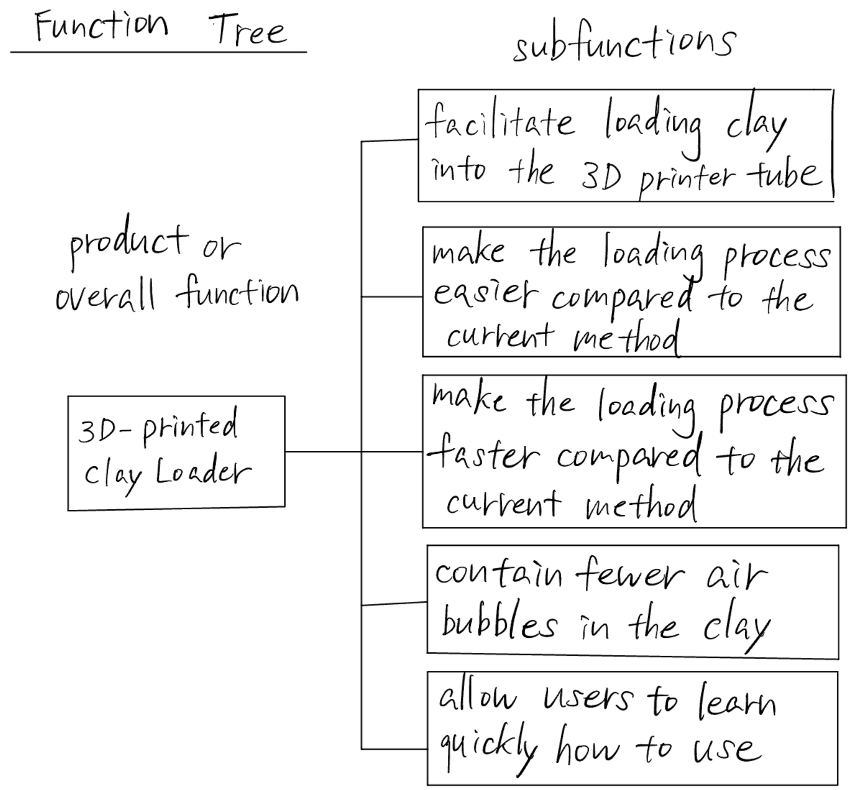

Figure 10: Function tree for 3D Printed Clay Loader, hand-drawn and scanned

3.3 Morphological Chart

Our morphological chart is shown in Figure 11. We came up with several design components to achieve each subfunction defined in the function tree shown above.

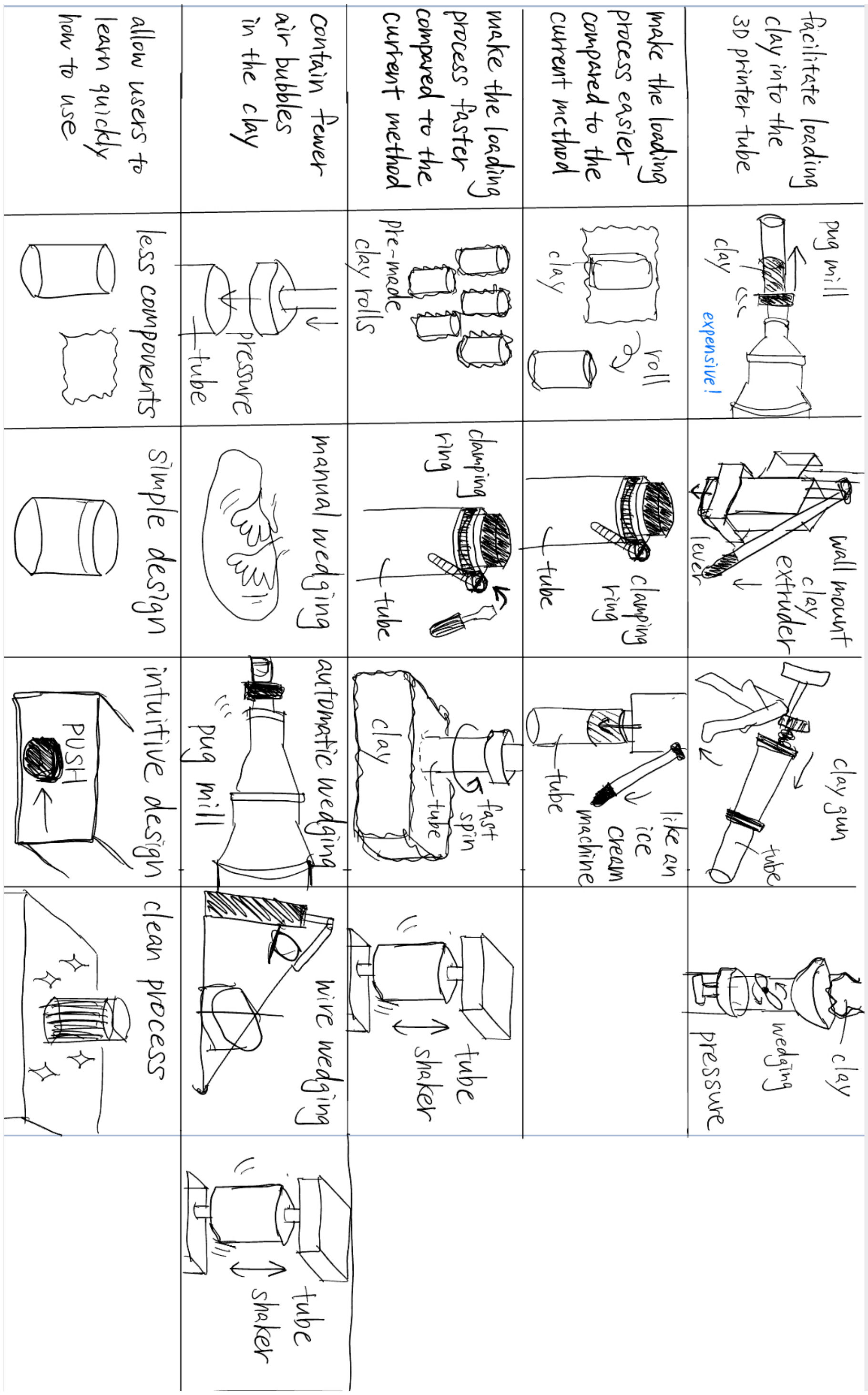

Figure 11: Morphological Chart for 3D Printed Clay Loader

3.4 Alternative Design Concepts

3.4.1 Concept #1: The Sushi Method

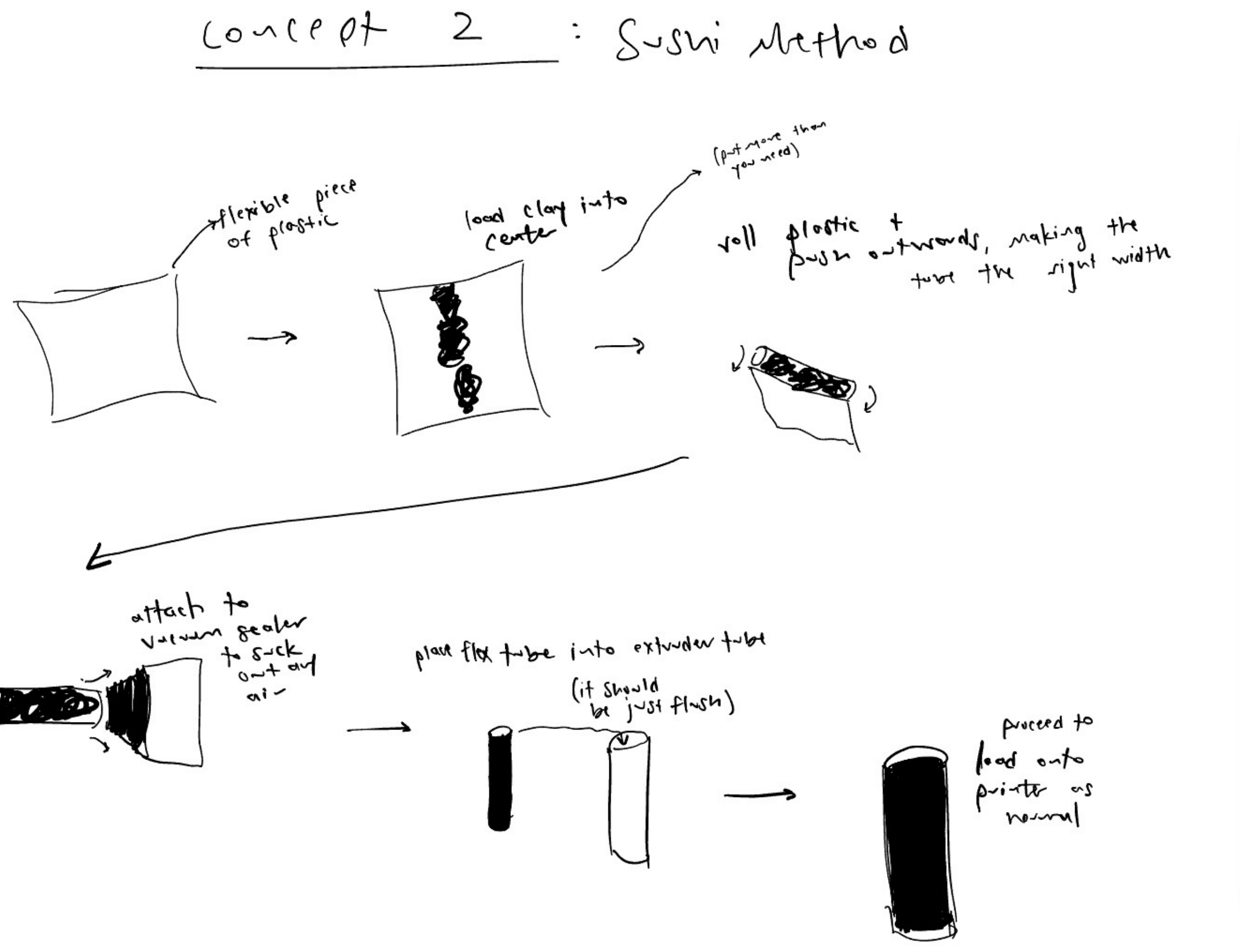

Figure 12: Sketch of the Sushi Method

<u>Description</u>: This concept is as much a process as it is a device. The user would have a thin, flexible sheet of plastic that he/she would load the clay onto. Once the clay is loaded in the middle, the user would role the plastic, as one does sushi, pressing down while doing so. This would eliminate air bubbles and ensure all the clay could all be loaded at the same time, as opposed to in different sections. The thin plastic sheet now filled with clay could be loaded into the 3D printer's tube chamber and left there for the print.

3.4.2 Concept #2: Log Extruder

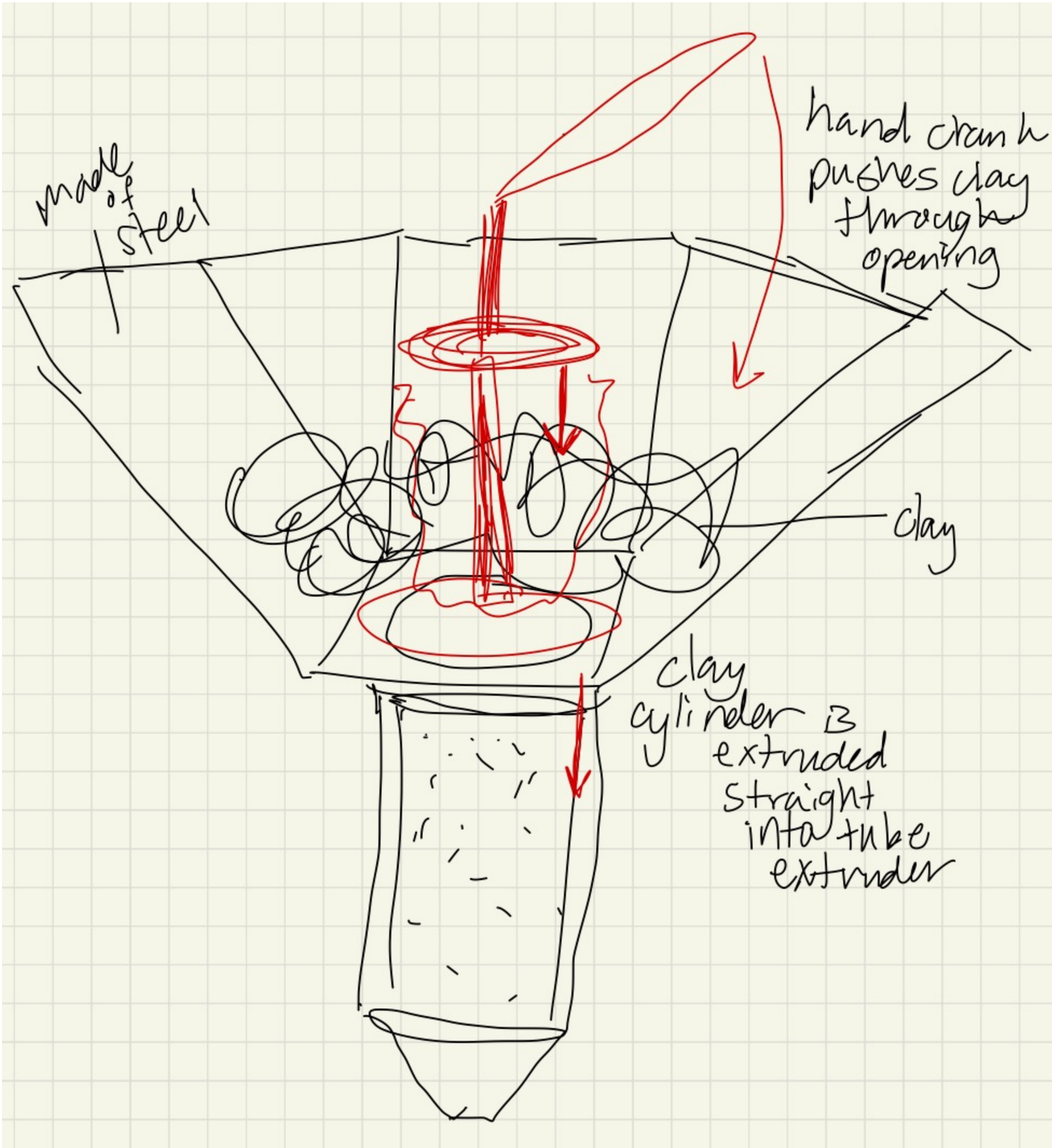

Figure 13: Sketch of Log Extruder concept

Description: The clay (at the right consistancy) is loaded into the funneling mechanism. A plunger or other device is used to compact the clay to the bottom of the funnel. The clear clay extruder tube with the nozzle at the bottom is attached at the bottom of the funnel. The clay is then extruded via a hand crank mechanism that pushes the clay through a circular opening that extrudes a clay log straight into the clay extruder that will be attached to the 3D printer. The log can be sliced off at the top of the clear tube so that it is ready to be loaded into the printer. The device is made of steel so that it is easy to clean.

3.4.3 Concept #3: Dual-Shaft Compressor

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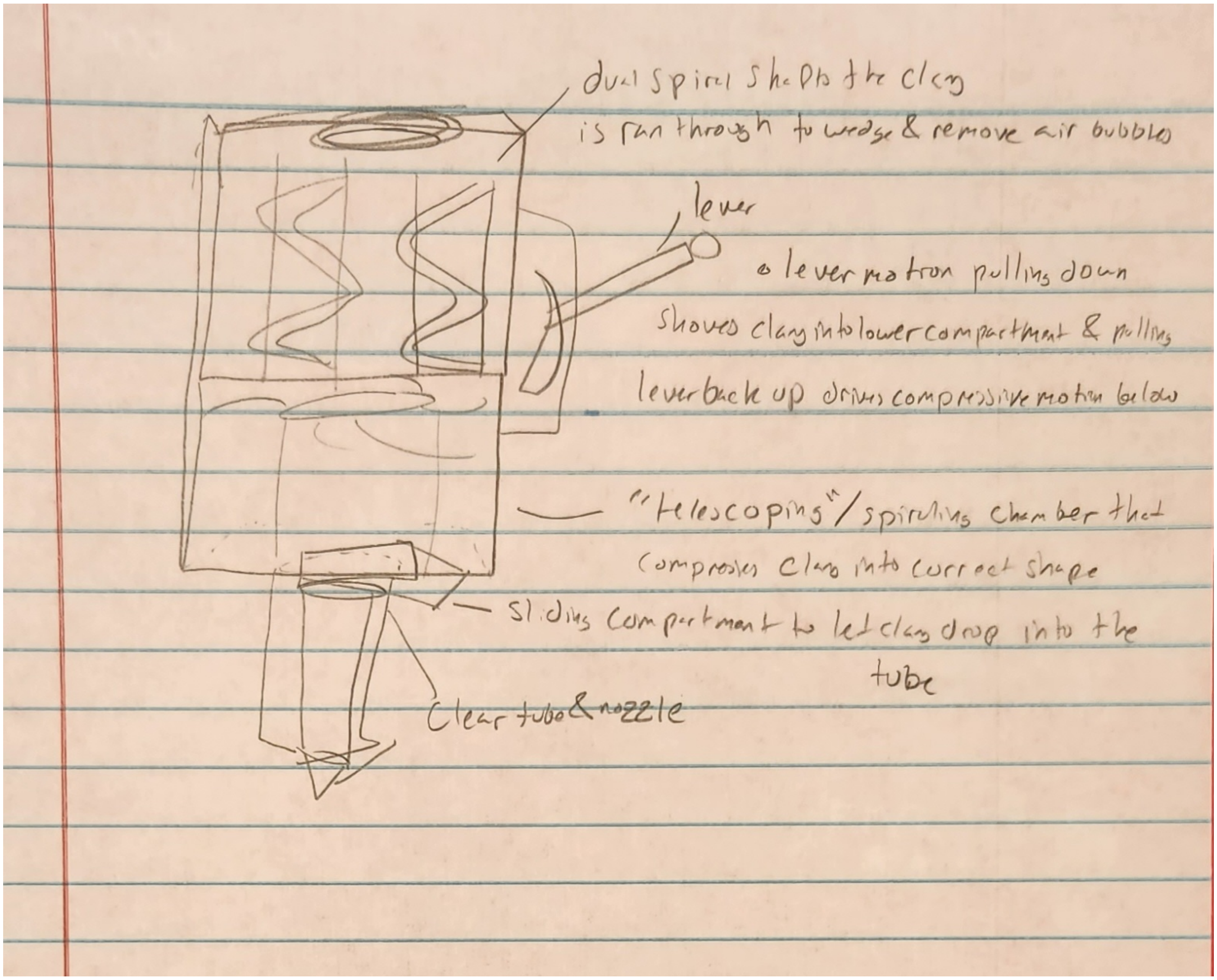


Figure 14: Sketch of Dual Shaft Compressor concept

Description: There is a compartment in which the clay is placed. Once a liter of clay has been inserted, noted from a fill line in the compartment that denotes 1 liter, the user pulls down a lever that shoves the clay down past dual spiral shafts like a manual version of a pug mill removing air bubbles and into a compressing chamber. The clay is then compressed by a twisting of the compartment similar to a camera lens or wrapping and of a piece of paper into a tube shape. This motion is driven by the lever being pushed back up. The lever drives both stations of the machine in opposition, so that when the upper station pushes down on the clay the lower station is returning to the uncompressed state. When the lever is pushed back to its initial state, the lower chamber compresses and the upper chamber has the shafts returned to their starting positions. The shape the clay is compressed into is cylindrical to fit into the clear tube for 3D printing. The tube is inserted in a slot below the exit nozzle with the 3D printing nozzle already attached.

3.4.4 Concept #4: Screw Plunger

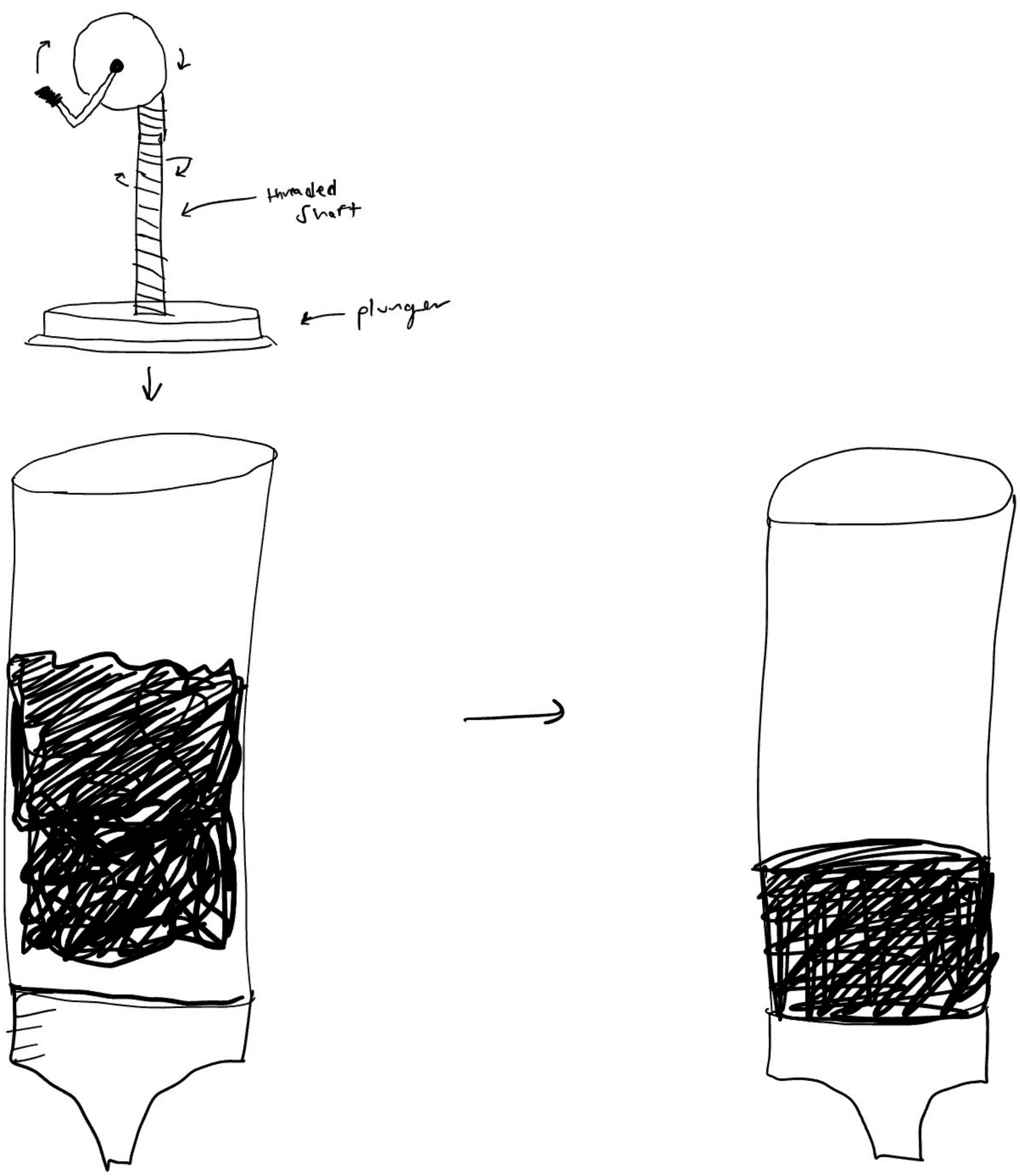


Figure 15: Sketch of Screw Plunger Concept

Description: The screw plunger concept works much like a hand-crank-powered drill. The user turns the handle, which in turn turns the large threaded shaft attached to the plunger. The plunger pushes the clay down, and also pushes out air as it compresses the clay. this option would be simple to set up and clean, and easy to use.

4 Concept Selection

4.1 Selection Criteria

To determine which design concept to move forward with, the criteria for selection were first determined based on the user and design needs of the device. These were compared and scored relative to each other using the Analytic Hierarchy Process as seen below in Fig. 16. This process involves choosing how much more important the first criterion is compared to the second. The scale is from 1/9 (being much less important) to 9 (being much more important). For example, if "Easy to Assemble" was much more important than "Easy to Clean", we would give this a higher score, such as 7. After filling out this chart, we had our weights for which criteria were most important.

	Easy to Clean	Easy to Assemble	Minimal Air Bubbles	Light Weight	Easy to Learn How to Use		Row Total	Weight Value	Weight (%)
Easy to Clean	1.00	0.33	0.20	5.00	3.00		9.53	0.17	16.63
Easy to Assemble	3.00	1.00	0.33	7.00	5.00		16.33	0.28	28.49
Minimal Air Bubbles	5.00	3.00	1.00	9.00	7.00		25.00	0.44	43.61
Light Weight	0.20	0.14	0.11	1.00	0.33		1.79	0.03	3.12
Easy to Learn How to Use	0.33	0.20	0.14	3.00	1.00		4.68	0.08	8.16
					Column Total:		57.33	1.00	100.00

Figure 16: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Next, the four design concepts were compared using the selection criteria and their weights determined from the Analytic Hierarchy Process. The design concepts were compared using the Weighted Scoring Matrix as seen below in Fig. 17. Each criteria was rated on a scale of 1-5 for each design concept, 1 being the worst and 5 being the best at that criterion. The designs were then ranked based on the weighted criteria and their ratings.

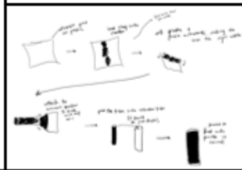
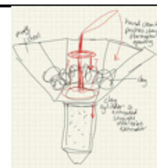
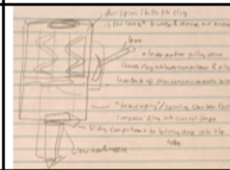
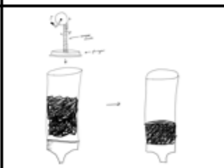
Alternative Design Concepts		**Sushi Method**		**Log Extruder**		**Dual-Shaft Compressor**		**Screw Plunger**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Easy to Clean	16.63	5	0.83	4	0.67	3	0.50	4	0.67
Easy to Assemble	28.49	4	1.14	3	0.85	3	0.85	3	0.85
Minimal Air Bubbles	43.61	2	0.87	3	1.31	5	2.18	4	1.74
Light Weight	3.12	5	0.16	3	0.09	3	0.09	4	0.12
Easy to Learn How to Use	8.16	3	0.24	3	0.24	3	0.24	3	0.24
	Total score	**3.244**		**3.167**		**3.873**		**3.634**	
	Rank	**3**		**4**		**1**		**2**	

Figure 17: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

As shown in Figure 17, the Dual-shaft Compressor Concept won. This was due mostly to its high rating in "Minimal Air Bubbles". The purpose of the dual rotating shafts in this design is to mix or "wedge" the clay instead of doing it manually. This, in turn, gets the air bubbles out of the clay, and allows the customer to use fragmented scraps of clay as opposed to one new store-bought section. Minimizing air bubbles is the most important element to our design because this was the user's most pressing and important need. The other criterion were also important, but all were secondary to the air bubble problem.

Another criterion was making the device easy to clean. This was important because as clay dries, it becomes hard and can clog up machines. This was an important consideration as we chose a design. Being easy to learn how to use was also an important consideration, as this device will be used by students in a class, and the loading time should be kept to a minimum. The customer wanted the process to be as quick and easy as possible for the students. Overall, the Dual-Shaft Compressor performed well in all categories, and most importantly, in minimizing air bubbles.

4.4 Engineering Models/Relationships

4.4.1 Engineering Model #1: Gear Train/Ratio

Figure 18 shows the description and the equation for the gear ratio model.

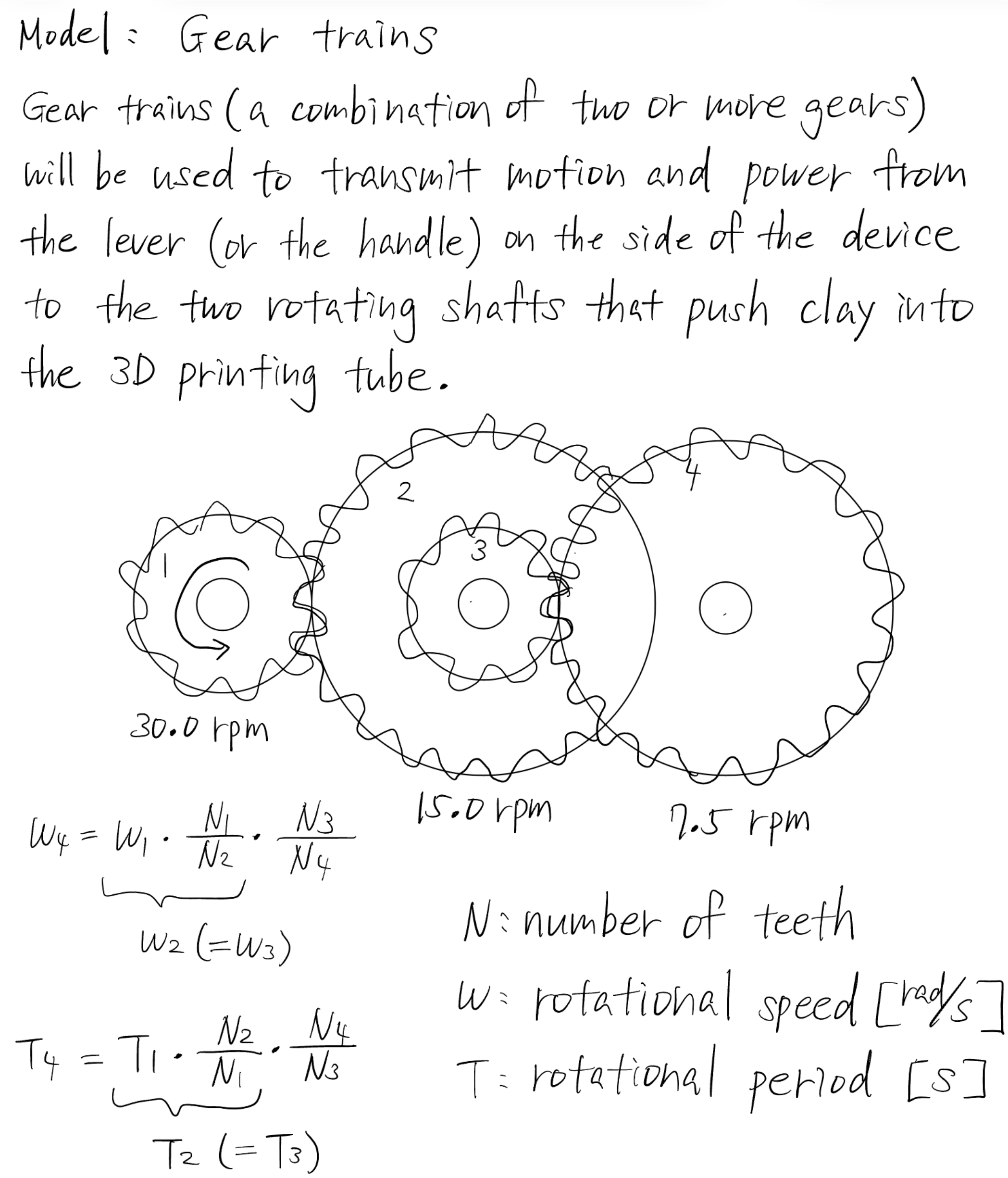


Figure 18: A description of the gear train model.

Gear trains, a combination of two or more gears, will be used to transmit motion and power from the lever (or the handle) on the side of the device to the two rotating shafts that push clay into the 3D printing tube. Using the equation or relationship will help us determine the combination of different gears we use because we can calculate the number of teeth based on the rotational speeds.

4.4.2 Engineering Model #2: Torque on Lever

The design uses a lever to turn the gears, so the torque equation (Eq. 1) is a useful engineering relationship.

$$\tau = r \times F \tag{1}$$

Because we know the realistic amount of force that a person can exert on the lever (F) and the torque needed to turn the gear (τ), we can figure out the optimal length of the lever (r). This would be helpful to know the ideal length of our lever and to make sure that it does not require too much force to turn.

4.4.3 Engineering Model #3: Pressure/Stress in Shaft

A part of our design is going to be squashing down on clay with a lever in a cylindrical chamber. One limitation is the amount of stress that chamber can take in terms of the pressure it is taking from the clay. This pressure would be a direct result of the force being applied to the top of the clay. If we assume the 'plunger' interfacing with the top of the clay in the chamber is a circle then we can create a relation between the force of the plunger on the top of the clay and the pressure the chamber is experiencing. This is seen in Figure 19 here.

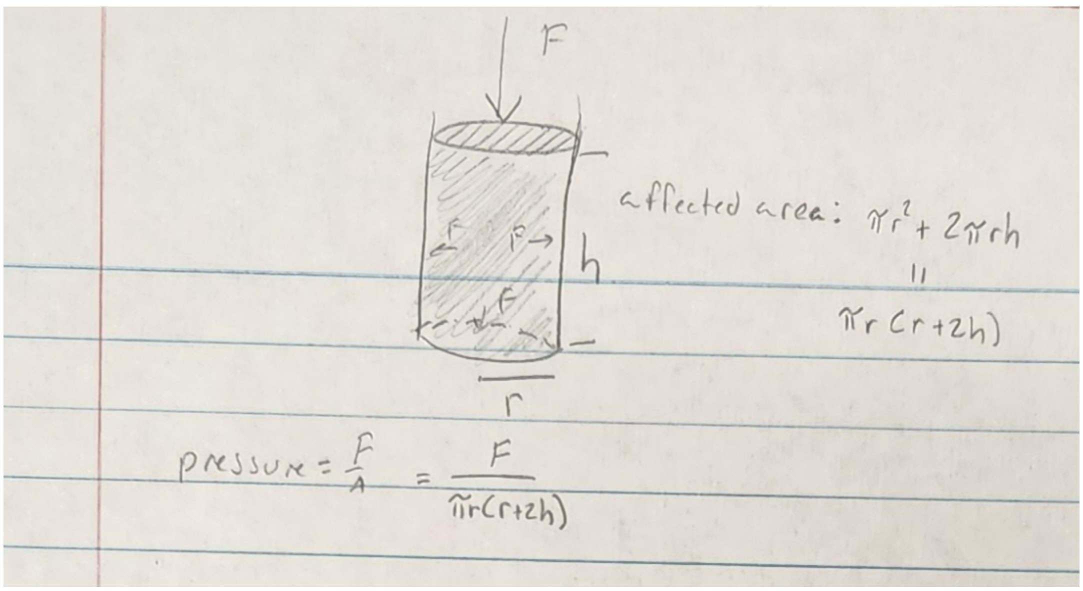


Figure 19: A model of the clay in compression chamber.

The chamber should be strong enough to take the stress of the clay being forced down into shape. This is most poignant when considered at the seam or edge where the bottom of the chamber and the walls meet. This is most likely where any failure would occur. So specifically at the point described in Figure 20 would the chamber need to withstand the stress as well as minimizing any deformation.

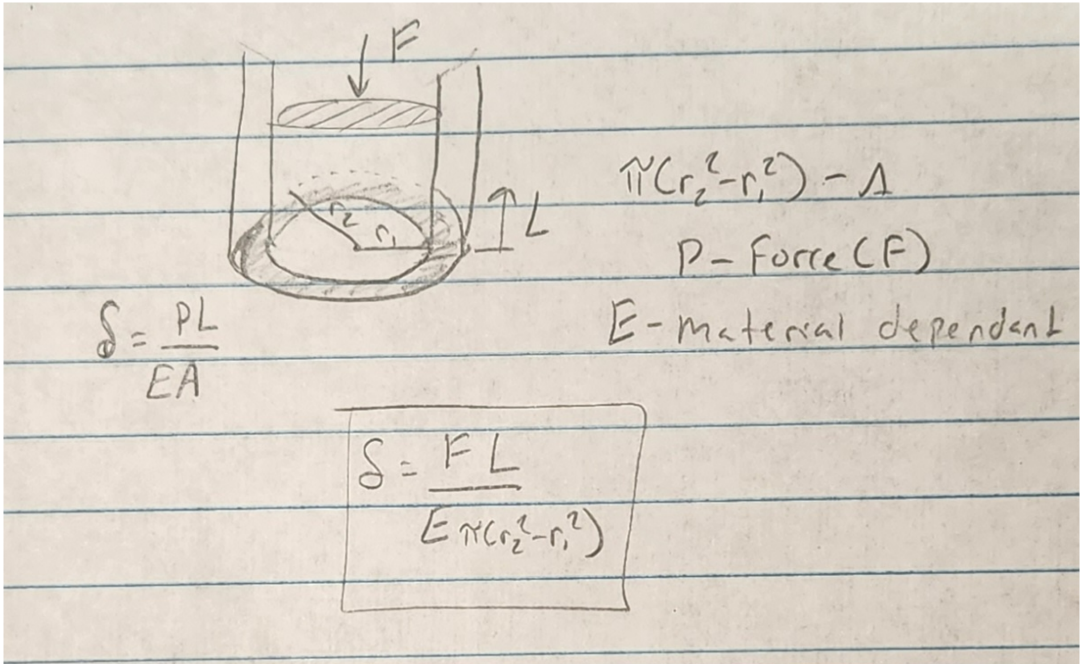


Figure 20: Stress and strain at chamber seam.

5 Concept Embodiment

5.1 Initial Embodiment

Here are the new prototype performance goals for the nozzle adapter. (See Section 5.3: Design Changes.)
1. The new nozzle adapter enables a higher percentage of successful prints than the current process.
2. The new nozzle adapter requires less physical effort and inconvenience to **set up a print** than the current adapter, measured by time it takes to set up.
3. The new nozzle adapter requires less physical effort and inconvenience to **disassemble and clean** than the current adapter, measured by time it takes to disassemble and clean the system.
Figure 21 shows the initial prototype assembly showing top, right, and side views with basic overall dimensions. Figure 22 and Figure 27 show a large isometric view of the assembly and an exploded view of the assembly with a Bill of Materials (BOM) and balloon callouts showing each item's BOM# rspectively.

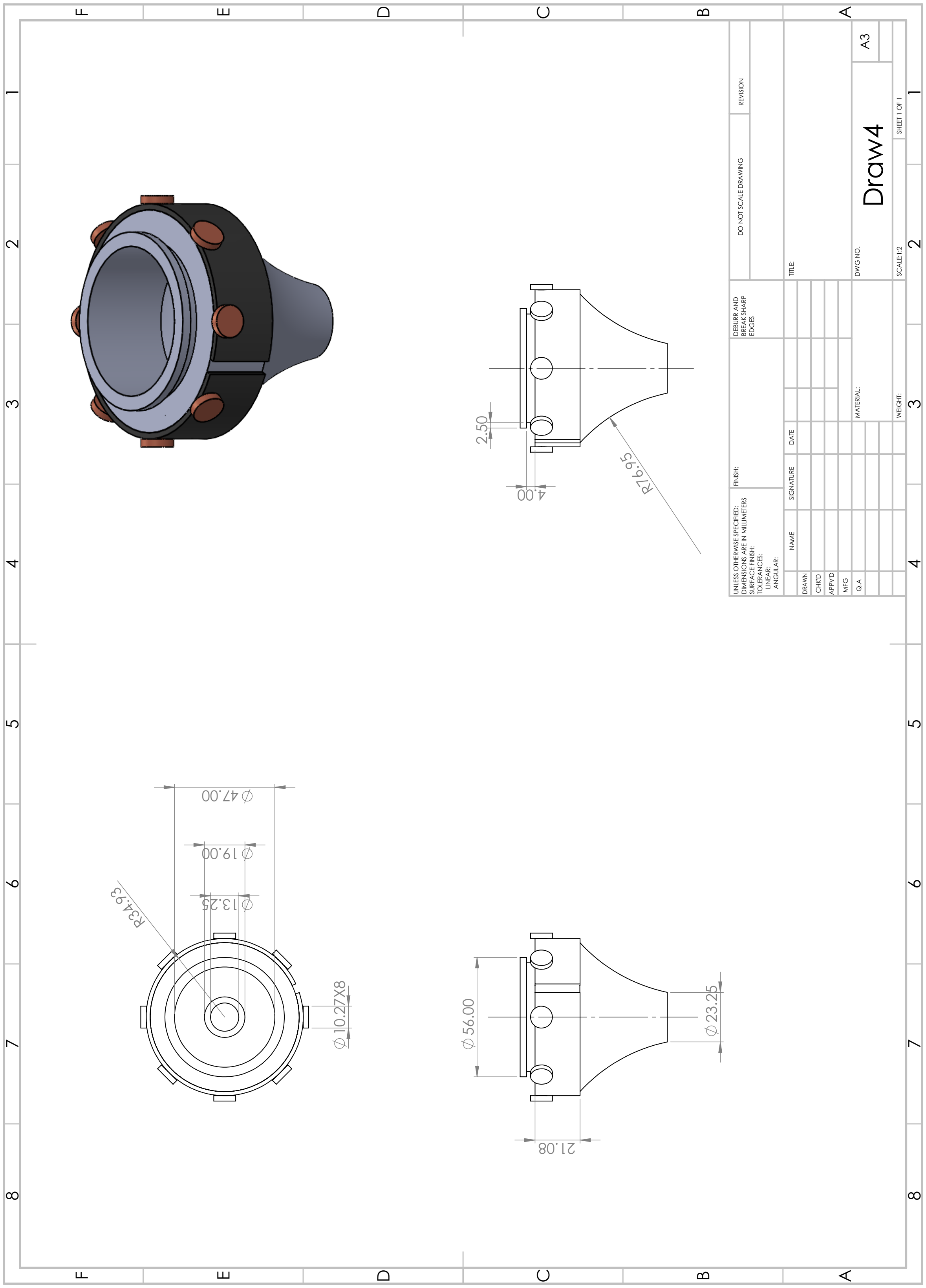


Figure 21: Assembled projected views with overall dimensions

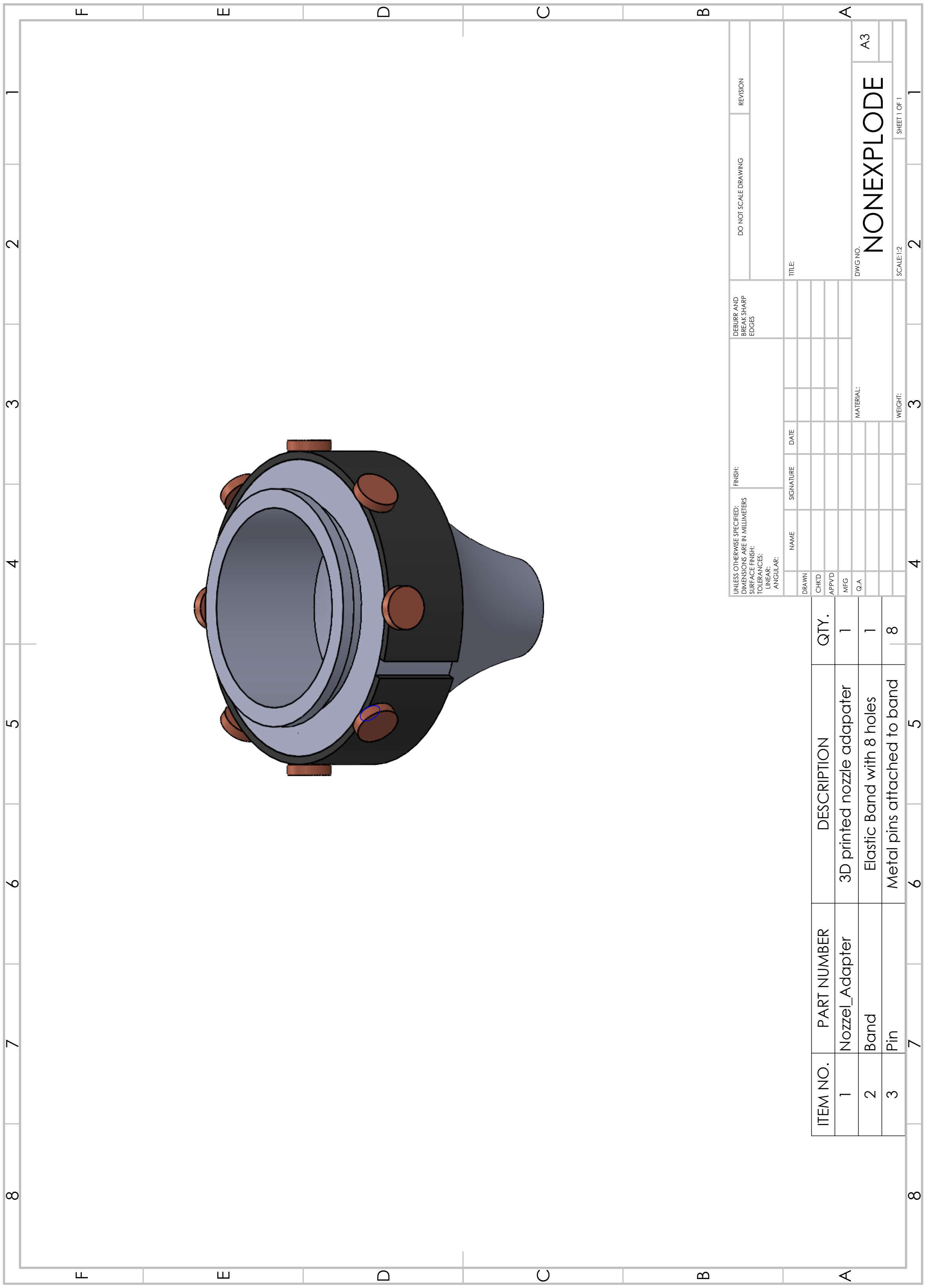


Figure 22: Assembled isometric view with bill of materials (BOM)

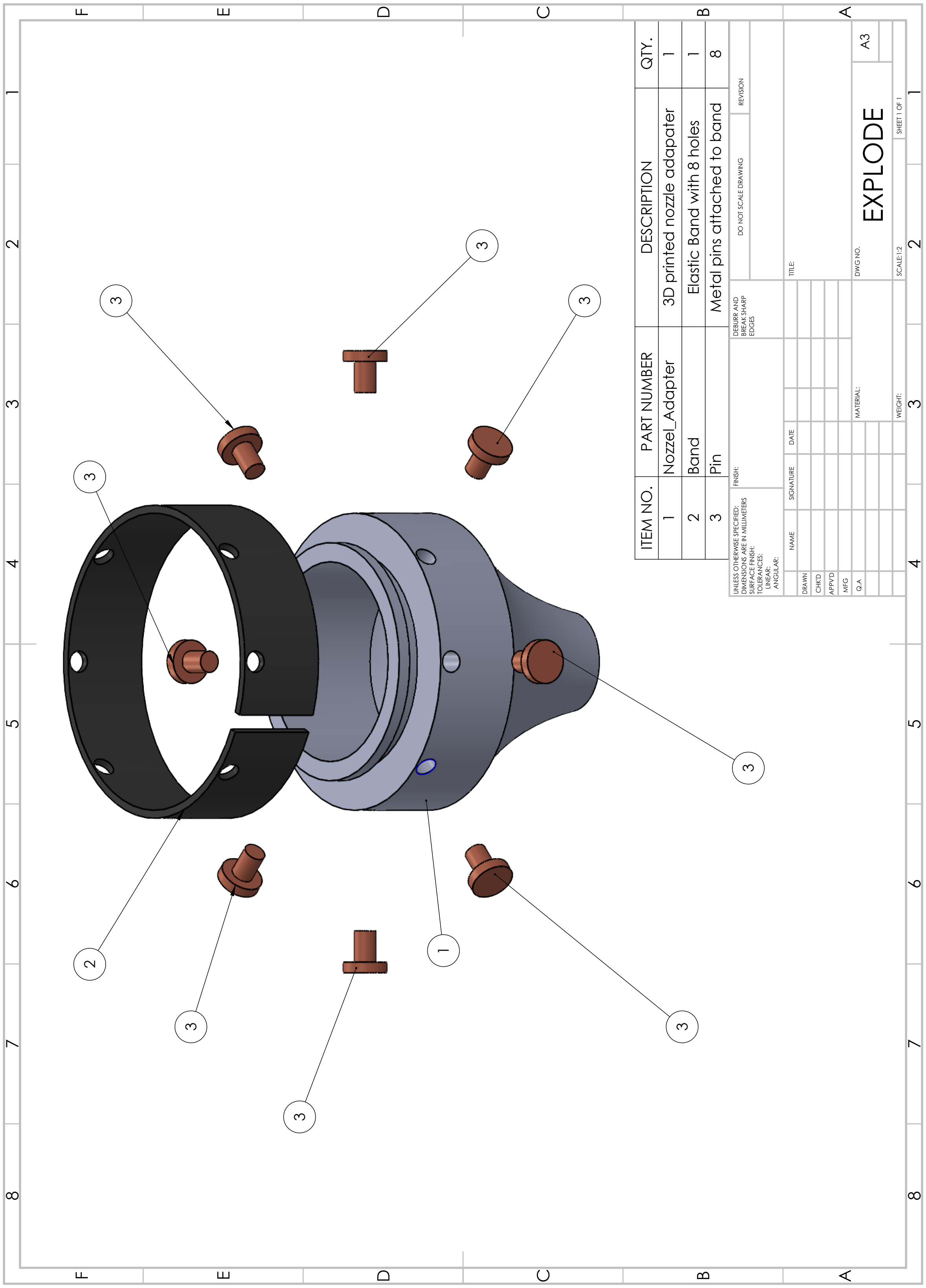


Figure 23: Exploded view with callout to BOM

5.2 Proofs-of-Concept

After making a proof-of-concept of the dual-shaft compressor design, we realized that the design wasn't very practical to make in the time that we are given for this project. After discussion and reconsideration, the group decided to pivot and turn our attention to modifying the nozzle adapter and the method to attach it to the clay loader tube. Our goal was to CAD a new nozzle adapter and create a mechanism to attach the nozzle adapter to the tube with pins and some sort of clamp. After trying different approaches with a metal hose clamp or buckle clamp, the group decided that something with more give would be easiest to attach quickly while holding the pins. Our first proof of concept used an elastic with holes in it from a children's pair of jeans and several screws put into the holes. This proof of concept is seen in Fig. **??** and Fig. **??** below.

Figure 24: Proof of concept with an elastic band with holes in it from a children's pair of jeans around a cardboard tube.

Figure 25: Proof of concept with an elastic band with holes in it from a children's pair of jeans around the actual plastic tube.

After creating this concept, we decided that a thicker and more sturdy elastic might improve its ability to hold the pins and keep them attached to the tube in a more robust way. The holes in the jeans elastic were also too large to hold the pins, so cutting smaller holes in a thicker elastic would solve this problem. The proof-of-concept also made us reconsider how the elastic would secure itself together around the tube at its ends.

Figure 26: A photo of our first prototype showing our thicker elastic and pins.

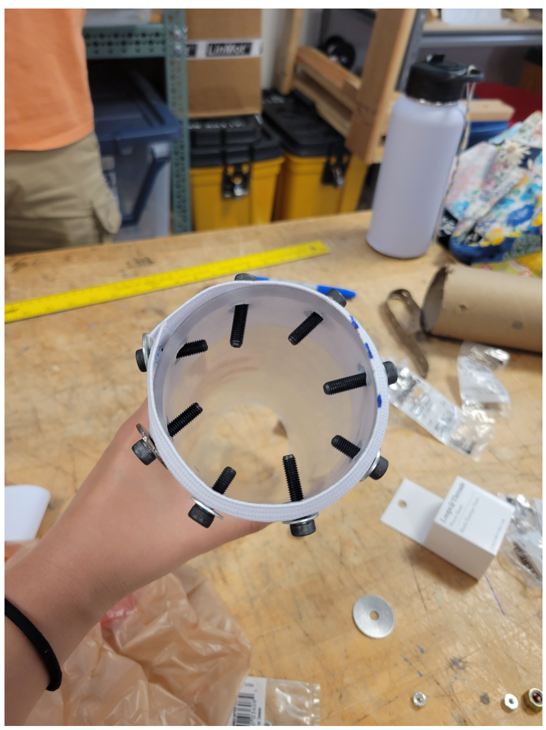


Figure 27: Top view of the tube with our prototype attachment.

5.3 Design Changes

When we started this project, we were initially focusing on minimizing air bubbles in the clay during and after loading it in the tube. We experimented with a few concepts for this including making prototypes for the "Sushi Roll" method and the dual-shaft manual pug mill. These proofs-of-concept ended up showing us that these methods were not going to work as we thought. After discussions with our professor and further research, we decided to pivot and focus on a different part of the loading process: the attachments between the tube, adapter, and nozzle. What we found during interviews with our customer was that the process of screwing in 20 total screws manually with a hex key was very inconvenient and caused the set-up process to take awhile. Furthermore, the screws often get stripped after repeated use and exposure to clay, so they often put the screws in and then secure it with blue painters tape to secure it. Another issue we saw first hand while watching the printing process was that the nozzle often fell out of the adapter during printing. The small channel design wasn't enought to hold the nozzle under the force of the clay being pushed out. We decided to create a new nozzle adapter that we could modify to make a better connection with the nozzle and the tube. For the tube, we decided to use pins instead of screws because it isn't necessary as long as they are attached well. For the nozzle, we created a tapered channel for the tapered nozzle to rest in to keep it from coming out.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Model #1: Radius and Circumference

In order to calculate the maximum length of the elastic band, the circumference of the plastic tube needed to be calculated. This was done using the equation for circumference $C = 2*\pi*R$ The radius of the tube is about 34.93 mm, so the circumference was calculated to be $C = 2*\pi*34.93mm = 219.47mm$. This is the maximum length that the elastic band could be in order to fit around the tube. We decided to shorten this length by 1-2 cm due to the stretch of the elastic. The spacing of the holes was then decided by dividing the length of the band by eight so that the screws would be equally spaced across the band. The equation used to find s, spacing of the screw holes, was $s = L/8 = 200mm/8 = 25mm$.

6.1.2 Model #2: Fitting the nozzle and the adapter

A key portion of our design was reworking how the nozzle was fit into the nozzle adapter to reduce the amount of failed prints. Our solution was to design the nozzle adapter to fit the nozzle in from the opposite side as originally designed. This side is where the clay enters the nozzle adapter and goes through and leaves the nozzle. To design this properly the CAD model for the adapter had to include a cavity in which the nozzle would sit, having a portion stick out from the adapter. The inside of the adapter where the clay comes in would have to have the top of the nozzle sit flush with the adapter so no clay is redirected. Creating this cavity required recreating the dimensions of the nozzle, including height inner and outer radii as well as the taper on the nozzle end.

6.2 Design for Safety

In order to ensure that the device is as safe as possible, we identified five different potential risks associated with the device and decided how the risks should be prioritized relative to each other by using the risk assessment heat map in Section 6.2.6.

6.2.1 Risk #1: Tube breaks or bursts

Description: The plastic tube of the 3D printer could break or burst. The severity and likelihood of the risk increase if there are cracks in the tube to begin with or if the pressure applied to the tube is too large because of wrong dimensions.

Severity: Marginal. If the plastic tube breaks or bursts in the middle of printing, printing would fail and some clay might come out of the tube. If the tube breaks or bursts during the setup, one might cut their finger while dealing with the broken tube. It would still not be critical because it is unlikely that it causes major health issues.

Probability: Occasional. Considering the scratches and cracks that are already in the plastic tubes that the customer is using, the tube might not be as strong as it is supposed to be.

Mitigating Steps: The severity and probability of the risk could be reduced by making sure that there is no crack in the tube to begin with and that proper pressure is applied in the proper direction. It is also important to make sure that different parts have the right dimensions to perfectly fit in/around the tube.

6.2.2 Risk #2: Accidental ingestion

Description: Since there are some small parts, such as screws and grommets, attached to the elastic band, someone (more likely, children) could accidentally swallow some of the parts if the customer loses them.

Severity: Critical. Swallowing some parts could lead to suffocation or other serious health issues.

Probability: Unlikely. Considering that the device is used by the architecture department of Washington University in St. Louis, it is unlikely that a college student or professor would swallow random parts near the device.

Mitigating Steps: The probability of the risk could be reduced by using the grommet of the right size and making sure that all the parts stay together and attached to the elastic band. It is also important to make sure that there is no little children near the device.

6.2.3 Risk #3: Nozzle adaptor breaks

Description: The 3D printed nozzle adaptor could break if the pressure is too large or the infill percentage of the 3-D printed part is too low. The failure is likely to be due to the pressure in the radial direction.

Severity: Critical. If the nozzle adaptor breaks in the middle of printing, small pieces of the part or clay might fly off. It could be critical if they hit someone's eye or body. If the nozzle adaptor breaks during assembly, it could damage someone's hand.

Probability: Occasional. Since PLA is not the strongest material, it is possible that the 3-D printed part fails especially with a lower infill percentage.

Mitigating Steps: The severity and probability of the risk could be reduced by 3D printing the part with the infill percentage that is high enough to support the applied pressure in the radial direction. It is also important to use the right dimensions to perfectly fit in the tube.

6.2.4 Risk #4: Elastic band breaks or flies off

Description: The elastic pin-band could break or fly off as the customer straps it around the tube or as the printer operates if too much force is applied to it.

Severity: Critical. If the elastic band breaks or flies off during the printer operation, it could be critical because not only the band itself but all the small parts attached to it would also fly off. It would be dangerous if they hit someone's eye or body.

Probability: Occasional. Because of its nature of wanting to go back to its original form when stretched, the elastic band could easily fly off if the applied force was too large or the customer was strapping it around the tube in a wrong way.

Mitigating Steps: The severity and probability of the risk could be reduced by using the material that is strong enough to support the applied force in the band. The probability of the risk could also be reduced by making the strapping process easy, fast and intuitive.

6.2.5 Risk #5: Screws break

Description: The screws on the elastic band could come out or break if the applied force is too large during the operation.

Severity: Marginal. Since there are eight different screw halls, the band will likely still stay even if one of the screws breaks. If all or most of the screws break or come out, then it would be a big issue.

Probability: Unlikely. Screws should be made strong enough to support decent amount of force. Since there are eight screw halls and force should be distributed among these screws, it is unlikely that multiple screws would break to a point where they cannot hold the parts together. Furthermore, this is the current method the customer uses to secure the nozzle adapter, and there have been no issues with screws breaking thus far.

Mitigating Steps: The severity and probability of the risk could be reduced by using screws that are strong enough to support the applied force and making sure that the dimensions of different parts match so that the force will not be excessive. It is also important to test different grommets for the holes and use good ones so that the screws will not easily come out.

6.2.6 Prioritization of Different Risks

Figure 28 shows the risk assessment heat map created by entering the risk names, impacts, and likelihoods into the provided Risk Assessment template.

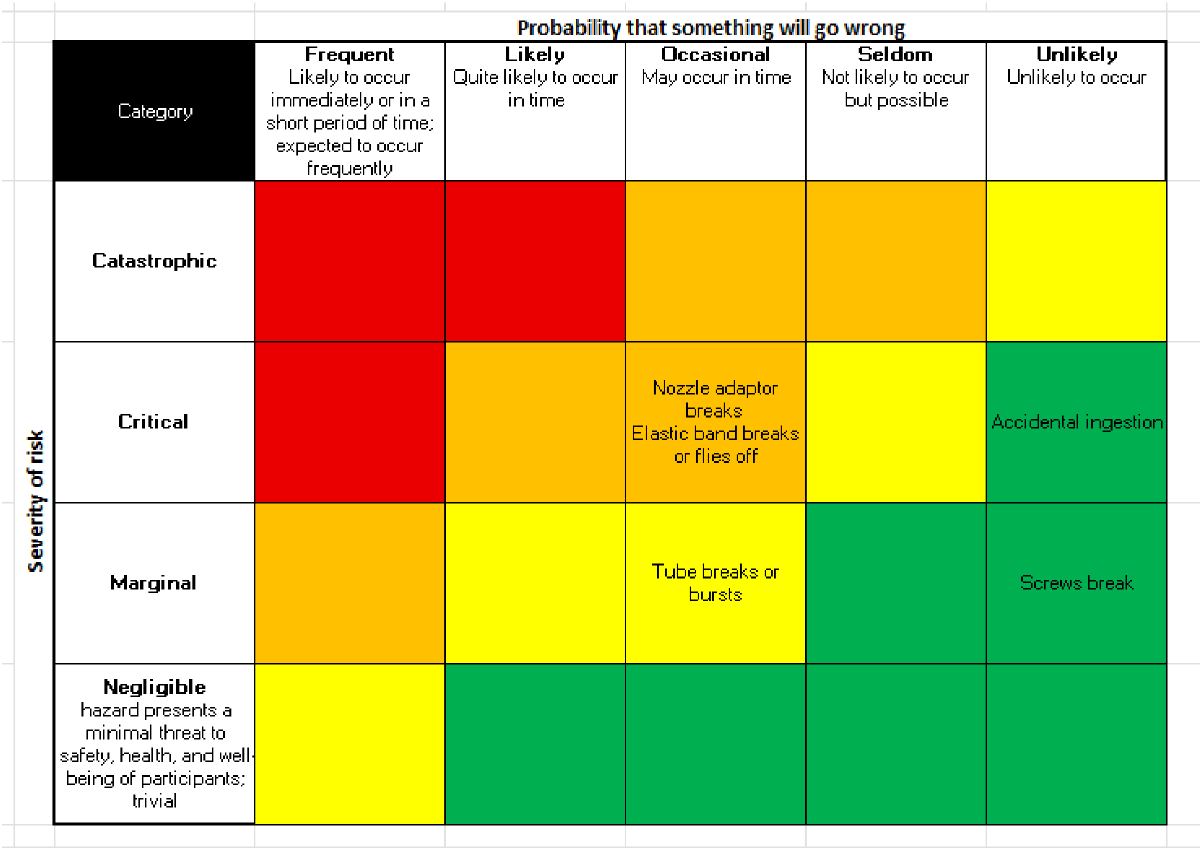


Figure 28: Risk assessment heat map

According to the heat map in Figure 28, "Nozzle adaptor breaks" and "Elastic band breaks or flies off" are the highest priorities because they not only have critical consequences but also could happen occasionally. The next highest priority was "Tube break or bursts" because even though the severity of the risk is marginal it happens occasionally. Although "Accidental ingestion" could have critical consequences, it is unlikely that it happens, so it is not a priority. The lowest priority risk is "Screws break" because it is unlikely that is happens and its consequences are marginal. Therefore, we should focus on the two risk of the highest priority, "Nozzle adaptor breaks" and "elastic band breaks or flies off". We can do this by using the materials that are strong enough to support the applied force, using the right dimensions for different parts, as well as making the band strapping process easy, fast and intuitive.

6.3 Design for Manufacturing

Our current prototype includes two main parts: the new nozzle adapter and an elastic pin-band. Together, these two parts have five components:

- Elastic strip with holes
- Rubber grommets (8)
- 3D printed nozzle adapter
- Rubber seal

- Machine screws (8)

The first piece is the nozzle adapter. This was 3D printed in one piece, and then a rubber seal was added around the top to ensure the clay doesn't come out around the edges. This component was easy to manufacture, as it is only made of these two pieces that one slides together after printing. This ensures that if it breaks, the customer can easily print another one using the Campus Makerspace.

The second piece is the elastic band that is used to attach the tube filled with clay to the nozzle adapter. This elastic band is stretchy enough to be able to fit the pins into the holes, and stiff enough to hold the pins in once in place. The grommets serve to keep the pins in place as well as to keep the fabric from fraying.

These needed to be separate pieces because the tube will go in between them. The customer needed to be able to take it all apart to clean it after running a print, so they had to be separated. Furthermore, the customer can have many nozzle adapters and many elastic pin-bands that can be used interchangeably by her students.

There are not many changes we could make to reduce the number of components, however, we could experiment with using only 4 or 5 screws/pins to hold the adapter in place instead of 8.

6.4 Design for Usability

A visual impairment, either being red-green color blindness or presbyopia, would not make it impossible for our device to be used. In the case of red-green color blindness this would have no effect on the usage of our device. For impairments that either make seeing things difficult or impossible this would hinder the usage of our device though not make it explicitly impossible to use. Aside from making the holes in which screws are put in more distinct by possibly color design there would be little to do to make those visually impaired have an easier time using our device.

In the case of a user having a hearing impairment there is no facet of our design that has any input or output based in sound. The whole process is done by touch and sight alone. Having the ability to feel the screws and nozzle fall into place is enough to fully utilize our device.

For users that have physical impairments this would be where some difficulties would occur in usage. To employ our devices and set them up requires a modicum of fine motor control and dexterity. So keeping hands and fingers steady and precise is largely key. Not to mention that for easy use, though not impossible, utilizing both hands is recommended. This is due to the fact that the nozzle adapter should be held while the strap and screws are inserted to keep it in place. To design with these limitations in mind possibly a clip on the adapter what would attach to the side of the printer tube to keep the adapter in place would make securing the adapter with the strap easier.

For those individuals who have their control impaired this is similar to the previous impairment and how the design would have to change for its consideration. Though in the cases of distraction or fatigue neither of these would make the usage of our device impossible. As mentioned previously a large portion of this process can be done entirely by feel if familiar enough with the process so absent-mindedly doing this task would be possible. Also this is a rather easy task which taxes the user little to none, so excessive fatigue would not be an issue for this device either.

6.5 Design Considerations

Table 3 and Table 4 list factors considered for design solution and contexts considered for ethical judgements respectively.

Table 3: Factors considered for design solution

Design Factor	Applicable	Not Applicable
Public Health		X
Safety	X	
Welfare		X
Global		X
Cultural		X
Societal		X
Environmental		X
Economic	X	

Table 4: Contexts considered for ethical judgments

Situation	Applicable	Not Applicable
Global context		X
Economic context	X	
Environmental context		X
Societal context		X

7 Final Prototype

7.1 Overview

Our prototype achieved all three performance goals.

1. The new nozzle adapter requires less physical effort and inconvenience to set up a print than the current adapter.

The old method took 30 min to one hour to set-up the print. This was largely due to having to manually screw in 16 screws into holes which are often stripped or clogged with clay. The screws alone took 5-7 minutes. Our method reduced this time to just 20-30 seconds for the screws. This reduced the overall set-up time.

2. The new nozzle adapter requires less physical effort and inconvenience to disassemble and clean than the current adapter.

Similar to the first goal, our same method reduced the time it takes to removing the screws significantly from 3 min to 10-20 seconds.

3. The new nozzle adapter enables a higher percentage of successful prints than the current process.

Our new nozzle adapter design includes a tapered hole for the nozzle to fit in, allowing it to be placed from the top instead of the bottom. This keeps the nozzle from falling out, as it is no longer secured by set screws. Using this method, the nozzle did not fall out during printing, leading to a higher number of successful prints. We have not tested this long-term (over the course of a semester), but we assume this would be the case for multiple uses.

Images of our final prototype are below.

Figure 29: The final nozzle adapter after first use.

Figure 30

Figure 31: The final pin strap after first use.

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A Appendix

A.1 Instructions for the Customer to Recreate the Prototype*

*See next page for the pdf of instructions.

3D Potter Nozzle Adapter and Pin Strap

Supplies List:

- Rubber Seal
    - O-Ring-Loaded U-Cup Seal for 0.343" Groove Width, 2" ID x 2.625" OD x 0.313" Wide - McMaster
- Elastic
- Grommets (x8)
    - Circular - 0.312" (7.92mm) Grommet 0.187" (4.75mm) Black - DigiKey
- Screws (x8)
    - M5-0.8 x 16mm (anything of this size will work)
    - Flat Head OR
    - Hex Head Bolt (for easier handling)

1. Nozzle Adapter

If you want to get a new nozzle adapter, simply use an on-campus 3D printer or submit the .STL file to an online, 3rd party 3D printing company. The file is located on a USB file. Once printed, add a grommet to get a better seal between the adapter and tube wall.

2. Pin Straps

Use any kind of stiff elastic band or strap. Ensure that it is wide enough (+1 inch). Cut the strap to be 23cm / 9in in length when not stretched. Measure and cut 8 small holes, evenly spaced, and in the center of the elastic. Place a grommet in each hole, but leave one hole empty at the end. Place a screw in each grommet, all facing the same direction.