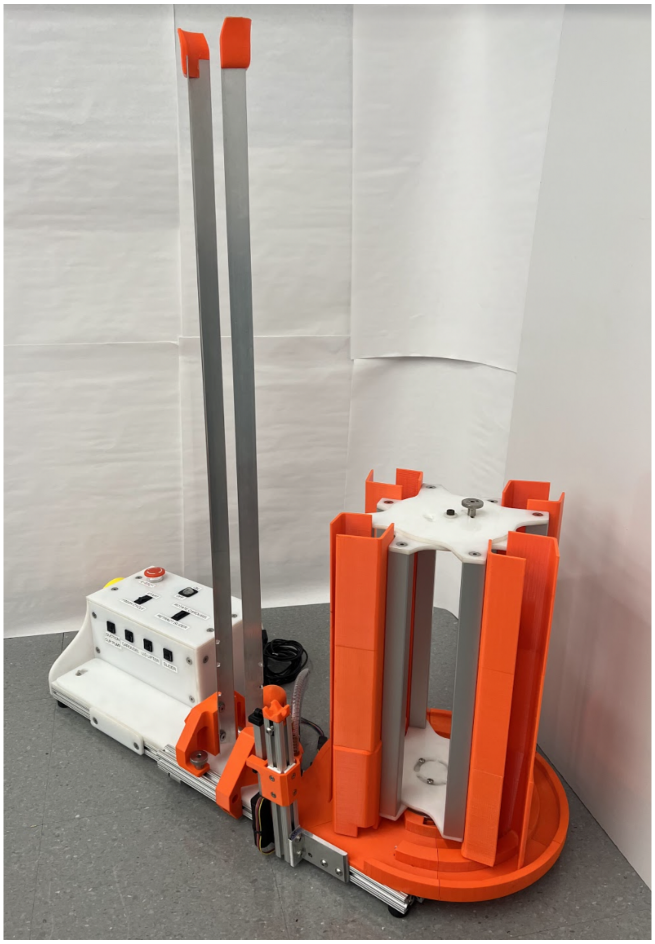
Automated Plate Filler Project

Team 23:
Edanjen Lin
Erica Liu
Matthew Pan
Karen Reyes Carmona

Project Sponsor:
Matthias Truttmann

Section Instructor:
Randy Schwemmin

MECHENG 450 Winter 2023
4/24/2023



Abstract

In research, plates (petri dishes) are used to contain and study various processes under controlled conditions. For instance, Dr. Truttmann's lab uses petri dishes to breed Caenorhabditis elegans. The research conducted on these organisms is used to study neurodegeneration under a range of controlled conditions, so having a ready supply of prepared and petri dishes filled with a growth medium (agar) to breed these worms is paramount for the lab ecosystem. Usually undergraduate lab assistants are tasked with manually filling the plates for the lab, but automating this process would free them up for more rewarding work and would produce a steadier flow of filled dishes for the lab. For 2 semesters of ME 450, students have worked on developing a low cost alternative to the prohibitively expensive automatic plate fillers that would usually find their way into a lab like Dr. Truttmanns, albeit for operations with a much higher throughput. The developed prototype was able to reliably work on 3 sizes of plates, until the lab switched to plates with ridges on the lids, which prevented the mechanism inside the machine which pushed the plates into a feeder from removing the bottom plate in the stack. The goal of our project is to modify this existing machine to minimize the time the undergraduate assistants spend on the plate filling process by making the existing prototype compatible with the different lid profiles. Our team has gone through the concept creation, concept selection process, as well as performed engineering analysis and testing to develop a solution to the machine's compatibility to different plates problem. We developed two alpha designs and after some analysis created a finalized wedge system that would enable the machine to separate the bottom plate from the rest of the stack and push it through to get filled up with medium and continue on to the next subsystem of the machine. The next steps are verification of our engineering specifications and validation of our implemented solution. The verification process was successful in that all eight requirements were verified through cycle testing of the machine, engineering analysis, and working closely with the project sponsor, Dr. Truttmann, throughout the whole process. The verification process was physical testing heavy as this project was small scale with there not being intense load cases involved and it being easy to prototype and physically test the machine. Validation process was not fully completed but the team looked for Dr. Truttmann's feedback all throughout the design process to ensure he was satisfied with the results and the design problem was fully addressed. The team feels confident delivering the design implementation to Dr. Truttmann's lab. The fully functional machine will directly compete against the industry standard and indirectly against prefilled plate companies. The main goal is to have a positive impact on the experience for undergraduate researchers and increase the efficiency and productivity of the lab with the machine's reliability being the top priority to avoid waste of agar.

Table of Contents

Introduction

The Truttmann Laboratory is a Michigan Medicine Laboratory which conducts research with the goal of determining the impact of post translational protein modifications (PTMs) on proteostasis in the context of aging and aging-associated neurodegenerative diseases.[1] Proteostasis involves the regulation of production, conformation, interactions, and clearance of proteins within the cell. Dr. Matthias Truttmann is the main investigator of the laboratory. A big portion of his experiments in the lab are *in vitro* and *in vivo* models to study proteostasis in eukaryotic cells, such as *C. elegans.* These are tiny, transparent worms that are easy to cultivate, low maintenance and have a short life cycle.[8] They are therefore ideal candidates to be studied. The Truttmann Laboratory experiments consist of the *C. elegans* living in a small petri dish filled with agar and being studied through a microscope. Agar is a gelatinous substance that can grow bacteria that serve to feed the worms. The petri dishes need to be filled with agar before any *C. elegans* can be placed inside. In the Truttmann Laboratory, the petri dishes or plates are usually filled by hand which is a long and tedious process. The lab assistant would have to manually prepare the dish and use manual pump to dispense the gelatin like medium into the dish.[14] This process can take up to five hours a week for a graduate student and even longer for a paid undergraduate research assistant from the Undergraduate Research Opportunity Program (UROP) with a salary of $15/hour.[3] Mirella, a graduate student studying Neuroscience and conducting her research at the Truttmann Lab, informed the team that she has to manually fill plates for her experiments. She also mentioned that the lab can go through up to 8L of the agar medium a day which fills up approximately up to 480 dishes depending on the dish size.[4] Plate filling takes a lot of the laboratory's time and resources.

Dr. Truttmann is the sponsor for this project. He is looking for a solution to minimize the time that research assistants have to spend on the plate filling process so they can gain a more meaningful research experience and the lab can be more productive with its experiments timeline and resources. Dr. Truttmann wants a fully functional machine that automates the plate filling process that serves to meet the laboratory's budget, space limitations, and experiment capacity needs. Dr. Truttmann has worked with previous MECHENG 450 teams to create an existing prototype for this automated process. This prototype is functional and meets the needs of the Truttmann Laboratory; however, the laboratory had to change plate distributors due to COVID shortages and the existing prototype is not compatible with the new plate designs. Our team is tasked with working alongside Dr. Truttmann to solve this problem.

Problem Statement

The version of the automated plate filler we were presented with at the start of the project was designed to work with petri dishes that had a flat geometric profile on the top of the lids. The new petri dishes the lab switched to have circular ridges on top of the lid to allow the lids to easily stack with each other, however the pushing mechanism this machine initially functioned off of cannot push the bottom petri dish out from under the stack, due to the ridges interfering between each petri dish. **We need to redesign the feeding mechanism of this automated plated filler to be compatible with the three industry-standard sized petri dishes used in Dr. Truttmann's lab, regardless of the lid profiles.** We discussed our plans with Dr. Truttmann, and since he is satisfied with every other function of the machine, we are defining the scope of our solution to exclusively solve the feeding mechanism. Any improvements to the rest of the machine's functionality will be welcomed, but not expected. The big deliverable for this project would be a fully functional machine that meets the requirements and specifications below.

Plate Filling Process

In order to learn more about the plate filling process, we interviewed Dr. Truttmann and Mirella. We learned the lab uses nematode growth medium (NGM) agar.[13] We learned the laboratory is not looking for a large scale automatic plate filler found in the market because of space limitations in the lab. The Truttmann Laboratory processes the agar medium in batches of 2L, which fills up approximately up to 120 plates, and therefore is not looking for a large industrial plate filler that can process hundreds or thousands of plates at a time.[4] We asked Dr. Mirella about the possibility of changing the existing prototype to have a larger process capacity but the lab prefers to process smaller medium batches in order to properly monitor the medium and prevent any waste if the agar hardens before being properly dispensed into a plate. There are also some smaller scale marker plate fillers and the team asked about those. Dr. Truttmann let us know that the cost for market plate fillers are high and that the lab is looking for a more cost-effective solution specialized to their space layout, budget, and processing requirements.

The team asked about the extent to which the plate filling process could be automated. Mirella let us know that the lab is still expecting the undergraduate research assistants to interact with the machine. The research assistants will have to input the empty plates to the machine in some form, will have to turn on the machine through some interface, and will have to pick up the output of filled plates once the machine processes all the agar medium.[4] We learned that the lab uses plates of different diameters (30, 60, and 100 mm) so the machine must be able to fill up all of the different size plates. The team further asked about the concern for cross-contamination when filling up the plates. Mirella informed us that for the purposes of this lab cross-contamination is not an issue as the bacteria that grows in the petri dishes serves to feed the tiny worms that live in the dishes for the duration of the experiments. While this means that we do not have to worry about cross-contamination, this limits the scope of labs to which our plate filling machine can be useful as some labs do require extreme cross contamination protocols. Furthermore, the lab researchers are the ones responsible for manually sanitizing the machine. This means that we will have to make sure the materials are not corrosive to cleaning chemicals or prone to rusting.

Mirella went on to let us know that the laboratory is happy with the existing prototype that previous teams have delivered. The laboratory is looking for a solution to make the existing machine able to process the new plates that the laboratory transitioned to during COVID. Dr.

Truttmann and Mirella agree that the team should prioritize a fully functional machine, compatible with the new plate design, over further improvements to the machine as they are happy with the other aspects of the existing prototype. However, the laboratory did give our team creative freedom with the machine to improve it as we see fit. The interviews helped the team understand the objectives and deliverables of this project: a fully functional plate filler machine with any improvements a plus and separate from the project scope. Dr. Truttmann considers a fully functional plate filler a successful project outcome.

Benchmarking

The team did some research on market automatic plate filling machines. We wanted to determine if any of the machines in the market meet the needs of the Truttmann Lab and could serve as a solution and better use of resources and time over developing a plate filler. Table 1 summarizes the benchmarking research.

Table 1: Summary of benchmarking of other automated plate fillers on the market.

Machine	Manual Filling	Pre-filled Agar Plates[7]	PS3900[6]	APS One[5]	450 Prototype
Supplier	Lab Assistant	Mycology Supply	Neutec Group	Biomerieux	Trutmann
Price ($)	15 per cycle of 120 dishes	195 per cycle of 120 dishes	52,377	40,000	1200
Capacity (Plates)	N/A	40	900	560	120
Feed Rate (Plates/hour)	120	N/A	650-800	900	120
Dimensions (m)	N/A	N/A	0.6 x 1.8 x 0.76	0.71 x 0.89 x 0.64	1.1 x 0.43 x 1.4
Weight (kg)	N/A	N/A	36.2	59.87	13.61

For benchmarking, the team first wanted to consider if the lab benefits from automating the plate filling process over filling the plates by hand. For this cost-analysis, the team considered that an undergraduate student assistant is paid 15 dollars an hour and the average undergraduate student assistant fills 120 dishes in an hour of work.[4] This would mean that it costs the laboratory 15 dollars every time they use up 2L of medium if they fill the plates by hand. This is without considering the price of the plates and agar. To monetize the automated plate filling process, the team considered the budget we discussed with Dr.Truttmann of 1500 dollars to fix the plate filling machine. If we use all the budget, it would take running the machine through 100 cycles of 2L of medium until it becomes free compared to filling the plates by hand. It is important to note that this is an overestimation as we expect to be well under budget and that we have considered our labor to be free. Talking to Mirella, we learned that the laboratory runs about 11 cycles of 2L of medium a week, and this is an underestimation. So, it would take the laboratory less than 10 weeks to see cost benefits from using an automated plate filling process. As this lab will continue to carry out research for far longer than 10 weeks, it is clear that automating the plate filling process is more cost effective for Dr. Truttmann's laboratory in the long term.

The team also considered the possibility of buying pre-filled petri dishes instead of automating the process. We analyzed this by comparing the cost of pre-filled petri dishes with the cost of empty plates and the agar associated with them as well as the cost of filling them by hand. We found the pre-filled plates from the Mycology Supply to cost 195 dollars per cycle, here we defined a cycle as 120 dishes because that is approximately how many plates the 2L batch of medium will fill up in the Truttmann laboratory.[7] We found the empty plates to be 50 cents each from the lab's supplier VWR, meaning it is 60 dollars per cycle of 120 dishes.[15] We found the agar medium to fill one plate to be 5 cents, meaning that filling up 120 dishes would cost 7 dollars. The last cost to consider is the 15 dollars it takes for an undergraduate lab assistant to fill up 120 plates. By adding up the cost of the empty plates, the cost of the agar it takes to fill them, and the cost of filling the plates by hand we can see that it would cost about 82 dollars to fill up the 120 dishes in the lab. The price of the empty plates and supplies is much more cost-effective compared to buying the plates pre-filled, about 82 dollars compared to 195 dollars.

Looking at Table 1, the two market plate fillers, PS3900 and APS One, are outside the laboratory's budget for this machine and therefore would not be good solutions to this project. These are also larger capacity machines that do not fit with the laboratory's needs of handling approximately 120 dishes per medium cycle. This benchmarking analysis proved to the team that fixing the machine to work for the new lab plates is a good use of resources as it is the best solution for the problem compared to other solutions in the market.

Information Sources

Early in the semester we had a meeting with the librarian, Paul Grochowski, during which we focused on looking for standards applicable to our machine. Searching through the 450 databases has worked best for us. Another source that was helpful to us was looking at previous 450 team reports of the team who worked on the automated plate filler and their cited sources. Accessing some of the standards presented a challenge and working with the librarian helped us in this regard.

Existing Prototype

As mentioned above, there is an existing prototype that previous MECHENG 450 teams have developed and built. Figure 1 depicts the existing prototype and the main working components to the machine: the plate guides, the electric box, the pushing mechanism, the filling up station, and the carousel storage. We explain how this prototype works below.

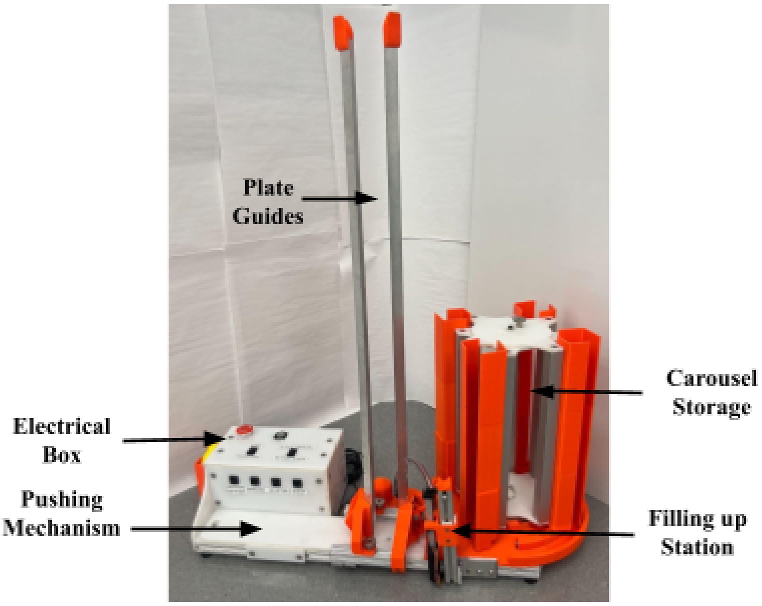


Figure 1: The plate filler existing prototype and the five main sections: plate guides, electric box, pushing mechanism, filling up station, and the carousel storage.

<u>Plate Guides</u>

The first step to working the plate filler is for the user to input the empty plates into the plate guides component of the machine. First, the user must make sure that the plate fits in between the two vertical railings. The plates should fit so that the plates can be stacked in between the railings and not fall out but also move up and down freely. Figure 2 depicts the stacked plates in between the railings. The user can place up to 120 dishes in between the guides. Since the labs used different size places, as seen in Figure 2B, previous MECHENG 450 teams have made the railing closer to the electric box adjustable. The user can unscrew the railing at the bottom and slide it further or closer away from the opposite railing according to the dish size and then tighten it at the desired size. Figure 2A also depicts the screw that fixes the adjustable railing. Previous teams have also 3D printed plate templates, as seen in Figure 2C to aid in adjusting the plate guides to the correct position.

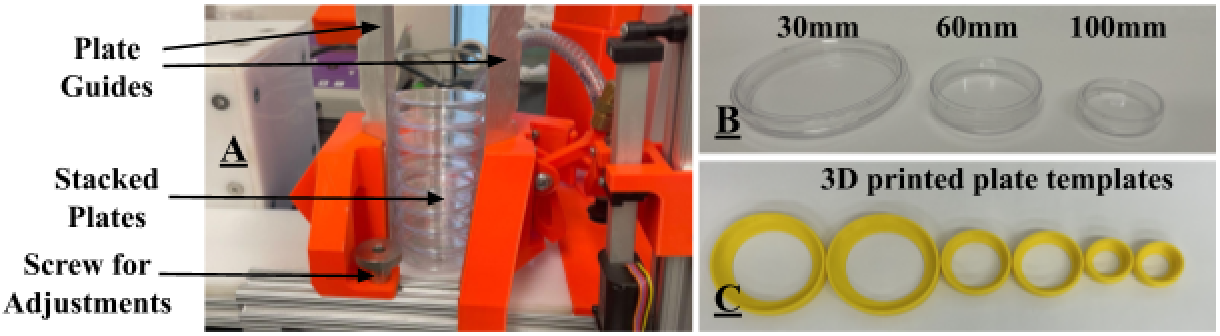


Figure 2: Figure 2A depicts the stacked plates in between the guides as well as the screw to adjust the leftmost railing position. Figure 2B shows the different plate sizes while Figure 2C shows the 3D printed plate templates.

Electrical Box

Once the plates are stacked and ready to be processed, the user must turn on the machine through the electric box. The user should also prepare the external pump tubing to dispense the medium, as seen in Figure 3. The electrical box serves as the interface for the user and is where the user inputs the desired settings. The user includes an emergency stop. Figure 3 shows the electrical box.

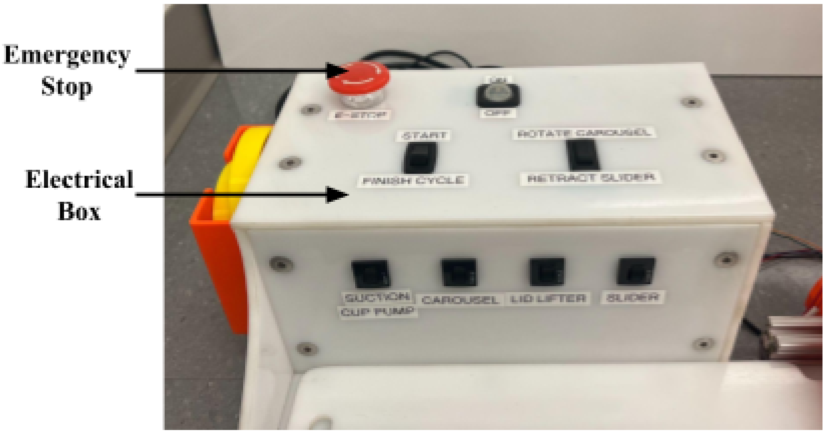


Figure 3: The electrical box component of the machine.

Pushing Mechanism

After the user turns on the machine, the autonomous portion of the process begins. The pushing mechanism is responsible for pushing the bottom plate from the stack towards the filling up station. The pushing mechanism simply consists of a flat acrylic part that moves forwards, or in this case to the right in the pictures, and slides the bottom plate out from the bottom of the stack to under the suction up shown in Figure 4. Since the lid of the design plate that the previous MECHENG 450 groups worked with was flat, the plate could easily be pushed out from under the stack and through the space underneath the rightmost railing. Figure 4 depicts the motion of the plate. Once the plate is filled up in the filling up station, which is the next step, the machine automatically pushes the next plate through.

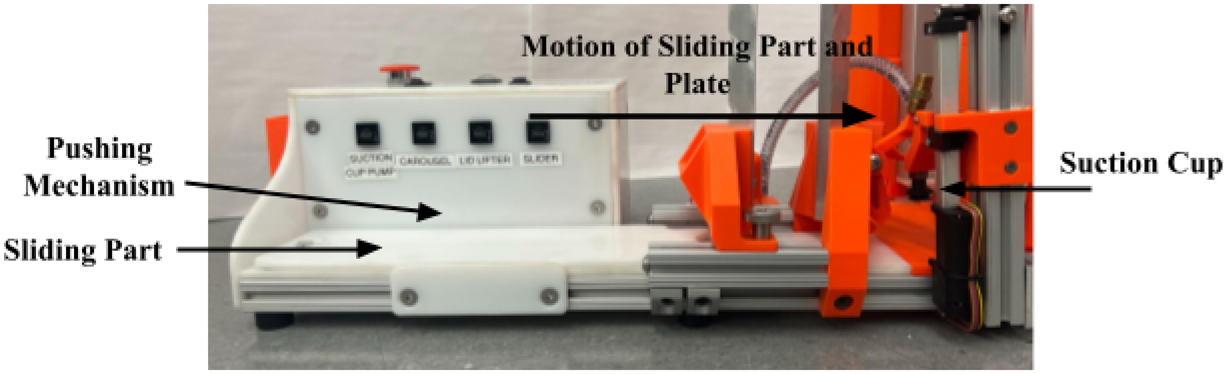


Figure 4: The pushing component of the prototype. The motion of the sliding part and the bottom plate is depicted as well as the suction cup that makes up part of the filling up station for the plate.

Filling up Station

After the plate is pushed under the suction cup, the suction cup lifts the lid and gives clearance for the external pump to dispense the preset amount of agar into the plate. It is important to note that the user should set up the tubing for the external pump before starting the machine. The suction cup pump is depicted in Figure 5 and the external pump and tubing in Figure 5 . Once the plate is filled up, the lid is placed back on and the plate is pushed into the carousel storage.

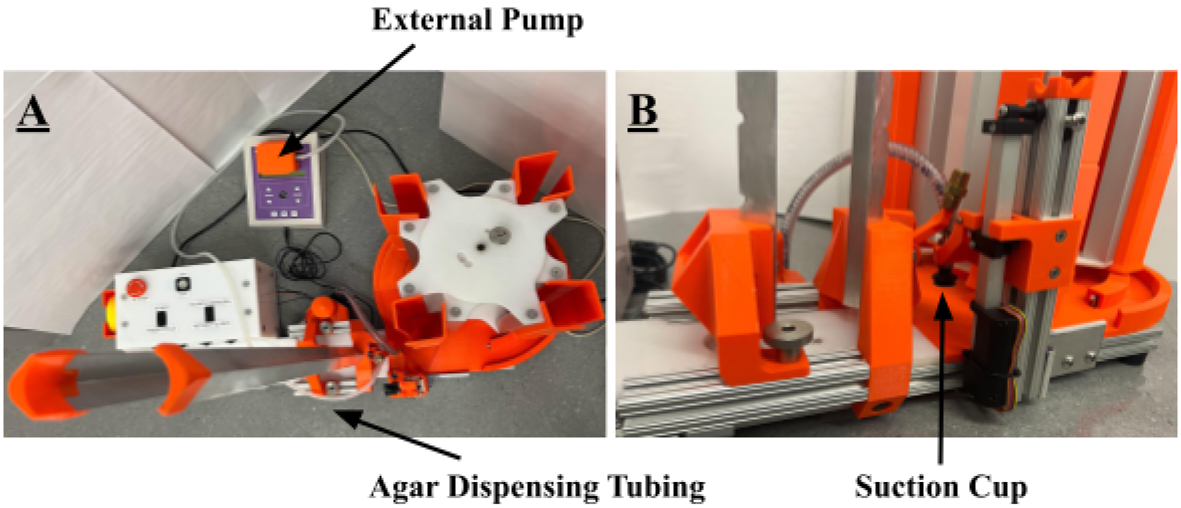


Figure 5: Figure 5A shows the external pump used to dispense the medium and the tubing connecting the pump to the plate fling machine. Figure 5B shows the suction cup that lifts the lid.

Carousel Storage

The last step of the automated process is for the filled plate to be pushed to the carousel storage area by the new incoming plate, which is pushed by the pushing mechanism. The carousel storage spins and the filled plate is stacked into one of the towers as seen in Figure 6. Then the process starts again as the next plate in the stack starts being filled up. The plates stack up in the towers and the user must manually turn off the machine once all of the plates are filled up.

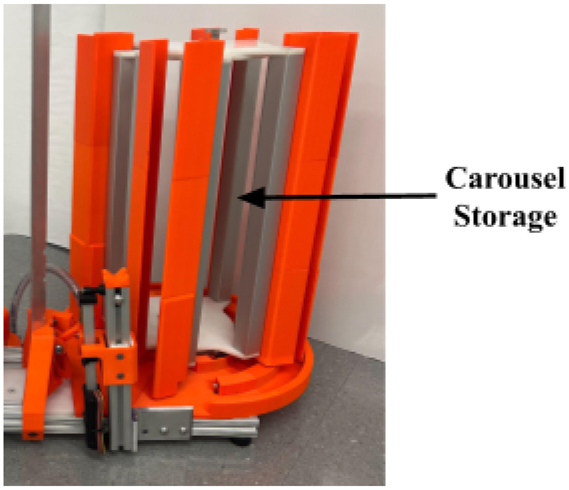


Figure 6: The carousel storage component of the machine where the filled plates are stacked.

This is a great working prototype and should allow for modifications so that our team can make it compatible with the new plate designs adopted during COVID. This machine solved the problem for Dr. Truttmann's laboratory in the past. However, this is no longer the case as the laboratory can no longer use it with the current plates.

Standards

The first standard we must adhere to is the IEST-RP-CC004.3 from the American National Standard Institute(ANSI).[21] This standard ensures that our materials have to resist corrosion when being cleaned with 70% ethyl alcohol after each use. The second standard adapted from ANSI is IEST-STD-CC1246E which guides the acceptable level of contamination allowed on laboratory equipment.[22] The standards referenced are important because they limit the number of contaminated petri dishes to increase the effectiveness of the lab output. Another standard we are adding to our engineering specifications is 1910.212(a)(3) from OSHA. This standard satisfies the safety requirement as it protects the user by guarding any operation points. The most recent standard added is 1926.251(D)(6)(i) from OSHA, which relates to our durability requirement. This standard relates the current wear of the design parts to the potential time till failure . These standards are discussed in more detail in the User Requirements and Specifications section below.

Intellectual Property

As of now Dr. Truttmann is not looking at protecting intellectual property. This project is meant to be a one time manufacture for the Truttmann Lab. There is a potential for mass manufacturing if our sponsor is interested since this machine is a more affordable option to small labs like the Truttmann lab when compared to other market machines. If Dr. Truttmann pursues mass manufacturing, he should look at acquiring patents and checking that our design does not interfere with other active patents, which from our benchmark research it does not. Dr. Truttmann would own the intellectual property in this case.

Design Process

We have decided to go with the ME Capstone Design Process Framework and are currently working on the problem definition stage of the project. We had considered the Dym and Little model due to the simplicity of our project, but we also wanted to take advantage of the full process in case we found other problems that arose later. We also considered the Pahl and Beitz model due to its popularity, but it was far too complex for our project, and also focused too much on marketing. After familiarizing ourselves with the problem, we decided that the "creative leap between problem definition and solution concept"(Wynn and Clarkson, 44) would not be too much of a problem for us. We would have to cycle through several different geometries of the plate pusher, but the solution itself seems pretty straightforward.

We felt that the ME Capstone Design Process Framework is the most useful since it is relatively straightforward while still having an iterative process. We have moved through the problem definition stage fairly easily and have gathered enough information to understand what is expected of us. During our initial meeting with Mattias Truttmann and Mirella Hernandez-Lima, we saw the machine in action as well as asked all of our preliminary questions in order to establish a foundation for our project. From there, we were able to take the machine and test it out in the X50 lab. We have also conducted an interview with the primary stakeholder, the lab assistant, who uses this machine on a daily basis.

So far, we have made no changes to the original framework presented by the ME450 Capstone besides simplifying the requirements for Solution Development & Verification. There are no major forces that would require an FEA, and would be made of one material and so would not require a full bill of materials. We would make sure, however, that it can run for 1000 plates with only 10 jams as a stress test. As mentioned previously, we see a straightforward path from problem definition into concept generation. From there, once we have a precursory design, we could easily iterate through it a few times in order to fix any problems that arise. We think that the ME Capstone Design Process Framework fits our project perfectly since it encapsulates the basic needs for what needs to get done, while still being flexible enough to accommodate any unforeseen issues.

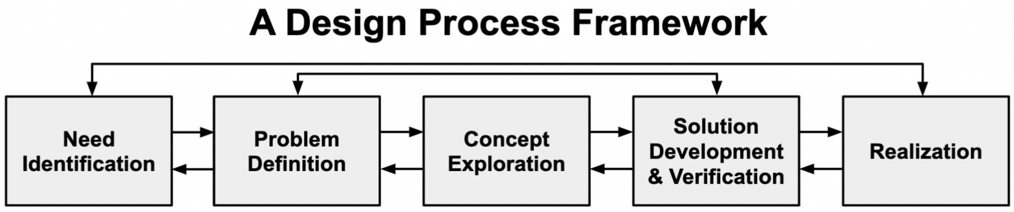


Figure 7. ME Capstone Design Process Framework

Design Context

We created a colored-coded stakeholder map including the primary, secondary, and tertiary stakeholders as seen in Figure 8.

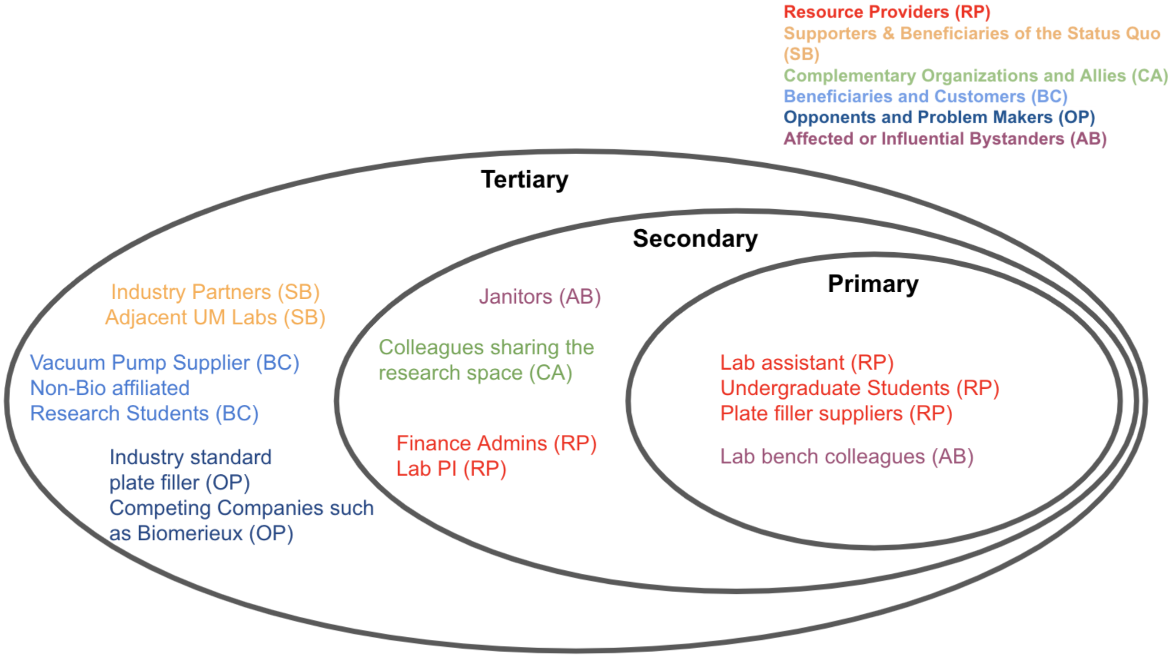


Figure 8. Stakeholder map

The main resource providers are the University of Michigan, and the institutions that fund the lab through grants or other means. Dr. Truttmann has allocated $1,500 for the project, but due to the expensive nature of biological research, more will be available if necessary. We currently do not foresee any large expenditures, as the main cost will be the nylon used in 3D printing during the concept exploration and the solution development and verification stages. 3D printed materials are quite cheap, and even through multiple iterations, will still be inexpensive.

The primary stakeholders will be the ones that are working in the labs, and will be the only ones who are affected directly by our project. Currently, the machine does not accept plates with ridges, and they have to be put in manually by the undergraduate students, which is time-consuming and not the most efficient use of their time. The janitors would be the next group of people to be immediately affected by our project, as our prototype will introduce more plates with ridges into the lab, leading to less spilled plates and messes. This will also save them time cleaning up unnecessary and foul odor spillage. These are the people who will be positively affected by our project, and is one of the specific goals brought up by Dr. Truttmann at the start of our meeting. Furthermore, from the tertiary stakeholders, the plate filler suppliers will also benefit from our project, since they will no longer have to manufacture one specific plate in order for our lab to function properly. They may also have more business since our machine will be able to use more plates because our machine is faster than humans and can run automatically.

Another thing to consider is the power dynamics of the lab that we would be affecting. Even though the undergraduate students would be the ones who are directly impacted by our machine, we only interface with Dr. Truttman and Mirella. Neither of them use the machine, as Dr.

Truttman deals with higher level tasks in the lab, and Mirella prefers to hand inject the solution since her experiments require a higher level of specificity. Since we cannot contact the undergraduate students, we have to trust them as our contact point for the project. This however, may not always line up, as what is best for the lab will not always be better for the students. An example of this could be prioritizing the efficiency of the lab over ease of tasks for the students.

However, the stakeholders that will be negatively impacted by this project are the industry standard plate filler manufacturers and pre-filled plate suppliers. These are the direct competitors to our model, and would be the only other options if our project does not succeed. They are both much more expensive options for the lab, which they could get away with since the options are limited. On the other hand, the manufacturers of the raw plates and gel solutions would be positively impacted by our machine. Since our machine would increase the efficiency and productivity of the lab, they can perform more experiments, and also use more raw materials. This will increase the amount of business that these companies get, and may ripple out into other labs if our machine becomes patentable.

Socially, we would be improving the wellbeing and development of the two undergraduate students. Instead of doing a mindless task that must be done, they could leave it to the machine, and do work that is more fulfilling. Often, the lowest members of labs have to do the grunt work that, while essential for the lab, is not work that is directly related to their field of study. In removing these tasks from their jobs, they will not be mere tools in the lab, but helpful assistants who can learn and contribute in a more meaningful way. Our sponsor is prioritizing this over the other impacts because he also wants the undergraduate students to be able to take away something from the lab and be able to contribute to research at the university. The project’s effect in other spheres will be much smaller since our project is on a very small scale as of now.

Our project also has minor effects on the environment. Since the machine will put in the same amount of gel everytime while putting in the agar, there will be less waste in the long run. The ridges on the lids also provide a tighter seal around the agar, meaning that there will be less possibility for contamination, therefore reducing waste.

The automated plate filler can also lead to more efficient medical research to better public health and welfare. The Truttmann Lab is currently doing neurodegenerative disease research that serves to develop better medical treatments in the future, and maybe even for diseases that currently do not have cures.

There is potential for the project to grow into a larger scale once our initial project is finished since the patent on the carousel storage mechanism has recently expired. Dr. Truttmann has a colleague with a patent on the vacuum pump component of our project. Plate filling is a common practice found in most labs that require a culture, and if we can find a way to manufacture our project cheaply, this could be a viable way to undercut the current standard plate filler which currently has a price tag of $40,000. However, this is not a concrete goal as of now, and will depend on how our main objective goes.

User Requirements and Engineering Specifications

One of our first steps in developing the constraints of our project was by talking to Dr. Truttmann about his expectations for what the plate filler should do, and how the existing prototype falls short. Together, we generated a list of requirements for how this machine should be tailored to fit within his lab. We took note of how important each requirement was to the functionality of this machine within his lab, and labeled each requirement accordingly. From there, we created engineering specifications to achieve each requirement using measurable quantities of the plate filler's performance. It is important to note that this list is evolving throughout the design process and reflecting new feedback from Dr. Truttmann. We interviewed Mirella and based on her feedback we overestimated the lab would be running 3 cycles per day on a daily basis. This is the basis for the calculations in engineering specifications.

Table 2. Table of user requirements with priorities presented in high, medium, low levels. Specifications calculations are based on the overestimate that the lab will run 3 cycles per day.

Requirement	Specifications	Qualitative Importance
Reliability	- Machine must be deliver up 120 dishes without interruption -1 out of 720 dishes jams (once every 6 cycles or once every 2 days)	High
Safety	- 1910.212(a)(3)(OSHA): Moving parts > 25 cm from operation points - 1% plates break during usage (18 out of 1800 plates)	High
Accommodates different plates	- Plates with lids of varied profiles (flat lid and lid with dimensions as seen in Table 3) - Compatible with plates of diameter 35, 60, and 100mm.	High
Durability	- Lasts for 10 to 15 years (7800 cycles) - 1926.251(D)(6)(i) (OSHA): Wear on wedge edge < 10% after 50 cycles	Medium
User Friendly	- Require less than 6 steps to operate - Research Assistant can repair in under 5 minutes - Easily replaceable parts (3D printed or readily available)	Medium
Sanitizable	- IEST-RP-CC004.3 (ANSI): Use only non-corrosive materials	Medium
Compact	- Fit within a 1.1 x 0.43 m footprint - Weigh less than 15 kg	Low
Affordable	- Costs less than 1500 USD for modifications	Low

Reliability

Associated Specifications:

- *Machine must be deliver up 120 dishes without interruption regardless of dish design*
- *1 out of 720 dishes jams (once every 6 cycles or once every 2 days)*

The operation of this machine is expected to only require user input while starting, and resupplying the plate filler with the associated growth medium. We were told that the carousel can hold approximately 120 plates per cycle, so we expect that it should be able to fully fill the capacity of the carousel with each round of growth medium. We aim for the machine to jam at most once every 2 days (6 cycles or 720 plates).

Safety

Associated Specifications:

- *1910.212(a)(3)(OSHA): Moving parts > 25 cm from operation points*
- 1*% plates break during usage (18 out of 1800 plates)*

For any machine with automatic functions, safety must be taken into consideration if humans are within its operating vicinity. The machine will have to follow the OSHA standard 1910.212(a)(3)(OSHA). This standard relates to point of operation guarding. We want to ensure that any areas in the machine that the user will interact with while the machine is running are at least 25 cm from any moving parts. The user will also not have to interact with any moving parts while setting up the machine. Additionally, to eliminate any chance of injury to the user, only 1% of plates should crack or break during usage.

Accommodates different plates

Associated Specifications:

- *Plates with lids of varied profiles (flat lid and lid with dimensions as seen in Table 3)*
- *Compatible with plates of diameter 30, 60, and 100mm.*

One of the motivations behind our involvement in this project involves the inability for the current machine to accommodate a wide range of petri dishes. Its first 2 iterations only dealt with petri dishes that had a smooth, featureless lid, so the mechanism used to feed it into the rest of the machine was able to push the bottom dish off the bottom of the stack without interfering with the rest of the stack. Due to supply shifts during COVID, the plates being supplied had to be sourced elsewhere, so the dishes that met the needs of the lab did not necessarily function within the automated plate filler. By tailoring this new design to work with more than one type of petri dish, it will be more resistant to changes in the plates being fed into it. Table 3 shows the dimensions of the new lid and the ridges that prevent the pushing mechanism to push the bottom plate from under the stack. Figure 9 then depicts the dimensions on a plate.

Table 3. Dimensions of the new plates, lids and ridges that prevent the pushing mechanism to push the bottom plate from under the stack.

Size (outer diameter)	Ridge ID (mm)	Height (mm)	Ridge Height (mm)
35 mm	23	11	0.4
60 mm	46	15	0.4
100 mm	79	12	0.6

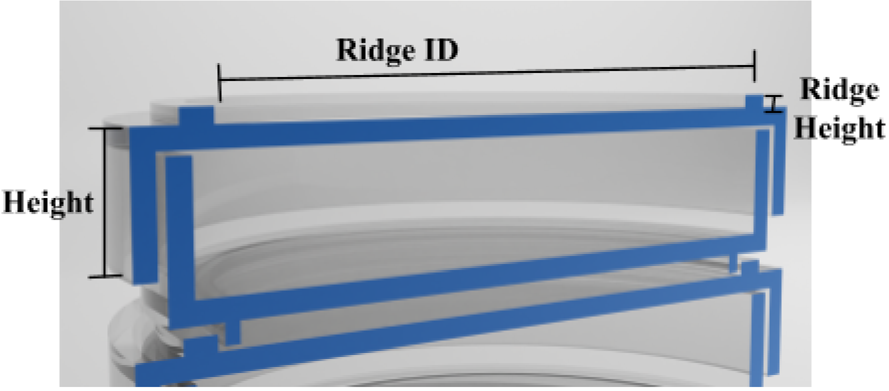


Figure 9: Dimension callouts for the plate lids

Durability

Associated Specifications:

- *Lasts for 10 to 15 years (7800 cycles)*
- *1926.251(D)(6)(i) (OSHA): Wear on wedge edge < 10% after 50 cycles*

In a research setting, having a machine that produces consistent results over a long period of time is paramount to the success of whatever experiments it is being used in. Ensuring that this machine can be maintenance free for around 10 years ensures that it lasts long enough to justify its cost. This time frame was designated per the sponsor's request. We then calculated how many cycles the machine would run in this time according to the 3 cycles per day ratio. In addition, the wedge will only function if it maintains the precise separating edge that allows it to slip between the bottom 2 plates. After 50 full cycles we expect the wedge to degrade less than 10% of its initial geometry to ensure this machine doesn't require constant replacement of the wedges.

User Friendly

Associated Specifications:

- *Require less than 6 steps to operate*
- *Research Assistant can repair in under 5 minutes*
- *Easily replaceable parts (3D printed or readily available)*

The purpose of automating this process is to free up the personnel that would have been manually filling the petri dishes. We were told that it was undergraduate students undertaking this at the start, so one of the first things we decided upon was that it should be intuitively easy to use by whoever needs to interact with the machine. The existing prototype has 5 points of user interaction to operate it, so we want to develop a solution to this project that maintains the low level of complexity for the user interface. After further discussion with Dr. Truttmann, we decided to increase the user friendly requirement from low to medium priority level. In case our solution breaks or needs maintenance a research assistant should be able to replace the mechanism or fix it without advanced knowledge. Therefore we added the specifications that the machine should be repairable in 5 minutes and the parts easily replaceable. Easily replaceable in this case means that the parts are 3D printed, since our sponsor has access to a 3D printer, or readily available to buy online. These specifications are important as they play a big part in the decision process for the final design later on.

Sanitizable

Associated Specifications:

- *IEST-RP-CC004.3 (ANSI): Use only non-corrosive materials*

This machine is being used alongside research involving the growth of microorganisms. For a machine that dispenses growth medium in a non sterile environment, it is expected that some of the surfaces of this machine will see accelerated bacterial growth. In order to combat that, the lab regularly sanitizes its equipment with 70% ethyl alcohol. We want to ensure that the methods used to sanitize this machine does not end up being the cause behind material degradation problems.

Compact

Associated Specifications:

- *Fit within a 1.1 x 0.43 m footprint*
- *Weigh less than 15 kg*

During our visit to Dr Truttmann's lab, we were able to tour the space where this machine was being used. It was set on a table to the side of the room, where it could be accessed separately from the countertops where the majority of the equipment was being stored and utilized. In a small space, it is essential that equipment takes up as little real estate as possible. While vertical space used is not a huge concern, taking up a larger footprint on wherever it is placed would have to have a large benefit in the design in order to justify the increased space it takes up.

Affordable

Associated Specifications:

- *Costs less than 1500 USD for modifications*

Research is unavoidably expensive. According to our benchmarking research, comparable machines that carry the same automated process cost upwards of 40,000USD. For this task, in the capacity required by this lab, it was more economical to pursue an in-house solution to this automation instead of the extra costs associated with an industry standard machine. By staying within the 1500USD budget afforded to us by Dr. Truttman's lab, we maintain the expectation that our solution will be more economical than what is currently on the market.

Concept Generation

The next step in the design process was for the team to start concept generation. The team decided to go through the concept generation process together and come up with possible designs to make the existing plate filling machine compatible with plates of different lid designs and size. We used two techniques for concept development and exploration:

Design Heuristics

The team decided to utilize the design heuristics as our first strategy for concept generation because we were looking for ways to modify the pre existing machine to accommodate different plate and lid profiles. Design heuristics help explore alternative concepts in the early conceptual design process and in our case they helped introduce variations derived from the already existing machine structure to fulfill our project statement of redesigning the plate feeding mechanism of the automated plated filler to be compatible with the three industry-standard sized petri dishes used in Dr. Truttmann's lab, regardless of the lid profiles.[23] There are 77 design heuristics cards, the descriptive titles of all can be seen in Figure 10.

1. Add levels
2. Add motion
3. Add natural features
4. Add to existing product
5. Adjust function through movement
6. Adjust functions for specific users
7. Align components around center
8. Allow user to assemble
9. Allow user to customize
10. Allow user to rearrange
11. Allow user to reorient
12. Animate
13. Apply existing mechanism in new way
14. Attach independent functional components
15. Attach product to user
16. Bend
17. Build user community
18. Change direction of access
19. Change flexibility
20. Change geometry
21. Change product lifetime
22. Change surface properties
23. Compartmentalize
24. Contextualize
25. Convert 2D material to 3D object
26. Convert for second function
27. Cover or wrap
28. Create service
29. Create system
30. Divide continuous surface
31. Elevate or lower
32. Expand or collapse
33. Expose interior
34. Extend surface
35. Flatten
36. Fold
37. Hollow out
38. Impose hierarchy on functions
39. Incorporate environment
40. Incorporate user input
41. Layer
42. Make components attachable/ detachable
43. Make multifunctional
44. Make product recyclable
45. Merge surfaces
46. Mimic natural mechanisms
47. Mirror or array
48. Nest
49. Offer optional components
50. Provide sensory feedback
51. Reconfigure
52. Redefine joints
53. Reduce material
54. Repeat
55. Repurpose packaging
56. Roll
57. Rotate
58. Scale up or down
59. Separate functions
60. Simplify
61. Slide
62. Stack
63. Substitute way of achieving function
64. Synthesize functions
65. Telescope
66. Twist
67. Unify
68. Use common base to hold components
69. Use continuous material
70. Use different energy source
71. Use human-generated power
72. Use multiple components for one function
73. Use packaging as functional component
74. Use repurposed or recycled materials
75. Utilize inner space
76. Utilize opposite surface
77. Visually distinguish functions

Figure 10: The 77 design heuristics that the team used to brainstorm variations of the existing plate filler machine that would accommodate different plate lid profiles and sizes.[23]

As a team, we looked through all the design heuristics and tried to take inspiration from them to create a variation concept of the preexisting machine so that the machine could accommodate different lid profiles. We looked for ways to modify the preexisting machine given to us. Sometimes multiple team members would have concept ideas and sometimes we would come up with a concept together. For example, when we looked at heuristic card number 2, *Add Motion,* we decided to implement movement to the storage of the plates before they are fed to the filling up station. Our idea was to implement a conveyor belt like mechanism that stored the plates individually and released one at a time to the filling up station where the pump dispenses the medium. The conveyor belt storage would have small compartments to separate the plates and avoid them getting stuck regardless of their lid profile. This conveyor belt concept is illustrated below in Figure 11.

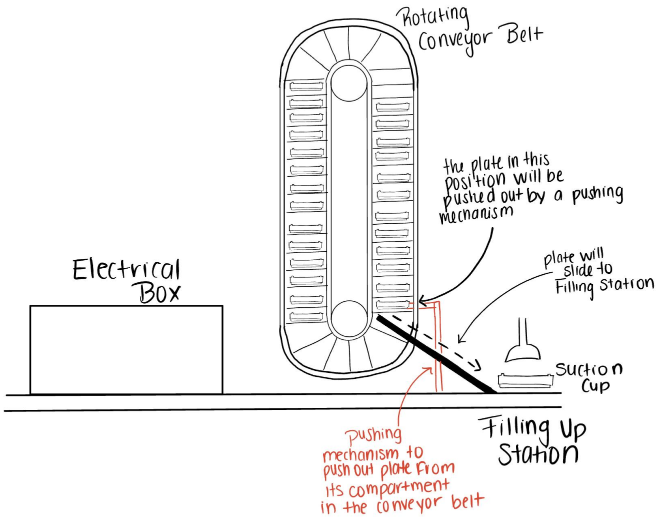


Figure 11: The concept generated from heuristic card: *Add Motion.* The plates are stored in a rotating conveyor belt like system and then one plate is released at a time to the filling up station so that the agar can be dispensed.

Another example of a concept generated comes from the heuristic card *Apply Existing Mechanism In a New Way.* This concept involves implementing the carousel mechanism used to store the plates after they are filled with the medium to also feed them to the filling up station. This concept is illustrated in Figure 12. The team thought of duplicating that carousel mechanism and making it rotate in the opposite direction so that the plates could be released one plate at a time to the filling up station before they are pushed to the second carousel storage once they are filled.

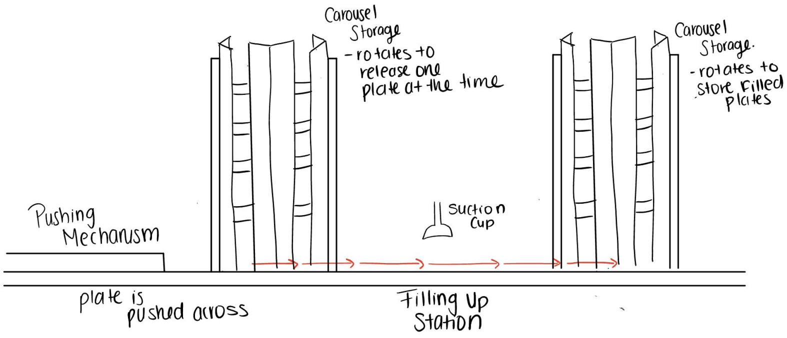


Figure 12: The concept generated from heuristic card: *Apply Existing Mechanism In a New Way.* The plates are stored in a rotating conveyor belt like system and then one plate is released at a time to the filling up station so that the agar can be dispensed.

While we were able to generate over 50 possible solutions designs using the design heuristics, we were aware that this concept generation technique was limited or constrained by the pre existing machine and structure. Our ideas were influenced by how the existing prototype works and what previous teams implemented. In our next, concept generation meeting we wanted to address this and decided to focus on ideas that were not limited by the preexisting machine.

Morphological Chart

We created a morphological chart for further concept generation. A morphological chart helps generate more ideas in an analytical and systematic manner.[24] We first established the sub-functions needed to achieve the plate filler machine being compatible with different lid profiles and plate sizes. The two sub functions we need to implement for the plate filler machine are that the machine must store or organize the plates in some way at the beginning of the automated process before the plates are filled, the machine must transport the plates from the storage mechanism to underneath the suction cup where the plate will be filled with medium, and (if needed) the machine must have a way to separate the plates so that when one is transported they do not get stuck. After coming up with these subfunctions, we brainstormed solutions or easy to accomplish them. This process is shown in Table 4 below. The solutions for each sub function were generated independently.

Table 4: Morphological chart for concept generation.

Subfunctions	Solutions
Store the Plates pre-filling	Ramp, Plate Guides, Funnel, Horizontal Stack, Vertical Stack, Below Surface Level Stack, Vending Machine Mechanism
Separate the plates so they do not clash when transported (if needed)	Stack Spacers, Individual Compartments
Transport plates to the filling station	Slide, Pulley, Robotic Arm, Conveyor Belt, Pushing Mechanism , Elevator Mechanism

We created concepts by combining solutions from the sub function categories. An example design is the horizontal conveyor belt concept pictured in Figure 13. This concept involves a simple conveyor belt. The plates would have to be placed on the conveyor belt. The plates would slide off of the conveyor belt and under the suction cup one plate at a time. This concept is a combination of the conveyor belt storage and slide transport system. In this case there is no need for a method to separate the plates in the storage method.

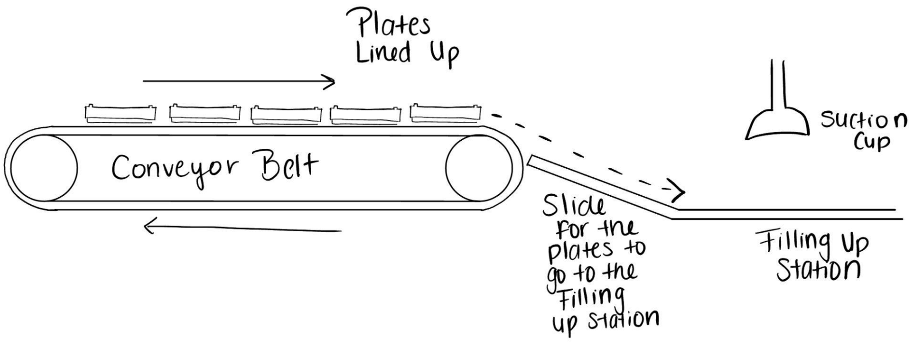


Figure 13: Horizontal conveyor belt with a slide concept generated using the morphological chart.

Another example of a concept that we created using the morphological chart is the elevator mechanism with individual compartments along the plate guides. This concept is illustrated in Figure 14. In this concept, the plates are placed into individual compartments and an elevator-like mechanism moves up and down to transport the plates to the filling station one plate at a time. This concept is a combination of the plate guides storage method, with individual compartments to separate the plates, and an elevator-like mechanism to transport the plates to the filling up station.

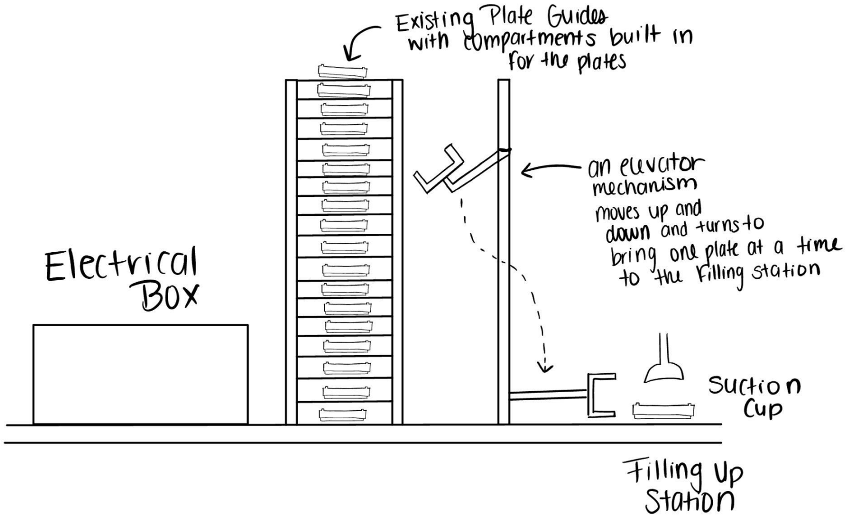


Figure 14: Elevator mechanism with individual compartments along the plate guides concept generated using the morphological chart.

The morphological chart allowed us to brainstorm concepts without being constrained to the previous plate filling machine's design or structure. We created a blank slate for concept ideas with the functional decomposition of the project statement of creating a plate filling machine compatible with plates of different lid designs and size. We brainstormed mechanisms that would feed the plates to the filling up station without consideration of what the machine already looks like. The morphological chart helped us explore the idea of completely getting rid of the plate guides and pushing mechanism and creating a concept from scratch. We generated more distinct and creative concepts as they were very different from the pre existing plate processing machine.

We generated about 75 possible solution concepts using the two concept generation techniques described above. The next step was using concept evaluation techniques to narrow down our brainstorming ideas to fewer and fewer concepts and eventually to decide on our alpha designs, which we will prototype and test in the next project phase. The first screening process we implemented was looking through all our concept ideas and eliminating some through the gut-check method. We eliminated some ideas because they were not feasible given our resources, timeline, skill sets, etc. We eliminated other ideas because the implementation could not meet all the requirements, especially those who could not meet the size specifications. We also reached out to Dr. Truttmann for this first phase of concept elimination to get some of his input. After this initial concept evaluation, we narrowed it down to 25 ideas that we wanted to systematically evaluate. These 25 concepts are pictured in Appendix A. We describe the entire concept selection method in more detail in the next section.

Concept Selection

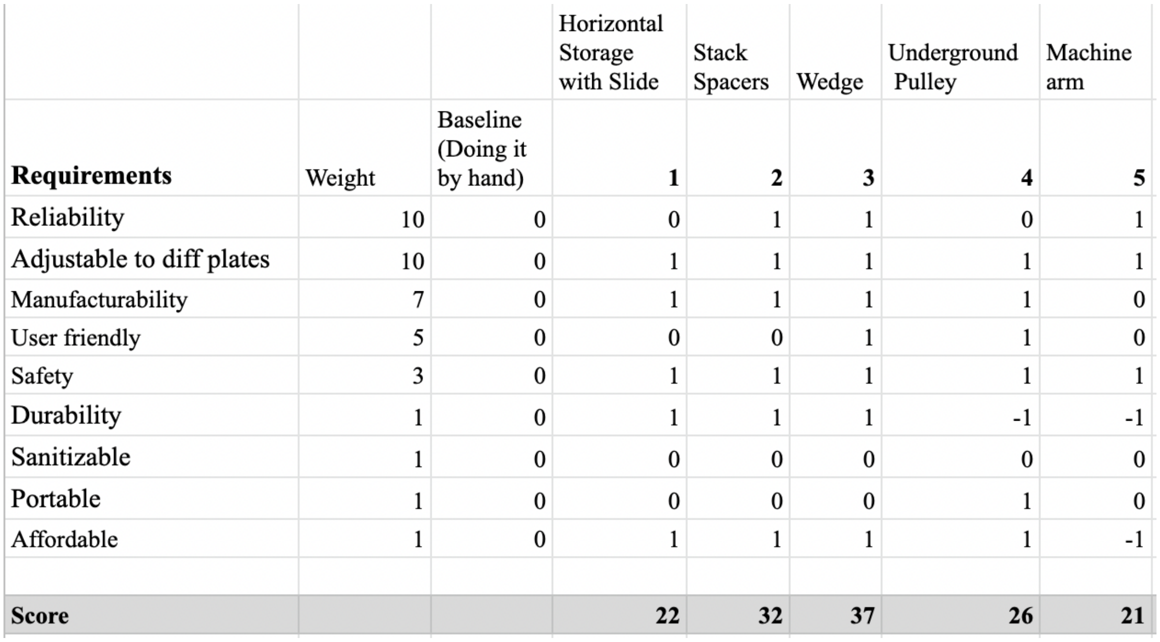
During concept selection, we started off assuming that keeping the stack of plates vertical would be the best solution since it was the preexisting one. However, we had a lot of horizontal designs with different ways of plate delivery that we had to consider. After coming together as a group to critique the ideas, we eliminated a lot of ideas that were obviously infeasible, and then narrowed down that list by taking out the ones that were not as practical based on our gut check. The remaining ideas were ranked based on our pugh chart.

The requirements that were ranked the highest were reliability and the ability to adjust to plates of different sizes. These were the requirements that our sponsor specifically asked for, and so we made sure that these were the top priorities that we kept in mind while selecting designs. The requirement that was given the most weight after these was manufacturability. Due to the simplistic nature of our project and the small physical scale of the designs, engineering analysis would not be very accurate. Therefore, the best way of verifying our designs would be through physical testing and many trials. In order to do so, we would need a design that can be easily manufactured and prototyped. Not only would this allow us to start our process much earlier, it would allow us to iterate and improve on our design much easier. This push for a shorter design cycle will allow us to test out more variations on the same idea, increase the sample size of the designs we have tested, and therefore increase the validity of the final solution we have chosen from our rounds of testing. This would also keep us on target much better since we could see what number prototype we are on, which would physically indicate to us where we are in the design process.

Following this, we ranked the ability of being user friendly next. We discovered the issue of the current prototype being potentially destructive when testing it ourselves with various plate types. However, this was linked to the machine not having clear instructions and the design not being obvious to the user. Certain designs will inherently have more risk of damage to the plates, but we can minimize this by making it more user friendly. In the extreme case of plate damage, there is the possibility of plates being shattered, resulting in a safety issue and a requirement of safety glasses while operating the machine. We have done further testing of the machine, and find this extremely unlikely to happen again, but we considered this while picking designs. The inability for a machine to consistently handle the dishes in a controlled manner . The remaining four requirements are either lower priority requirements, or requirements that a lot of the designs fulfill since they are necessary to the base designs.

We originally considered using the existing prototype as the baseline to score against our other designs, however, we found that it would score a negative score against some of our criteria as it was flawed, which was the reason we were given this project. We ended up going with hand loading the plates as the baseline, since that was what the machine was originally designed to replace. We then scored the different designs by looking at the designs and coming up with a score for each of them individually. Afterwards, we looked at the top five designs to see what came out of it. We found that although certain designs scored very well, after reviewing them, we had issues with them that did not reflect the requirements. We added a few more requirements that we did not put in since we all assumed it was a requirement we would all put in our designs. In this way, the pugh chart helped us see what exactly we wanted out of our project and how we would get there.

Table 5: Pugh chart results for the top five scoring concepts. Requirements, weights, and baseline included.



			Horizontal Storage with Slide	Stack Spacers	Wedge	Underground Pulley	Machine arm
Requirements	Weight	Baseline (Doing it by hand)	**1**	**2**	**3**	**4**	**5**
Reliability	10	0	0	1	1	0	1
Adjustable to diff plates	10	0	1	1	1	1	1
Manufacturability	7	0	1	1	1	1	0
User friendly	5	0	0	0	1	1	0
Safety	3	0	1	1	1	1	1
Durability	1	0	1	1	1	-1	-1
Sanitizable	1	0	0	0	0	0	0
Portable	1	0	0	0	0	1	0
Affordable	1	0	1	1	1	1	-1
Score			**22**	**32**	**37**	**26**	**21**

Table 5 above depicts the pugh chart results for the top 5 scoring concepts. We will now describe what these concepts look like, how they work, and their advantages and disadvantages. We describe the top five concepts in ascending order of their pugh chart scores.

Machine Arm

This concept involves an electromechanical arm that would pick up the top plate from the stack and transport it to the filling station. The machine arm would place the plate underneath the suction cup that lifts the lid so that the pump could dispense the medium. The plate would then be pushed to the carousel storage area. This concept scored 21 points in the pugh chart. Figure 15 depicts the machine arm concept.

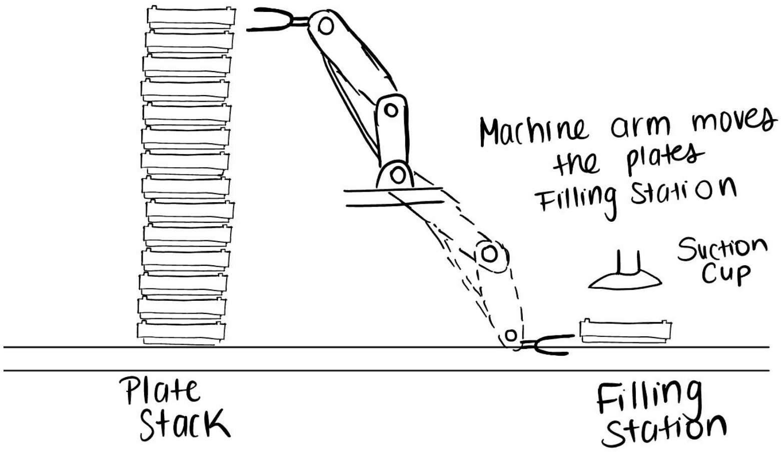


Figure 15: Machine arm design

Advantages

Since the landing zone for the plates does not change, it should be very precise once we eliminate backlash in the actuator transmissions and develop a control scheme to minimize the settling time. The pickup zone is also the same, with the same change in height every time a plate is removed. It also bypasses the problem of jamming by lifting the plate from the top of the stack instead of taking it from the bottom. This would take off the different plate sizes easily, since we will not have to adjust a container to fit different plates, and could just have the claw clamp down until it contacted the sides of the plate.

Disadvantages

While nDOF robotic arms have been established into a well developed subfield of robotics, it is because they are fundamentally difficult to design and control. We would first need to establish necessary output torques and maximum joint speeds, and balance it with acceptable efficiency and noise levels from the transmissions. On the control side, we would need to develop a lead lag control scheme to quickly respond to perturbations and minimize the steady state error when it travels between its states. The plant would need to be compensated for to adjust for residual dynamics in the actual motion of the manipulator. The machine arm would also need a large area of motion that would increase the footprint of our machine and make the lab more cramped. If implemented correctly, it ensures a predictable and robust delivery system between the stacked plates and the filling mechanism, however it is significantly more expensive in every aspect to accommodate the redundant degrees of freedom.

Horizontal Storage with Slide

This concept involves the plates being stacked horizontally and the first plate of the stack sliding down towards the filling up station. The plates are held together or in place by some railings. However, the plate stack is not held together super tightly so that the first plate can slide down. In this design, the pre existing pushing mechanism to push the plate stack forward so that the plates keep sliding down one at a time to the filling station. This concept scored 22 points in the pugh chart. Figure 16 depicts this concept.

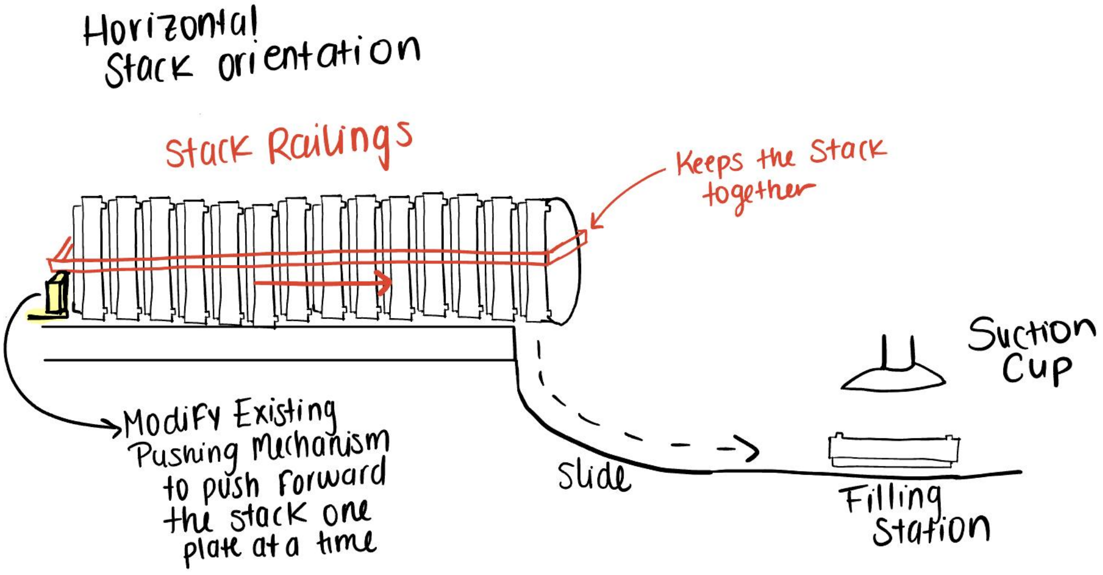


Figure 16: Horizontal storage with slide design

Advantages

We avoid jamming in this case by moving the plates horizontally so that the edges of the plates would not catch on the ridges of the next plate. The ridges only constrain the plates to being stacked due to the weight of the stack on top of the plates, so by removing the constraining force of gravity from acting in that manner it eliminates the root cause behind the jamming. It also does not use a mechanism to move the actual plates into the final landing zone, just a simple pushing mechanism to move the plates one at a time.

Disadvantages

The entry speed of the plates into the filler is dependent upon the geometry of the slide, which means any adjustment we make to adjust the cycle time of the system will require us to completely remanufacture the slide. There is also a possibility of the slide wearing over time and changing that geometry may affect how future plates contact it. The increased horizontal space also limits where on the prototype we can place it, which has the downstream effect of limiting how much we can change our design to alter the plate dispensing.

Underground Pulley

This concept involves the plates being stacked below surface level and a pulley mechanism transporting the to plate to the filling up station one plate at a time. This concept scored 26 points in the pugh chart. Figure 17 depicts this concept.

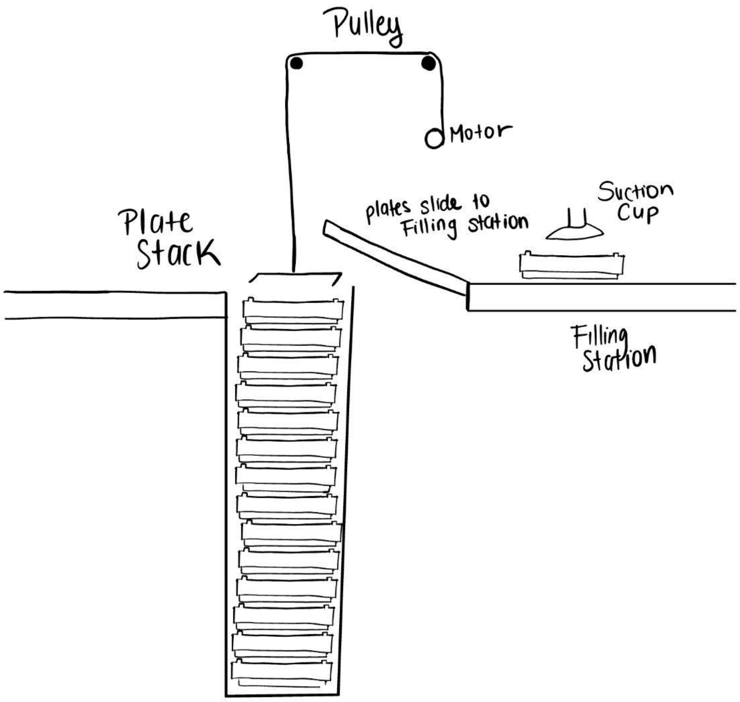


Figure 17: Underground pulley design

Advantages

This design is very efficient in space since we are looking to keep the storage container of the plates below the table instead of taking up space on top or to the side of the machine. The mechanism is also less prone to jamming since we are once again removing plates from the top.

Disadvantages

It will be slightly difficult to accommodate different sizes of plates. We will either have to change out the size of the gripper, and also have the size of the container be flexible. In addition, it changes how the machine can be placed on the existing tabletop the lab set aside for it. The plate stack would have to be cantilevered off the side, which increases the working volume of the prototype.

Stack Spacers

This concept is more of an adaptation of the pre existing machine. This concept involves the addition of a spacer mechanism to the existing plate guides. The spacers will separate the bottom plate from the rest of the stack so that the bottom plate can easily be pushed through to the filling station. The spacer will lift the stack. This concept scored 32 points in the pugh chart. Figure 18 depicts this concept and the spacer mechanisms. The spacers will fold out when holding the stack up. The spacers will quickly flatten out and fold out again to let the next plate drop.

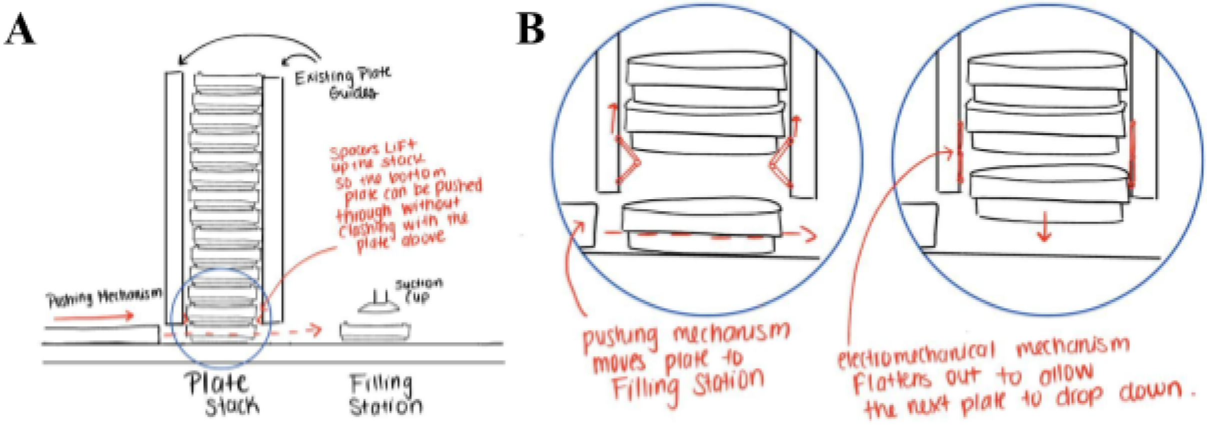


Figure 18: Stack spacers design

Advantages

This design fits in the preexisting design, and so it will not require too much modification to the current storage container. It also separates the plates in a very clean manner, as it only allows one of the plates to drop at a time, and solves the jamming issue by preemptively separating the lowest plate on the stack from the next.

Disadvantages

It is complex and has the possibility of allowing the plates to drop prematurely if not tuned correctly for each size plate. This addition would likely include very small parts due to the size limitation of being right next to the bottom edge of the stack, which could have a negative impact on the longevity and repairability of this design.

<u>Wedge</u>

This concept is also an adaptation of the pre existing machine. This concept involves adding a wedge-like part to the pushing mechanism so that the second plate of the stack is lifted off of the bottom plate when the pushing mechanism moves forward. This concept was the highest scoring in the pugh chart with a score of 37 points. Figure 19 depicts this concept.

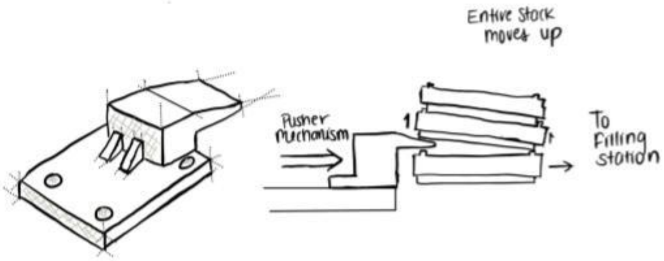


Figure 19: Wedge design

Advantages

The wedge only has a single part, with only a few critical dimensions. Namely, the height of the wedge and the angle of the wedge surface will impact how it interacts with the gap between the 2 plates, so compared to other designs the timeframe for iterating is much smaller. Especially considering that prototype prints have taken under 50 minutes, it will be very easy for us to produce dozens of variations in its design and critical parameters.

Disadvantages

Fundamentally, the way it interacts with the dishes does not change regardless of the circumstances. It will contact the 3 sizes of dishes in the exact same manner, and impact the stack at the exact same height every time. If we can tune the edge height and attack angle sufficiently, there might be a combination that works for all dishes. But if some of the dishes have a slight fillet on the bottom edge, which would create a larger gap for the wedge to interact with, it will have a significant positive impact on its performance compared to dishes with a smaller gap between the stack plates. During testing, we will find out if the minute differences between the dish geometry will disqualify this concept.

Design Justifications

Our proposed designs are intended to overcome the initial shortcomings of the prototype plate filler by minimizing the contact between the individual plates to prevent potential jamming. Between each one, they all attempt to solve the problem by changing how the plates interact with each other by either physically manipulating the mating surface between the plates, or by adjusting the stack's position to decrease the impact of the ridges on the stacking capabilities of the plates. Especially considering some of the dozens of designs we disqualified before our functional analysis methods, many of our approaches were over engineered or if they were appropriate, they were only appropriate for one of the sizes of dishes, where adjusting the machine to be accommodating of different sized plates would be a significant change to the structure of the machine between each use. So when we narrowed down our acceptable concepts until we were left with just two, the criteria we used to disqualify the rest of the designs ensured that our resulting two designs matched our stakeholder's requirements the most, and had the best chance at achieving our engineering specifications out of all of the ones we considered.

A lot of our first designs involved picking the dish off the top of the stack. In fact, we can see it represented in the machine arm concept, where the major drawback of the design was the inappropriate application of an nDOF arm. This was not a bad way to start off our brainstorming, since it indicated we understood the root cause of what allowed the ridges to cause the jamming problem. However, we ended up shifting most of our ideas back towards removing the bottom plate in the stack because as we saw with the underground pulley design, packaging a system that took the dish off the top would create more problems than the issue it was trying to solve in the first place. In contrast, pushing the plates off the bottom of the stack of empty plates allows us to actually utilize the stacking features of these dishes to our benefit, and it decreases the amount of work we need to dedicate to handling the stack of plates being fed into the machine. We were able to successfully avoid fixation on our idea by constantly questioning what we already knew about the problem thanks to our thorough background research and our extensive analysis of our proposed concepts.

Alpha Designs

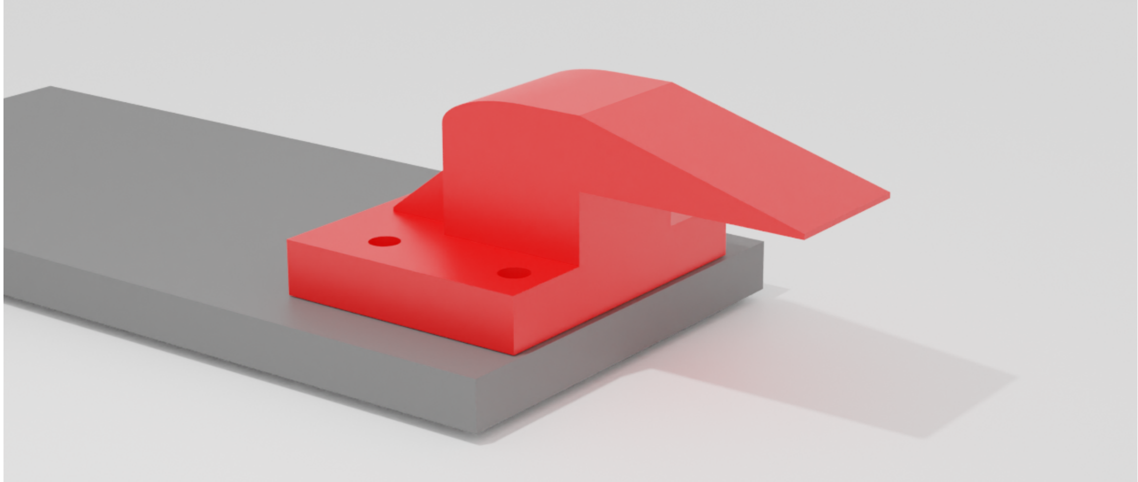


Figure 20: Preliminary render for the wedge design

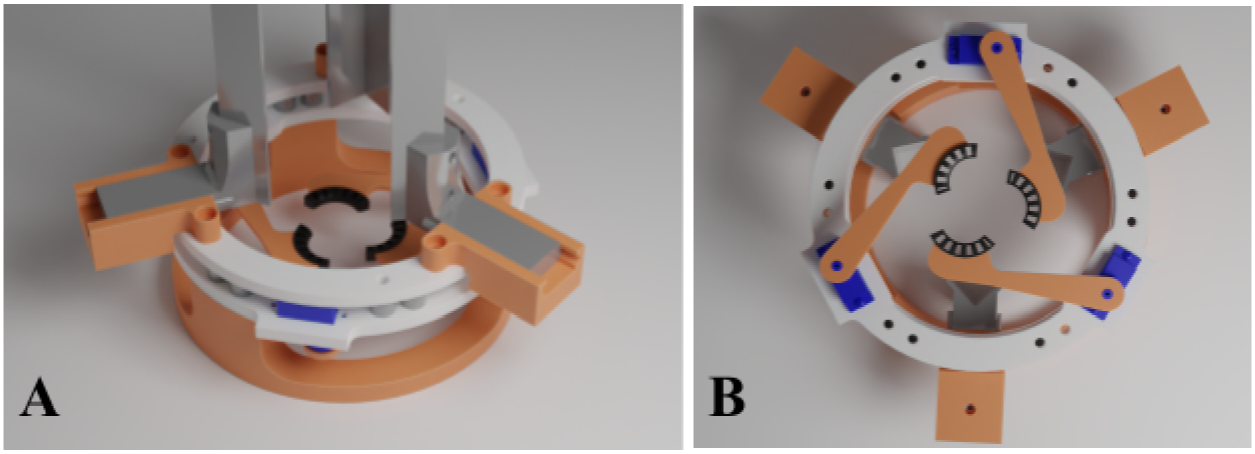


Figure 21: Preliminary render for the spacer design

Our final alpha design concepts were narrowed down to the two highest scoring concepts from our pugh chart, which are the wedge and the stack spacer designs. Once we were confident that our pugh chart selected the two best ideas, we proceeded to continue the development of these ideas into a more polished state for prototyping. Considering our future timeline, going with one alpha design would allow us to concentrate all of our focus on one design to fully realize it without distractions. However, since one of the main advantages of the wedge is how simple it is, it makes sense to pursue two designs in the event that we wrap up prototyping quickly. In addition, if we discover that these two designs compliment each other during testing, implementing them together is another option we have entertained. They approach the problem in two fundamentally different ways and interface with the plates on different surfaces, so they would be able to coexist on the same machine without an issue.

Wedge

The wedge will initially be printed on a Prusa i3 mk2s with PLA using FDM printing. The wedge will be elevated above the pushing mechanism, where the base of the printed part will be temporarily adhered to the pushing mechanism while we test the critical parameters. Once we finalize the dimensions and form, our next step will be to optimize the material use to see if different FDM filaments or manufacturing processes would result in a more robust design. Our sponsor has never encouraged us to choose a specific design, and the criteria is that he just wants this machine to work. Ultimately the more we can test our design and the more we can find ways to improve it, the closer our design will be to achieving the requirements. Since our objective selection process was our pugh chart, it weighed all designs against the same criteria, and since this design aligns with our most important criteria this was chosen to be our best design with unbiased judgment without the possibility of changing the numbers to qualify it. From our initial prototyped print, this is already well defined enough to begin testing, as the CAD stage was expedited by the simplicity of this design. To address the disadvantages, a wedge with new dimensions will need to be manufactured for each plate variation, this may increase the manufacturing time however since the wedge is 3D printed the manufacturing time of additional components will be shortened as much as possible. We plan on doing static FEA analysis to see the range of forces our prototype is expected to withstand, and then we will physically test the strength of several prototypes to not only verify our simulations, but to ensure that it is not expected to fail during normal operation of the machine. Since we are working within the constraints of ME 450, this design will have no issue working within the timeframe we need to finish our project within. In fact, we found that it might leave us with more time at the end of the semester to work with another design, so that is how we ended up pursuing a second alpha design.

Stack Spacers

If we were to judge the alpha concepts by how well they serve as a capstone design project, the spacers will require more time, knowledge, and technical knowledge to implement compared to the wedge alpha concept. While looking at the mechanisms already in place in the machines around us, we found a similar indexing function that we needed to handle the plates for this machine in a vending machine. The design includes 2 actuated folding bars on either side of the feeding tray, so we can secure the entire stack above the bottom plate to ensure the stacking features do not jam the bottom plate. Since there is a singular motion associated with this, we would only need a single additional actuator to drive this addition. In utilizing a combination of machined, 3D printed, and off the shelf parts, we will be able to fine tune this mechanism to only release one plate at a time into the filling stage of the machine. As far as the process goes, we followed the exact same judgements as we did for the wedge, and the only reason this did not rank as high in the pugh chart was because of the complexity this introduces to the design relative to a single 3D printed part. We currently have enough groundwork laid for the stack spacers to begin prototyping for it, but before we will be able to test it or do any engineering analysis on it we will need to fine tune the mechanism to ensure it behaves as we expect it to. This is something that will not concern the wedge as much since in theory it is functionally done as soon as the printer turns off. Within the constraints of 450, this definitely fits tighter into the timeline we have created for our team, however it will not necessitate another semester of 450 students working on it since we anticipate this being done well before we plan on presenting the finished automated plate filler to Dr. Truttmann's lab.

Engineering Analysis

We started off by brainstorming multiple sketches of how we thought the wedges would look like. A lot of focus was placed on the shape of the wedge end since this part would be crucial to lifting and separating the ridges of the plates. We decided to go with a rectangular wedge instead of a tapered wedge since it would provide the most stability during the lifting of the plate. Once we had our very first design, we decided to empirically test our design in the lab since it was the quickest and clearest way to find any problems with our design. Almost immediately, we found out that we did not account for a component for holding on to the rest of the stack once the bottom plate was moved. This caused the stack to fall at angle, resulting in a jam after the wedge retracted. We remedied this by attaching popsicle sticks to the back of our wedge and continued testing to ensure that our basic wedge would work.

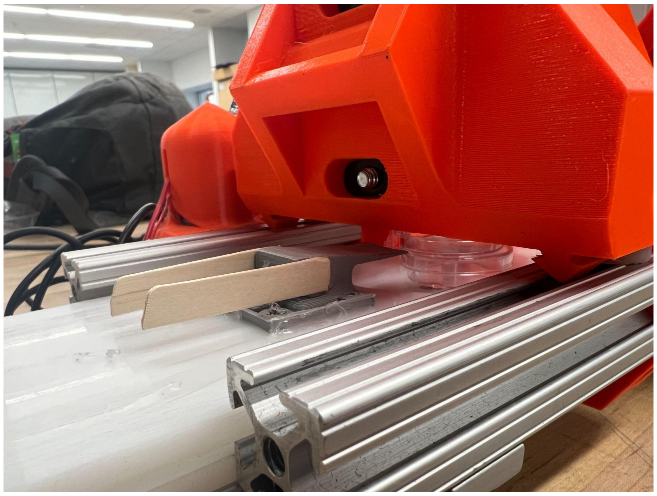


Figure 22: Initial wedge design with popsicle sticks attached to prevent stack from falling at an angle and jamming the machine.

We then replaced the popsicle sticks with a flat shelf on the back of our mounting component to provide a more stable way of keeping the stack level. Furthermore, we realized that the wedge would only work for certain sizes of plates due to their differences in height. Originally, we had planned for three different wedges, but found it very inconvenient to switch wedges each time so a mounting mechanism was developed. We then took an average of the heights of the wedges to create the height for our mounting component. Afterwards, we used simple geometry to find the optimal angles for each different plate size since the height of the mounting component and its distance from the plate stack remained constant while the plate height was the only thing that changed. Reference Appendix C figure C.4 for this mounting piece and wedge piece design.

Our first step in beginning the engineering analysis of our alpha design was to fully assess the failure modes of our design. We decided that our primary focus would be on studying the worst case static loads our system would see, as this is a strictly mechanical subsystem we are analyzing. With the aid of finite element analysis (FEA), we developed several simulations to determine the viability of the current iteration of the wedge design. Our first approach focused on the worst case loading scenario of the cantilever wedge, where the entire weight of the stack was supported by the thinnest part of the wedge (Figure 23). A total of 5 FEA simulations were performed modeling different loading conditions. All simulations showed similar wedge performance, increasing our confidence in the analysis conclusions. From our measurements, we estimated a worst case load of 17.4 N on the tip, which included a safety factor of 2. This will account for cases where the stack suddenly drops onto the wedge, or for material imperfections during the manufacturing of the wedge. We assumed PLA to have a tensile strength of 37 MPa and a Young's modulus of 4 GPa. With our load case and constraints established, we generated the following results:

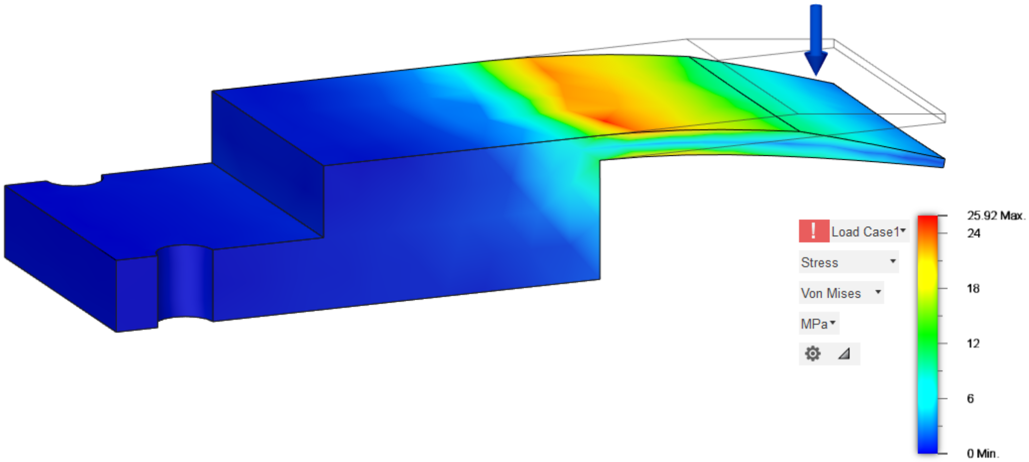


Figure 23: Results of the first FEA simulation. From this, we can see that with the proposed geometry, the maximum stress is estimated to be 25.92 MPa, where it is encountered on both sides of the cantilevered edge. This puts it within the working boundaries of the material properties we designated to PLA.

For our second simulation, we assessed the viability of the snap fit design we initially integrated into the mounting bracket. In theory, this incorporated compliance would allow us to easily insert and remove the wedge pieces we created, where little notches in the wedges would interface with the snap fit limbs embedded in the mount. We have high confidence in this FEA simulation of the snap fit since we referenced Finite Element course material (ME305) with a similar shape to perform the simulation. We also read research papers to cross check our results. We simulated a load of 20N on the proposed geometry, with the tip of the limbs seeing the maximum displacement. By using the same material properties established in the first simulation, we obtained the results of our second simulation:

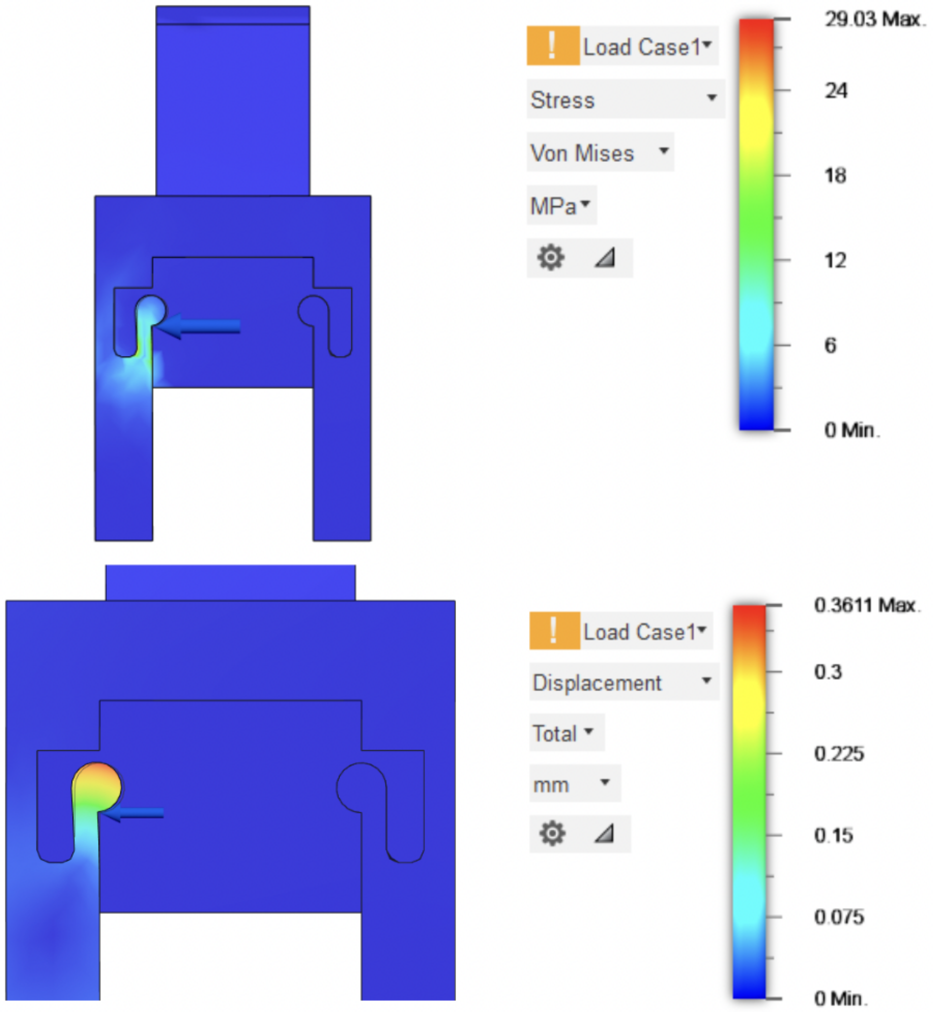


Figure 24: Results of the second FEA simulation. With 20N of force centered on the bulge of the snap fit limb, it only sees 0.36 mm of deflection. Since the bulge requires 2 mm of deflection, this is not enough to satisfy the functionality of the snap fit mechanism. Ideally, the limb could fully deform into its cavity to allow the insert to slide in.

This told us that our current geometry was not able to accommodate the snap fit mechanism. Since the deflection of complex geometry is hard to assess using first principles models, and there are limitations with FEA analysis since these are 3D printed parts, we were interested in bypassing these problems with ball detent inserts. These inserts allow us to have the same mechanical functionality of the snap fit mechanism without any of the concerns of manufacturing or the material fatigue associated with repeatedly deforming the limbs. The ball detent mechanism is shown in Figure 25 below.

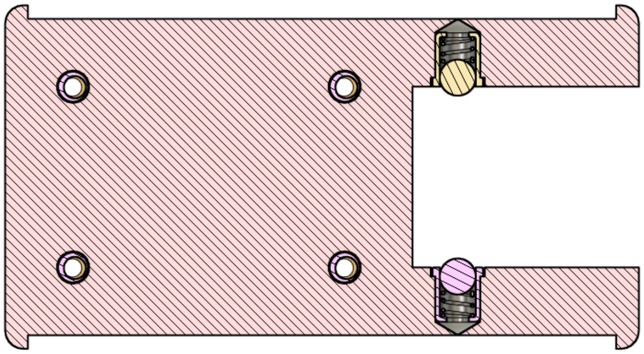


Figure 25: Ball detent mechanism on the mounting piece of the wedge alpha design.

Compliant plastic mechanisms are a great tool for mass producing parts that require joints/springed elements without adding to the assembly costs, but our application differs by the desired production quantity. In this case, we are only making a small number of these parts, so the additional assembly associated with inserting the ball detent inserts is preferred to the additional effort spent manufacturing a more complicated mechanism on our own. These components have a force rating of 20 N, which matches what we were looking for with the previous snap fit design. Ultimately, we have decided to leave this solution as a backup to the snap fit design, since we are able to run more tests with the existing snap fit mechanism in the foreseeable future. Iterating on a design dependent upon off the shelf components will introduce shipping time as a factor in our testing, and since the critical aspect of this design is the interaction of the wedge with the plates we will prioritize fine-tuning the wedge geometry before adding more complexity to the mounting scheme.We have tested the entire wedge and snap fit mounting mechanism and the results are displayed in Table 6 below.

Table 6: Results of physical testing of the final wedge design for the three different plate sizes.

Wedge (Plate Diameter)	**Performance Results**
Small (35mm)	50/50
Medium (60mm)	50/50
Large (100mm)	50/50

It is clear that two of the wedges did not pass the specification failure rate therefore we will be analyzing this further with more design iterations, potentially adjusting the angles. We are confident in the physical testing results because we mounted the wedge onto the machine and ran it as it would in an actual lab setting. We are confident future iterations will meet the engineering specifications.

We also decided against our secondary stack spacer alpha design for various reasons. Firstly, the manufacturing costs were much higher compared to that of our wedge design. Having metal parts compared to 3D printed PLA parts raises the price of this alpha design significantly as well as its complexity. A related concern of the sponsor was that it was uncommon for the people who worked in his lab to be able to machine parts, and would therefore have to go through others in a complicated process to manufacture the parts if they were ever damaged. Furthermore, the stack spacer required many different components, meaning that if one part was broken, it would stop the entire machine. The wedge design on the other hand, only has two parts, and can be easily 3D printed. It is also significantly faster to manufacture than any metal parts that the stack spacer would require. This point was especially important to our sponsor, who aside from the cost, wanted a product that could be easily replaced in the future without a significant level of manufacturing expertise and lost in production time, as this machine would be used daily.

A Pugh chart was used to numerically determine which design to pursue and further develop. The Pugh chart factors in each design requirement: reliability, safety, accommodates to different plates, durability, user friendly, sanitizable, compact and affordable. All these requirements were assigned a weight and the two designs were evaluated. The wedge scored much higher than the spacers, showing this is the better design to pursue. The Pugh chart can be seen in Table 7.

Table 7: Pugh chart results comparing the wedge and stack spacer alpha designs after engineering analysis.

Requirement	**Weight**	**Baseline (doing it by hand)**	**Wedge**	**Stack Spacers**
Reliability	10	0	1	0
Safety	10	0	0	-1
Accommodates different plates	8	0	1	0
Durability	7	0	1	-1
User Friendly	7	0	1	-1
Sanitizable	5	0	0	-1
Compact	3	0	1	0
Affordable	2	0	1	-1
Total		0	37	-31

Build Design and Final Design Description

The final design is the wedge attached to a snap fit mount that is mounted onto the pushing mechanism. The mount is attached via hot glue and the wedge can be removed and replaced by simply pulling it out of the mount. The mount and wedges are currently printed with PLA. At the end of the mount is a 10 x 20 x 203 mm piece of acrylic to support the plates as the pushing mechanism completes its cycle. A picture of the mount and mounting piece extension attached to the pushing mechanism is shown below.

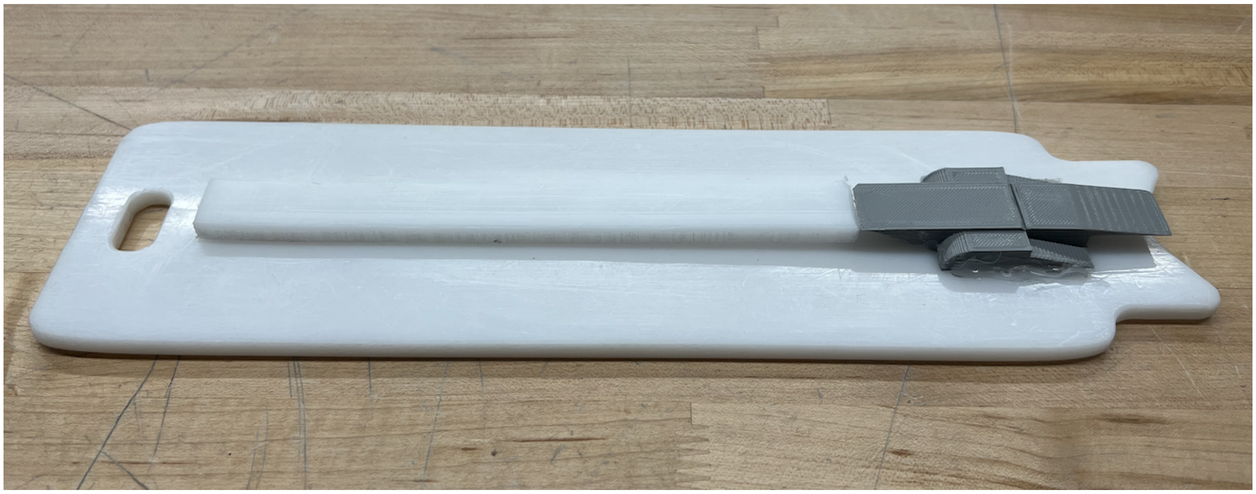


Figure 26: Picture of acrylic mount extension and PLA printed mount and wedge attached to plate pushing mechanism by hot glue. The detailed engineering drawings of the wedge can be found in Appendix C.

The plate supporter will support the plates to ensure that the plates do not fall at angle leading to the machine jamming. The mount holds the wedge and the wedge is inserted between the base of the plate and the top of the last plate in the stack. The final design is manufactured by 3D printing the wedge and the mount with PLA, the University provides 3D printing services. The plate supporter is made of the same material as the plate pushing mechanism as well as other components of the machine and can be acquired easily and cut to the desired dimensions by a handsaw. 3D printing has its limitations and tolerance issues which are the broad issues associated with manufacturing the wedge and the mount. The sponsor may need to spend extra time in the post processing steps (sanding, removing supports and more) to ensure the pushing mechanism works smoothly. The test results of the final design can be Table 6 of the Engineering Analysis section.

What we have learned is that FEA cannot be a reliable method of analysis in 3D printed components, especially in this application. In addition, in the previous iterations, a ball detent design was chosen however we learned that the replacement process is more complicated compared to a simple replacement of the snap fit design so we returned to the snap fit design as part of the final design solution. Therefore, we revisited the snap fit mechanism however since this component is 3D printed it may have to be replaced sooner, we recommend having extra mounts easily accessible and we will print extra for the sponsor. We also recommend exploring different materials, the 3D printing services at the University only provided us with SLA and PLA therefore we were only able to test with those two materials and PLA performed the best since SLA is too brittle for our application. However, based on literature, nylon may be worth exploring due to its flexible material property making the snap fit mount a great application of this material. The Bill of Material and Manufacturing Bill of Materials can be located in Appendix H.

The wedge is the final design and build design since our solution can be manufactured within a reasonable amount of time and is a reasonable size to be 3D printed. The drawing of the wedge is attached below.

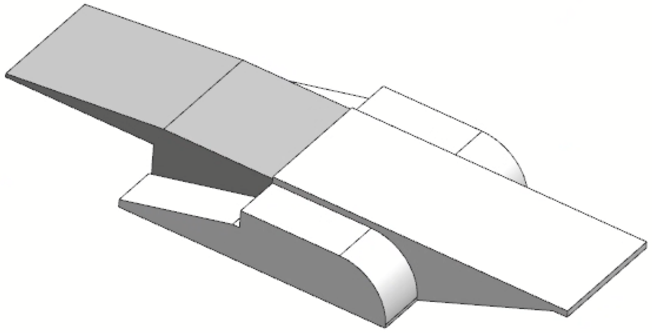


Figure 27: Isometric view of the wedge and the mounting mechanism. A total of 3 wedges have been created for the 3 different plates since their heights differ. See Appendix C for detailed engineering drawings of the 3 wedges and mounting bracket.

The wedge will be 3D printed with PLA at 300 micron resolution and 40% infill. Since the University provides 3D printing services and Dr. Truttmann's lab has access to 3D printers, we can omit machine operating costs, which only leaves the material cost of $0.05. This wedge will be mounted onto the slider component of the plate filler. With this, all of the parts can be easily removed and maintained if needed. The wedge is inserted between the bottom most plate's lid and the second to last plate. The bill of materials can be located in Appendix C.

From the initial design, multiple wedges have been designed varying the angle, length, and thickness of each and tested by attaching it to the pusher of the plate filler with hot glue and running the machine. We have concluded that with the different plate dimensions, there will need to be different wedges therefore each plate has its own wedge. Testing each wedge physically, we have collected the data that can be found in Table 6 of the Engineering analysis section. The performance of the wedges all fell below the specification listed in the table of requirements. Based on the previous physical testing we learned that the wedge must be thin enough to be fully inserted between the two plates and based on the initial prototypes we learned that the motion of the plates dropping affected the performance of the wedge because it would lead to the machine jamming. Another important lesson learned is that the height of the wedge is an important factor, it is rather difficult to implement a wedge that fits all 3 plate dimensions since their heights vary so the base of the wedge must be directly touching the top of the plate to be successful. Therefore, 3 different wedges were created. More tests will be run between now and the final design expo day to ensure that the wedge will meet the requirements and specifications determined for this project.

Problem Analysis and Iteration

The purpose of designating two designs as our alpha designs is to see them through to a prototyped stage, where we can assess their performance beyond just first principal analysis and collision checking within CAD. Their performance will be judged by how well they achieve each requirement, and their eventual viability will be determined by how they perform relative to each other. The next step is to test our completed solution once it is implemented. For each requirement, we have established methods to get a binary check of whether or not the requirement has been met. These include tests ranging from simple measurement checks, or extensive experimenting on the consistency of subfunctions. Our initial checks will be to ensure that the mechanism can process the plates off of the main plate filler. Based on our preliminary tests of the existing prototype, we will be focusing our tests on the largest of the plates since that size was the one that jammed the most.

We have created a testing procedure for each requirement and the linked specifications. For example, we estimated earlier in the report that the machine will run three cycles a day, and each cycle is 120 dishes, so we will run the machine at this rate for a couple of days to test the reliability requirement and linked specifications. As of now we plan on running the machine for 2 days but we will do more testing if we have available time at the end of the semester. This will satisfy our assessment of the reliability requirement. For the safety requirements, there are two specifications: our solution must meet the OSHA 1910.212(a)(3) standard by developing a risk matrix and identifying components of concern (Appendix C Table C.1) and only 18 out of 1800 plates can break. To abide by the OSHA standard, we will ensure that the operating points in the machine are 25 cm away from the moving parts during operation. We will then run 1000 plates through the machine and ensure to meet the breakage percentage of 1%. To test the machine accommodates the different profile and size plates we are running a cycle with each design and size. That is the planned testing for safety and accommodation of all plate sizes and designs.

For the durability requirement, we will conduct more physical testing by simulating normal lab usage over 10 days. However, the durability requirements relate to the longevity of our design as we have a specification that the machine should last up to 10 years. In order to test this, we have incorporated finite element simulations, as shown in the Engineering Analysis section above, and physical testing to see the failure cases for our expected forces during operation. Between our two alpha designs, up to this point our testing procedures have been kept similar, since they both aim to solve the same problem. However, they will inherently have different durability performances, especially considering how different our alpha designs are. For the wedge, we plan on using FDM to create our initial prototypes. By using static and dynamic FEA simulations that accommodate for the cyclic nature of the forces it will experience over time, we will get an initial prediction of how appropriate fused layers of PLA (polylactic acid) is for creating this addition to the filling machine. If our predictions anticipate failure once we account for the anisotropic nature of this manufacturing process, we will widen our scope of materials to ones used in subtractive manufacturing, such as delrin and 6061 aluminum. Our final judgment of durability will be to design a test rig to repetitively stress the wedges under our expected load values to see when they experience failure, if at all. From the prototypes that survive testing, we will choose the one that is most likely to meet the lifetime expectations of this machine that Dr Truttmann suggested we achieve. Another specification to consider regarding durability is that the machine must meet the 1926.251(D)(6)(i) OSHA standard. The wear on the machine must be less than 10 percent after 50 cycles. To verify this we will measure the wedge component and then run the machine for an additional 50 cycles and measure the wedge again to quantify the wear. We will verify wear to the wedge to be less than 8 percent as we want a tiger limit than the specifications.

Once we are confident in the given mechanism's performance, our next step will be to solidify our bill of materials and ensure that all of the materials meet the designated standards for their ability to be sanitized. This verified subsystem will then be combined into the existing prototype, and the remaining requirements regarding the footprint and the user friendliness can be assessed. The footprint is easy to check, since it only takes a small set of measurements to ensure that the working volume is within the acceptable limits we established. We will also be able to test affordability by creating and keeping track of a bill of materials to ensure we stay well under budget. As far as the user friendliness goes, we need to approach it in a more subjective manner. We plan on including a set of test participants to use the machine under various conditions, perform different operations on it, and provide us with feedback that lets us know if our adjustments made the machine more intuitive, and to what degree. We are also aiming to create a user manual with no more than 6 steps to keep the machine user friendly. From sponsor feedback, we have also determined that a simplistic solution is preferred over a more complex engineering solution. If the machine does break in the future a research assistant will be able to fix or replace parts. A simpler design is favored over one of a complex system with mechanical and electronic subsystems. To test this aspect of user friendliness, we will create a bill of materials to ensure the parts are 3D printed (Dr. Truttmann's lab has access to a 3D printer) and the University provides printing services. We will also keep track of how many parts the system has to eliminate unnecessary complexity.

All the testing described above is summarized in Table 8, in the Verification and Validation Plan section. This table also includes the verification of our engineering specification results.

We are specially looking at maintenance testing concepts. Furthermore, we expect our engineering analysis to be testing-heavy as we need to test durability and reliability. Regarding upcoming challenges, we will have to design or identify the best way to attach the wedge mounting piece to the current pushing part of the machine. Since the plate pusher is thin we are currently against using screws to mount our mechanism. Another challenge we will face is carrying out physical testing in the most efficient way. For our project, we believe the more testing the better. However, we want to make sure that all the testing we carry out serves to fully verify at least one of the engineering specifications.

All of these require our team to demonstrate the knowledge we have gained in our undergraduate degrees. For all of the testing we plan to carry out, various members of our team have skill sets in human subject interaction, finite element analysis, DFM/A design practices, assisting in labs across the University of Michigan, and most importantly, being able to communicate and discuss our ideas with each other, especially when we have different ideas on how to approach the same problem.

Verification and Validation Plans

The section above describes our plans to test and analyze our final design once implemented into the plate filler machine. We have planned a specific test or analysis for every specification. The next step of our design process is the verification and validation of our final solution. Below we describe our verification and validation plan.

Verification Plan

The verification plan will serve to ensure our solution works as we designed it to and meets our stakeholder requirements and engineering specifications. Since the verification process aligns with the testing of our specifications, we decided to use the specification testing and analysis plan that we have described in the section: Problem Analysis and Iteration above to serve as the basis for our verification process. In the sections above, we designed a specific test and/or engineering analysis process for each specification. Each test and analysis was made specifically to test the performance of our design in terms of each specification. We therefore are confident that these tests will help verify that our design meets the specifications. Table 8 on the next page shows the testing and analysis methods for our specifications as described above but also includes a column for our verification plan. The verification results will be in the form of a Pass or Fail given the results of the tests and if the design meets the specifications.

Most of the specifications will be verified through physical testing as our project is small scale and it is easy for us to test our implemented design in our workspace. All testing we did to verify project specifications included running the machine, following the Testing Protocol included in Appendix D. However, some specifications relate the longevity and durability of our final design and for these we will carry out some engineering analysis as we cannot fully ensure longevity over the few weeks we have for testing. Other specifications will be verified through documentations such as our bill of materials and material technical reports. From the results of our tests and analyses, we will be able to verify the compliance of our design to the requirements and specifications. Our confidence in our design will be dependent on the results of the test and analyses. Since we have the chance to physically test our implementation, we are confident that we will get to verify most if not all of our requirements.

Reliability

Associated Verification and Results

- *Run 12L of medium over 2 days (720 dishes): PASS*
  The team successfully ran 720 plates through the machine over 2 days of testing. This is an appropriate simulation of lab usage conditions. Of the 720 plates that were filled over 2 days of testing, no plates jammed. We had a 720/720 success rate. Given the results, the team is confident that the machine meets the reliability requirement.

Safety

Associated Verification and Results

- *Measure distance between moving parts and operation points: PASS*
  The team was able to measure the distance between moving parts in the machine and the operation point, in this case the electrical box. The smallest distance between a moving part and the electrical box is 30 cm, meeting the safety specification.
- *Run 1000 medium dishes with maximum 1% of dishes break: PASS*
  We ran 1000 medium sized plates through the machine with 3 plates cracking or being scratched up due to collision with other parts in the machine. This means that 0.03% of the plates broke, which is well below the maximum of 1% . The team is confident that the machine meets the safety requirement because even though 3 plates cracked, there were no big shards of plastic that could hurt the user. The plates were still intact.

Accommodates different plates

Associated Verification and Results

- *Run 2 L of medium for each plate profile and size (120 plates per design): PASS*
  The team successfully ran 2L of medium or 120 plates for each plate size and profile to demonstrate that the machine is compatible with all plate sizes and designs. The success rate for this testing was 120/120 dishes for all plate sizes and designs.

Durability

Associated Verification and Results

- *Run machine for 10 days (in a row) with 3 cycles per day: PASS*
  We ran 3 cycles on the machine for 10 days successfully. Some plates were scratched but remained intact. It would be up to the user to separate these if deemed necessary when the microorganisms are transferred into the plates at a later date. Otherwise, that medium was correctly dispensed into the plates. We believe that this is an overestimate of what lab usage will look like given stakeholder interviews and therefore a good test for durability.
- *Measure the wedge after 50 cycles, compare to initial, wear < 8%: UNDETERMINED*
  We were not able to run the machine for 50 cycles given our timeline and we therefore were not able to analyze the wear of the wedge. This is something we would have completed if we had more time. We would like to note that throughout the testing we did

complete there was no visual wear that impeded the wedge from performing successfully. The durability requirement was the hardest to fully assess as we could not perform enough testing to ensure the machine would last 10 years during the time we had available. All other requirements could be properly tested with physical testing as described in this section. However, the durability requirement verification would benefit from the analysis which we completed in the Engineering Analysis section. Given the analysis we were able to do and all the testing for the other requirements we feel confident delivering our design to Dr. Truttmann and believe that it will last for years if the parts are replaced when needed as described in the Replacement Plan in Appendix F.

User Friendly

Associated Verification and Results

- *Create a user manual (< 6 steps): PASS*
  The team created a user manual with 4 steps, meeting this specification.
- *Obtain user feedback (5 users): UNDETERMINED*
  The team was not able to conduct 5 user interviews within our timeline. However, we were able to show the working machine to Dr. Truttmann at the end of our implementation and all throughout the design process. We kept his feedback in mind and made design decisions accordingly to make sure he was happy with the end result. Moreover, we got some user feedback from our design exposition where we had the public briefly test out the machine. Moreover, since we were not able to conduct user interviews, we could not verify that the machine can be fixed in 5 mins through user interviews but the public did test it during our design expo and was able to easily replace the parts in about 3 minutes.
- *Create a BOM: PASS*
  The bill of materials shows that all materials are off-the-shelf or 3D printed, meeting the specification.

Sanitizable

Associated Verification and Results

- *Check all BOM materials are non-reactive: PASS*
  The bill of materials shows that our design uses only non-reactive materials.

Compact

Associated Verification and Results

- *Measure and weight the machine: PASS*
  The team confirmed that the machine measures fits within the space constrictions. It is 0.86 m long, 0.36 m wide, and 1.05 m tall. The machine weighs less than 14.2 kg, less than the threshold of 15 kg.

Affordable

Associated Verification and Results

- *Create a Bill of Materials: PASS*
  The bill of materials shows that the team stayed well under budget as the cost of the implemented design was under 50 dollars and the budget was 1500 dollars.

Table 8. Table of engineering analysis plan for engineering specifications and a column for the verification process results.

Requirement	Specifications	Analysis/Testing Method	Verification (Pass/Fail)
Reliability	- Deliver up to 120 dishes without interruption -1 out of 720 dishes jams	- Run 12 L of medium over 2 days (720 medium plates)	- Pass
Safety	- 1910.212(a)(3)(OSHA): Moving parts > 25 cm from operation points - 1% plates break during usage (18 out of 1800 plates)	- Measure distance between moving parts and operation points - Run 1000 medium dishes with maximum 1% of dishes break	- Pass - Pass
Accommodates different plates	- Plates with lids of varied profiles (flat and ridged lids) - Compatible with plates of diameter 35, 60, and 100mm	- Run 2 L of medium for each plate profile and size (120 plates per design)	- Pass
Durability	- Lasts at least 10 years (7800 cycles) - 1926.251(D)(6)(i)(OSHA): Wear on wedge edge < 10% after 50 cycles	- Run for 10 days (in a row) with 3 cycles per day - Measure the wedge after 50 cycles, compare to initial, wear < 8%	- Pass - Undetermined
User Friendly	- Require less than 6 steps to operate - Can be repaired in under 5 minutes - Easily replaceable components (parts 3D printed or readily available)	- Create a user manual (<6 steps) - Obtain user feedback (5 users) - Create a BOM	- Pass - Undetermined - Pass
Sanitizable	- IEST-RP-CC004.3 (ANSI): Use only non-corrosive materials	- Check all BOM materials are non-reactive	- Pass
Compact	- Fit within a 1.1 x 0.43 m footprint - Weigh less than 15 kg	- Measure and weight the machine	- Pass
Affordable	- Costs less than 1500 USD	- Create a BOM	- Pass

Given the results discussed above and shown in Table 8, we were able to verify our designs completely meets or passes 6 out of the 8 requirements and we are confident in these verification methods and results. We were unable to fully verify the Durability and User Friendly requirements due to time constraints. However, we tested the machine enough cycles during other testing that the team feels confident the machine will be durable for Dr. Truttmann's lab. We also performed sufficient engineering analysis during the design process that we feel comfortable with the durability of the design. Plus, our solution is designed such that Dr. Truttmann will easily be able to replace the wedge and mounting piece if necessary, which we do not expect to happen often. As for the User Friendly requirement, the machine takes less than 6 steps to operate as specified in the requirement and our design consists of only 3D printed or off the shelf parts, shown in the bill of materials. We were not able to conduct user interviews but were able to have enough volunteers try out the machine during the design exposition, and all of them were able to easily run the machine and switch out wedge designs without trouble. Furthermore, our wedge implementation added a very short and easy step to the preexisting procedure of running the machine. Overall, we are confident delivering our design to Dr. Truttmann given our verification process and experience throughout the semester.

Validation Plan

The validation process will help us decide if our solution addresses the problem statement successfully and if our sponsor, in this case Dr. Truttmann, will be happy with our solution. Our validation plan is to create a testing procedure or protocol that allows for user feedback. We are planning on creating a user manual, having multiple people test out the machine and then conduct interviews to attain user feedback. We are going to ask lab GSIs, research assistants, and some classmates that do not have a lot of lab experience but should be able to work the machine given the user manual. Once we get to look over the user feedback, we will be able to validate our design.

The team created a user manual as shown in Appendix G. However, we did not have time to carry out interviews and collect user feedback. The validation process was not completely finished but we were able to show the working machine to Dr. Truttmann at the end of our implementation and all throughout the design process. We kept his feedback in mind and made design decisions accordingly to make sure he was happy with the end result. We also carried out sufficient testing and are confident that our design addresses the problem statement successfully.

Problem Domain Analysis

At the end of the semester, the deliverable will be a fully functional plate filler. We are focusing on the pushing mechanism because the other components of this device are already fully functional. We need to create a solution that ensures the plate pushing mechanism is compatible with the rest of the machine since the plate supplier changed during COVID 19 so the lid profile of the plates differed.

This plate pushing mechanism can be prototyped and simulated for the remaining half of the semester. Simulations will be done on the two alpha concepts and 3D printed to prototype. At least three 3D printers have been secured (Team member and the Duderstadt makerspace at UM). The first design driver is manufacturability and that will influence the design decision since our deliverable is to have a fully functional machine and if it is not manufacturable in the remaining half of the semester the design will not be further considered. The other design drivers are the list of requirements used in the Pugh Chart (Table 5).

The alpha concept of the spacer is a more difficult design to implement compared to the wedge since the spacer is an electromechanical component and must fit within the plate guides. The wedge design will not be difficult to prototype, the dimensions can be easily adjusted and printed off again (~45 minutes) to prototype.

The major problem expected is the time constraint. The prototyping will be done via 3D printing so manufacturability within a set time will not be a constraint since there are resources readily available. The time constraint during the design iteration process will be of a challenge since there are two designs to explore simultaneously and with the limited amount of time, the design iteration process will be very fast paced and consuming. This will be addressed by dividing the team in half and having two members work on each alpha design and communicating frequently, both internally and with the sponsor.

We will also need to use our resources efficiently and be flexible, for example, when a simulation is being run, the other member can work on the prototyping and physically testing the component to minimize the down time, additionally stepping in to work with the other team when extra help is needed will be crucial maximizing our efficiency. Another strategy to maximize the efficiency and minimize the resources wasted is documenting and communicating the tests performed as well as its results so no experiments will be repeated. In addition to the technical knowledge, information gaps, and challenges discussed in DR1, another foreseeable challenge has already been mentioned which is the time constraint and having two teams working on two different designs simultaneously. The time constraint challenge will require an efficient design iteration process and that entails documenting the tests performed already to ensure that no tests will be repeated. Using equations of interest and referring to literature will help to minimize the number of tests needed. Splitting up the team will result in a lack of communication and a possibility of repeated work and different expectations, to address these issues there will need to be frequent meetings within the team. The meetings should always start with a detailed agenda to keep the entire team up to date. There will need to be formal meetings at least once a week to discuss the progress of each design and informal meetings in between. Being flexible in terms of resources allocated to each design will ensure the maximum efficiency and address the issue of completing all tasks in the remaining half of the semester.

Currently, the engineering specifications were determined based on the feedback received from the primary and secondary stakeholders. However, there will be challenges in assessing the engineering specifications based on the limited knowledge of the laboratory. Dr. Truttmann is just asking for a fully functional machine, however we do not have the full scope of his research and that limits our understanding of the capabilities he desires from this machine. For example, we know that it does not need to be in a fully isolated chamber for the petri dishes to be filled; however how isolated this machine needs to be is a question of concern. Additionally, we received permission to redesign the entire machine however this is already a fully functional machine and we lack the knowledge of the design process from the previous two teams. Even

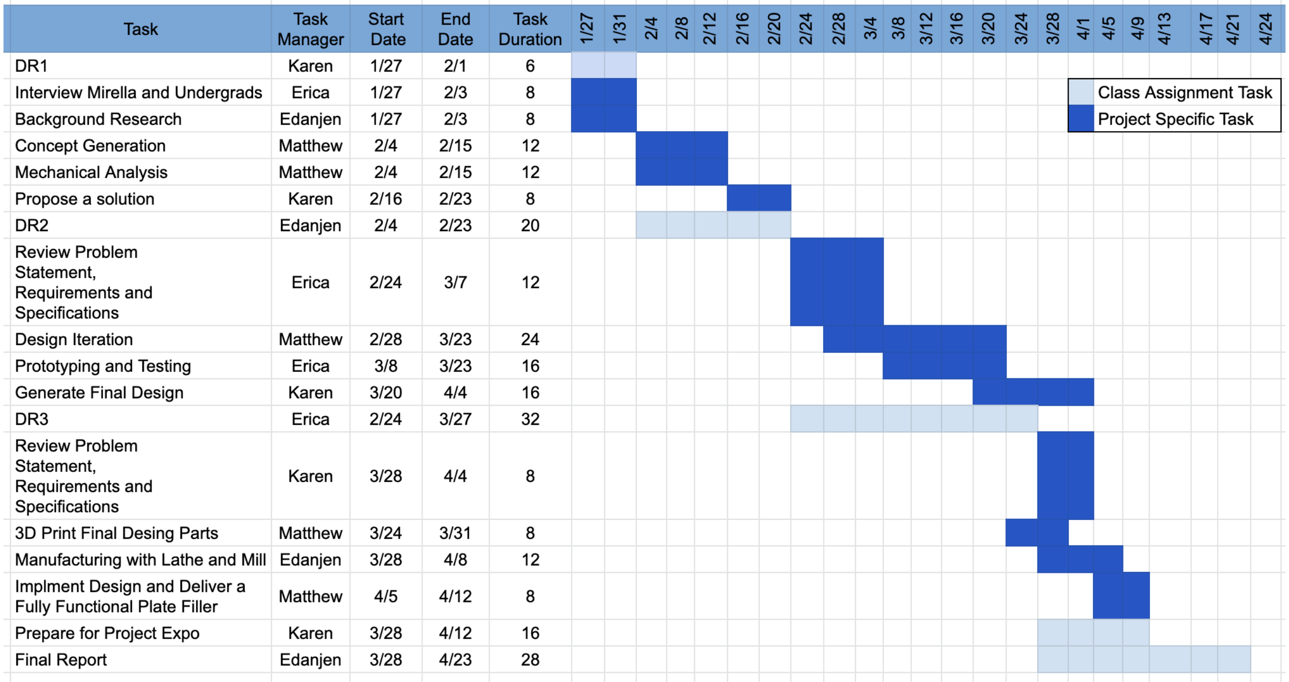
though the final report of one team has already been located there is still one team that we are not knowledgeable about their design process. A major problem expected in developing concepts to meet the specifications is the compatibility of our solution with the existing machine. This can be addressed by testing with the machine consistently and remaining focused on just the plate pusher mechanism. Another major problem is making modifications that are better than the current device. Therefore, a thorough understanding of the previous two teams' design process is crucial. Different parts of the machine requires different levels of expertise, the vacuum pump will require a technical vacuum pump expert (possibly the supplier of the pump), Dr. Truttmann has explicitly stated that no janitorial staff are to be in contact with the machine and the undergraduate students will be trained to operate the plate filler. A quick start guide to operate the machine has been provided and the GSI has extensive experience with the operation of this machine from the training of the previous two MECHENG 450 teams therefore they will be able to train the undergraduate students. To solve the critical problems the lab assistant should refer to a common problem guide that will be created by Team 23 of MECHENG 450 based on their observations of the machine. We will be in contact with the primary stakeholders during the initial uses (~15 uses). Our contact information will be provided as well so the GSI can contact us in case of any emergencies in the future. If a critical problem does arise and requires us to troubleshoot then the process will be recorded in detail and added to the common problem guide so the lab members will be able to reference it in the future. The GSI will also be present so they will be trained on how to fix this particular problem. If a serious problem arises that requires a part replacement, it may be necessary to transport it back to the X50 workspace and logistically that will require at least two people for transportation. The critical problems mentioned above will require additional training and resources to ensure the machine performs as intended while meeting the engineering specifications. Currently there exists a gap in the understanding of biological cultural growth. We are seeking more information related to that field from Dr. Truttmann, the lab team as well as outside resources to address the gap in knowledge.
We also lack a complete understanding of the lab as mentioned above but specifically who can handle this machine and what type of training is required. Finally, we are further strengthening our knowledge in how the plate filler is incorporated in the lab from beginning to end and all of this information mentioned can be acquired from our sponsor as well as the primary stakeholders with extensive interview questions.

After developing the 2 design solutions, we introduced both designs to the sponsor and received feedback from him. From his feedback we revised the table of requirements to reflect his desires. And based on the information we received from interviewing Mirella we learned the importance of simplicity. Our 2nd alpha design (stack spacers) was a great concept however it was significantly more complex than the wedge design and difficult to replace. The initial plan of developing two designs simultaneously was a great use of resources and is something that can be applied to future projects. One thing we lacked is meeting with the sponsor frequently, we proposed both designs to him after developing the design but there was an apparent favored design solution after the call with him so we should have spent less time on developing the spacer.

After testing the ball detent design, a snap fit design was chosen due to its simplicity and ease of implementation and manufacturability. This snap fit design is easy to replace, aligning with the requirements of the sponsor. The ease of manufacturing is achieved by the 3D printed components but that may lead to print quality issues as well as durability of the components. Therefore, adjusting the resolution in the slicing application will improve quality and other materials can be used other than PLA and SLA.

Project Plan

This initial project timeline is based off of our sponsor expectations regarding deliverables and class assignments as they guide us through the design process we have discussed above. We know the timeline might change especially since it is very early on in the project and no solution brainstorming has taken place so the team does not know how extensive any manufacturing or testing will be. The gantt chart in Figure 28 depicts our initial project timeline.



Task	Task Manager	Start Date	End Date	Task Duration	1/27	1/31	2/4	2/8	2/12	2/16	2/20	2/24	2/28	3/4	3/8	3/12	3/16	3/20	3/24	3/28	4/1	4/5	4/9	4/13	4/17	4/21	4/24
DR1	Karen	1/27	2/1	6	░	░																					
Interview Mirella and Undergrads	Erica	1/27	2/3	8	█	█																					
Background Research	Edanjen	1/27	2/3	8	█	█																					
Concept Generation	Matthew	2/4	2/15	12			█	█	█																		
Mechanical Analysis	Matthew	2/4	2/15	12			█	█	█																		
Propose a solution	Karen	2/16	2/23	8						█	█																
DR2	Edanjen	2/4	2/23	20			░	░	░	░	░																
Review Problem Statement, Requirements and Specifications	Erica	2/24	3/7	12								█	█	█													
Design Iteration	Matthew	2/28	3/23	24									█	█	█	█	█	█									
Prototyping and Testing	Erica	3/8	3/23	16											█	█	█	█									
Generate Final Design	Karen	3/20	4/4	16														█	█	█	█						
DR3	Erica	2/24	3/27	32								░	░	░	░	░	░	░	░								
Review Problem Statement, Requirements and Specifications	Karen	3/28	4/4	8																█	█						
3D Print Final Desing Parts	Matthew	3/24	3/31	8															█	█							
Manufacturing with Lathe and Mill	Edanjen	3/28	4/8	12																█	█	█					
Implment Design and Deliver a Fully Functional Plate Filler	Matthew	4/5	4/12	8																		█	█				
Prepare for Project Expo	Karen	3/28	4/12	16																░	░	░	░				
Final Report	Edanjen	3/28	4/23	28																░	░	░	░	░	░	░	

░ Class Assignment Task
█ Project Specific Task

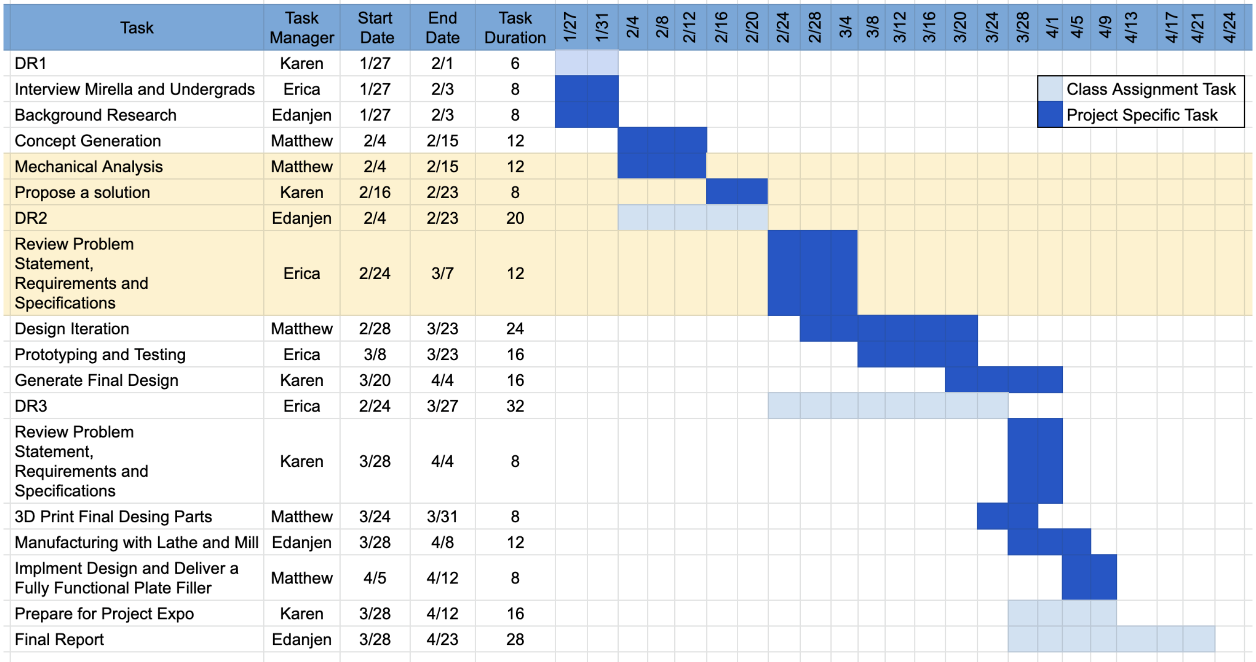
Figure 28*:* Gantt chart representation of project timeline. Tasks have a manager, start date, end date, and task duration. Legend shows light blue coded tasks are class assignments the team must complete and darker blue tasks are specific to our project and deliverables.

The initial tasks for the team are to complete stakeholder interviews and begin concept generation while keeping in mind the DR2 deadline. The gantt chart shows the following tasks for the semester and provides the critical path or team must follow. The gantt chart also lists a task manager who will be responsible for making sure we stay on track regarding that specific task and stay making progress. Some smaller tasks the team has on their to-do list are: look into acquiring agar for proper testing, spend time running the machine, and discuss our progress and plan with Dr. Truttmann in our bi-weekly meetings.

This is a realistic schedule for the team to follow throughout the semester. The tasks are specific enough to provide a direction for the project and make sure all deliverables are accomplished. Subtasks may be created later on in the semester as we learn more details. An important aspect to point out regarding our project plan is that we have included time for design iteration if our initial design prototype does not meet the requirements or just does not solve the problem. We also allocated some weeks during the semester to reviewing the project requirements and specifications as these might change or evolve as we get more experience working with the machine. We wanted to make sure to demonstrate the iterative nature of the design process in our timeline.

The scope of the project is reasonable for a semester long project and we believe that there are enough team members to successfully complete this project. The budget was discussed with our sponsor and in the specifications section. The team thinks it is more than enough resources to complete the project given there are remaining usable materials from the previous teams on this project. The team is confident we will be able to implement a solution to make the plate filler machine compatible plates of different profiles and designs. A fully functional plate pusher that is compatible with the rest of the machine will be delivered at the end of the semester. We were given creative freedom by Dr. Truttmann to make any improvements to the machine that we believe will make it more efficient. The focus is not on making improvements at the moment as it is out of the scope of the problem statement. However, there is a possibility to develop improvement ideas and designs but they may not be fully implemented this semester due to time constraints. In addition, there is another possibility of developing manufacturing plans and this will be something the team will start and set a foundation for but may not have time to for a complete implementation. The main priority is to create a functioning plate pusher that is compatible with the rest of the machine by the end of the semester. Dr. Truttmann may pursue our recommendations or designs in future semesters if desired.

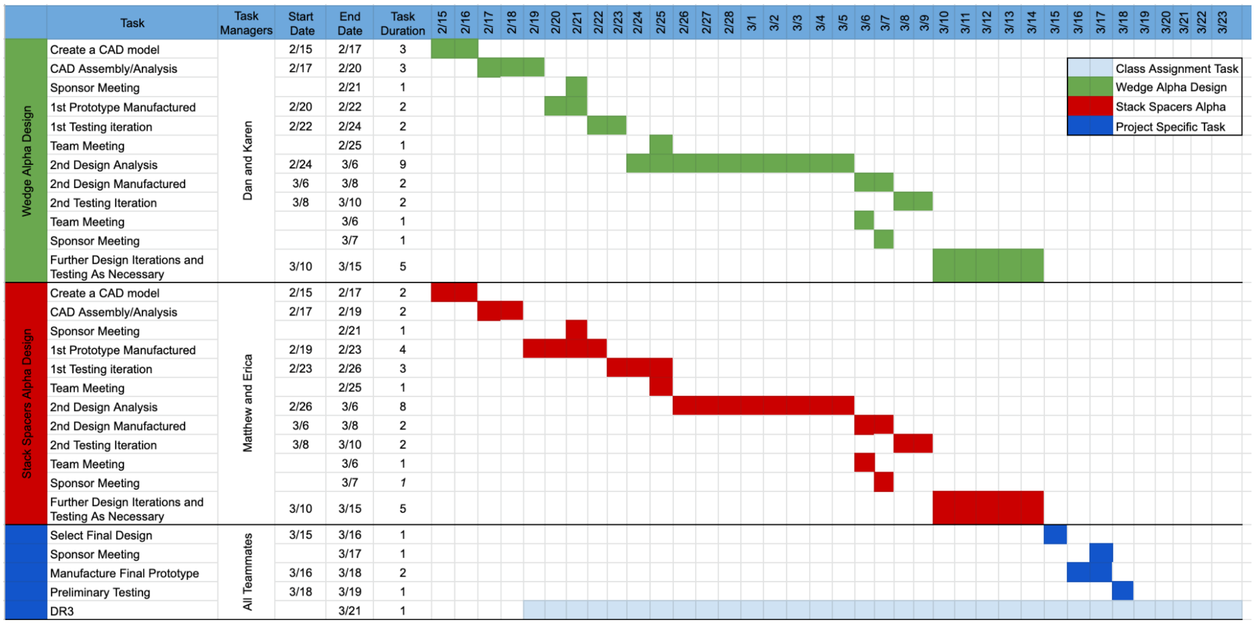
After discussing with our sponsor and taking into consideration the design process for the alpha concepts, the existing project plan has been revised. This revised project plan is shown below in Figure 29.



Task	Task Manager	Start Date	End Date	Task Duration
DR1	Karen	1/27	2/1	6
Interview Mirella and Undergrads	Erica	1/27	2/3	8
Background Research	Edanjen	1/27	2/3	8
Concept Generation	Matthew	2/4	2/15	12
Mechanical Analysis	Matthew	2/4	2/15	12
Propose a solution	Karen	2/16	2/23	8
DR2	Edanjen	2/4	2/23	20
Review Problem Statement, Requirements and Specifications	Erica	2/24	3/7	12
Design Iteration	Matthew	2/28	3/23	24
Prototyping and Testing	Erica	3/8	3/23	16
Generate Final Design	Karen	3/20	4/4	16
DR3	Erica	2/24	3/27	32
Review Problem Statement, Requirements and Specifications	Karen	3/28	4/4	8
3D Print Final Desing Parts	Matthew	3/24	3/31	8
Manufacturing with Lathe and Mill	Edanjen	3/28	4/8	12
Implment Design and Deliver a Fully Functional Plate Filler	Matthew	4/5	4/12	8
Prepare for Project Expo	Karen	3/28	4/12	16
Final Report	Edanjen	3/28	4/23	28

Figure 29*:* Revised Gantt chart representation of project timeline after further discussion with the sponsor and considering the two alpha designs. Tasks have a manager, start date, end date, and task duration. Legend shows light blue coded tasks are class assignments the team must complete and darker blue tasks are specific to our project and deliverables. The yellow highlighted portion are the tasks we are currently completing.

The new tasks for this project are the design iterations for the two alpha concepts. In the previous project timeline it briefly covers a design iteration process for each member however with this revised project plan, a detailed plan outlines the timeline for both alpha concepts and the design process as well as the team members assigned to each task. The main task that needs to be accomplished before the 3rd design review is selecting, manufacturing and testing a final design. This will be done by creating a CAD model and assembly for each alpha concept, then an initial analysis done on CAD for dimensions, then an initial meeting with the sponsor to provide him updates of the two designs and a 1st prototype will be manufactured and tested then a team meeting to review the test results and design changes to consider and implement. Then a second design iteration and a team meeting and sponsor meeting to discuss the results and provide an update on the status of the two alpha concepts. Then further design iterations and testings and finally the two teams will come together and select a final design, inform the sponsor in a meeting, provide the advantages and disadvantages and manufacture the prototype and perform preliminary testing and prepare for the 3rd design review. Team members Edanjen and Karen will be working on the wedge and Matthew and Erica on the spacer. There is dedicated time (~1 week) for further design iterations and testing as necessary. And this time will be used if more information is discovered. The detailed project plan for the two alpha designs is shown below in Figure 30.



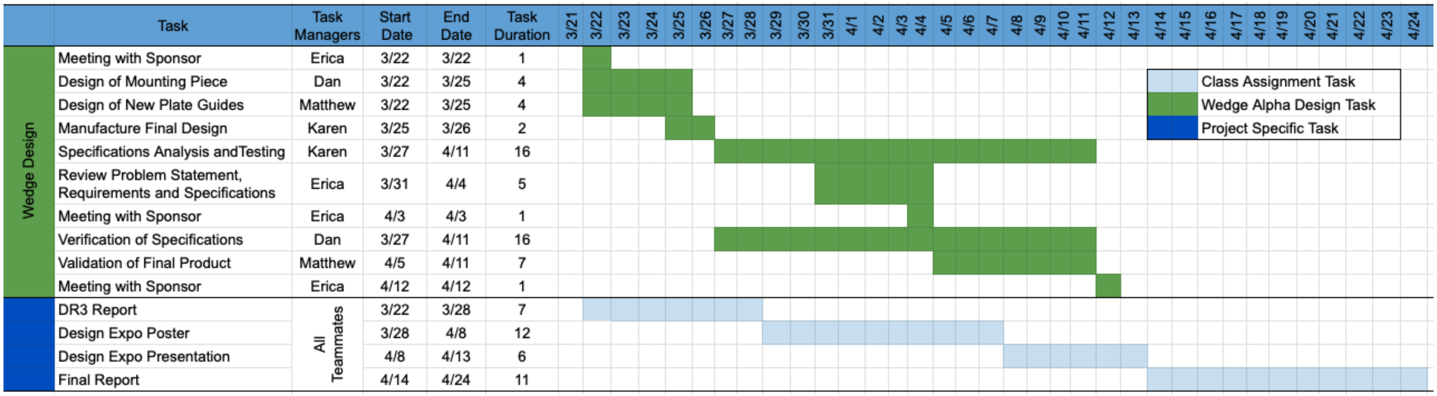
	Task	Task Managers	Start Date	End Date	Task Duration
Wedge Alpha Design	Create a CAD model	Dan and Karen	2/15	2/17	3
	CAD Assembly/Analysis		2/17	2/20	3
	Sponsor Meeting			2/21	1
	1st Prototype Manufactured		2/20	2/22	2
	1st Testing iteration		2/22	2/24	2
	Team Meeting			2/25	1
	2nd Design Analysis		2/24	3/6	9
	2nd Design Manufactured		3/6	3/8	2
	2nd Testing Iteration		3/8	3/10	2
	Team Meeting			3/6	1
	Sponsor Meeting			3/7	1
	Further Design Iterations and Testing As Necessary		3/10	3/15	5
Stack Spacers Alpha Design	Create a CAD model	Matthew and Erica	2/15	2/17	2
	CAD Assembly/Analysis		2/17	2/19	2
	Sponsor Meeting			2/21	1
	1st Prototype Manufactured		2/19	2/23	4
	1st Testing iteration		2/23	2/26	3
	Team Meeting			2/25	1
	2nd Design Analysis		2/26	3/6	8
	2nd Design Manufactured		3/6	3/8	2
	2nd Testing Iteration		3/8	3/10	2
	Team Meeting			3/6	1
	Sponsor Meeting			3/7	*1*
	Further Design Iterations and Testing As Necessary		3/10	3/15	5
	Select Final Design	All Teammates	3/15	3/16	1
	Sponsor Meeting			3/17	1
	Manufacture Final Prototype		3/16	3/18	2
	Preliminary Testing		3/18	3/19	1
	DR3			3/21	1

Figure 30*:* Detailed project plan of the two alpha designs through the iteration process. Tasks have a manager, start date, end date, and task duration.

The critical path we must follow closely entails exploring both alpha concepts thoroughly with the specific tasks and deadlines in the Figure 22. That way the final design can be implemented into the plate filler to solve our goal of having a fully functional plate filler. The spacer may require more resources than the wedge therefore we have allocated extra time and acknowledged that we must be flexible with our resources to make sure both concepts are fully designed. We have to fully explore both designs before proposing a final design and the critical path will ensure we do that.

Consideration for ordering parts has been noted and with McMasterCarr there is a maximum 3 day delivery therefore the week of buffer allocated will allow for ample delivery and implementation time [25]. The team members have access to other locations that will provide the same resources as McMasterCarr. As mentioned before, a budget has been considered however Dr. Truttmann has provided us with $1500 however Dr. Truttmann mentioned more will be provided if needed. In addition, the previous teams have unused material that is still applicable to our project. In addition, 3D printing is a very low cost prototyping method [26]. Therefore, budgeting is not considered to be an issue of high priority. After receiving feedback from our sponsor and more research we have revised the project plan to maximize our resources and efficiency.

Now that we have decided on a final design, our next steps are to finalize the design, prototype, build, test, run analyses, and verify and validate our implementation. We therefore have created a schedule for the rest of the semester that allows us to do all of these things while also allocating time for stakeholder feedback as well as time to review our requirements and specifications as necessary. This is especially important as we start verifying our specifications and may have to make more changes to the requirements and specifications once again. The design process is an iterative process so we have also allowed some iteration opportunities in the schedule. These iteration opportunities are important as those give us multiple opportunities to work through our anticipated challenges. The schedule also aligns our design process with the class deadline that we have for this last month of the semester. The revised schedule for the rest of the semester can be seen in Figure 31.



	Task	Task Managers	Start Date	End Date	Task Duration
Wedge Design	Meeting with Sponsor	Erica	3/22	3/22	1
	Design of Mounting Piece	Dan	3/22	3/25	4
	Design of New Plate Guides	Matthew	3/22	3/25	4
	Manufacture Final Design	Karen	3/25	3/26	2
	Specifications Analysis andTesting	Karen	3/27	4/11	16
	Review Problem Statement, Requirements and Specifications	Erica	3/31	4/4	5
	Meeting with Sponsor	Erica	4/3	4/3	1
	Verification of Specifications	Dan	3/27	4/11	16
	Validation of Final Product	Matthew	4/5	4/11	7
	Meeting with Sponsor	Erica	4/12	4/12	1
	DR3 Report	All Teammates	3/22	3/28	7
	Design Expo Poster		3/28	4/8	12
	Design Expo Presentation		4/8	4/13	6
	Final Report		4/14	4/24	11

Figure 31*:* Detailed project plan for the rest of the semester as we focus on finalizing, verifying, and validating our final design. Tasks have a manager, start date, end date, and task duration.

The tasks in green are geared towards finalizing, verifying, and validating our final design. The tasks in blue are the class assignments and the time we have allocated to working on them.

We have successfully carried out the majority of our verification and validation process as described in the section above. Next steps involve getting the modified pate filler machine to Dr. Truttmann, explaining our design, and helping him set up the machine in his lab space.

Discussion

If more time was allocated, the other components of the machine can be improved upon, such as the wire management system and the time it takes to run a whole cycle. Improving the wire management system can be done by shortening and removing unnecessary wires. Lowering the time it takes to run a whole cycle can be done by optimizing the code and identifying which parts of the process can be completely eliminated and what steps can be added or combined to shorten the time.

The biggest strengths of this design is that it can be easily manufactured and has a very low cost since two of the three components are 3D printed. It is a very simple design to understand since it only has 3 components and it is very easily replaceable because of how the components are manufactured and number of parts, aligning with the requirements from Dr. Truttmann. The main weaknesses of this design are the tolerance and longevity of the components since they are 3D printed. 3D printed parts have a low tolerance and will require post processing and since we adapted a snap fit design, the parts may wear out earlier than anticipated. These weaknesses can be mitigated by exploring other 3D printed materials. The resources available to us through the university were limited in terms of 3D printer materials, but we experimented with two different materials, and PLA had the best results. Another design path that we chose was making 3 different wedges for the 3 different plate dimensions. However, in the future maybe one wedge can be designed to fit all 3 different plate dimensions. One of our earlier designs was only one wedge, however, it was tested and proven that it would not be a fit for all 3 plate designs. In the future, they can explore a different mechanism, such as using a previous alpha design to make it applicable to other plates. Reviewing the design process, more time could have been spent in the earlier stages to develop the other alpha design since it would apply to a broader range of plates, however, with the time and resources available the wedge design was the most reliable design solution.

The challenges encountered in the design process included the print quality and design changes. To minimize the effects of poor print quality, extra attention was dedicated to the post processing by sanding down, removing supports, and adjusting the settings in the slicer application by refining the resolution. Every small design change required a new printed piece, and to minimize the number of prints that needed to be done, temporary changes using popsicle sticks and sanding down the wedge more and melting parts of the 3D printed pieces were done. Once the final dimensions were achieved, the CAD was modified and printed, and this resulted in reduced print time and increased efficiency of the design iteration process. The risks associated with the end user of our final design includes finding the correct printer that will produce a high quality print in a reasonable time and the use of the post processing equipment (sand paper, file and tweezers). To mitigate the risks associated with using the post processing equipment, users should be conscious of the work being done and follow standard safety procedures. And to mitigate the low quality print, the user can adjust the print resolution in the slicer application and test out different 3D printers available to them.

Reflection

Biology related labs would benefit from an automated plate filler machine. A machine like this helps experiment productivity and output of the entire lab as a whole. An automated pate filler machine would also allow the research assistant, who would previously be the one manually filling up the plates, to do something more productive with their time. Research assistants will be able to carry out some experiments on their own and will learn more from their experience in the lab. Our specific project will help the Truttmann Lab because it is designed to their lab space and their petri dish lab capacity. Furthermore, our machine is an affordable solution to the lab’s need for an automated plate filler. Other plate filler machines on the market are too expensive and not right for the space. The Truttmann Lab directly benefits from our project and other small biology labs could benefit as well in the future. The team’s initial perspective was that the machine would be extremely beneficial to Dr. Truttmann's lab and has only been reinforced as we learned how many plates they go through on a weekly basis.

Understanding the design context was important to the team to be able to make educated design decisions. We created an ecosystem map as seen in the Design Context Section above. This tool allowed us to study the stakeholders playing a part in our design process. Otherwise, we would not have considered our design problem from all different points of view and considered all possible consequences of our design decisions. From our ecosystem map we were able to get research, interview, and reach out to our stakeholders and study all aspects of our project.

Public Health, Safety, and Welfare

The automated plate filler project has some public health and welfare applications. An automated plate filler machine will lead to more medical research to better public health and welfare. The Truttmann Lab is conducting neurodegenerative disease research that can lead to medical treatments in the future.

Global Context

Regarding a global marketplace, our machine can very well be mass produced, sold, and distributed to other labs that handle a large quantity of petri dish experiments but do not have the funding, space, or the need for the extremely large and expensive machines on the market. Our machine is smaller scale but just as effective and can really help with the productivity of research labs. This would benefit smaller labs globally and advance scientific research.

Social and Economic Impacts

Currently our project is small scale with manufacturing a single machine for Dr. Truttman lab so there is no big impact with manufacturing or disposal of materials. However, if our sponsor pursues mass production of the machine, sourcing sustainable materials and responsible manufacturing would be definitely something to consider. Regarding waste and disposal of materials, it is important to our team to have as few plates fail, crack, or break as possible to minimize the waste created.

Economically, our design should not have any negative repercussions. Smaller labs would utilize our smaller design while larger labs would still buy and benefit from the larger automated petri dish fillers available in the market. Actually, if mass produced our machine would allow the smaller labs to get access to the automation petri dish process that they currently do not have access to.

Inclusion and Equity

Some power dynamics present during our design process include the power dynamic between Dr. Truttmann and us, the one between Dr. Truttmann and research assistants in his lab, and the one between the team and research assistants. The power dynamic between our tema and our sponsor was especially important because we had to keep his wishes in mind and make design decisions accordingly. We had to engineer a solution that met all his requirements while also keeping engineering principles and limits in mind. Dr. Truttmann was a great sponsor and always took our engineering feedback into consideration. However, it was also important to keep the power dynamic between Dr. Truttmann and his lab's research assistants in mind. Dr. Truttmann is the head of the lab but it was also important to understand that at the end of the day the research assistants would be the day-to-day users of the machine. We had to keep in mind their wishes because they are the ones who would have to interact with the machine. We wanted the machine to be functional but also as user friendly as possible for the research assistants. The team had a different perspective to that of the research assistants because our background is engineering based but the research assistants have a biology background. They brought up some machine requirements for the machine that we would have never thought of if we had not interviewed them.

Since none of the team members had experience working with petri dishes it was important for us to keep open communication with lab staff. All team members agreed that we should interview or research any and all stakeholders available. We wanted stakeholder input from plate distributors, other medical labs, Dr. Truttmann, to research assistants. We wanted as many diverse viewpoints as possible. If we found different viewpoints, we prioritize those of stakeholders who would have the most contact with or be most affected by our design implementation. But, we were lucky enough to not have crazy opposing viewpoints that could create issues in the design process. Most stakeholder recommendations and requests aligned with each other.

Even though team members have different and diverse backgrounds, we agreed on most design decisions. Different opinions, strategies, and approaches were introduced and explained by different team members but we were always able to come to an agreement. A team member explained his reasoning and other team members gave their opinions and a decision was then made as a team. This approach worked for us because we would often end up combining ideas or build off of each other's to come up with the best solution. Something else important to point out is that we never faced severe differences in opinion with our sponsor. We kept the relationship professional and were always able to work through challenges together. We did not let cultural differences impede our work.

Ethics

The team faced an ethical dilemma regarding Dr. Truttmann's future plan for the research assistants in his lab. We worried that since research assistants would no longer be needed to fill and prepare the petri dishes they would no longer be asked to come back and work in the lab. The team asked Dr. Truttmann and was happy to learn that research assistants would instead be given more serious responsibilities. Research assistants will play a more serious role in the lab and can learn much more during their time in the lab. Research assistants no longer being needed in research labs could be an issue that arises if our design enters the marketplace. However, we believe that labs will always have more tasks that need to be completed. There will always be more research to be completed in labs that would acquire our machine. We believe that our ethical concerns align with that of the universities and future employers. It is important to consider all possible consequences (good or bad) that would result from any engineering work.

Recommendations

We find our solution to satisfy the design requirements and specifications to a degree that our sponsor will be happy with. However, we have a few recommendations in order to ensure that our machine functions to the best of its ability. Firstly, it is best to have more than 2 plates in the column at all times. This ensures that the stack has enough weight to keep its momentum while falling, and prevent any jams against the side. The machine does not jam when given large quantities of plates, but we sometimes experience trouble finishing out the cycle. We also recommend changing out the mounting component if the snap fit feels loose. This is to ensure the quality of the snap fit to keep the wedge from jamming the plates.

Conclusion

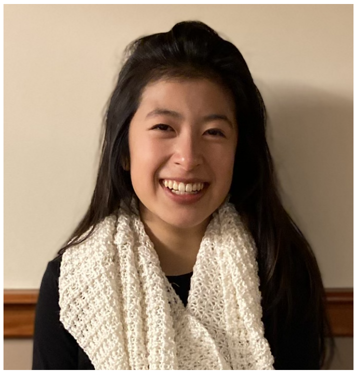
In conclusion, we have been tasked with retrofitting a custom made automated petri dish filler to work with different types of petri dishes. Automated plate fillers can cost upwards of 40,000USD, so the Truttmann lab sought the aid of two separate MECHENG 450 teams to create an automated plate filler. It works by pushing a dish out from a stack of petri dishes, where it is received by a suction cup mechanism to remove the lid, fill it with a calibrated volume of agar growth medium, and place the closed lid into a rotating carousel storage mechanism. Initially, Dr. Truttmann's lab has used dishes with flat-topped lips, which were able to be easily pushed from the bottom of a stack of dishes. During the COVID pandemic, supply shifts forced them to switch to a type of petri dish with a ridge on top of the lids to facilitate stacking, however it rendered the pushing mechanism of the automated plate filler unreliable. We have come up with a list of user requirements and engineering specifications that will constrain our design process to the set of solutions that will maintain the utility this machine provides for the lab. Up to this point, we have learned a sufficient amount about the nature of what research this lab conducts to make educated decisions about how this machine is expected to function, and we were also able to learn about the decisions that motivated the design of the existing prototype. After an extensive concept generation process and using a convergence based criteria system to judge each design, we have produced 2 alpha concepts that we will move forward with as we prototype the solution to the disk compatibility issue present within the machine. We have eliminated the second alpha design and have opted to go for the wedge design due to manufacturability and cost. We have done sufficient analysis to be confident in its design based on our analysis, and are starting to move forward with more robust testing in order to be certain of its ability. As we approach our final design, we have decided to go with a two part wedge that is able to adapt to all three sizes of plates, while still being easy to manufacture in the case of wear and tear. We will move on to the verification of our engineering specifications and validation of our finaled design.

Our final design proposed is a 3D printed PLA wedge attached to a 3D printed PLA snap fit mount and acrylic mount extension. It is currently implemented on the machine and is a sustainable and reliable solution. Tests were conducted with this final design; it has been demonstrated to meet all the requirements determined by the sponsor and the team. In the future, a different 3D printed material can be explored as well as manufacturing processes to extend the longevity of mount and wedges. This automated plate filler will enrich the experience of the undergraduate research assistants by allowing them more time to perform more meaningful tasks and increase the overall productivity of Dr. Truttmann's lab. This machine will also contribute to the progression of other laboratories that will need to use agar filled petri dishes in bulk but have a financial and dimension constraint, this machine is a significantly lower cost than industry petri dish fillers and has a smaller footprint. Contributing to the overall productivity of not just medical reserach but also biological. .

Acknowledgements

This project was made possible by the ME450 instructional team and Dr. Truttmann. We would like to take this opportunity to acknowledge and thank the Graduate Lab Assistant, Mirella Hernandez, she was very helpful and responsive to our request. We also would like to thank the ME450 Instructor, Randy Schwemmin, for his constant feedback and assistance. Finally, we would like to thank Dr. Truttmann for providing us with this project and the resources.

Team Bios



Erica Liu is from Ann Arbor, MI (she went to the high school right across from the Big House). Initially she had interest in Speech Pathology and then medicine but she realized she cannot tolerate blood so she went on to take an Introduction to Engineering course and developed an interest in Mechanical Engineering because of how diverse this major is. She plans on returning in the Fall to get a master's degree in Mechatronics but still uncertain on what she wishes to do after that. Outside of the classroom she enjoys hammocking, reading, jogging and golfing.

Karen Reyes is from Charlotte, North Carolina. She is a senior undergraduate student getting her Mechanical Engineering degree from the University of Michigan. Her interests lie in the product development of medical devices and hopes to someday work in industry research. She plans to continue on with her education and pursue a master's degree next Fall. Some of her hobbies include reading, hiking, volunteering at the dog shelter, trying new foods, and traveling.

Edanjen Lin, a junior in Mechanical Engineering, is currently attending the University of Michigan. He is interested in pursuing a career in robotics to continue the push to replace menial labor with dispensable robots, such as delivery fulfillment and search and rescue applications. After graduating in the Winter of 2024, he will move into industry research, with eventual plans to pursue a master's degree as well. His hobbies include guitar, calisthenics, and cooking.

Matthew Pan is a senior majoring in Mechanical Engineering with a minor in Computer Science, and is graduating in the Fall of 2023. He is from New York City, and misses a city where a car is not needed. He is interested in working in the aerospace industry, with a focus in manufacturing. At school, he is a member of the M-Fly Aero Design project team, where they design and build airplanes from scratch. In his free time, he enjoys watching movies, shooting pool, and other activities that occur in places with pool tables.

References

[1] *Truttmann Lab Site*. https://truttmann.lab.medicine.umich.edu/.
[2] Truttmann. *Get to Know Me* . In Person, 20 Jan. 2023.
[3] *Work-Study | U-M LSA Undergraduate Research Opportunity Program (UROP)*.
[4] Hernandez Lima, Mirella. *Get to Know the Lab* . 1 Feb. 2023.
[5] “APS ONE Plate Filler.” *BioMérieux*,
https://www.biomerieux-usa.com/industry/aps-one-plate-filler.
[6]*Disposable Petri Dishes*. https://www.weberscientific.com/disposable-petri-dishes.
[7] “Pre-Poured Agar Dish, PDA Formulation 40 Pack.” *Mycology-Supply*,
https://mycology-supply.com/products/copy-of-pre-poured-agar-dish-pda-formulation-40-pack.
[8] “Why Use the Worm in Research?” *@yourgenome · Science Website*,
https://www.yourgenome.org/facts/why-use-the-worm-in-research/.
[9] Baniya, Sushmita. “Petri Dish: Types, Uses, and Automated Petri Dish Filler • Microbe Online.” *Microbe Online*, 12 Oct. 2022,
https://microbeonline.com/petri-dish-types-uses-and-automated-petri-dish-filler/.
[10] “NEUTEC Group PS900 Agar/Media Filler - Laboratory Automation, Automated Agar and Media Plate Filler.” *Neutec Group PS900 Agar/Media Filler Agar/Media Filler:Laboratory Automation, | Fisher Scientific*,
https://www.fishersci.com/shop/products/neutec-ps900-agar-media-filler/14910423#?keyword=.
[11] *Student Research | U-M LSA Program in Biology*.
https://lsa.umich.edu/biology/undergraduates/student-research.html.
[12] Claeys, G., et al. “Modified Granada Agar Medium for the Detection of Group B Streptococcus Carriage in Pregnant Women.” *Clinical Microbiology and Infection: The Official Publication of the European Society of Clinical Microbiology and Infectious Diseases*, vol. 7, no. 1, Jan. 2001, pp. 22–24. *PubMed*, https://doi.org/10.1046/j.1469-0691.2001.00156.x.
[13] Stiernagle, Theresa. *Maintenance of C. Elegans*. WormBook, 2006. *www.ncbi.nlm.nih.gov*, https://www.ncbi.nlm.nih.gov/books/NBK19649/.
[14] Byerly, L., et al. “The Life Cycle of the Nematode Caenorhabditis Elegans.” *Developmental Biology*, vol. 51, no. 1, July 1976, pp. 23–33. *DOI.org (Crossref)*,
https://doi.org/10.1016/0012-1606(76)90119-6.
[15] “Standard and Specialty Petri Dishes, Bioplast Manufacturing.” *VWR*,
https://us.vwr.com/store/product/12610567/standard-and-specialty-petri-dishes-bioplast-manufacturing.
[16] “Agar, Powder.” *VWR*, https://us.vwr.com/store/product/7489087/agar-powder.
[17] *Y14.5 - Dimensioning and Tolerancing - ASME*.
https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing.
[18] Fox , Andrew, et al. *ME 450: Final Report* . 23 Apr. 2019,
https://drive.google.com/drive/u/0/folders/1NSPis-so3-qOdrAXeNE4iRQjqpFS7fmo.

[19] Batterbee, Ian. “Design Frameworks: What Are They and Why You Should Be Using Them.” *Medium*, 15 June 2022,

https://uxdesign.cc/design-frameworks-what-are-they-and-why-you-should-be-using-them-f480a7a5b349.

[20] Wynn, David, and John Clarkson. “Models of Designing.” *Design Process Improvement: A Review of Current Practice*, edited by John Clarkson and Claudia Eckert, Springer, 2005, pp. 34–59. *Springer Link*, https://doi.org/10.1007/978-1-84628-061-0_2.

[21] *Chemical Disinfectants | Disinfection & Sterilization Guidelines | Guidelines Library | Infection Control | CDC*. 4 Apr. 2019, https://www.cdc.gov/infectioncontrol/guidelines/disinfection/disinfection-methods/chemical.html.

[22] *Cleanroom and Controlled Environment Standards*. https://webstore.ansi.org/industry/lab-equipment/cleanrooms. Accessed 2 Feb. 2023

[23] Christian, J.L, S.R. Daly, S. Yilmaz, C. Seifert, and R. Gonzalez. (2012). Design heuristic support two modes of idea generation: Initiating ideas and transitioning among concepts. *American Society for Engineering Education*. 101(4): 601-629.

[24] Dr. Panos Papalambros' research lab with visuals from: Ullman, D. G. (1992). *The mechanical design process* (Vol. 2). New York: McGraw-Hill.

[25] *McMaster-Carr*. https://www.mcmaster.com/.

[26] “3D Printing Prototypes: How to Improve Your Manufacturing Process?” *Sculpteo*, https://www.sculpteo.com/en/3d-learning-hub/3d-printing-business/3d-printing-prototypes/.

[27] *McMaster-Carr*. https://www.mcmaster.com/.

[28] *McMaster-Carr*. https://www.mcmaster.com/.

[29] “Prusament PLA Prusa Orange 1kg | Original Prusa 3D Printers Directly from Josef Prusa.” *Prusa3D by Josef Prusa*, https://www.prusa3d.com/product/prusament-pla-prusa-orange-1kg/.

[30] Hulbert, Gregory “ME305” University of Michigan

[31] *McMaster-Carr*. https://www.mcmaster.com/.

Appendix A: Concept Generation

The 25 concepts compared in the pugh chart during the concept evaluation process.

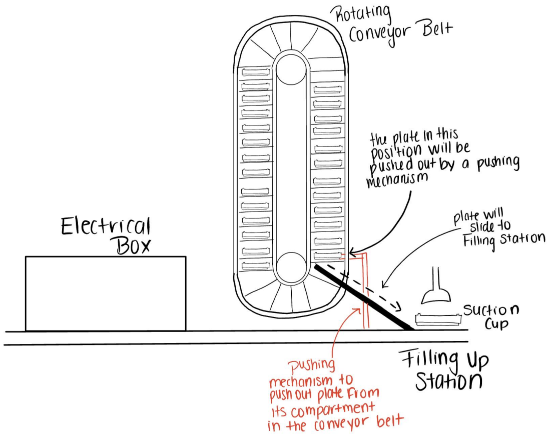


Figure A.1: Conveyor belt system with individual plate compartments and slide concept

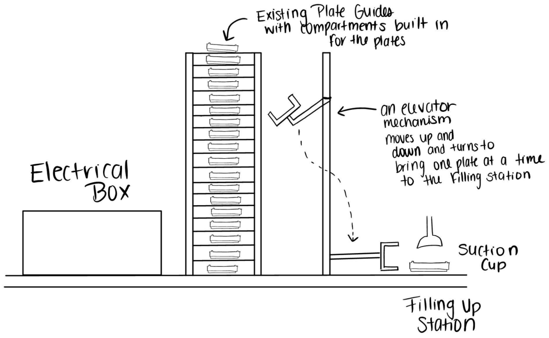


Figure A.2: Plate guides with individual compartments and elevator mechanism concept.

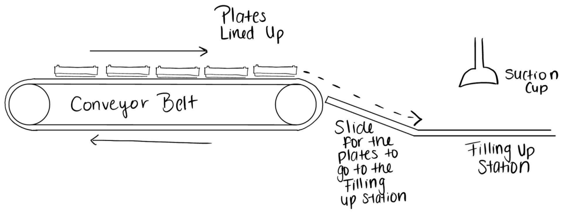


Figure A.3: Horizontal conveyor belt system with slide concept

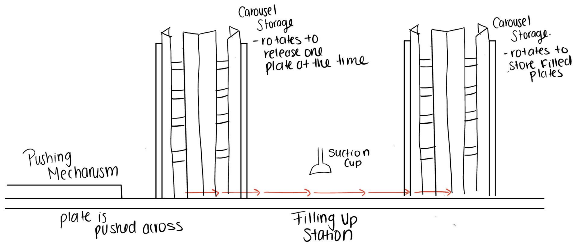


Figure A.4: Double carousel storage concept

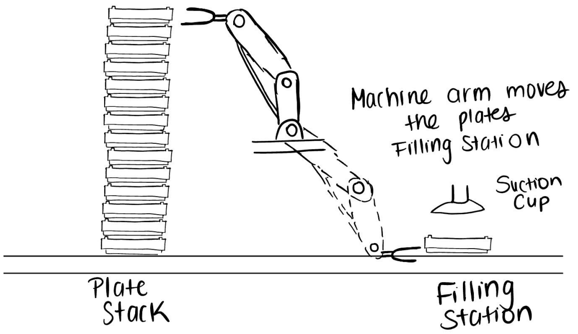


Figure A.5: Machine arm concept

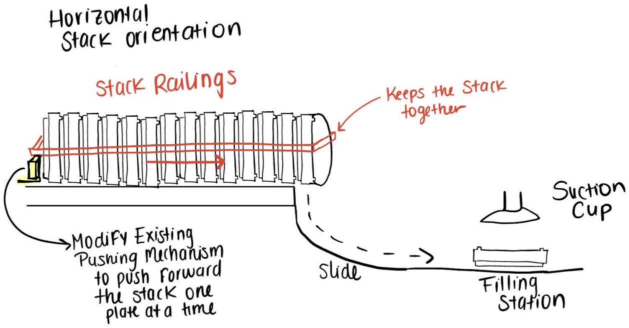


Figure A.6: Horizontal plate stack with slide concept

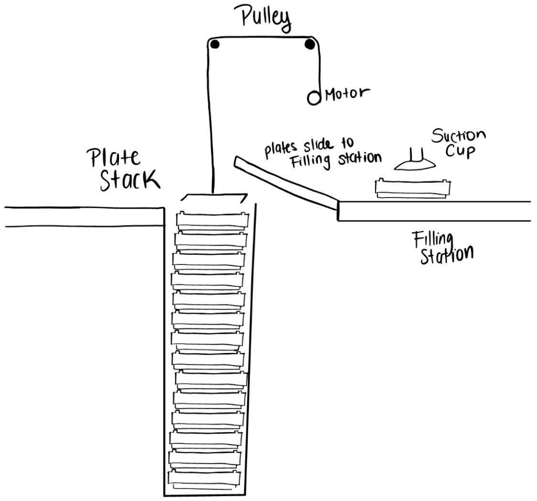


Figure A.7: Below table surface plate stack with pulley and slide concept.

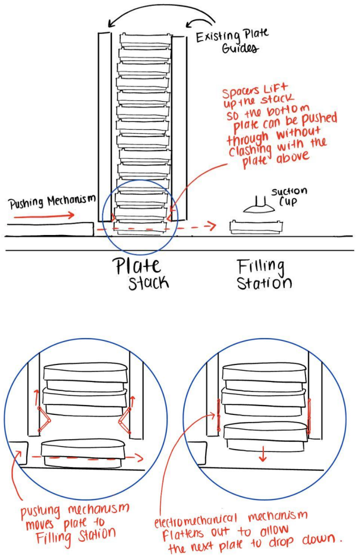


Figure A.8: Stack spacers concept

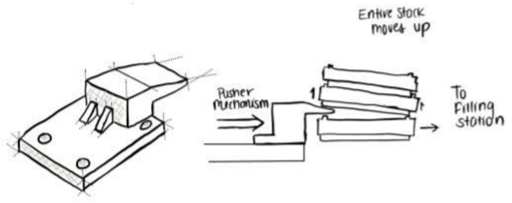


Figure A.9: Wedge concept

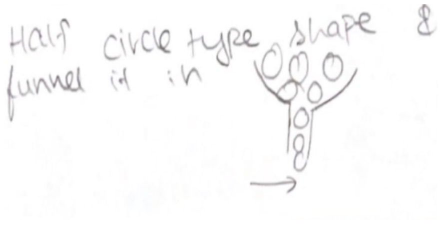


Figure A.10: Funnel concept

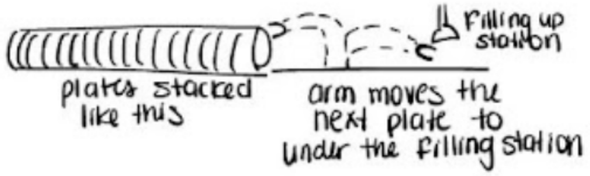


Figure A.11: Horizontal plate stack with a machine arm concept

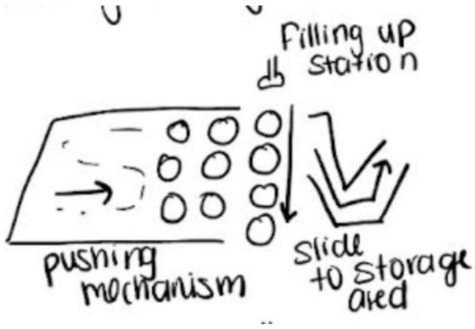


Figure A.12: Flat storage are for the plates with a pushing mechanism concept

Figure A.13: Ramp plate storage mechanism concept

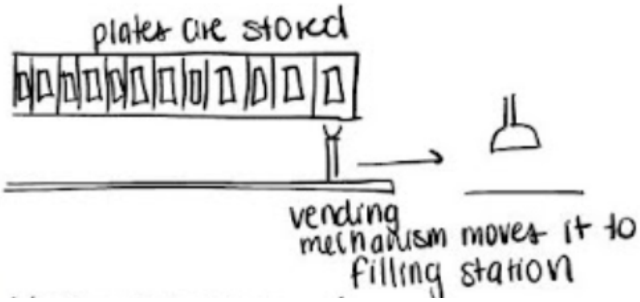


Figure A.14: Horizontal plate stack with individual compartments and a elevator mechanism concept

Figure A.15: Compressed air concept

Figure A.16: Horizontal plate storage with brushes and a pushing mechanism concept

Figure A.17: Spiral Ramp Concept

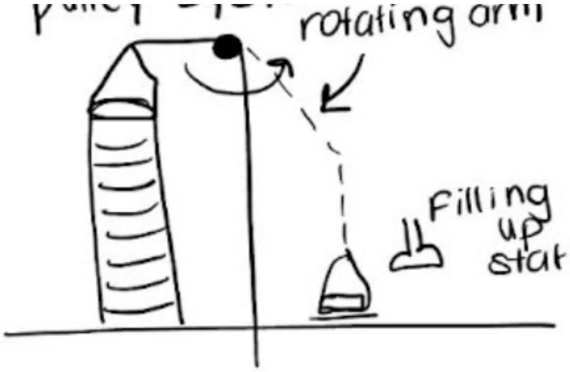


Figure A.18: Vertical places stack above table level with a pulley mechanism concept

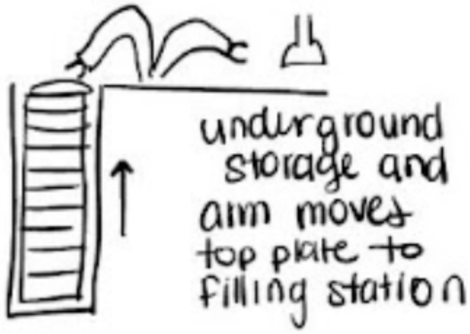


Figure A.19: Below table surface plate storage, plate stack, machine arm concept

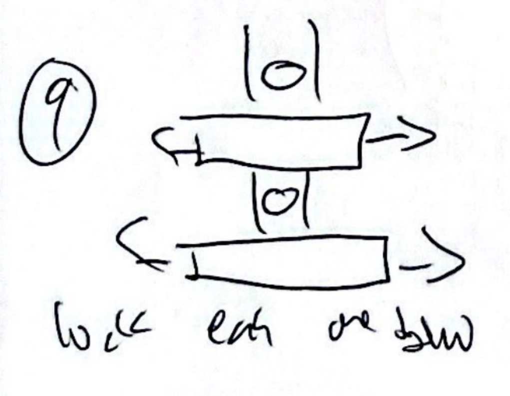


Figure A.20: Moving full spacers with vertical plate stack concept

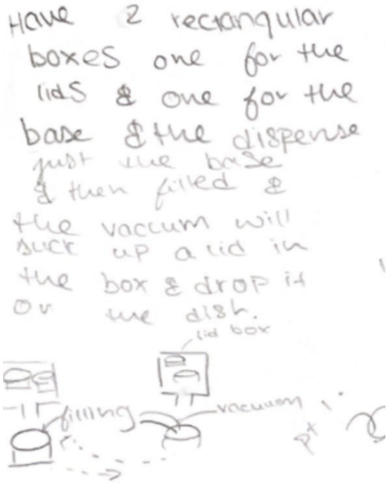


Figure A.21: Separating the lids and base of the plates concept. Drop one plate base, dispense the medium, drop a lid on top

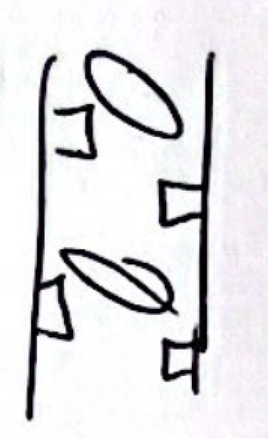


Figure A.22: Spacers align the plate guides concept.

Figure A.23: Vibration of the vertical plate stack concept.

Figure A.24: Disks to allow one plate at a time through to the filling station concept.

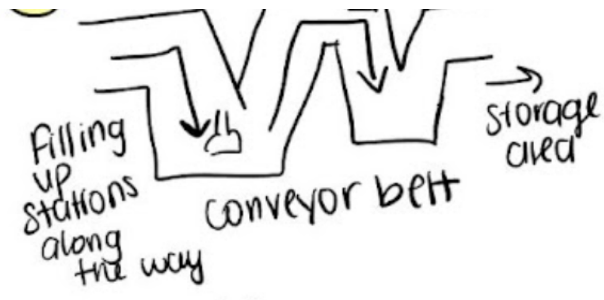
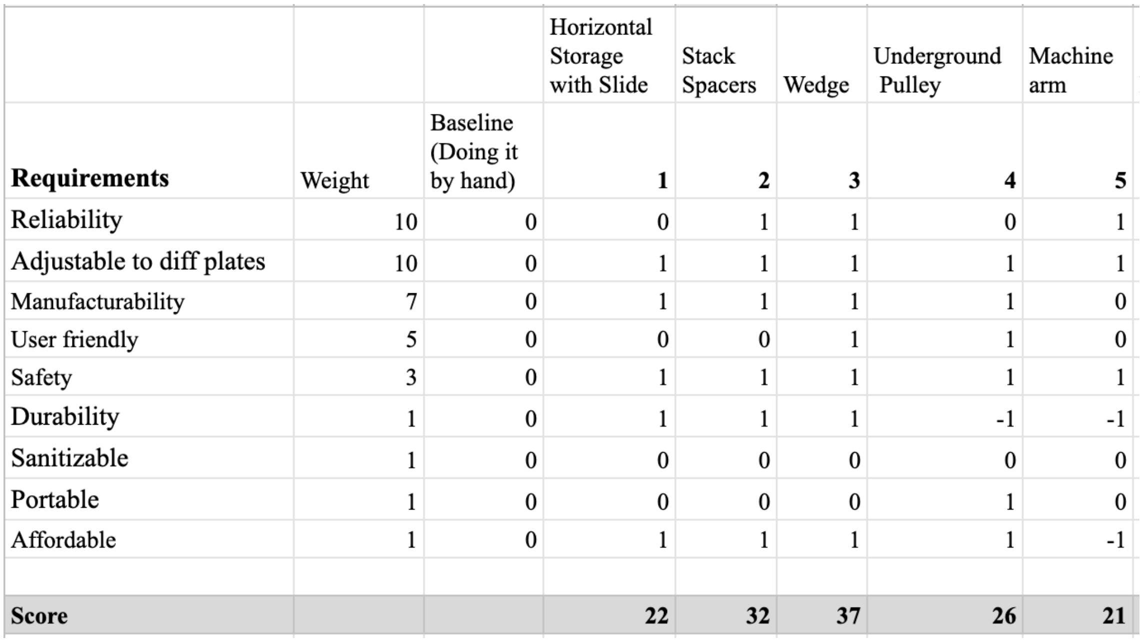


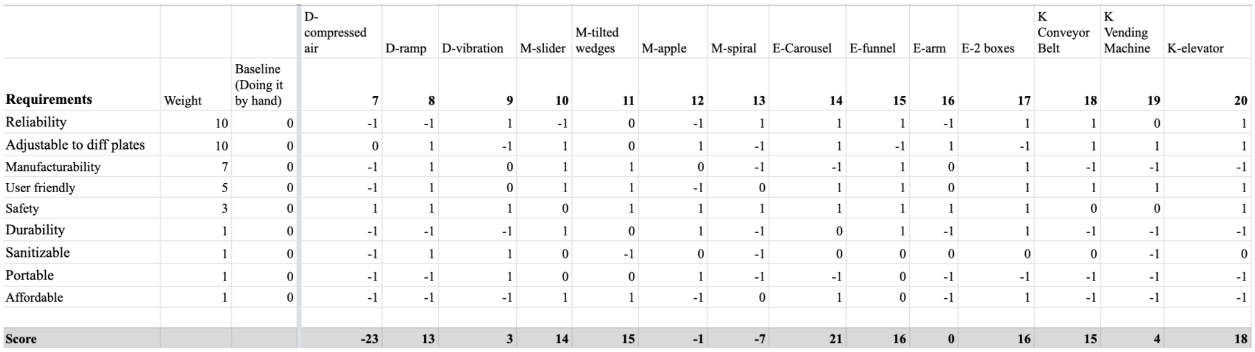
Figure A.25: Second conveyor belt concept to save counter space.

Appendix B: Concept Evaluation



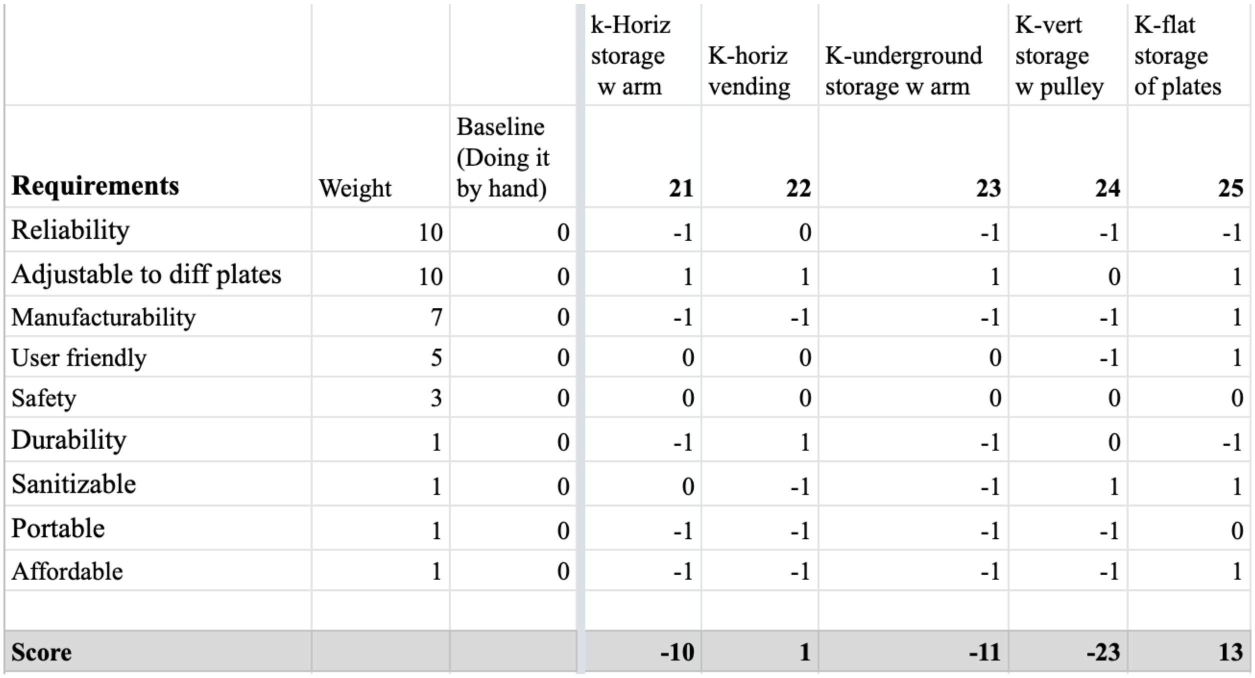
			Horizontal Storage with Slide	Stack Spacers	Wedge	Underground Pulley	Machine arm
Requirements	Weight	Baseline (Doing it by hand)	**1**	**2**	**3**	**4**	**5**
Reliability	10	0	0	1	1	0	1
Adjustable to diff plates	10	0	1	1	1	1	1
Manufacturability	7	0	1	1	1	1	0
User friendly	5	0	0	0	1	1	0
Safety	3	0	1	1	1	1	1
Durability	1	0	1	1	1	-1	-1
Sanitizable	1	0	0	0	0	0	0
Portable	1	0	0	0	0	1	0
Affordable	1	0	1	1	1	1	-1
Score			**22**	**32**	**37**	**26**	**21**

Fig B.1: Pugh chart for the 5 out of 25 concepts generated compared to the baseline.



			D-compressed air	D-ramp	D-vibration	M-slider	M-tilted wedges	M-apple	M-spiral	E-Carousel	E-funnel	E-arm	E-2 boxes	K Conveyor Belt	K Vending Machine	K-elevator
Requirements	Weight	Baseline (Doing it by hand)	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Reliability	10	0	-1	-1	1	-1	0	-1	1	1	1	-1	1	1	0	1
Adjustable to diff plates	10	0	0	1	-1	1	0	1	-1	1	-1	1	-1	1	1	1
Manufacturability	7	0	-1	1	0	1	1	0	-1	-1	1	0	1	-1	-1	-1
User friendly	5	0	-1	1	0	1	1	-1	0	1	1	0	1	1	1	1
Safety	3	0	1	1	1	0	1	1	1	1	1	1	1	0	0	1
Durability	1	0	-1	-1	-1	1	0	1	-1	0	1	-1	1	-1	-1	-1
Sanitizable	1	0	-1	1	1	0	-1	0	-1	0	0	0	0	0	-1	0
Portable	1	0	-1	-1	1	0	0	1	-1	-1	0	-1	-1	-1	-1	-1
Affordable	1	0	-1	-1	-1	1	1	-1	0	1	0	-1	1	-1	-1	-1
Score			**-23**	**13**	**3**	**14**	**15**	**-1**	**-7**	**21**	**16**	**0**	**16**	**15**	**4**	**18**

Fig B.2: Pugh chart for the 13 out of 25 concepts generated compared to the baseline.



			k-Horiz storage w arm	K-horiz vending	K-underground storage w arm	K-vert storage w pulley	K-flat storage of plates
Requirements	Weight	Baseline (Doing it by hand)	**21**	**22**	**23**	**24**	**25**
Reliability	10	0	-1	0	-1	-1	-1
Adjustable to diff plates	10	0	1	1	1	0	1
Manufacturability	7	0	-1	-1	-1	-1	1
User friendly	5	0	0	0	0	-1	1
Safety	3	0	0	0	0	0	0
Durability	1	0	-1	1	-1	0	-1
Sanitizable	1	0	0	-1	-1	1	1
Portable	1	0	-1	-1	-1	-1	0
Affordable	1	0	-1	-1	-1	-1	1
Score			**-10**	**1**	**-11**	**-23**	**13**

Fig B.3: Pugh chart for the 5 out of 25 concepts generated compared to the baseline.

Appendix C: Engineering Drawings and Risk Matrix

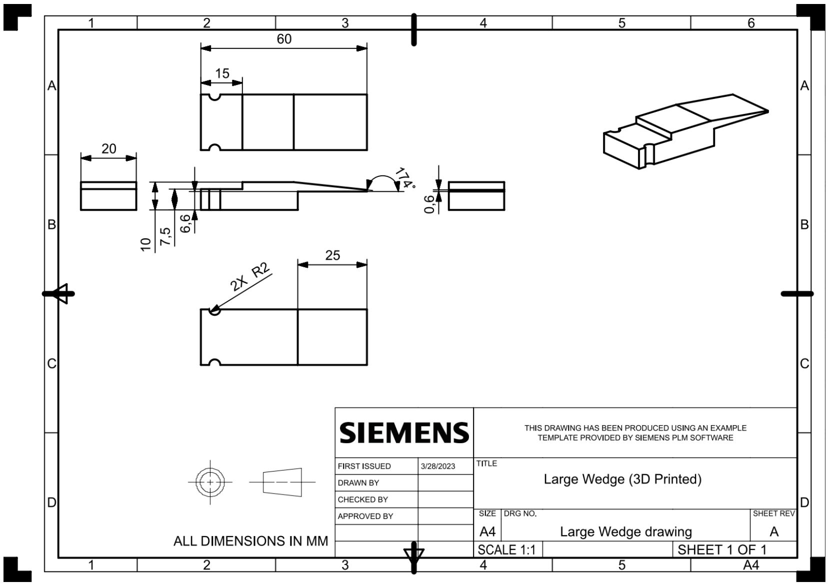


Fig C.1a Engineering Drawing of the Large Wedge (3D Printed)

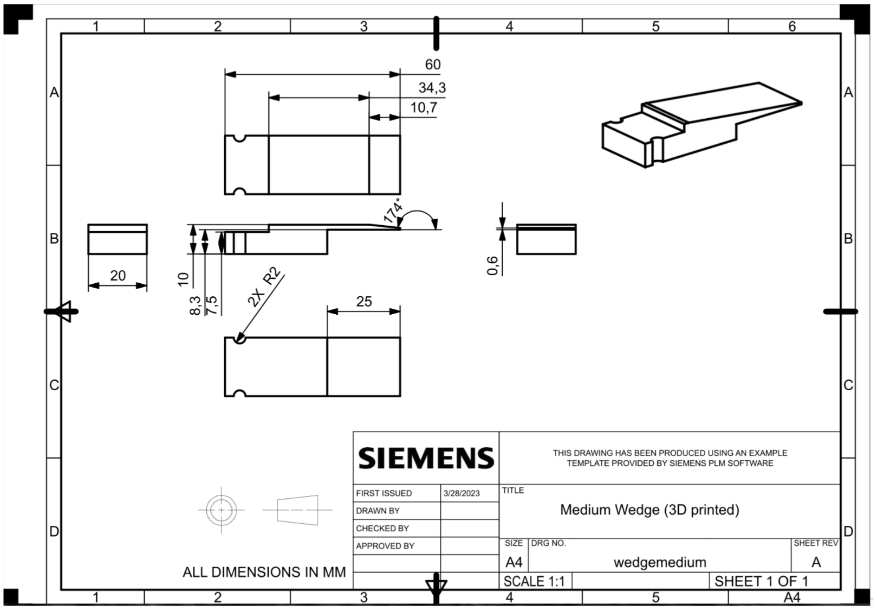


Fig C.1b: Engineering Drawing of Medium Wedge (3D Printed)

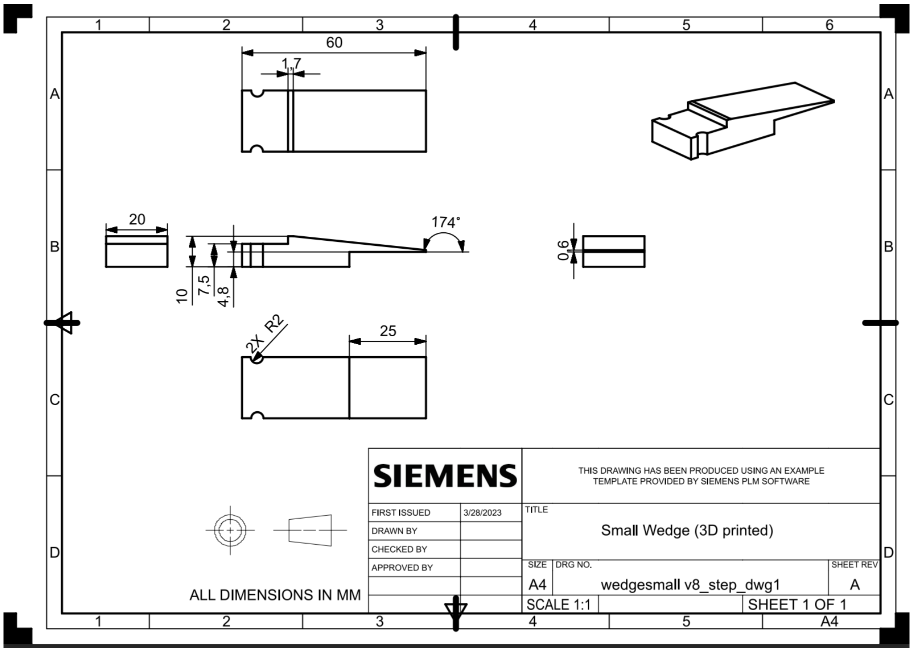


Fig C.1c: Engineering Drawing of Small Wedge (3D Printed)

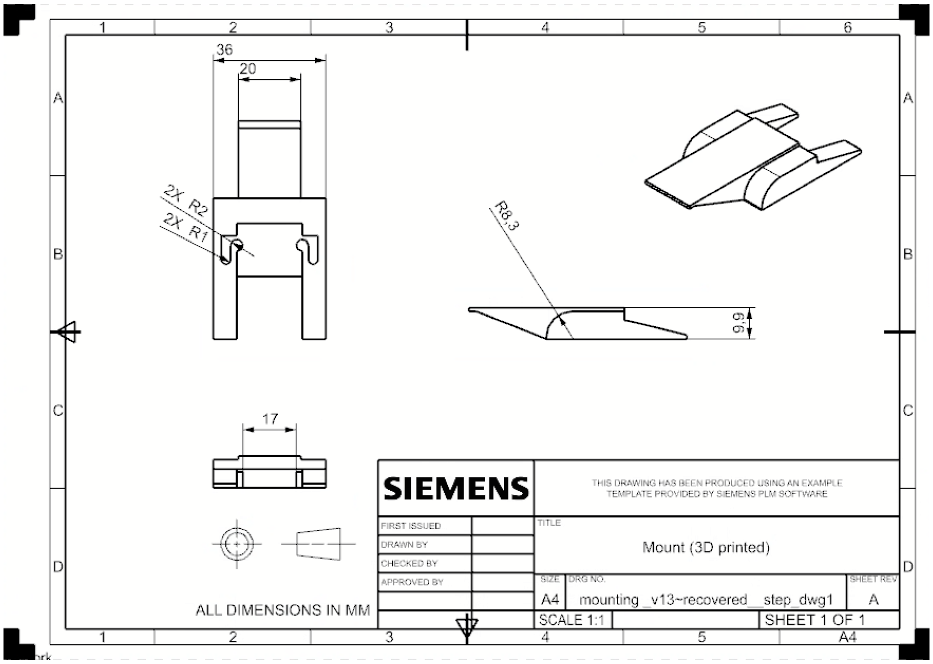


Fig C.1d: Engineering Drawing of Mount(3D Printed)

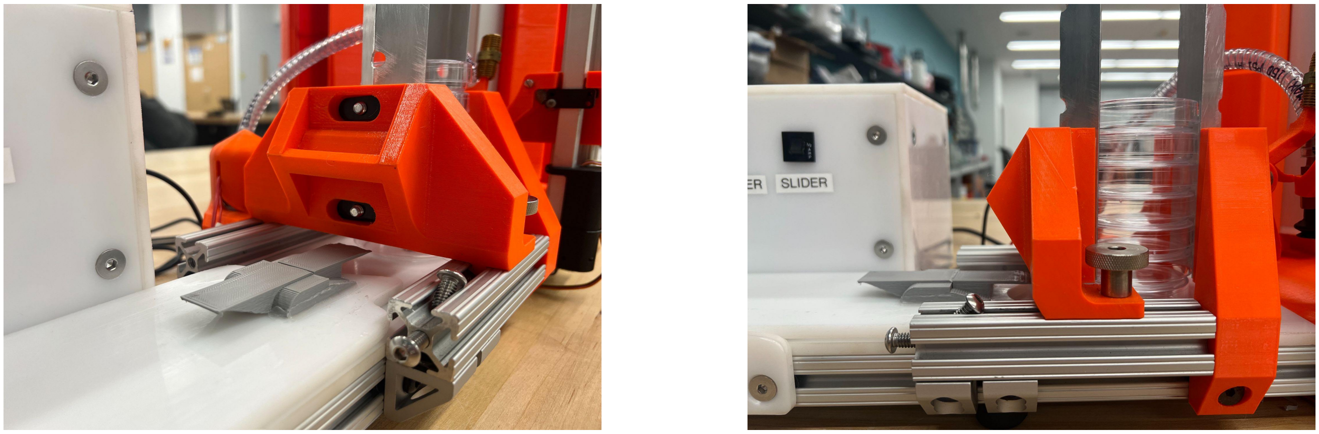


Fig C.3: Wedge and mounting mechanism attached to the plate pusher.

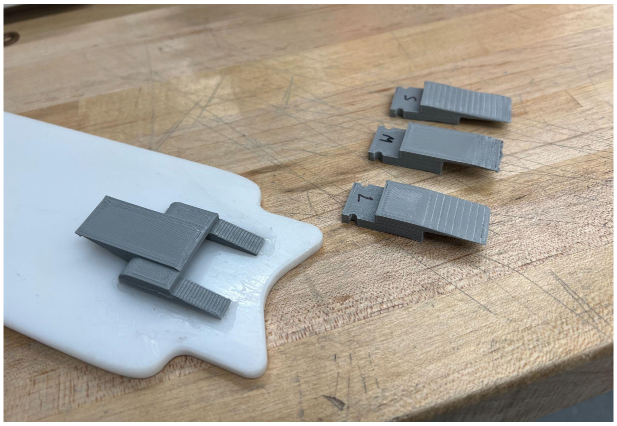


Fig C.4: Mounting mechanism and the 3 wedges (small(S), medium(M), large(L)).

Table C.1: Risk matrix conducted to determine the likelihood of each impact and an OSHA standard was identified.

Impact **Likelihood**	**Negligible**	**Marginal**	**Critical**	**Catastrophic**
Certain		User may not place wedge on fully		
Likely	Guides are not adjusted to the right distance and plate falls through			
Possible	Machine will jam (plate will be stuck)	Break petri-dish		
Unlikely			Pusher will push past vacuum pump	Finger will be stuck between guides
Rare				petri-dish shards hitting user

Appendix D: Testing Protocol

1. **Preparation**
    a. Ensure the machine and area around is clean and sanitized
    b. Wear safety glasses and hand gloves
    c. Gather all necessary equipment and supplies:
    - Test plates of the same size (120 plates to run a full cycle),
    - Sterile medium (agar), heated and ready to dispense
    - Medium pump and tubings necessary to connect it to the machine

    d. Plug in the machine and pump. Connect the pump tubing to the machine and to the medium reservoir
    e. Turn on the pump and set it to the right pre-set setting depending on the plate size
2. **Machine Preparation**
    a. Size the plate guides to fit the desired plate size and stack the plates
    - Place the plate of the desired size between the two guides.
    - Unscrew the mourning guide of the leftmost plate guide and move it to the desired distance from the other plate guide
    - Stack the plates in between the two plate guides

    b. Size the towers in the carousel storage
    - Unscrew the screw at the top of the carousel so the the tower size is adjustable
    - Place a plate of the desired size in one of the towers
    - Screw the screw at the top of the carousel again so that the tower size is fixed

    c. Insert the correct wedge size
    - Verify the correct wedge size is inserted into the mounting piece on the white slider part. [small wedge = 30 mm plate, medium wedge = 60 mm plate, large wedge = 100 mm plate]
    - Change out to the wedge size if needed. Wedge should easily snap out of the mounting piece and another easily inserted.
3. **Run the machine**
    a. Turn on the machine
    b. And press the START button to start the cycle

    If during operation the machine malfunctions, press the EMERGENCY STOP button

    c. When the plates run out or you want to stop the machine, press the END CYCLE button
    d. Turn off the machine
    e. The machine will come to a stop, remove any empty plates as well as the prefilled plates
    f. Disconnect the machine, clean up any minor agar spillage, sterilize the machine, and clean the pump tubing, disconnect and turn off the machine

4. **Maintenance check**
   a. Inspect the machine for wear and tear, damage, or malfunction.
   b. Perform any necessary maintenance or repairs according to the manufacturing and replacement plan

For testing purposes,

- Observe the machine during operation, paying attention to any unusual noises, movements, or malfunctions.
- Verify that the machine dispenses the correct amount of media into each plate and that the plates are evenly filled.
- Remember to document all testing procedures and results thoroughly, including any issues that arise during testing and how they were resolved.

Appendix E: Manufacturing and Fabrication Plan

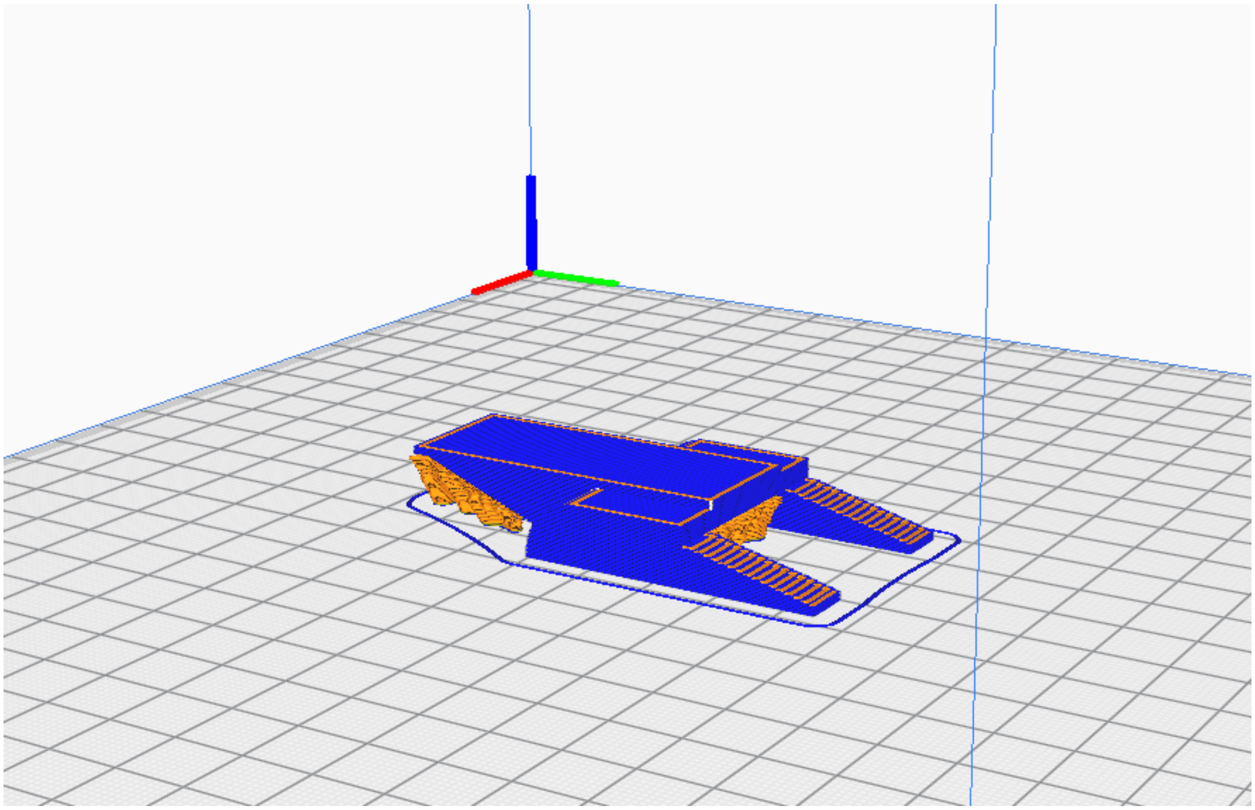
The primary components that need to be fabricated to adapt this machine to better accommodate all 3 plate sizes are the wedge mounting bracket, the 3 wedges that interface with that bracket, and the plate support piece that sits behind the mounting bracket to ensure the plates don't fall out behind the wedge during operation.

Plate support piece
Material: .25" Acrylic sheet stock
Dimensions: 20x2 cm
Manufacturing can be done with a bandsaw

Mounting Bracket
Material: PLA
Print settings:

Layer height	.3 mm
Wall thickness	.8 mm
Wall Line count	3
Infill Density	30%
Support	Yes
Build Plate adhesion	Brim

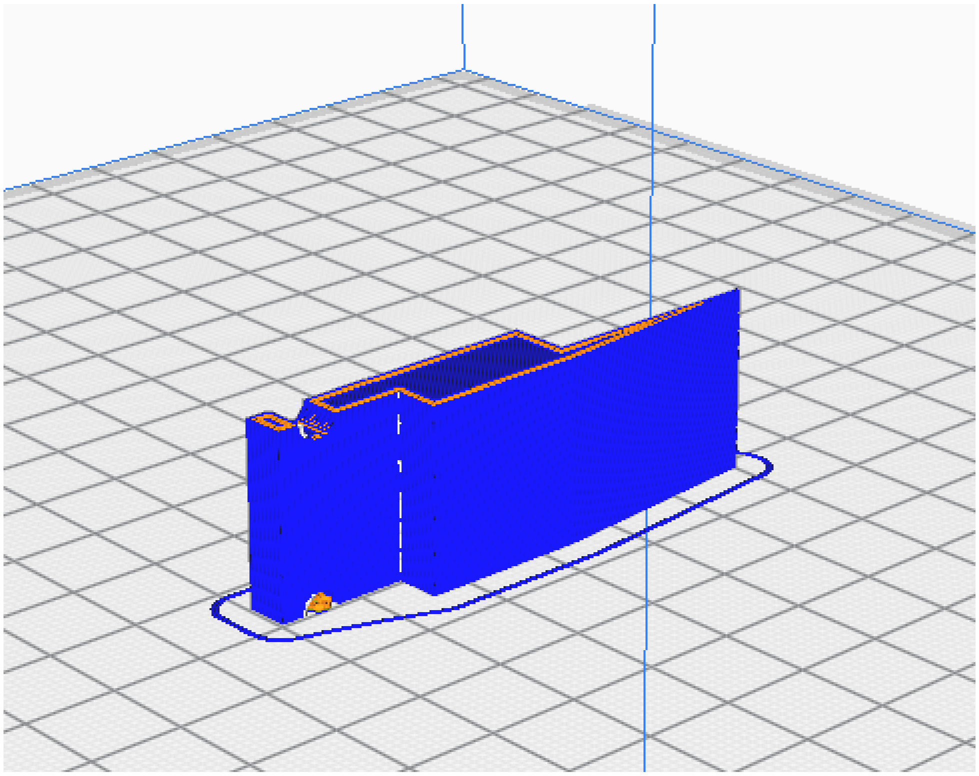
Print orientation



Wedges
Note: All wedges share the same print setup
Material: PLA
Print settings:

Layer height	.2 mm
Wall thickness	.8 mm
Wall Line count	3
Infill Density	40%
Support	Yes
Build Plate adhesion	Skirt

Print Orientation:



Appendix F: Replacement and Repair Plan

The replacement of each part can be done through the use of hot glue and replacement 3d printed parts. In the event that a wedge is damaged, it’s just a matter of printing off a replacement insert. If the mounting piece is damaged, it needs to be resecured to the pushing plate. Using a utility knife, slice the hot glue lines surrounding the piece to remove it. When securing the replacement part, it’s critical that hot glue only be used on the sides when the piece is flush on the pushing plate to maintain the tight clearances between the wedge and the rest of the mechanism. 2 lines of glue on either long side of the mounting bracket will keep it secure.

Appendix G: User Manual

1. **Preparation**
   a. Ensure the machine and area around is clean and sanitized
   b. Wear safety glasses and hand gloves
   c. Gather all necessary equipment and supplies:
      - Test plates of the same size (120 plates to run a full cycle),
      - Sterile medium (agar), heated and ready to dispense
      - Medium pump and tubings necessary to connect it to the machine
   d. Plug in the machine and pump. Connect the pump tubing to the machine and to the medium reservoir
   e. Turn on the pump and set it to the right pre-set setting depending on the plate size
2. **Machine Preparation**
   a. Size the plate guides to fit the desired plate size and stack the plates
      - Place the plate of the desired size between the two guides.
      - Unscrew the mourning guide of the leftmost plate guide and move it to the desired distance from the other plate guide
      - Stack the plates in between the two plate guides
   b. Size the towers in the carousel storage
      - Unscrew the screw at the top of the carousel so the the tower size is adjustable
      - Place a plate of the desired size in one of the towers
      - Screw the screw at the top of the carousel again so that the tower size is fixed
   c. Insert the correct wedge size
      - Verify the correct wedge size is inserted into the mounting piece on the white slider part. [small wedge = 30 mm plate, medium wedge = 60 mm plate, large wedge = 100 mm plate]
      - Change out to the wedge size if needed. Wedge should easily snap out of the mounting piece and another easily inserted.
3. **Run the machine**
   a. Press the ON button
   b. And press the START button to start the cycle

   If during operation the machine malfunctions, press the EMERGENCY STOP button

   c. When the plates run out or you want to stop the machine, press the END CYCLE button
   d. Press the OFF button
   e. The machine will come to a stop, remove any empty plates as well as the prefilled plates
   f. Disconnect the machine, clean up any minor agar spillage, sterilize the machine, and clean the pump tubing, disconnect and turn off the machine

4. **Maintenance check**

   a. Inspect the machine for wear and tear, damage, or malfunction.

   b. Perform any necessary maintenance or repairs according to the manufacturing and replacement plan

Appendix H: Bill of Materials and Build Design Bill of Materials

Table 1: Table of the Bill of Materials from the wedge designs including the filament used in 3D printing, hot glue and acrylic.

Item	**Cost**
1kg 1.75mm PLA Filament	\$35.00[29]
Hot glue	\$20.00[27]
Acrylic	\$7.71[28]

Table 2: Table of Build Design Bill of Materials including the wedge, mount and mount extension.

Item	Quantity	Material	Cost	Manufacturing Method	Source	Catalog number
Wedge	3	PLA	\$35@1kg 1.75mm	3D printed	McMaster.com	1317N26
Mount	1	PLA	\$35@1kg 1.75mm	3D printed	McMaster.com	1317N26
Mount extension	1	Acrylic	\$7.71 @ 12.7 x 305 x 305mm	Handsaw (cut to size)	McMaster.com	8505K741