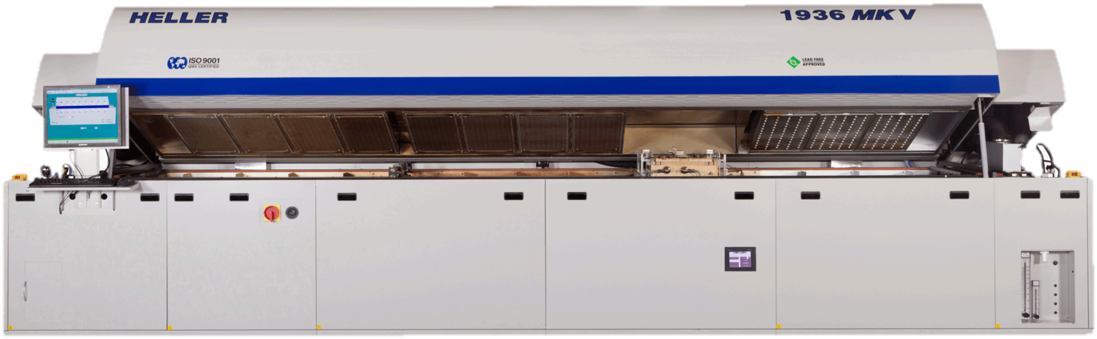
Design Review 4 - Semi- Automatic Lubrication System for Vacuum Reflow Oven Chain Conveyor



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ME 450 - Section 003 Team 05

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Executive Summary

Heller Industries is a premier manufacturer of vacuum reflow ovens which are a method of producing printed circuit boards, or PCBs. These machines operate on a conveyor system, and feature vacuum chamber technology to improve the quality of the boards. The vacuum chamber has an independent, internal conveyor that must be lubricated every 3 months, and the current lubrication system is inefficient and takes up to 2 hours. At present, maintenance personnel must reach through a small slot and manually paint lubricant onto the chain with a paintbrush, only accessing a small portion of the exposed chain at a time. Our team was tasked with designing, testing, and prototyping an automatic or semi-automatic solution to this problem over the course of approximately 4 months. First the team analyzed the context of the design problem by benchmarking and determining requirements and specifications that a given design would have to meet. The primary requirements and specifications were: withstanding temperatures up to 350˚C, withstanding pressures down to 10 torr, accommodating 50-350 mm of lateral movement for different sizes of PCB, lubricating the chain in under 15 minutes, and costing less than $5000.

After defining the constraints of the project, the team brainstormed possible solutions for several weeks. The chosen concept was an open-topped reservoir with an orifice drip feed that would reside permanently in the vacuum chamber, mounted onto an existing rail. The team ran several lubricant flow tests to determine how the reservoir would expel lubricant in theory and in practice, including flow analysis for different sized orifices and different reservoir geometries. In use, maintenance personnel would insert an extended tipped syringe with 5mL of lubricant through the chamber door and into the reservoir. The lubricant would then drip consistently through a 3 mm orifice onto the running chain below at 30 cm/min. The reservoir will reduce total maintenance time from 2 hours down to 12 minutes, while lowering the effort and active maintenance time required by maintenance personnel. Heller Industries did a cost evaluation of manufacturing this reservoir and estimated it would cost about $17.97 for two units, with a lead time of 7 days, $16.18 for twenty units, with a lead time of 9 days, and $12.03 for one hundred units, with a lead time of 15 days.

The advantage of this solution is in its simplicity; it effectively meets all requirements and specifications and significantly reduces the burden of lubricating the vacuum chamber chain. If we were to critique our design process, we would emphasize pursuing a fully-automatic lubrication system. While our solution effectively reduces maintenance time and effort, a fully-automated system would likely do so more efficiently.

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Introduction

Abstract

Heller Industries is looking to improve their lubrication technique for their in-line soldering machines by creating a new, automated method of oiling that is capable of functioning in a vacuum. The task specifically targets a periodic lubrication of the #35 chain in an attempt to avoid chain seizure and system failure through smooth, low-vibration PCB transport.

Goal Statement

The goal of this project is to design, build, and test a semi or fully-automatic system to lubricate a #35 chain conveyor in a vacuum chamber that is able to withstand pressures between 10 torr and ambient, a temperature between ambient and 480 degrees Celsius, and does not impact the overall cost of the machine by more than 2.5%.

Successful Outcome

A successful project outcome would include having designed, built, and tested a product that accomplishes the goal statement. The design process will include a CAD model and a detailed reasoning for design choices, as well as numerical and/or researched evidence to support the reasoning. The build process will include a physical, to-scale product manufactured and under budget. The testing process will include conducting tests which thoroughly examine the strengths and weaknesses of different design choices and show the approach to which we select defining qualities.

The Project Sponsor

The sponsor of this project is Heller Industries, in particular, Jim Neville, V.P. of Design Engineering, Xike Zhao, V.P. Product Management, and David Heller, CEO of Heller Industries. Heller Industries is the market leader in reflow oven technology, fluxless reflow technology, and curing oven technology, supplying solutions for electronics manufacturers and semiconductor advanced packagers worldwide [1]. For this task, the project scope revolves specifically around the reflow ovens which utilize a vacuum chamber, and it exists to make the tasks of the employees easier.

How the System Operates

The machine under analysis is the MK5-VR Conveyor System, specifically, the vacuum chamber subsystem. The MK5-VR Conveyor System can be seen below with all of its components.

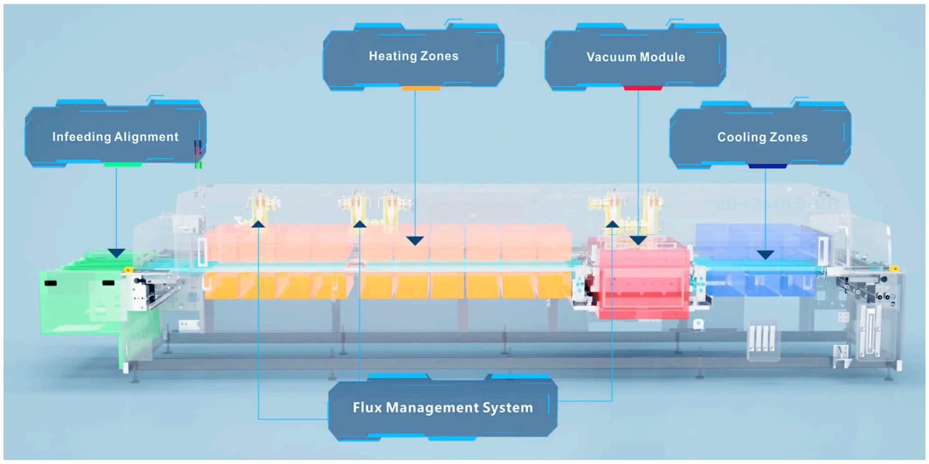


Figure 1. MK5-VR System Overview [1]

This machine is used to manufacture printed circuit boards (PCBs) by applying solder material to the surface of the board. There are three main stages to the machine: the heating zone, the vacuum module, and the cooling zone. The PCB begins in the heating zone, which has two main steps. Initially, the board temperature is gradually raised to the operating temperature of the machine, approximately between 250°C to 480°C, where the solder material applied on the board becomes liquid. The next step of the heating zone is the thermal soak. This step soaks the board at the ideal temperature, which varies with application, and confirms that all components of the board are at the same temperature so as not to damage the board in future steps. After the heating zone, the board proceeds into the vacuum, where it gets transferred onto a separate conveyor chain. The chain that the board was formerly on travels beneath the chamber and continues after the board exits the vacuum. Upon the entry to the vacuum chamber, rolling doors to the chamber close. This transfer can be seen below in **Figure 2:**

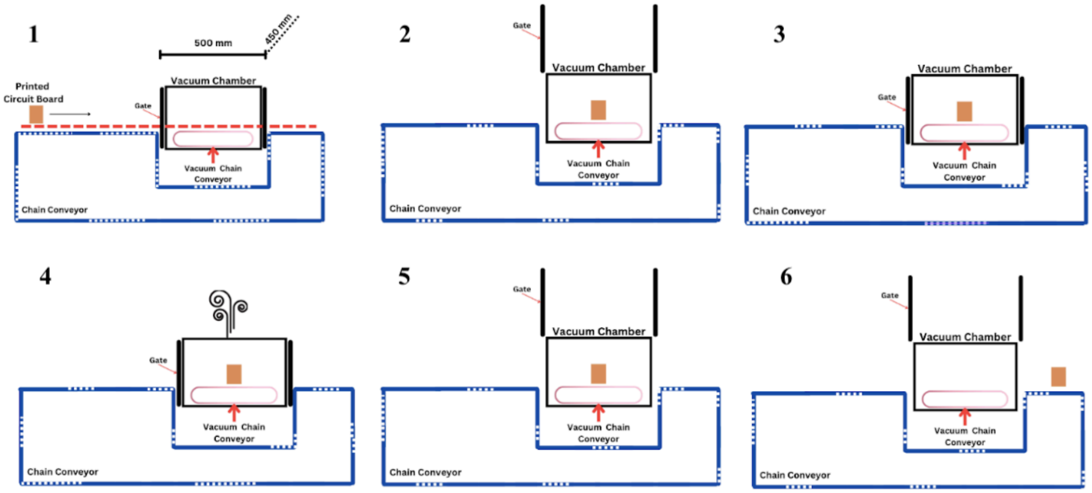


Figure 2. Chamber Entry and Exit

After the chamber doors close and the PCB is inside, the near-perfect vacuum is initiated to have a pressure of about 10 torr. This vacuum is used to eliminate voids that may form in solder material on the surface of the circuit board. The negative pressure causes the air bubbles in the solder material to enlarge and collide, upon which they are more likely to move to the edge of the board and disperse because of their size and momentum, as well as their larger buoyancy force. An image of a PCB after this process can be seen in **Figure 3** below along with a plot that shows the improvement in the amount of voids upon the use of a vacuum (**Figure 4**).

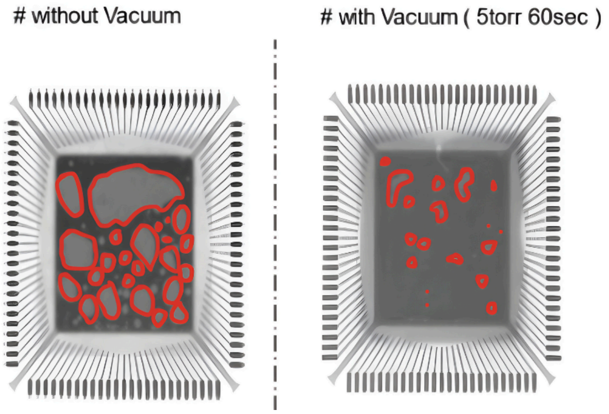


Figure 3. Solder Part With and Without Vacuum **[2]**

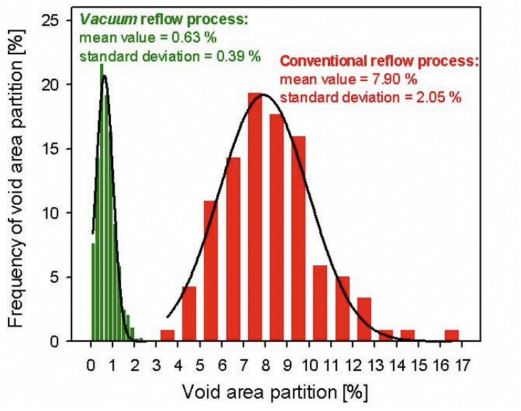


Figure 4. Reduction in Voids after Vacuum **[3]**

Figure 3 shows two solder boards side by side, one of which has had a vacuum application and one has not. **Figure 4** shows the decrease in the percentage of area occupied by voids from 7.9% without vacuum to 0.63% with vacuum. Both figures clearly indicate that a vacuum makes a significant difference in the number of voids and thus performance of the solder boards.

This absence or near absence of voids allows for better adherence of the solder material to the PCB, lower resistance of board conductivity, higher inductance, higher resistance to crack formation, and improved longevity of the product [4, 5].

After the vacuum force is applied and stopped, the chamber is refilled with inert nitrogen gas and the chamber doors are opened. The PCB then moves into the cooling zone, where the part is returned to ambient temperature.

What is the Problem? - Lubrication and Maintenance

After discussing system functionality, it is important to consider why the project is being pursued. This brings the discussion to system maintenance. Preventative maintenance needs to be done regularly to minimize machine fatigue and maximize functionality [4]. Due to the fact that the system operates via a conveyor chain and sprocket, it must be properly lubricated or the chain will wear down. This is because the chain is softer in material than the rail [4] and the applied forces cause degradation, causing the chain to fail. The lubrication helps to reduce friction, minimize corrosion and absorb shock from system movement [6].

For the models with a vacuum chamber (see **Figure 5** below), there are two chain drives used within the machine, one inside the vacuum chamber and one outside of it. In order for the oven to function properly, both of these chains need to be regularly lubricated, with the maximum allowable time between lubrications varying depending on user-chosen settings [2].

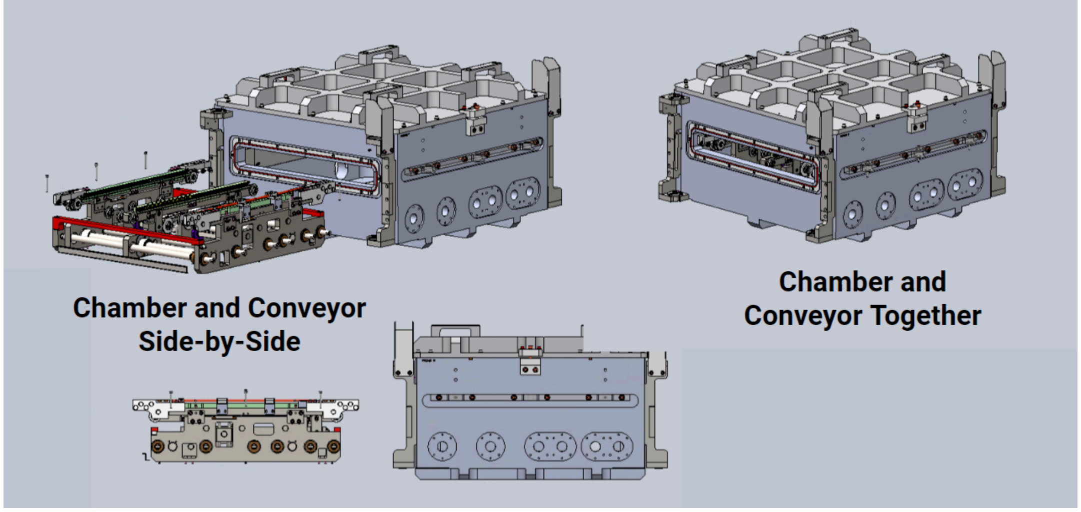


Figure 5. Computer Aided Design model of vacuum chamber and internal chain conveyor system from several views. [7]

Currently, to lubricate the chain drive in the vacuum chamber, a technician must manually paint the lubricant onto the chain; this process is tedious, halts production, and has the potential for human error leading to premature chain wear and failure [4]. In order to alleviate these issues, we have been tasked with creating an automatic or semiautomatic system which can be used to lubricate the chain within the vacuum chamber which is economical and easily operated.

History and Development of Lubrication

To approach the problem of lubricating a chain in the high temperature and low pressure conditions of the vacuum chamber, an understanding of general practices and existing solutions for chain lubrication in normal conditions is required. Lubrication of chain drives serves many purposes. Most importantly, it resists wear between pin and bushing surfaces, dissipates heat, and resists corrosion [6]. Lubricants for the chain should have a low enough viscosity to reach critical areas, a high enough viscosity to maintain an effective layer of lubrication, and should maintain the ability to lubricate in the full range of operating conditions [6]. There are several different methods of chain lubrication: manual, drip, bath, and oil-stream lubrication. Of particular interest are drip and oil-stream lubrication, and for both it is mentioned that application to the center of the chain is ineffective at lubricating [8].

Currently, Heller Industries has an automatic lubrication system which lubricates the chain outside of the vacuum chamber. This device operates at standard pressure (~760 torr) and temperatures lower than those of the vacuum chamber (adjustable by user), and employs the use of a solenoid valve, oil block, wick, and flexible plastic tubing [4]. The solenoid valve opens which allows the lubricant to flow into the oil block from a reservoir; lubricant freely flows from the oil block onto the wick, which paints the chain, and the plastic tubing is used to accommodate adjustment of the rail width. See **Figure 6** below for a visual of this system (note that the plastic tubing is not depicted). This system would encounter problems due to the higher temperature and much lower pressure of the vacuum chamber. Due to the higher temperature, the solenoid valve is unable to function, and the plastic tubing would melt. In addition, the vacuum would cause all of the lubricant in the oil block to be immediately expelled.

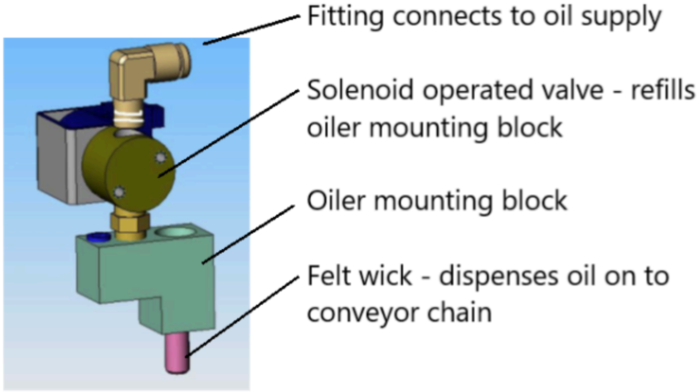


Figure 6. Heller assembled Automatic chain lubrication system outside vacuum chamber [9]

Using the recommended practices for chain lubrication and Heller Industries' existing lubrication system as a guide, there are several relevant areas where additional background information is necessary. These include: safety in the design of sealed reservoirs within the vacuum chamber, testing for the safety of sealed reservoirs, and methods of preventing unwanted lubricant expulsion (namely valves and oil-impregnated materials). In addition, there are also other topics relevant to fully understanding the problem, such as: existing methods of lubricant delivery, the potential environmental consequences of lubricant choice, the detection of faults in the chain drive, and other chain drive systems with better wear characteristics.

An important consideration in the design of a solution is that any closed reservoir of oil in the vacuum chamber, when subjected to vacuum, becomes a pressure vessel. Based on a secondary source of the ASME standards for pressure vessels, the safe design and testing of pressure vessels can be time consuming and costly, both of these being very limiting within the scope of this project [10]. For example, the effects of corrosion, stress, and any other relevant issues must be considered when designing pressure vessels, as designing without these in mind could lead to sudden and catastrophic failure. As a result, considerations such as material choice, dimensions, and the inclusion of pressure relief systems must be carefully considered. The expected time and monetary costs associated with ensuring that any pressure vessel remains safe under all operating conditions could make their use undesirable or unsafe.

In the testing of large oil tanks according to ASTM standards, the tanks are subjected to internal pressures of 35 kPa (~263 torr), and must show no leakage when subjected to an underwater or soap bubble test to ensure their safety [11]. Should any solution contain an oil reservoir within the vacuum chamber, this test could serve as a baseline for testing the efficacy and safety of such a reservoir.

Should an oil reservoir of some kind be utilized within the vacuum chamber, a robust system for ensuring the oil does not immediately evacuate the reservoir will be necessary. Butterfly valves provide a robust means of sealing off such a reservoir with little required maintenance and occupying a small footprint [12]. Adjacent to this, and relevant to the potential use of oil-stream lubrication in the high temperature environment of the reflow oven, is the operation of fuel injectors. Fuel injectors are a solenoid-operated valve, which deliver liquid fuel at high pressure. The nozzle of the fuel injector is normally closed, and applying a voltage to the solenoid opens the valve and allows for the high pressure fuel to exit, with very precise control over the amount of fuel released [13]. These principles could be beneficial to leverage to prevent unwanted evacuation of the lubricant while under vacuum.

Also potentially relevant to avoiding unwanted evacuation of the lubricant is the use of oil impregnated materials. Materials of these types could eliminate the need for an oil reservoir, and have been demonstrated to produce desirable wear characteristics in scenarios where insufficient lubrication is administered [14].

In terms of lubrication delivery systems, there are several existing methods of delivering lubricant to components. The grease gun is a manually operated solution, which is able to reliably dispense a consistent amount of lubricant with very simple operation. Constant level oilers are commonly used for centrifugal pumps, though they are sensitive to changes in pressure. While reliable in many circumstances, these systems require regular manual intervention for their operation and there is little control over the amount or rate of lubrication. There exist also centralized lubrication systems, which can be automated to provide automatic lubrication over a large range of operating temperatures, and are able to provide control over the amount of lubrication [15]. The methods of operation for the systems could be potentially leveraged in the creation of a solution, notably the ability to consistently portion lubricant and to exert precise control over the lubrication amount.

An important consideration for the choice of lubricant is the indirect effects it has on the environment. Lubrication can utilize harsh chemicals which may not be environmentally friendly, however there are potential environmentally friendly alternatives [16]. Additionally, insufficient lubrication can raise energy demand, which can have a negative impact on emissions.

Another important consideration is the possibility of detecting chain faults as a method of improving the system reliability. Through the use of acceleration and gyroscope sensors to measure chain vibrations alongside a machine learning algorithm, it was demonstrated that failure could be accurately and reliably detected [17]. Such a detection system could improve system reliability by allowing for advanced notice of issues with the chain and allowing for adjustment of the lubrication system accordingly.

Though potentially prohibitive due to cost, there exist other types of chains which may improve system performance irrespective of how the chain is lubricated, and could potentially reduce how regularly lubricant must be applied. Toothed chains can potentially provide better performance with less wear than roller chains (which are currently in use in the reflow ovens), though with the drawback of greatly increased complexity [18].

Besides the relevant standards already mentioned, there is also the SEMI S2 standard [19], which is related to ergonomics and operator, maintenance personnel, and service personnel safety. The standard is intended to provide a basis for improved safety during operation and maintenance of machines. Relevant for this project, it discusses the use of barriers to prevent accidental shock with electrical components, the use of proper safety factors for pipes and tubing, environmental effects such as hazardous waste and emissions, and safe sound levels. The standard is not intended to cover all potential considerations, but does serve as a strong outline for social considerations of the design.

Design Process and Strategies - Application to ME 450

Per the bounds of the ME450 class and the sake of learning, there are several objectives that are expected of students throughout the class who digest these design projects. Throughout the class, students are expected to have applied a structured design process, including iteration, divergent thinking, design embodiment, and reflection. To aid in this design process, they are expected to gather and synthesize relevant information from a variety of resources. From there, they must incorporate a context assessment, considering identity, inclusivity, and ethical decision making to create evidence-based design decisions. These decisions must be fully-justified based on rigorous and exhaustive research of both the problem and solution spaces.

By applying these skills in ME 450, students should be able to apply these skills to every design challenge they encounter. The overall goal of ME 450 is to help create and/or improve design habits and practices, so each student may contribute solutions that ultimately change our collective future for the better.

Design Process and Strategies - Design Process Models

In order to effectively diagnose a problem and step towards potential solutions, one must first decide how to approach the problem. There are several different classifications of design models which may be used: stage vs activity-based models, problem vs solution-oriented literature, and abstract vs analytical vs procedural approaches [20].

Within stage vs activity based models, an experimenter may choose how to structure their model and choose their iterative process by having either cyclical patterns or feedback loops. An activity-based model plans out specific, iterative, and concrete exercises throughout the entirety of the process. Stage-based plan out stages of design and iterate the process via feedback loops.

Within solution vs problem-oriented models, an experimenter may choose whether the emphasis of the project lies within a proposed solution and iteration of said solution (solution-oriented), or within the abstraction and analysis of the problem before posing a solution (problem-oriented).

Within the abstract vs analytical vs procedural approaches, there are several different ways to form a framework. An abstract approach does not provide specificity to the improvement process but rather a holistic view. A procedural approach is more concrete, following patterns that are more applicable to functional situations. An analytical approach utilizes specific strategies to describe a design approach, including a representation, such as a design structure matrix, and techniques, procedures, or computer tools to make the representation easier to understand.

Design Process and Strategies - Model of Choice

The design model for this task will include both a stage and activity-based approach. There will generally be a stage for each step of the way, however within each stage there will be more concrete activities scattered throughout. By combining the two, the group will be able to maintain the big-picture viewpoint to keep the end-goal in mind as well as not bind the group into certain tasks too early. This will also hold the group accountable for evidence collection for operating conditions. Additionally, due to the complexity of the topic, the group will use a problem-oriented approach so that the system can be thoroughly evaluated before making design decisions. Lastly, the group will also use an analytical approach at each stage of the process for organization and clarity in every design decision made.

While the design process model is subject to change and greater specificity, it will likely look something like **Figure 7** below. Our design contains six main stages: identify the problem, consider limitations, brainstorm ideas, model top ideas, build and test, and finalize and present. Within each of these stages there are sub-tasks that lead to the achievement of each stage. If the design needs revisions at any point in time, it will follow a path of iteration, either returning to consider limitations, brainstorm ideas, or model top ideas.

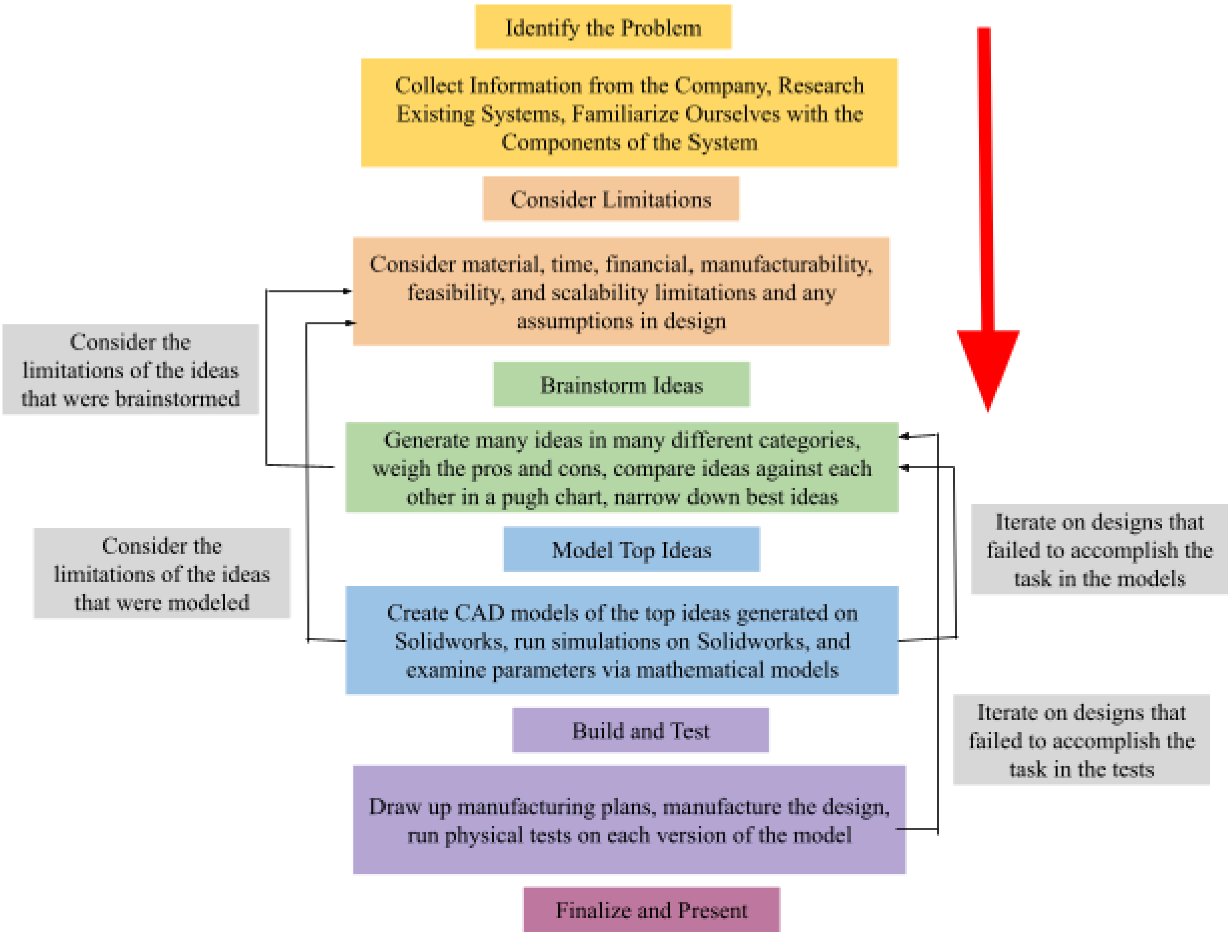


Figure 7. Design Process Model

Currently, we are in transition between the “Consider Limitations” and the “Brainstorm Ideas” stage. The group has researched the system, been in constant contact with the company, and given its first presentation of the project, indicating a familiarity with the system. Additionally, we have been considering limitations in design via a careful breakdown of the specifications and requirements of the project. Brainstorming is currently a work in progress.

Those first two stages are likely the most important part of the design process because they set up the foundation for the rest of the project. Without the baseline knowledge, we would not be able to dissect the intricacies of the machinery and all the details of the task at hand. It has worked well so far for our group as it approaches the brainstorming section of the project to have a fundamental technical background in the subject matter and therefore will be continuing with this problem-oriented method, focusing significantly more on the process and analysis than the outcome. The future will hold the rest of the general stages, but also include specific activities such as a Solidworks CAD model. The analytical approach will be demonstrated by the planning of each task in anticipation of the action itself.

How the Model Compares to the First Day of Class Model

The model from the first day of class presents a lot of similarities to the model generated for this project team. It also follows a problem-oriented approach and dominantly focuses on the process, rather than an idea to be iterated. The model from class is also slightly less specific, yet due to the flow pattern and arrows, is slightly harder to read. This is most likely because it was created to fit most design processes as a learning tool, rather than being specifically catered to one singular task. The process from class can be seen in **Figure 8** below.

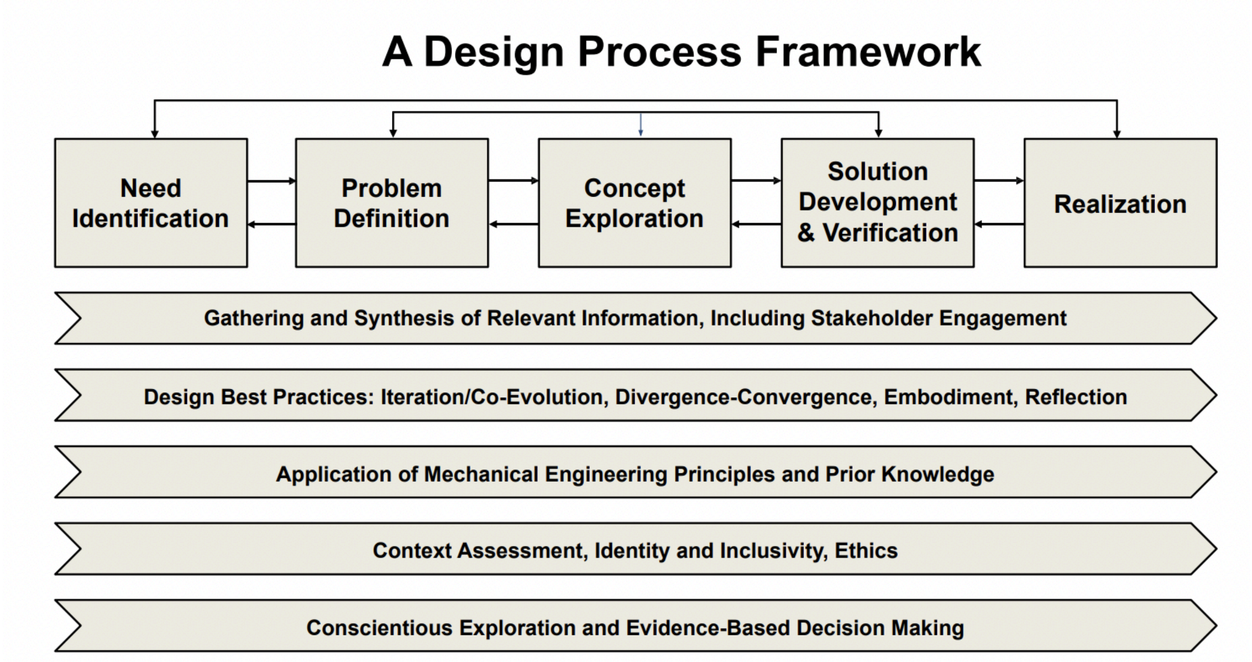


Figure 8. Design Process Model **[21]**

This design model is an excellent starting point and was also used as a launchpad for the design specific to this project.

User Recommendations and Engineering Specifications

In the Problem Identification and Limitations stages of the design process, the team has been gathering information on the parameters of which the design must follow. These specifications have come from the requests of the sponsor, from the current machine set-up, from spatial, financial, and feasibility limitations, as well as industry standards. The standards for this report are listed in **Table 1** in summary, and in full at this link (Requirements and Specifications).

Table 1. Sponsor Requirements and Engineering Specifications

Requirement	**Why**	**Specification**	**Priority Level**
Performance: primary operating characteristics of a product			
Robust against heat	- The oven reaches extreme operating temperatures	Can withstand temperatures up to 350 ℃	5
Accommodate lateral movement	- The chain moves laterally; the solution must do so as well - Must accommodate to different boards widths that run through the system	Needs to move laterally with a maximum width of 25 cm from leading edge of the PCB in either direction	4
Robust against pressure	- The oven reaches extreme operating pressures	Withstand pressures as low as 10 torr for 30 minutes	5
Automated	- Lubricant is currently applied manually - We need to simplify the system	During normal operation, it can lubricate chain at least one time per week without the need to open the reflow oven	5
Keep PCBs clean	- It is important to keep lubricant off the top of any board that passes through the system to avoid damaging them	30 cm spacing between PCBs	4
No-Slip Condition (If a pass-through tray is used)	- Sliding in the system could cause system misalignment and malfunction	Must have a coefficient of friction high enough to avoid slipping and a factor of safety of at least 3.5	4
Features: supplement product’s basic functions			
Consistency in timing of oil application/quantity of lubricant	- Settings must be flexible to not over or under lubricate in different environments (altitude, humidity, climate, etc.)	Must be able to apply the same amount of lubricant everytime the machine is used within 10% error	5
Corrosion Resistant	- Avoiding corrosion is essential to promoting device longevity	Must be finished with a corrosion resistant coating	5
Cost	- The new system must be economical compared to the current cost of maintenance to maintain marketability	Cost of production (including sourcing materials and manufacturing) must not exceed $5000	4

Reliability: probability of product failing			
Knowledge of Lubrication frequency	- To know that if a lubrication is delayed, early, or missed that it will not shut down the whole system	Must have a fault prevention system that can detect system stoppage within one week	3
Yield Strength	- If something were to happen: a sudden pressure drop or the product was struck, it needs to be able to survive	Any oil vessel within the vacuum will have a yield strength with a factor of safety ≥ 3.5	5
Limited complexity	- Complex designs can be less reliable and require more maintenance; solution outside of chamber is largely passive except for solenoid	Design should not contain more than 30 pieces	3
Ease of use	- The new solution should not be more difficult to use than painting on lubricant by hand	Should be able to operated with minimal supervision by a factory worker within two weeks of training	5
Durability: measure of product life			
Product Lifespan	- Know how long it will last and assess value	This product should last at least 10 years	4
Shipping Survival	- To make sure the product can survive being shipped overseas	The product should be able to be dropped on the ground from 6 ft and slide in a standard cardboard box 6ft laterally without cracks or breakage	5
Serviceability: ease and time to repair after breakdown			
Accessibility of system	- To know how small the system should be and where it will be most accessible - The device needs to be an addition to the current machine	The system must be able to fit in the current machine in use.	5
Tool Requirement	- To add to the ease of service without needing unique tools	Must be able to be maintained with the tools listed in the "Required Equipment" category in the user manual (page 144)	3
System Drawings	- To add to the ease of serviceability	There will be a CAD model of the whole system to-scale with correct material properties and dimensioning	5
Electrical Schematic Drawings	- To add to the ease of serviceability and follow compliance rules regarding "local" control and independence from cell controller	There will be a machine-to-machine electrical interface that includes electrical connections, grounding, and inter-machine control (per SMEMA [22])	5

Conformance: degree to which design and operating characteristics meet stakeholder expectations and established standards (e.g., safety, environmental standards)			
Conformance to SEMI S2	- SEMI S2 is the Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment. Companies purchasing products from Heller are required to follow these standards	Solution must adhere to all of the SEMI S2 standards that do not violate the necessary requirements	5
Conformance to SMEMA [9]	- SMEMA is the mechanical equipment interface standards designed to facilitate the manufacturing of surface-mounted printed circuit boards	The design strategy must not negate any SMEMA standards the machine already follows	5
Aesthetics: looks, sounds, organization			
Wiring Organization	- This is so that the machine remains easily accessible and maintainable and so that wires don't get tangled and rip each other apart or break.	Should the product have wiring exposed, the wires will be neatly organized and gathered together so that it is clear where each wire starts and ends and so that there is no tangling	5
Volume	- Having a volume that is too loud decreases the user experience and poses a safety risk for factory environments - Also is in accordance with SMEMA S2	The device should emit less than 80 dB continuously at distance 1 m horizontally and a height of 1.5 m	5
Vibration	- Having too much vibration takes away from the user experience and may increase fatigue on the system	The device should be moored properly to a surface so that it has negligible oscillation/vibration outside of the machines current hum	5
Surface and Edge Satisfaction	- This is for the user when handling the device, aesthetic, and for getting rid of small flaws in the material.	The surfaces and edges of the device should be thoroughly smoothed and deburred such that a person could run their hand across and not feel any roughness or imperfections.	5
Perceived quality: reputation			
Presentability	- To uphold the standards, precision, and class of the Heller company name.	The design must be organized and generally aesthetically pleasing. It must not look messy in any way.	3
Safety			

Device Temperature Control	- The device must not damage other parts of the machine if it gets too hot and it must be accessible to the user.	The device must either not get to a temperature high enough to melt surrounding materials and it must be able to cool down to ambient temperature within 20 minutes (design dependent)	5
Shields	- The device must have protection for the surroundings from any risky splatter or heat dissipation.	Any section of the device that poses a risk of expelling material or lubricant must contain a viable shield on it. Viability means protecting the potentially affected surroundings with 100% accuracy.	5
Notification of Issues	- This is important in catching an error or machine failure as soon as possible.	The device must have a way to notify the user of malfunction.	4
In-House Safety Standards	- Important to following company procedure and to best ensure the safety of the manufacturers and users.	The device must follow all In-House and Industry-Wide safety protocols.	5
Lubrication Standards			
Viscosity	- This is so that the lubricant is thin enough to flow and be dispensed of out of a valve, yet still thick enough to stay adhered to the chain	The lubricant must be able to flow through a valve without added assistance	4
Adherence to Chain	- This is important in making sure that the lubricant doesn't need to be reapplied every cycle.	At least 70% of the applied lubricant must remain on the chain after one cycle of the machine.	3
Type	- This is provided to us by the sponsor.	The lubricant must either be the Moresco brand or the Krytox brand.	3
Heat of Vaporization	- This is so the lubricant does not evaporate when the system is run	The lubricant must not evaporate under peak operating conditions of 10 torr and 480 degrees celsius.	5
Cost			
System Cost	- This would make the machine lose it's marketability if not achieved - This plays a role in the reproducibility of our design at the company	The cost of the lubrication system must not exceed 2.5% of the cost of the entire machine.	5

It is important to note as well that the project and system are very complex and some of these specifications are subject to change. More specifications and recommendations are likely to be added as well. Our team used direct communication from our sponsor to determine many of our engineering requirements and specifications seen in the table above. Our foremost requirements, listed as “Performance” in **Table 1**, come directly from conversations that our team had with Heller Industries. These performance requirements include robustness against temperature and pressure, automation, preserving printed circuit board cleanliness, accommodating lateral movement, and maintaining no-slip condition. These requirements not only relate to the functionality of the lubrication system, but also to the customer’s needs.

Robustness against heat is a performance requirement because the system has to operate at high temperatures, so any component must also operate at high temperatures. Robustness against low pressures is also important because the scope of our project is within a vacuum chamber capable of reaching pressures as low as 10 torr. Automation is the main motivation behind the project as a whole. Successfully automating the vacuum chain lubrication will significantly reduce the time required for maintenance to service the ovens, and can improve reliability of the chain over time. The need for lateral movement stems from the adjustability of the width of the conveyor. A computer modeled image below (**Figure 9**) shows how the chain can move within the vacuum.

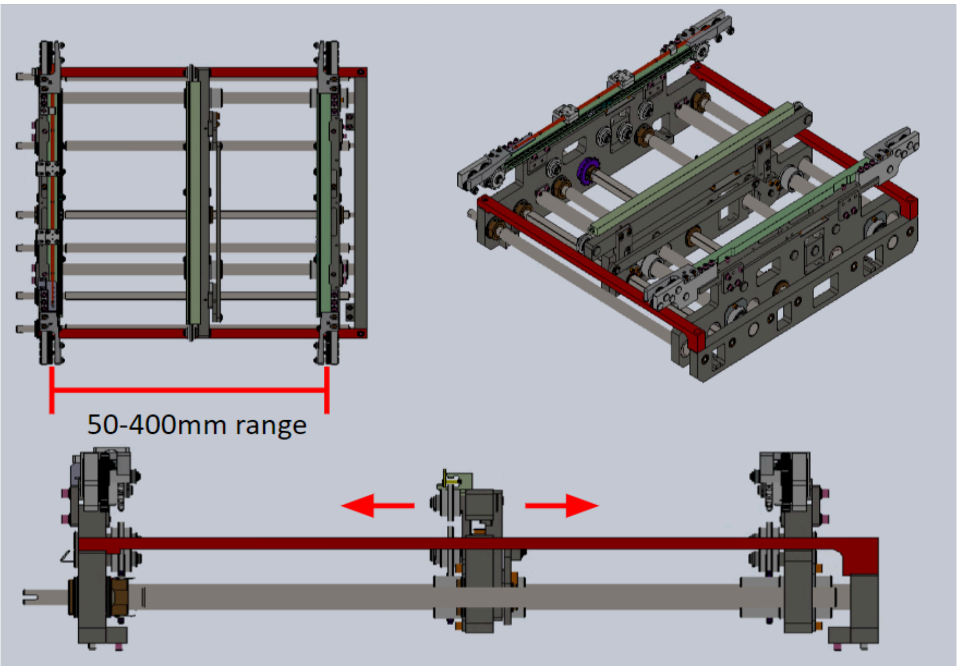


Figure 9. Visualization of the lateral movement that Heller’s chain conveyors are capable of. Any solution to lubricate the chain must do so at any position within the range [7]

The remaining performance requirements—preserving printed circuit board cleanliness and preserving no slip condition—may be more or less relevant depending on the type of solution implemented, but both are crucial regardless. Heller prides itself on improving the quality of printed circuit boards with its vacuum system, and dirtying the boards could lead to damage and fatigue via residues creating excess friction. Particularly, a spraying or dripping system would require special attention to this requirement. Unwanted particulates on the machines could leave buildup or jam mechanisms within the machine. The no slip condition refers to any solution that travels along the chain or is positioned near the vacuum chamber. If any object falls outside of its desired position, it could be detrimental to the functionality of the machine and could potentially warp the PCB.

As of now all of the requirements are stated, but if the project evolves to a point where more requirements and specifications are necessary, the team will adjust where relevant. The team is referencing specifications required for semiconductor manufacturing because the processes are somewhat similar and can be applied to our situation.

Specifically with a project of this scope and freedom in design, it is important to create a hierarchy of requirements so that we can design towards the largest needs accordingly. After compiling our requirements and specifications according to the processes above, we defined our performance requirements—needs that are necessary for the solution to function. As stated above, the six requirements that are completely non-negotiable are as follows: the solution must be robust against heat, accommodate lateral movement, be robust against pressure, operate in an automated fashion, keep PCBs clean, and maintain a no-slip condition. Specifications for each requirement can be found in **Table 2**. Beyond these six, a solution can function without a given requirement, but fulfilling each will lead to a better end product. Beyond the separation based on absolute necessity, each requirement is given a priority level between 1 and 5. When we are inevitably faced with a decision to choose between fulfilling requirements, we will refer to the priority weight of each in relation to the other.

Table 2. Primary Requirements and Specifications

Requirements	**Specifications**
Robust against heat	1. Withstand temperatures up to **350 °C** [1] OR 2. Operate when oven is not in use
Interface with vacuum	1. Withstand pressures between **10 torr** and **atmospheric (760 torr)** OR 2. Operate outside of the vacuum chamber [1]
Accommodate movement	Needs to move laterally to accommodate the adjustment of rails to accommodate PCBs ranging in width from **50-350 mm** [2]

Automated	Assuming no faults and typical function, manual setup of system can be completed, with minimal training, in under **5 minutes during the Preventive Maintenance Cycle** [1]
Cost	Material, labor, and production cost cannot exceed **$5,000**

We have also spent time quantifying and adding detail to requirements in the form of engineering specifications. Each of the primary requirements has a concrete number or value attached as a specification. Our solution must satisfy every one of the six to qualify as a success, which gives us a concrete goal to ideate towards. Other important categories of requirements and specifications include lubrication, cost, durability, serviceability, and more. It is important to note that no category is markedly more urgent than another, but each requirement within can be gauged by the priority weight given, as explained above. As a whole, we believe that these requirements are all individually reasonable; however, there are a total of 34 requirements, and implementing all of them to the fullest extent is unreasonable. We plan on conforming to requirements on the basis of priority weight without violating any of the six core requirements. Finally, we recognize that our requirements and specifications list can never be complete, and will continue to update it as we gain more information from stakeholders and our own research.

Stakeholder Analysis

As with any project, our design solution has many stakeholders who are or may be impacted by the development of a solution. Some stakeholders are obvious, like our sponsor Heller Industries, others are affected less directly, the University of Michigan. The following image, **Figure 10**, visually describes the levels of each stakeholder, and **Table 2** below details the impact, influence, priorities, contributions, and oppositions of each stakeholder.

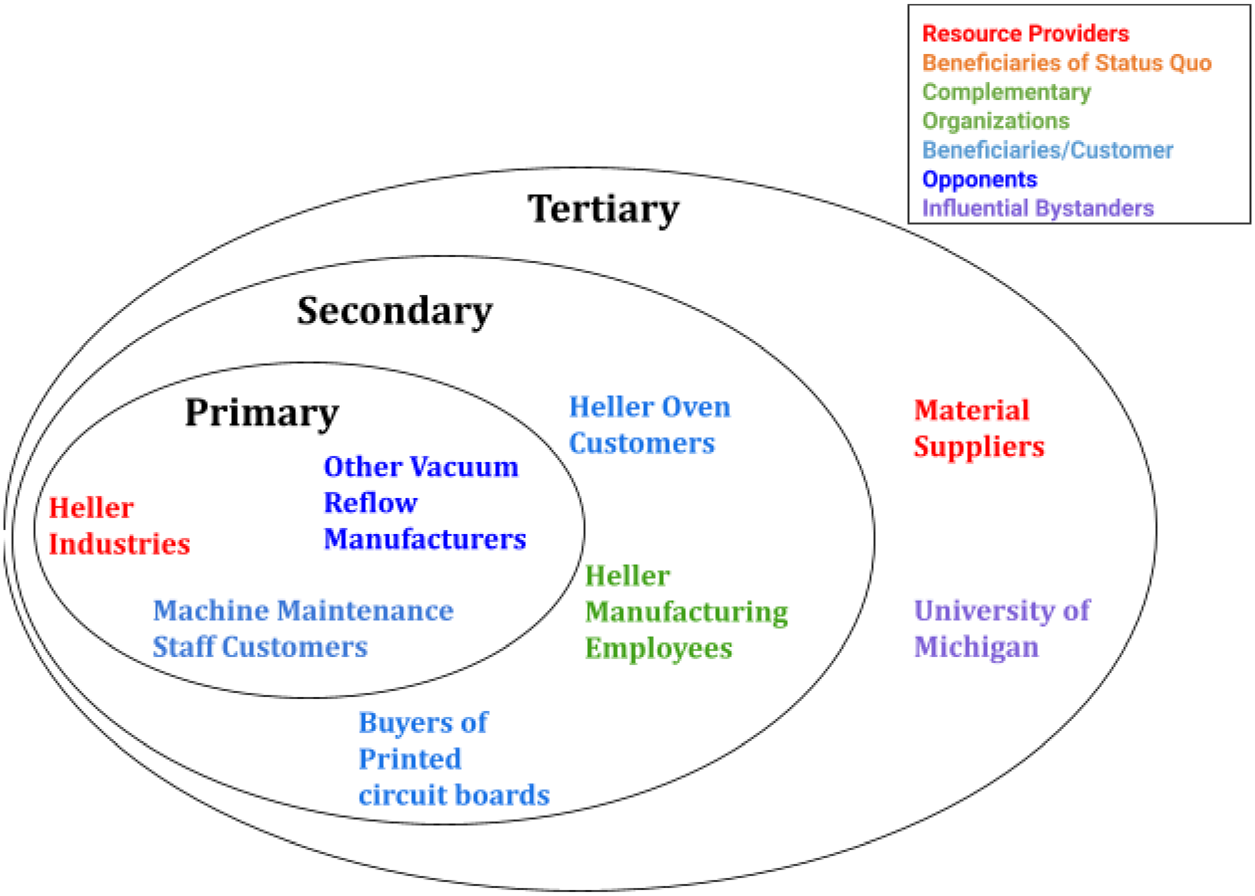


Figure 10. Stakeholder Mapping

The map above gives perspective to the level of involvement of each of the stakeholders in accordance with their proximity to the project. The primary stakeholders will have the loudest voice and are those most invested in the design. This level of engagement will decrease as the diagram approaches the tertiary region. An elaboration of the expected investment and engagement levels of each stakeholder can be seen in **Table 2** below. This helps the team in accommodating the needs of the stakeholders, but also making an effort to hear feedback that is relevant to project development.

Table 2. Detailed Stakeholder Information

Stakeholder Name	**Impact**	**Influence**	**Stakeholder Priorities**	**Potential Contributions**	**Potential Opposition**
Heller Industries	High	High	Increasing the efficiency of their Convective Reflow Ovens.	Provide resources for brainstorming, prototyping, and fabrication.	They could deny ideas and have authority over what is installed.
Maintenance staff	High	Low	Make chain lubrication less cumbersome.	Their feedback could help us to create the best possible system, due to their current engagement on a regular basis with the system.	Can refuse to implement or use a new system.
PCB customers	Medium	Low	Increase overall production of PCBs, which would increase revenue.	Through purchasing power.	They could decrease the demand for PCBs if the quality becomes lower.
University of Michigan	Medium	Medium	Making a quality project for students, and upholding reputation.	Provide resources in the form of library access and instructor guidance.	They could force students to stop working with Heller if the need arises.
Other Vacuum Reflow Manufacturers	Medium	Low	Being profitable in the reflow oven market.	Inspiration in the form of non-patented material.	They could utilize intellectual property rights to block some solutions.
Heller Oven Customers	Medium	Low	Decreasing the maintenance needed on the oven, while keeping the cost low.	Provide their priorities and concerns with the addition of a new system	They could refuse to purchase the new design.
Material Suppliers	Low	Low	Having reliable business from Heller Industries.	Information about materials that can or cannot be supplied.	Not supplying necessary materials to Heller.
Heller Manufacturing Employees	Medium	Low	Products being easy to manufacture and assemble.	Provide insight on the manufacturability of certain components.	Refuse to build objects above threshold complexities.

This project involves multiple stakeholders at varying levels of involvement and impact. The largest stakeholder is **Heller Industries**, the company that produces solder reflow ovens. They would reap the biggest positive impact from a successful project, as it would increase the efficiency of their product and have advertising potential towards customers. In addition to being a high impact stakeholder, Heller is highly influential, as they have the power to implement or scrap any solution brought to them. The next largest primary stakeholder is Heller's customer base: **reflow oven buyers**. Reflow oven buyers are also impacted heavily by our solution, since they would have reduced maintenance costs on a weekly basis. Unlike Heller, they are a low influence stakeholder. Our group can gather input from buyers (specifically Saline Lectronics, a Heller contact) but they have no power over our choices in implementing our solution. Their largest point of influence is in their decision to buy or not buy the final product. The final primary stakeholder are the **maintenance staff** employed by reflow oven buyers. They experience the highest impact of our solution, as they currently do the work that our solution would eliminate. There is some concern that taking away their work would decrease employment, however Heller Industries has stated that this tedious process is undesirable and would allow maintenance staff to redirect their efforts towards other work [23]. We have classified maintenance staff as medium influence, as they do not have power over our solution, but are the most knowledgeable about actual day to day care of the machines, and will be asked extensively about current and potential solutions for lubrication.

Secondary stakeholders are classified as those outside the immediate sphere of influence and impact. They include competitors to Heller Industries, Heller manufacturing employees, and end customers of printed circuit boards. First, **Heller's competitors** are classified as a low influence stakeholder. They will not be asked for direct advice, and the only influence they could have is from our group taking inspiration from their non-protected methods of chain lubrication. The impact our solution would have on them is medium, as they directly compete with Heller Industries in the space of solder reflow ovens, and a potential improvement upon Heller's machines would decrease the relative value of the competitor's products. The next secondary stakeholder—**Heller manufacturing employees**—are a low influence stakeholder, as they will not have any direct say in the design of the lubrication system. The impact our solution has on them is medium, and will only relate to the manufacturing of the device. Their motivation will be for us to design a mechanically simple product that is easy to produce. The final secondary stakeholder is **printed circuit board customers**. This group is removed from the sphere of influence of the project, therefore their influence level is low. Their impact is also low if our solution is implemented correctly; an automated or semi automated lubrication system should result in the same or better quality as manual lubrication. If our solution increases the efficiency of the reflow ovens, supply of printed circuit boards may increase slightly. We expect the impact on final production volumes and prices as perceived by the final customer to be low.

In addition to the other two groups of stakeholders above, tertiary stakeholders hold some influence or are impacted by our design solution. However, this group is the furthest removed from our project, meaning they tend to have a distant or low impact connection to our work. The first such stakeholder is **material suppliers**. This group sells resources to Heller Industries to create reflow ovens. Our solution would likely involve a small increase in needed parts, which creates a small incentive for Heller's suppliers to support the implementation of an automatic lubrication system. Their influence over the project lies in their ability or inability to supply certain parts to Heller as requested. Finally, the **University of Michigan** is a stakeholder in this project, along with staff therein. Michigan has an incentive to see their project teams succeed as a way to uphold their reputation and public perception. In the context of all stakeholders, the project has a low impact on them. They do have a medium level of influence over the project, as they have control over us as students working on the automatic lubrication system.

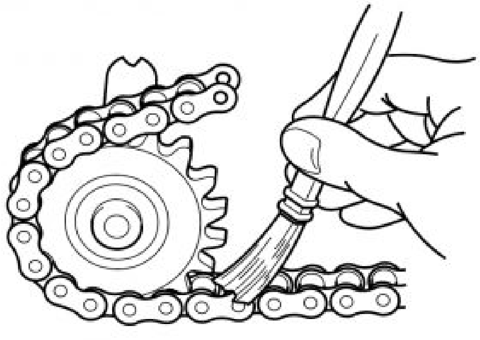


Figure 11. Hand painting lubricant image

Hand lubricating the chain is an aspect of the job that maintenance does not enjoy doing, so the team's design solution will be positively impacting the workplace of many maintenance workers who maintain Heller's vacuum reflow ovens. Holistically, Heller Industries cares greatly about the social impact of their company onto the industry they occupy, and those who they employ. The addition of our design could positively impact many of Heller Industries' valued customers, benefiting the social climate for those operations. By choosing to finance this solution, Heller Industries is also positively benefitting many parties including our team. By giving our team a Capstone project to work on and supplying consistent guidance and support, the team at Heller is endowing our team with a unique opportunity to learn in a hands-on environment. It is important to acknowledge that Heller exists as a company in a competitive space, so profit is an important factor for their success. However, we do not see this as obstructive to our project, as we have been given plenty of resources in the form of meetings with knowledgeable parties, access to machine shops, money, site tours and more. We are committed to being open with our sponsor about any issues surrounding their priorities and ours.

Intellectual Property Protections

As part of the vacuum chamber chain lubrication project, we were required to sign intellectual property rights to Heller Industries. This ensures that whatever design we create for them will remain as their property to be used or patented freely. While we understand the implications of this agreement, we are grateful to have had so much design freedom to explore our independent ideas as well. At the conclusion of the project, Heller Industries will be able to patent any new process or design created within the scope of the class, which could allow them to sell the design at a profit, which would benefit the company. IP protections such as patents could also give them an advantage over their competitors, as several other companies use vacuum reflow ovens [24, 25, 26, 27]. A patent for this application would allow them to charge their competitors for use of the patent, or withhold rights altogether.

Sustainability in Vacuum Chain Lubrication

Sustainability is a necessary consideration for our solution. Both elements of our proposal—lubrication and the vehicle for lubricant delivery—should be optimized to reduce resource use and pollutants. For the lubrication vehicle, heat resistant metals or composites need to be used to meet the design requirements, but they may also have unintended consequences when it comes to their method of production. Our group will pay attention to the toxicity of any heat resistant coating as well as the rarity of the material sourced when creating a bill of materials for our solution. Additionally, the high operating temperatures and low pressures of the vacuum chamber tend to push lubricants towards a gaseous state. Chain lubricants tend to be toxic to humans in general [19], and vaporizing them increases the risk of inhalation as well as damage to local environments. Heller Industries has already taken steps to reduce emitents by adding filters to their vacuum ovens, which is listed in their manual as "Vacuum pump exhaust filter [28]." Additionally, Heller vacuum ovens come equipped with exhaust monitoring systems for consumers. For context, a cross sectional view of the air flow exhaust system is included below in **Figure 12**. Our group will contribute to sustainability by considering toxicity, material rarity, and vapor pressure when selecting our lubricant.

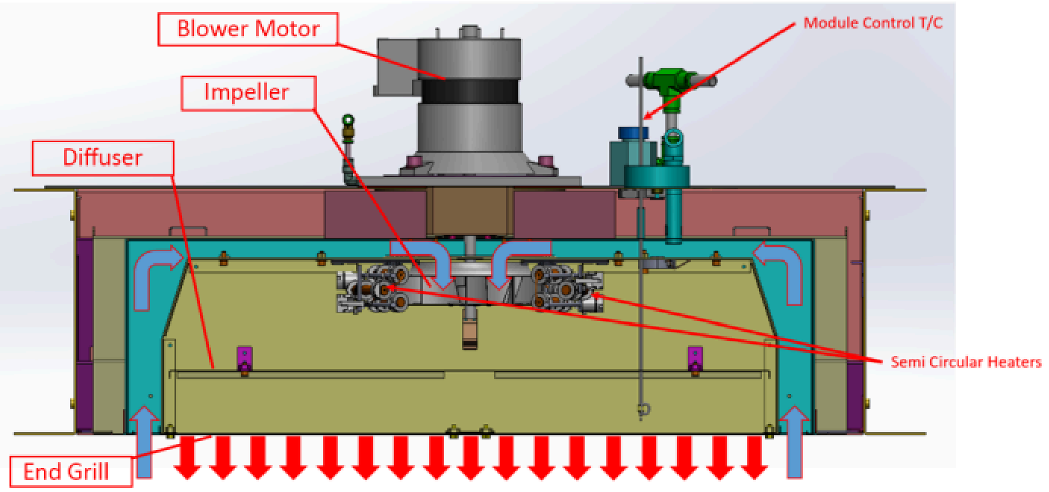


FIGURE 12. Schematic of air flow within the vacuum chamber of a Heller reflow oven. The exhaust air is filtered before returning to the ambient atmosphere [28]

While we are not considering air pollution as a primary factor in the development of the design, nor a major design parameter, it is important to not be negligent in consideration of the environment anytime one approaches a manufacturing challenge. Therefore, we find it imperative to mention any social consequences and considerations of the design choices we make.

Statement on Ethics and Power Dynamics

The purpose of Heller Industries' vacuum reflow ovens is to increase the quality of printed circuit boards for end use. Our group finds this to be an ethically positive pursuit, and does not find issue with the premise of Heller's products or the project we have been assigned. Initially, there was concern for the displacement of maintenance staff for companies that produce PCBs, but after conversations with Heller, we discovered that the job is undesirable, to the point that many companies neglect lubrication of the vacuum chain altogether, leading to consequent issues. We intend to continue raising any ethical issues as we see them. Leaving concerns unvoiced will only lead to issues later in the project, so a policy of being open and honest about any reservations will combat this issue.

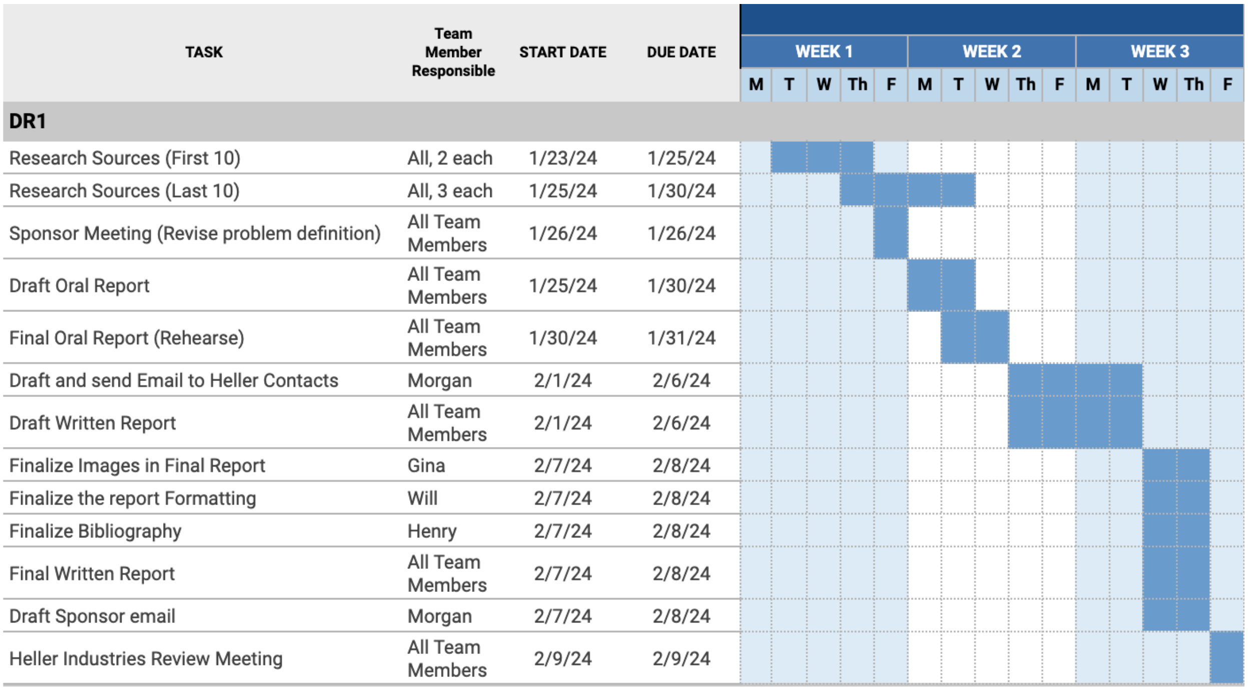
In addition to addressing ethics in the context of our project, we are committed to being cognizant of power dynamics within and outside of our group. Splitting work evenly and treating other team members with respect are two pillars of our team agreement that was signed early into the project. As a team, we have conversations weekly to uphold these values, and all of us are open to discussing issues with external mediators such as University of Michigan staff should the need arise. Two groups with power over our group are the university and Heller Industries. We have not experienced any abuse of power from either group; both our project sponsor and professor have given us plenty of resources and reasonable deadlines for work to be done. Should any issues come up regarding power dynamics, we plan to approach a third party to get a less biased view of our situation, and be open and honest with each party.

Just as the aforementioned groups have power over us, maintenance staff are a group that we have power over. One major way we need to address this is by talking to those who operate the reflow ovens. They are responsible for lubrication of the chain system we are working on, but we have not spoken to them yet to gain their perspective. We also need to consider the perspective of end users—the microchip manufacturers may have different viewpoints than Heller Industries, who make the reflow ovens to sell to microchip manufacturers. Both these groups are stakeholders in our project, but they have almost no influence over what we do unless we make an effort to include them. In order to identify future inclusivity or power dynamic issues, we will continue brainstorming as a team.

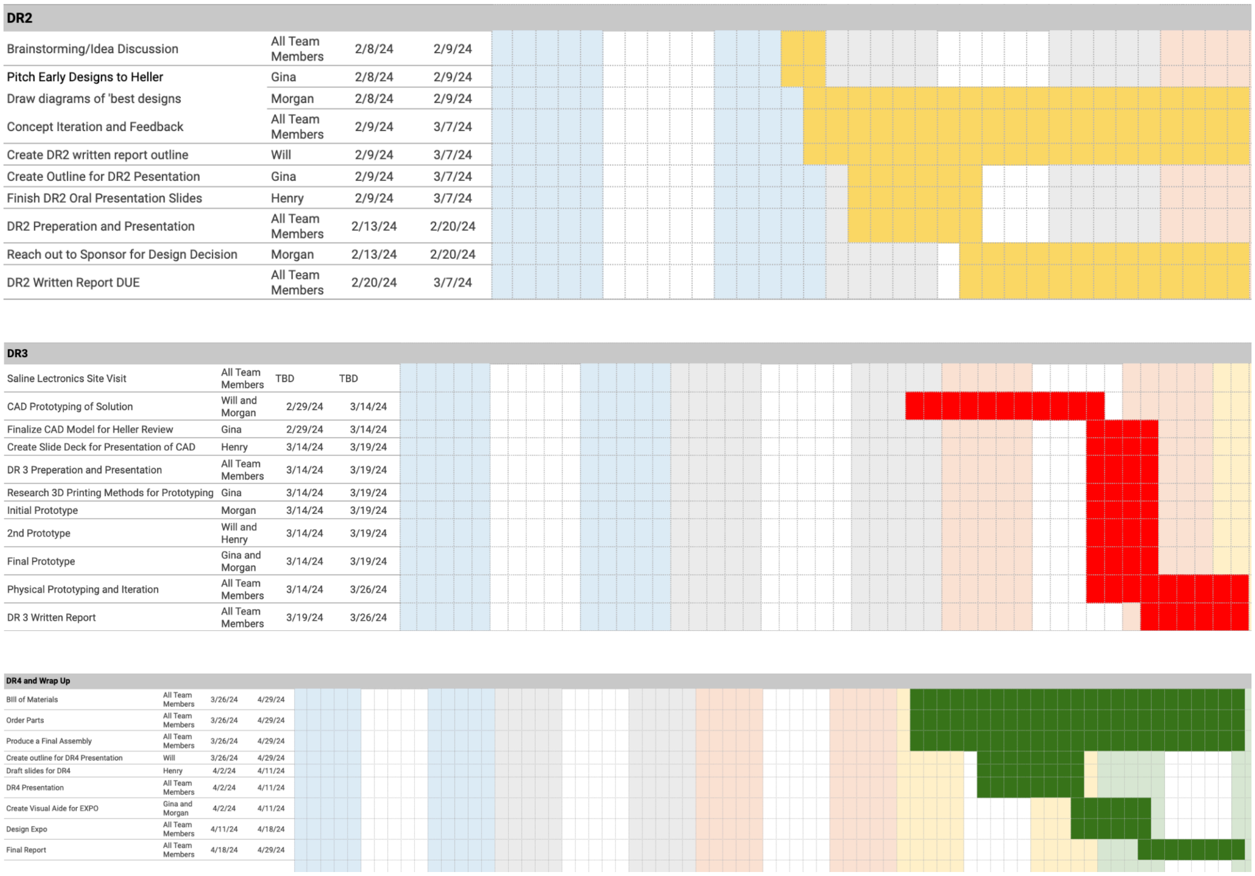
Problem Domain Analysis and Reflection

Our team believes that we are well-equipped to address Heller Industries' chain lubrication issue, but there are some potential obstacles that may slow our progress. It may be difficult to assess the engineering specifications because they will require a broad range of calculations and skills to accurately and precisely determine if our design meets those specifications. One challenge we can anticipate is determining how the viscosity of lubricant will affect the functionality of our design ideas. We have little experience doing complicated calculations of this nature and could see this becoming an obstacle in our analysis. To combat the difficulties of fluid mechanical analysis, the team is researching existing published calculations that could be relevant to our design problem. We are also reviewing our Fluid Mechanics coursework to give context and insight into our future analytical process, and in the future will connect with previous instructors if necessary. Additionally, the team anticipates obstacles in analyzing our chain lubrication system within a vacuum chamber and under high temperatures. These extreme conditions not only limit the feasibility of our designs, but also pose a unique set of challenges. In response to this obstacle, the team has spent time researching vacuum chambers and what type of features can operate in a vacuum environment.

While there is a large amount of information on vacuum chambers and chain conveyors separately, it has proven difficult to find extensive information on chain conveyors that operate in vacuum chambers. We will use our theoretical knowledge from coursework, research, and standards to counter the effects of this gap in information, and run simulations and Finite Element Analysis to approximate the conditions of the vacuum chamber. To combat these potential setbacks, the team will make sure to anticipate a plan to fill our toolbox as well as we can in advance. The better we can collaborate as a team, the more successful we can be, and this stems from day one organization. An anticipated schedule, as seen below in **Figure 13**, will ensure that deadlines are met and responsibilities are equally distributed between the four team members so that we can accomplish our design goals.



TASK	Team Member Responsible	START DATE	DUE DATE	WEEK 1					WEEK 2					WEEK 3				
				M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
DR1																		
Research Sources (First 10)	All, 2 each	1/23/24	1/25/24		■	■	■											
Research Sources (Last 10)	All, 3 each	1/25/24	1/30/24				■	■	■	■								
Sponsor Meeting (Revise problem definition)	All Team Members	1/26/24	1/26/24					■										
Draft Oral Report	All Team Members	1/25/24	1/30/24						■	■								
Final Oral Report (Rehearse)	All Team Members	1/30/24	1/31/24							■	■							
Draft and send Email to Heller Contacts	Morgan	2/1/24	2/6/24									■	■	■	■			
Draft Written Report	All Team Members	2/1/24	2/6/24									■	■	■	■			
Finalize Images in Final Report	Gina	2/7/24	2/8/24													■	■	
Finalize the report Formatting	Will	2/7/24	2/8/24													■	■	
Finalize Bibliography	Henry	2/7/24	2/8/24													■	■	
Final Written Report	All Team Members	2/7/24	2/8/24													■	■	
Draft Sponsor email	Morgan	2/7/24	2/8/24													■	■	
Heller Industries Review Meeting	All Team Members	2/9/24	2/9/24															■



DR2			
Brainstorming/Idea Discussion	All Team Members	2/8/24	2/9/24
Pitch Early Designs to Heller	Gina	2/8/24	2/9/24
Draw diagrams of 'best designs	Morgan	2/8/24	2/9/24
Concept Iteration and Feedback	All Team Members	2/9/24	3/7/24
Create DR2 written report outline	Will	2/9/24	3/7/24
Create Outline for DR2 Presentation	Gina	2/9/24	3/7/24
Finish DR2 Oral Presentation Slides	Henry	2/9/24	3/7/24
DR2 Preperation and Presentation	All Team Members	2/13/24	2/20/24
Reach out to Sponsor for Design Decision	Morgan	2/13/24	2/20/24
DR2 Written Report DUE	All Team Members	2/20/24	3/7/24

DR3			
Saline Lectronics Site Visit	All Team Members	TBD	TBD
CAD Prototyping of Solution	Will and Morgan	2/29/24	3/14/24
Finalize CAD Model for Heller Review	Gina	2/29/24	3/14/24
Create Slide Deck for Presentation of CAD	Henry	3/14/24	3/19/24
DR 3 Preperation and Presentation	All Team Members	3/14/24	3/19/24
Research 3D Printing Methods for Prototyping	Gina	3/14/24	3/19/24
Initial Prototype	Morgan	3/14/24	3/19/24
2nd Prototype	Will and Henry	3/14/24	3/19/24
Final Prototype	Gina and Morgan	3/14/24	3/19/24
Physical Prototyping and Iteration	All Team Members	3/14/24	3/26/24
DR 3 Written Report	All Team Members	3/19/24	3/26/24

DR4 and Wrap Up			
BIll of Materials	All Team Members	3/26/24	4/29/24
Order Parts	All Team Members	3/26/24	4/29/24
Produce a Final Assembly	All Team Members	3/26/24	4/29/24
Create outline for DR4 Presentation	Will	3/26/24	4/29/24
Draft slides for DR4	Henry	4/2/24	4/11/24
DR4 Presentation	All Team Members	4/2/24	4/11/24
Create Visual Aide for EXPO	Gina and Morgan	4/2/24	4/11/24
Design Expo	All Team Members	4/11/24	4/18/24
Final Report	All Team Members	4/18/24	4/29/24

Figure 13. Interim Team Schedule

The scope of our project is ambitious for the semester due to the open-ended design process, but we are confident that we can meet expectations and deliver a final result by the conclusion of our course. We have developed the above schedule to ensure that the team can deliver all of the sponsor's requirements by the end of the school semester, April 29th. The initial tasks have already been completed, including: initial research, revisionary meetings with sponsor, in depth research on sponsor company, drafting and delivery of the Design Report 1 presentation, and lastly Design Report 1 for submission. Coming up, the team will start to brainstorm possible solutions to the chain lubrication problem and present them to Heller Industries for review and potentially approval. From there, the team will pursue one design that meets the sponsor's requirements and edit the design until all requirements are met and the team maximizes the effectiveness of the design. This portion includes Computer Aided Design prototyping and assembly if necessary. At this time, the most important task is to fully develop our brainstorming list into feasible ideas with visuals and metrics to judge each design's efficacy. The team has delegated to each of our strengths to ensure the smoothest possible track towards choosing a design, which can be seen in the Gantt Chart above. There are no glaring tasks that need to be completed immediately as of now, but as they come up the team will evaluate and delegate the task to the appropriate party.

The simplified “critical path” of our design project is as follows: Idea Generation, Internal Idea Review, Sponsor Idea Review, Idea Selection, Virtual Prototyping, Physical Prototyping, Failure Testing Iteration, and Final Product. As we follow our critical path, the team must consider budgetary restrictions in the development of our project. We have been given a rough initial budget of $400, but if the constraints of the project necessitate a higher budget Heller Industries will consider raising the limit. We believe that with our team of Mechanical Engineering students, Heller Industries management and CEO, and University of Michigan staff, we can produce a working prototype to address the chain lubrication problem the Heller Industries faces.

Concept Generation

Upon approaching concept generation, our group considered several different methods of exploration. The first method we used was simply a rapid-ideation round table group discussion. The four members of our group first identified the primary goals of our project and its core functionality. We discussed the values of each core functionality and how heavy of a hand each specification would have when creating our design. From there, with no preparation, we simply threw out as many ideas as possible. We spoke in no particular order, hearing out each person’s ideas in completion and then built off each other in a quick Brainstorming session. Due to the spontaneity of this process, ideas were described as they rose to each person’s imagination, often through pictures, drawings, hand motions, sounds, google searches, and verbal explanations. The thought process of this is that the impulsivity was fostering creativity and rapid pace would pose many ideas very quickly and early on with which we could build on. Throughout this session, if any of us thought an ideal had potential, we would jot it down in an idea file shared Google Doc. The results of this can be found in the *Concept Generation* section of the Appendix.

The second method we used came from a more strategic approach to brainstorming. This meant we started with an individual brainstorm, where we started once again with an initial consideration of specifications and requirements to define our goals. This led us to consider subfunctions of our project and we were brainstorming ideas for all the subfunctions. Some of these sub functions included valve solutions, solutions for considering extreme temperature and pressure, solutions for spreading the lubricant across the chain, and solutions for moveability. We then each individually proposed an idea. It could have been an existing idea that we were familiar with as engineers, or it could have been a new idea. These new ideas we considered individually were mostly based off of things we found outside our subject matter that had similar mechanics to the details of our task. We then considered what a solution in that circumstance would be and if that could be applicable to our project. Some of the areas where we looked for similar mechanics were the human body, food systems (like restaurant supplies or cooking or baking), and nature and ecology. Once we had each generated 40 concept ideas, we did a self-evaluation and categorized ideas we thought were possible and those we did not think were possible. The ones we thought were possible, we shared with the group at the next meeting where we did the same evaluation again, but as a group. Finally, all the ideas that were considered “possible” were dissected into a list of pros and cons. The ideas with the right balance of pros made it to the next stage, where we created a pugh chart. We ended up with about five top ideas to propose to our sponsor for feedback. Some of the results of this concept generation process can be found in the *Concept Generation* section of the Appendix, but is also shown through a flow diagram below for better representation:

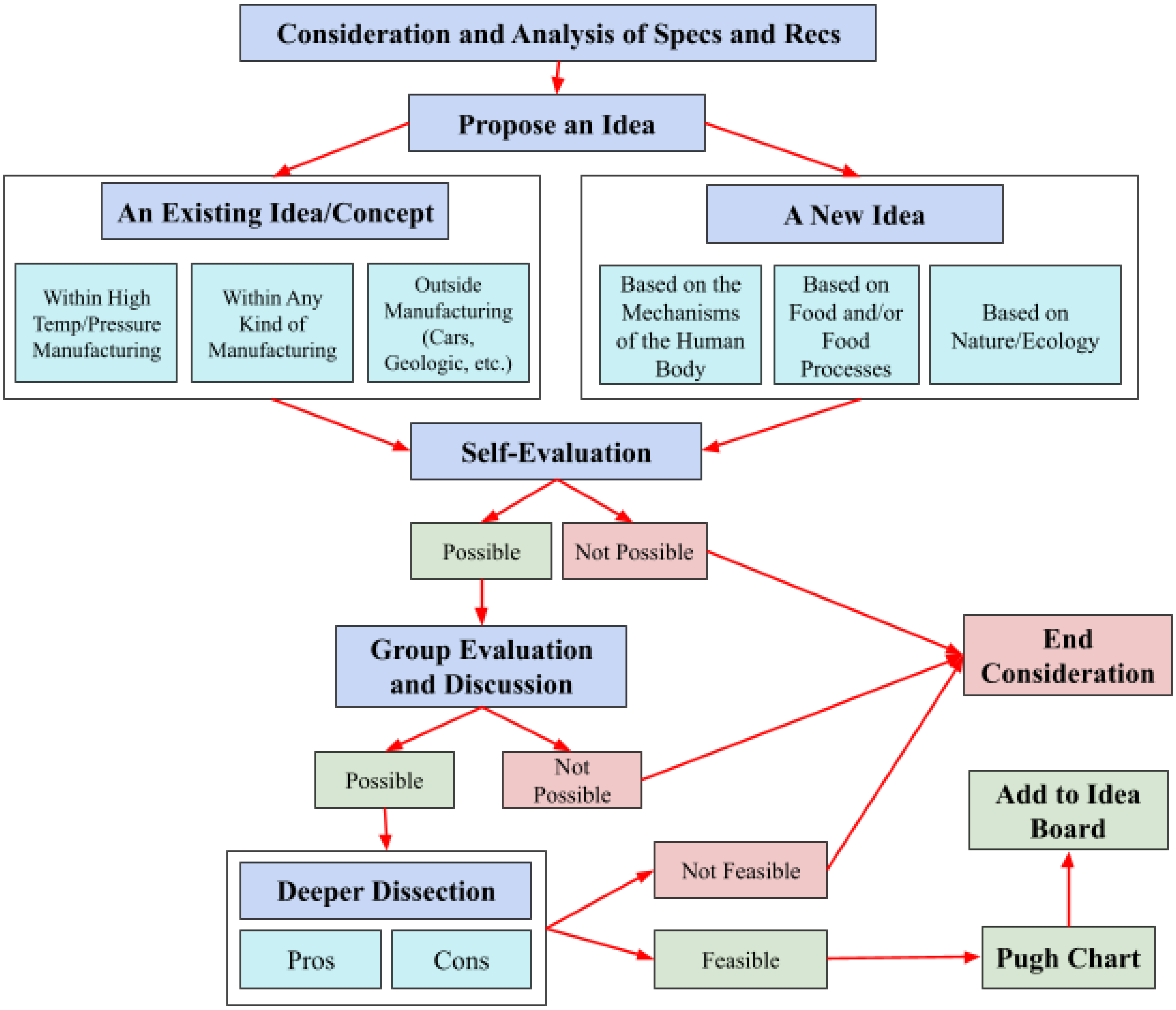


Figure 14. Brainstorming Flowchart

The rapid brainstorming processes resulted in many very different ideas in a variety of different categories. For example, there were many suggestions for different valve types, such as a butterfly valve or an electromagnetic valve, for storage systems, such as a submarine-like oil reservoir or a reservoir outside the system, and for lubrication application methods, such as a jet sprayer or a wick. There were lots of suggestions in different sub-function groups that revolved around quick brainstorming, but also showed divergence and critical thinking. For the individual brainstorming, oddly, we had a lot of overlap amongst the group but also this is where our most creative and unrealistic ideas came in too. For example, we all had some variation of a mechanical arm and an oil jet spray as one of our posed solutions. There was a spectrum of ideas posed, all the way from obviously infeasible to we are more than likely capable of accomplishing this. But with this scale and each idea, there were drawbacks like if it met all of the customer needs, complexity, manufacturability, and time scale. Some of the ideas landed in the obviously infeasible category simply because they are not accomplishable in a single semester's worth of time. Others were too complex, too far-fetched, or just generally unreasonable. An example of an individual brainstorm before group discussion can be seen in the *Concept Generation* section of the Appendix as well.

A more detailed reflection and discussion of our Pugh chart and pros and cons lists we did to narrow down the top ideas can be found in the section below, *Concept Selection Process*, however the top five ideas we settled on as a group after the generation process above were a cup reservoir, a modified sprocket lubricator, a pass-in tray, a helical lubricant conveyor, and an external mechanical arm. Per our list of specifications and requirements and for clarity for our sponsor, each design was labeled in three categories: semi-automatic or fully-automatic, operates during a standard function or a preventative maintenance cycle, and whether any of the parts had permanent residence inside the vacuum chamber when the standard cycle was in use or if everything left the chamber after its cycle.

The Cup Reservoir

The cup reservoir is an open topped, metal 'cup' filled with lubricant that leads into a wick system similar to the wick system used outside of the vacuum chamber, but without a valve. The system would need a maintenance person to fill the reservoir to a visual fill line and it would soak into a wick with lubricant that is in constant contact with the chain. The fill line corresponds to the amount of lubricant needed for a single lubrication cycle so there is no leftover lubricant in the reservoir after the cycle. This idea is a semi-automatic process and would operate during a preventative maintenance (PM) cycle. While all of the lubricant within the reservoir would be used up after each PM cycle, the cup reservoir would have permanent residence in the vacuum chamber.

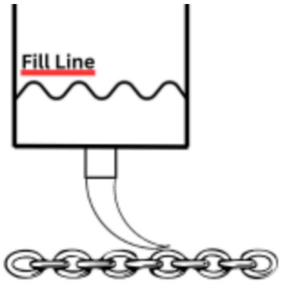


Figure 15. Cup Reservoir Initial Drawing

The Modified Sprocket

The modified sprocket lubricator is an extra and/or modified sprocket whose sole job was to lubricate the machine. It would screw into the system like the others but would apply lubrication to the chain upon contact via a flow from the outside of the chamber connected through valves to the sprocket. This idea is a fully-automatic process and would function during normal operation cycles. The sprocket would have permanent residence inside the vacuum chamber.

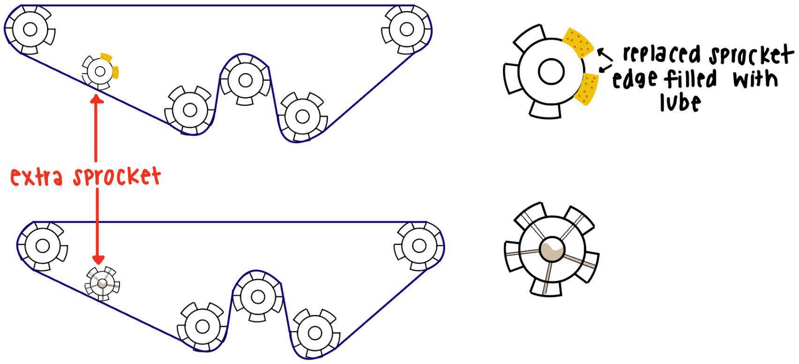


Figure 16. Extra Sprocket

The Pass-In Tray

The pass-in tray is a tray that follows the typical path of the PCBs in the machine and contains a lubricant reservoir that sits on top of the tray. As it runs through the machine, a wick connected to the reservoir would grease the chain as it ran through the system and then the tray would exit the chamber. This idea is a semi-automatic process and would operate during a preventative maintenance (PM) cycle. No parts of this system would have permanent residence in the vacuum chamber.

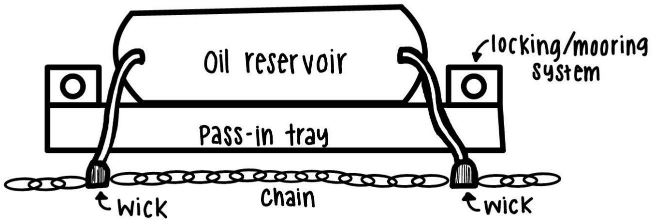


Figure 17. Pass-In Tray

The Helical Lubricant Conveyor

The helical lubricant conveyor is a screw within a cylindrical housing which rotates, allowing the lubricant to flow onto the chain (similar to a grain conveyor). This would theoretically control lubricant dispensing in a way that would better manage the pressure than some of the other options. This idea is a fully-automatic process and would function during normal operation cycles. The device would have permanent residence in the vacuum chamber.

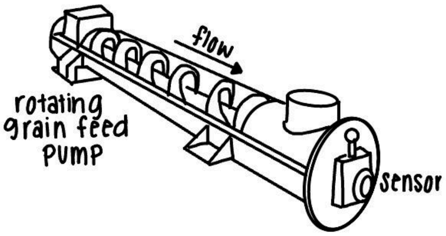


Figure 18. Helical Lubricant Conveyor

External Mechanical Arm

The external mechanical arm would sit just outside the door to the vacuum, and would reach into the chamber to paint on the lubricant. This would either be similar to a mechatronics system or a four bar linkage so that it could reach into the machine and retract back out. This idea is a fully-automatic process but would function during preventative maintenance cycles. The device would have permanent residence in the machine but reside just outside the vacuum chamber doors.

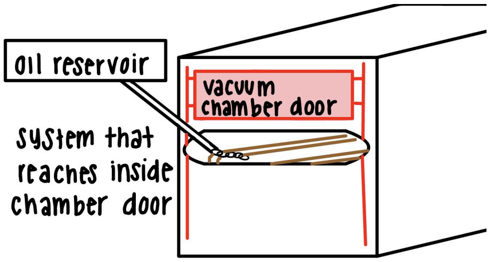


Figure 19. External Mechanical Arm

The pros and cons of each of these systems will be discussed in the sections that follow. The latter sections will also elaborate why we chose the design we did.

Concept Selection Process

After generating concepts using the methods described above, we continued by narrowing down selections through several different methods. The first of these was to eliminate concepts that were obviously infeasible. To quantify "obviously infeasible," we defined it as any concept that failed three or more performance requirements (see **Table 1**). The remaining designs were further narrowed by conglomerating similar concepts with one another, leading to 12 remaining concepts, which were arranged in a Pugh chart as shown below in **Table 3.**

The Pugh chart utilizes six criteria, each of which holds equal weight and corresponds to one of six performance requirements. In **Table 3**, each green box represents 3 points and signals a complete fulfillment of the requirement. A yellow box is weighted for 2 points and represents a partial fulfillment of the requirement. A red box is weighted for 1 point and signifies a failure of the requirement. The justification for making each requirement weighting the same is that each of them are necessary for the system to be implemented. If any are not met, the solution will be considered a failure. Finally, the six requirements are summarized below, and correspond to 1-6 in **Table 3**.

Table 3. Pugh chart that ranks each design idea on 6 metrics

Idea Name	**Temp Resistance**	**Pressure Resistance**	**Ability to Adjust Lubrication**	**Ability to Move Laterally**	**Level of Automation**	**Cost (<$5000)**	**Score**
Cup Reservoir	🟩	🟩	🟩	🟩	🟨	🟩	17
Sprocket for Lubrication	🟩	🟩	🟨	🟩	🟩	🟩	17
Pass in tray	🟩	🟩	🟩	🟨	🟨	🟩	16
Helical lubricant conveyor	🟨	🟨	🟩	🟨	🟩	🟩	15
External moving arm	🟩	🟥	🟩	🟩	🟩	🟨	15
Drip onto sponge	🟨	🟥	🟩	🟨	🟩	🟩	14
Compression Driven Hydraulic Valve	🟥	🟥	🟩	🟨	🟩	🟩	13
Linkage with sponge	🟨	🟥	🟨	🟩	🟩	🟨	13
Lubricant Jet	🟥	🟨	🟩	🟨	🟩	🟨	13
Martensitic Tray	🟥	🟥	🟨	🟨	🟨	🟩	11
Oil impregnated materials/Frozen Oil	🟥	🟥	🟨	🟨	🟨	🟩	11
Oil-Soaked Ring	🟥	🟥	🟨	🟨	🟨	🟩	11

After placing each design on the Pugh chart, their relative values became much clearer, and the top three designs were taken for further analysis. This was done in **Table 4** below, which showcases the pros and cons of each of the top three designs.

Table 4. Final Decision Chart

Concept	Survivable Temperatures	Pros	Cons
Cup Reservoir	High and Low	● Significantly lower labor required ● Simple design (easy to execute and test)	● Can only be used during down time ● Maintenance would need to set up cups and pour lubricant
Pass In Tray	High and Low	● Bypass temperature and pressure requirements ● Easily customizable	● Cannot operate with vacuum active ● Hard to verify quality of lubrication ● Can only interface with a couple inches of gear
Adjusting Sprocket for Lubricant	Low Only	● Could be easily installed in current system ● Size effective ● Moves automatically with rails	● Dispersing lubricant from sprocket is complicated ● Must comply with pressure and temperature requirements

Survivable temperatures is one element of the chart that may seem out of place; there is no mention of temperature stratification in the primary requirements, so why does it exist here? As we conducted background research for the feasibility of different concepts within the reflow oven, we found that many common flexible parts—such as tubing, valves, and pumps—had temperature ceilings below 350° C. For example, teflon tubing that was suggested by Heller Industries [31] had a maximum operating temperature of 250° C. Many elements of the potential sprocket design followed similar temperature restrictions, so the "survivable temperatures" column was added, with 250° C being the cutoff temperature separating "low" and "high" values.

Elimination of Automatic Solution

With the aid of **Table 4** and multiple conversations with representatives from Heller Industries, we decided not to pursue a fully automatic design. Low survivable temperatures was one of several reasons for this decision; other reasons included complexity and difficulty of testing. We recognize that we are operating on a limited and accelerated timeline, which means that increasing the complexity of the design will cost us in time and resources. We are committed to create a design that functions, or is as close as possible to functionality, when we hand off the project in April. Both Heller and our team are in agreement that pursuing a semi automatic system will make fabrication less complex and testing easier. This will allow us to create a solution that functions and makes life easier for maintenance staff, at the price of not being the most automated solution possible.

Reflection on Iteration and Future Development

Throughout the concept generation and selection process, solutions were combined, altered, and redesigned at various stages. Comparing our final two designs—the cup reservoir and pass in tray—to the first ideas our group came up with is a useful exercise to identify any biases or fixations we may have retained. Many of our first designs were focused on thoroughness and automation but did not pay much attention to manufacturability or adherence to requirements. This is reasonable, as we had much less insight into our restrictions at the time.

One design that has remained throughout concept selection is the pass in tray. It was suggested in a very early meeting by Heller staff and we sketched it at our first brainstorming meeting. Despite its persistence, we don't believe that it represents an unreasonable fixation on our end. Rather, it was a design that was simple from the start, received positive feedback from Heller representatives, and has been iterated upon by adding different wick styles and slimming down parts.

Regardless of how much we have improved our design up to this point, our team places a high value on improvement and iteration. Within the selection process, we have put an emphasis on simplification of designs, both to reduce cost and complexity. We plan to continue improving our designs through testing and machining prototypes ourselves, so that we can provide Heller Industries with the most optimal design that we can produce with our skillset.

Selected Design - *Alpha Design*

The current design is a reservoir which would be filled with the lubricant, and would freely flow onto the chain via a wick. This design needs to be capable of surviving in the extreme conditions of the oven, but would not operate in them; instead, during regular preventative maintenance, the reservoir would be filled by a maintenance worker and allowed to freely lubricate the chain until it is empty. Seen in **Figure 20** below, the design involves an axially symmetric reservoir with an open top, a taper internally towards the wick, wick aligner, and notches to keep a bracket in place. The use of an open top allows for pressure to equalize when the vacuum is pulled, reducing the stresses that the system is exposed to. The internal taper towards the wick ensures that the wick base is always properly wetted even when there is little lubricant remaining, and decreases the risk of pooling. The wick aligner allows for wicks to be replaced as necessary, and the mounting notches allow for the system to be mounted in place within the vacuum oven securely.

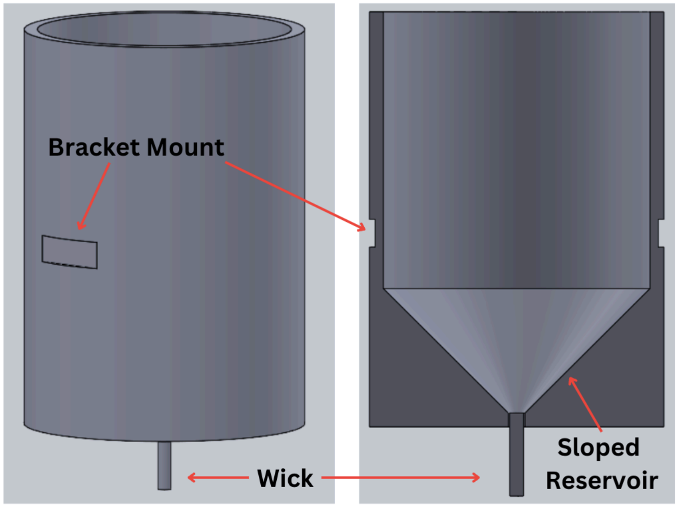


Figure 20. CAD Model of Cup Lubrication System

This design was chosen with consideration of all design ideas from the team (see **Table 3** for the Pugh Chart), which was done as objectively as possible with the limited information available. With additional input from the sponsor it was decided that due to the constraints of ME 450, moving forward a semi-automatic design would be the most appropriate choice. Based on this, the cup design was selected for its simplicity and ability to meet requirements.

While this is the current design, it is subject to change based on new data, especially data collected via experiments. Notably, the dimensions of the reservoir and wick opening could face large changes after measuring the material constant to calculate flowrate through the wick, and after measuring the amount of lubricant required to properly coat the chain (see appendix for experiments).

With knowledge of the dimensions, this design is well-defined enough to calculate the expected flow rate of lubricant through the wick using Darcy's law (seen below in Equation 1), and to calculate the thermal stress and strain on the design when the oven is at temperature. For further discussion on the calculations needed for the design, refer to Problem Analysis and Iteration. The following is Darcy's Law, where q is volumetric flux, k is permeability, μ is dynamic viscosity of the fluid, and Δp is the pressure drop.

$$q = \frac{-k}{\mu} \bigtriangledown p \qquad \textbf{(1)[34]}$$

We believe that the constraints on ME 450 significantly limit the solutions we can produce, primarily due to the time constraints. If the team had more time, we believe we could have been able to create a fully automated solution as opposed to the semi-automatic solution we are pursuing.

Problem Analysis and Iteration

Relevant to the design of this solution are solid mechanics and fluid dynamics. Specifically, being able to predict the effect of thermal expansion on the system when the oven is at temperature, and being able to predict the rate of lubricant flow are of great importance.

First and foremost, the solution should be able to meet the primary requirements and specifications (Table 2). To meet the temperature specification, the device must be able to withstand 350 ºC. Since the system will not be facing significant external loads, the only major effect of the large temperature variation on it is thermal expansion; this could pose issues with the current idea for mounting, which involves a bracket which would wrap around the cup (similar to a hose clamp). Due to thermal expansion, such a bracket could potentially become looser or tighter depending on the materials used. In order to prevent this causing failure, theoretical stress and strain calculations due to thermal expansion would allow for the bracket to be designed tight enough to hold the cup without causing it to fail.

For the pressure specification, the system must be able to withstand pressures between 10 torr and 760 torr (standard atmospheric pressure). Due to the open top of the design, changes in pressure do not cause any stresses in the system. Since the system merely needs to survive in these conditions, not operate in them, this specification is met inherently by the design.

To meet the requirement regarding lateral movement of the rail, the system will be mounted directly to the rail. By doing this, the system will always remain in contact with the chain regardless of its position.

To meet the requirement of increased automation, the system must be able to be set up with 5 minutes or fewer of manual input from the maintenance worker. In order to verify that this specification is met, a prototype would need to be made. Using this prototype, several people could be timed to see if it is possible to reliably prime the system in 5 minutes or fewer. If this requirement is not met, the design could be iterated to make this process faster or the procedure for using it could be modified.

There are several other requirements which are relevant, but for brevity the most important ones regard the cost of manufacturing and the effectiveness of the system to lubricate the chain. Due to the simplicity of the design, involving standard stock and tooling, manufacturing costs are very unlikely to exceed the $5000 limit per unit; a cost analysis could be performed to verify that this is the case.

In order to evaluate the effectiveness of the system in lubricating the chain, there are several possibilities. The easiest solution would be to do a simple hand calculation on the rate of lubricant delivery; this could be used to verify that the system is at least capable of delivering the lubricant in a reasonable timeframe, but cannot account for factors such as how the lubricant is dispersed across the chain. To better predict the complicated interaction between the lubrication system and the chain, running an experiment with a prototype would be the most effective way to verify that the solution does meet the requirements and specifications. This would better capture the interaction between the lubrication system and the chain, and could indicate what changes might be needed if it does not meet the requirements and specifications.

Updated Domain Analysis and Reflection

We remain committed to delivering a working solution for lubricating a chain within a vacuum reflow oven by the end of the semester. In addition to a prototype, we plan to deliver a bill of materials, documentation of our process, and guidelines to use our product, if applicable. Since DR1, we have added a new deliverable: documentation of tests surrounding the solution. Heller Industries has asked that we document and report the results of any tests surrounding lubrication, wicks, or the solution itself. We plan to record and organize all test data to deliver to them by the end of the semester.

We recognize that the pace of our work must be fast in order to prototype a solution in the next half semester. To keep up with this requirement, we have been regularly updating our schedule as we learn more about events in our timeline, and continue to work on tests, documentation, and CAD models of our solutions. With the pace we have set for ourselves, we anticipate needing outside knowledge and resources to keep our timeline intact. As such, we have contacted ME495 staff to request assistance in testing, and ME course staff for assistance with fluid simulation on COMSOL. We will continue contacting staff as needed to obtain resources for prototyping, additional knowledge, or general advice for our solution. Additional knowledge and resource gaps can be filled by utilizing the many resources made available to us by ME450 course staff as well as the College of Engineering as a whole.

There are many design drivers for our project, but for the sake of clarity and making our main motivation clear, we will discuss the top three drivers. The first is a design decision and involves how we add and modify deliverables. At the introduction of the vacuum oven chain lubrication project, our main deliverables were: “3D CAD Layout, Design review, 2D drawings, [and] Assembly dwg / BOM /Cost estimate” [23], as well as fabrication as time permits. As the semester has progressed, our team has discovered several additional elements that require testing, such as the ideal amount of lubricant needed for the chain, the flow rate of the wicks that deliver oil, a threshold for failure in terms of lubrication, and more. These discoveries have led us to define additional deliverables in the form of testing. Delivering more is beneficial to our stakeholders, but as a team we only have a finite amount of time to realize the project, and adding more tasks will slow progress on a broader scale. To optimize the usage of our time, we will reduce the load on the design side by pursuing the cup reservoir design over the pass in tray.

We also plan to replace any experiment we can with research into existing experiments. These changes should allow us to reach our deliverables before the end of the semester. Further changes to deliverables will be documented in future DR reports.

The second design driver comes in the form of a critical subsystem: the wick-chain interface. This system is critical because it will deliver oil to the chain, which is the main purpose of our solution in the first place. Several experiments are dedicated to making this subsystem successful, and can be found in the *Problem Analysis* section above.

The final design driver is the need to account for the needs of our stakeholders. Stakeholders are an important part of every project, but our project in particular houses a high impact, low influence stakeholder: maintenance staff. It's critical to our project that the needs of this group, along with all other stakeholders, be considered when designing and prototyping our solution. Within this design driver, one challenge we've faced thus far is the inability to get in touch with maintenance staff for the reflow ovens. To address this issue, a site visit is scheduled for March 14th at Saline Lectronics—a reflow oven customer—at which our team will have the opportunity to gain insight from maintenance staff.

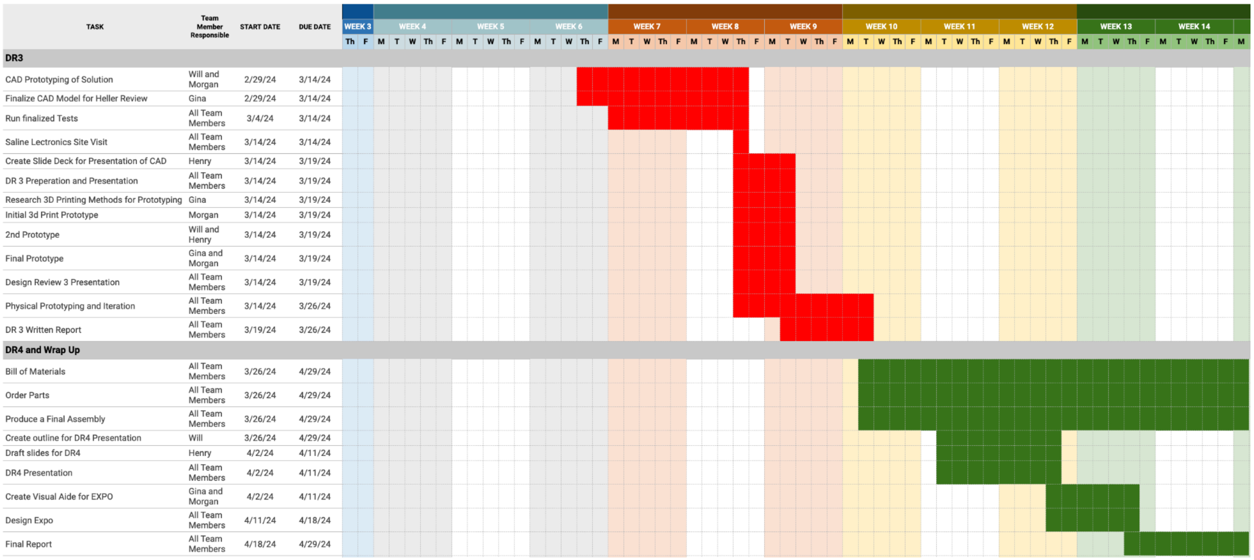
Updated Anticipated Challenges

Our team feels prepared to face any challenges that arise, but we are specifically anticipating obstacles in our experiments timeline. We have many experiments and tests planned, but due to time constraints we may have to make changes to accommodate an accelerated schedule. For example, our load current test will take a significant amount of time to plan and set up, so it may need to be adjusted depending on the progress we make. Another challenge we anticipate is determining how a wick will behave under the 350 °C temperature environment of the vacuum chamber, and to address this we are going to conduct an experiment. If the wick cannot withstand the temperature of the vacuum chamber, we may switch to a drip feed where the lubricant would drip out of a small hole in the reservoir's base.

Updated Project Plan

Moving forward, the team will be putting efforts immediately into testing and quantifying the amount of lubricant needed for a single lubrication cycle. After realizing that the data we would need to dimension the project is non-existent or not stored in the company database, we have chosen to revise our plan slightly in order to conduct experiments to get the metrics we need. We are hoping to use these experiments for our own product development as well as company standardization. Since we need this data to be able to dimension our product, these experiments take immediate priority as our next task at hand. There are two experiments in particular that we have considered most pertinent to design continuation.

First, we will test the flow rate of water through the wick to estimate the flow of lubricant through the wick. Second, we will be finalizing our design for a motor current fault detection. An initial description of each of the experiments we are considering conducting in the next two weeks can be found in the Appendix of the report under the section *Expected Experiments*. All of these experiments will be conducted using the resources supplied to us by our company as well as those in the MEX50 shop and the Mechatronic Lab on campus. Alongside these projects, we are also going to fabricate an early stage prototype through 3D printing or clay modeling. For more detailed project information, view **Figure 21** below.



TASK	Team Member Responsible	START DATE	DUE DATE
DR3			
CAD Prototyping of Solution	Will and Morgan	2/29/24	3/14/24
Finalize CAD Model for Heller Review	Gina	2/29/24	3/14/24
Run finalized Tests	All Team Members	3/4/24	3/14/24
Saline Lectronics Site Visit	All Team Members	3/14/24	3/14/24
Create Slide Deck for Presentation of CAD	Henry	3/14/24	3/19/24
DR 3 Preperation and Presentation	All Team Members	3/14/24	3/19/24
Research 3D Printing Methods for Prototyping	Gina	3/14/24	3/19/24
Initial 3d Print Prototype	Morgan	3/14/24	3/19/24
2nd Prototype	Will and Henry	3/14/24	3/19/24
Final Prototype	Gina and Morgan	3/14/24	3/19/24
Design Review 3 Presentation	All Team Members	3/14/24	3/19/24
Physical Prototyping and Iteration	All Team Members	3/14/24	3/26/24
DR 3 Written Report	All Team Members	3/19/24	3/26/24
DR4 and Wrap Up			
Bill of Materials	All Team Members	3/26/24	4/29/24
Order Parts	All Team Members	3/26/24	4/29/24
Produce a Final Assembly	All Team Members	3/26/24	4/29/24
Create outline for DR4 Presentation	Will	3/26/24	4/29/24
Draft slides for DR4	Henry	4/2/24	4/11/24
DR4 Presentation	All Team Members	4/2/24	4/11/24
Create Visual Aide for EXPO	Gina and Morgan	4/2/24	4/11/24
Design Expo	All Team Members	4/11/24	4/18/24
Final Report	All Team Members	4/18/24	4/29/24

Figure 21. Updated team project plan

Contingency Planning

To give careful thought to building in some contingency planning when things don't go as planned, we have allotted larger windows of time than are likely necessary within our Gantt chart above. Additionally, we currently do not work on our project on the weekends and schedule most of our work to be done within the class periods on Tuesdays and Thursdays 12 pm - 4 pm as well as during our hour-long meetings on Friday mornings at 8 am. If we were to have a major roadblock or reached a place where we would need to follow a "critical path", we would schedule at least one additional time during the week to meet and would likely work on occasion on the weekend to make up for the added time commitment. Right now, since we also do not see any large and eminent charges to our budget, (because everything we are using for the experiments is accessible in the mechanical engineering labs on campus), we also have some wiggle room there. If we are pinched for time and needed to order a part or seek outside resources that would cost money, we have plenty of budget to feel comfortable and safe in our project timeline to have "emergency funds." The only cost we are likely to incur in the next two weeks is if we spend money for materials for a prototype. This would likely be for either a clay model or to 3D print a prototype. The details of these potential prototypes are not narrowed down so we do not yet have a price estimate, however we do not expect them to cut into a large portion of our budget.

Engineering Analysis

In order to realize our proposed solution in a quantitative manner, our team employed several methods of engineering analysis, including research, experimentation, and calculations. Each engineering analysis ties back to a primary requirement and corresponding specification (see **Table 2**), but for the purpose of this report, analysis will be split into subsystems of the vacuum reflow oven: the wick/orifice system, the physical reservoir geometry, lubrication (including application and its interaction with the chain), and ergonomics of the system.

Wick and Orifice Testing

The first method of engineering analysis—wick and orifice testing—was conducted with the purpose of determining how Krytox XHT-1000 lubricant flows through different mediums. This line of analysis corresponds to the automated requirement in that understanding flow of Krytox is integral for placing the system in a vacuum to dispense autonomously as the chain runs below it. The first test was an experiment to determine the porosity and permeability of the wicks supplied to us by Heller Industries (an example of which is seen below in **Figure 22**). These values would prove useful in creating a model for wick flow for Krytox.

Figure 22: The wick used by Heller Industries to lubricate the chain external to the vacuum chamber

For the sake of brevity, only the essentials of the setup will be listed for each experiment. The complete procedure for every experiment is listed in the *Appendix* section below. The permeability experiment setup began with filling the top reservoir with a wick attached at the bottom as seen in **Figure 23** with water to a known height. After a predetermined amount of time, the weight of water in the lower reservoir was measured.

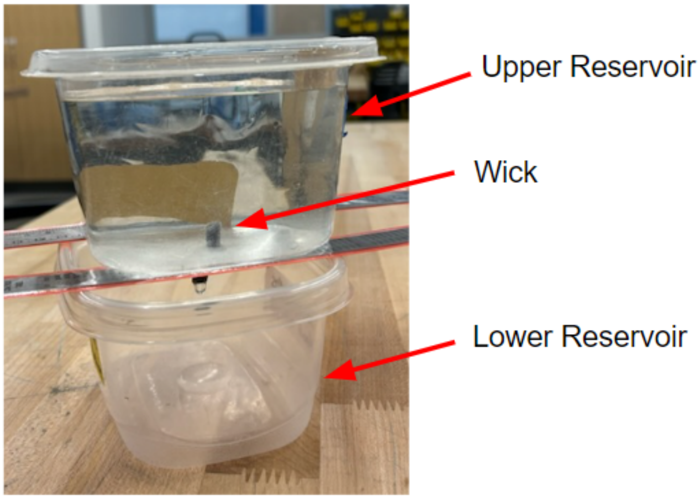


Figure 23. Experimental setup for wick permeability test

The flow rate equation (see *Appendix*) was used to determine a mean permeability of $6 \times 10^{-10}\, m^2$ for the wick supplied to us. In addition, we measured the porosity (a metric of how the 5 ml volume of fluid the material holds when saturated) of the wick. This required a simple experiment in which the difference in weight was measured before and after the wick was saturated with water, and the porosity was determined using **Equation 2** below:

$$\phi = \frac{V_{void}}{V_{total}} \qquad (2)\ [34]$$

The total volume was calculated using the measurements of the cylindrical wick, and the void volume was estimated using the measured mass of water and the standard density of water. After obtaining the values of porosity and permeability, we built a MATLAB script to approximate the rate of flow for various geometries of reservoirs as well as a wick or orifice setup. We recognize that we could have collected direct experimental data for a given geometry and lubricant, but felt that a generalized model would have a more sustained use as we continue to evolve our design. The use of a more general model allowed for permissible accuracy in determining suitable dimensions and geometry, and which would later be verified with physical testing.

Orifice Size Test Plans and Execution

Using the experimentally determined values and Darcy's law [34], it was determined that fully draining the reservoir of 5 mL of lubricant (at both 20 °C and 40 °C) would take upwards of 8 hours. This amount of time is impractical for a preventative maintenance cycle, and was in large part due to the high viscosity of the lubricant used inside the vacuum chamber; the viscosity of the lubricant is a parameter that we have limited control over, and so it was determined that the use of a wick inside the vacuum chamber would be infeasible.

Based on this, it was decided that an orifice would be a more suitable choice than a wick. As described above, having a model which generalizes well is of greater importance than having a highly accurate model, especially considering that any design will be verified with empirical testing regardless. A model was derived using the equation for Sampson flow, which predicts that it will take approximately 9 minutes for approximately 5 mL of lubricant to drain from the reservoir with the 3 mL hole (though the time can be varied by changing the diameter of the drain hole). The chain is capable of moving at a linear speed up to approximately 150 cm/min [35], which would allow even a long chain over one meter long to make several revolutions before the reservoir is depleted; this ensures that the chain can be fully lubricated with just a single filling of the reservoir (see Lubricant Testing for the calculation of the necessary amount of lubricant), and is therefore a suitable amount of time.

Reservoir Analysis

For the sake of clarity, we will define the reservoir as the physical body holding lubricant above the chain. Lubricant must be added to the top of the reservoir in a safe and ergonomic manner. then drain at a controlled rate (per the *automated* primary requirement). Additionally, the reservoir must withstand both temperatures up to 350ºC and pressures of as low as 10 torr (per the *robust against heat* and *interface with vacuum* requirements) to safely exist within the oven while the oven operates. Many tests for this system centered around geometry; CAD software, 3D printing, and clay modeling were all used to add context to this analysis in a three dimensional space.

The first round of analysis surrounding the reservoir was Solidworks modeling to give the idea form. Early models can be seen below in **Figure 24**. These models were unscaled, and served as a way to showcase the thrust of the solution rather than function as a real prototype.

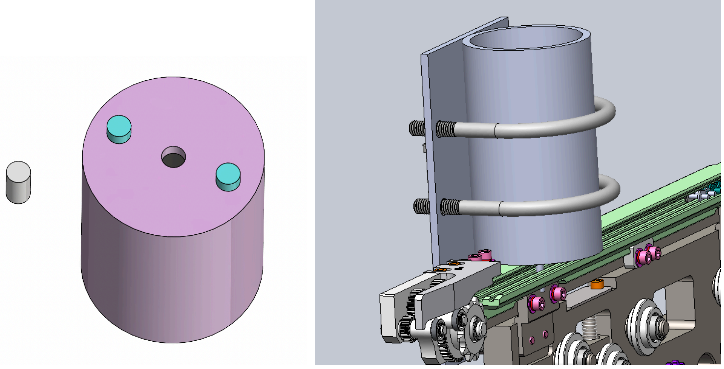


Figure 24. The first (left) and second (right) CAD prototypes of the reservoir solution.

The second generation of reservoirs were derived from the first generation and scaled correctly, which was made possible by a reservoir volume requirement obtained from testing within the *Lubricant Testing* section below. The scaled designs were able to be physically prototyped and set onto the rail, as seen in **Figure 24**. We began with the cup reservoir at an 8 mL volume, but after physically setting it on the rail, we discovered that it hung over the rail due to its round geometry. This caused us to pursue a rectangular cross section, which is also displayed in **Figure 25** below.

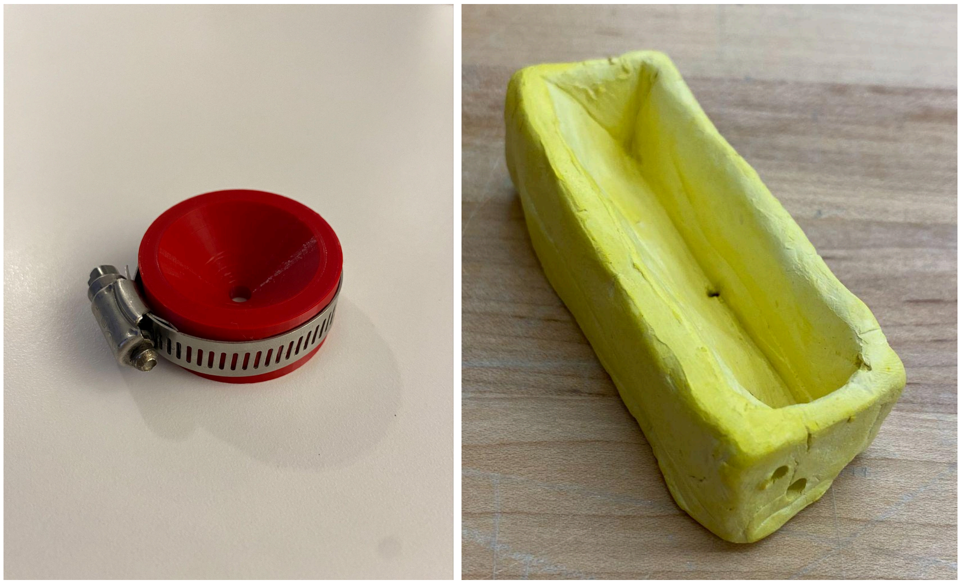


Figure 25. Physical cup reservoir (left) made out of PLA and trough reservoir (right) made from clay

As a whole, much of the iteration regarding the reservoir was based on visual analysis and supported by other forms of engineering analysis. Modeling and fabricating prototypes allowed us to gain insight on how the cup existed in the physical world, which pure calculations wouldn't have allowed for. For more detailed information on the final reservoir design, see the *Build Design* section below.

Lubricant Testing

The lubricant being applied within Heller's vacuum reflow ovens—Krytox XHT 1000—is a highly viscous -3,000 cSt- liquid that serves to extend the life of the chain, as well as prevent wear and seizing within the system. The properties of the lubricant itself are well classified, but our goal with this line of analysis was to determine its effects on the system. Specifically, this section covers a test performed to determine an ideal amount of lubricant applied, analysis therein, and a filter smoke wick test for the purpose of determining when lubricant should be applied. This analysis covers requirements structured around the frequency, volume, and consistency of lubricant application to the chain (see **Table 1**).

Before conducting any physical tests, we performed analysis to roughly determine the quantity of lubricant that would be required to smoothly operate the chain. For this calculation, there were many assumptions and simplifications; a lubricant layer thickness of 100 µm was assumed based on NASA research of gear lubrication of a specific layer thickness [34]. The chain was assumed a chain length of 1.5 m, and standard width for a #35 (0.188” or 4.8 mm). The chain was treated as being a flat sheet, with both sides needing to be covered. A safety factor of 5 was assumed due to the simplicity of underfilling the reservoir, and the potentially extreme consequences of not having enough lubricant. By this same reasoning, the layer thickness and chain length are also overestimated by 5%.

Once we possessed a ballpark figure for lubricant needed, we decided to conduct a test to experimentally deduce the correct amount of lubricant for the chain. We hypothesized that current (a measure of load on a motor) would decrease as more lubricant was added up to a certain point, at which returns would diminish for adding additional lubricant. To test and quantify our theory, we mounted a DC servo motor to the chain-rail assembly using a custom made bracket, and attached a loop current measurement device to read the current through the wire, as seen in **Figure 26**.

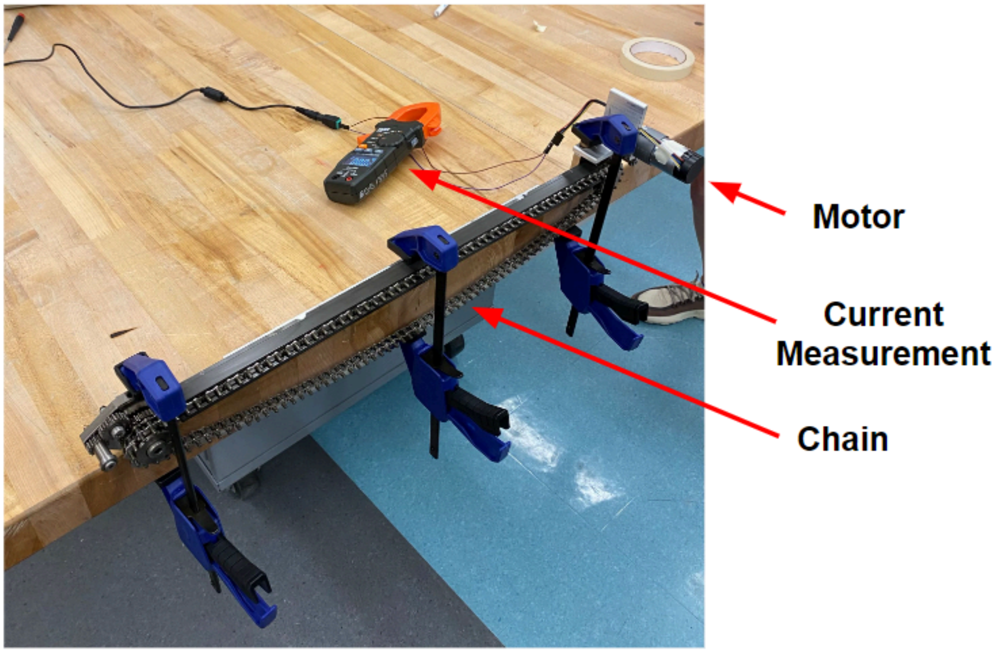


Figure 26. Experimental setup for chain lubrication test.

The chain was run by a power supply at three and six volts for lubricant quantities ranging from zero to ten grams at two gram increments, and the current readings with their respective error bars are shown below in **Figure 27**.

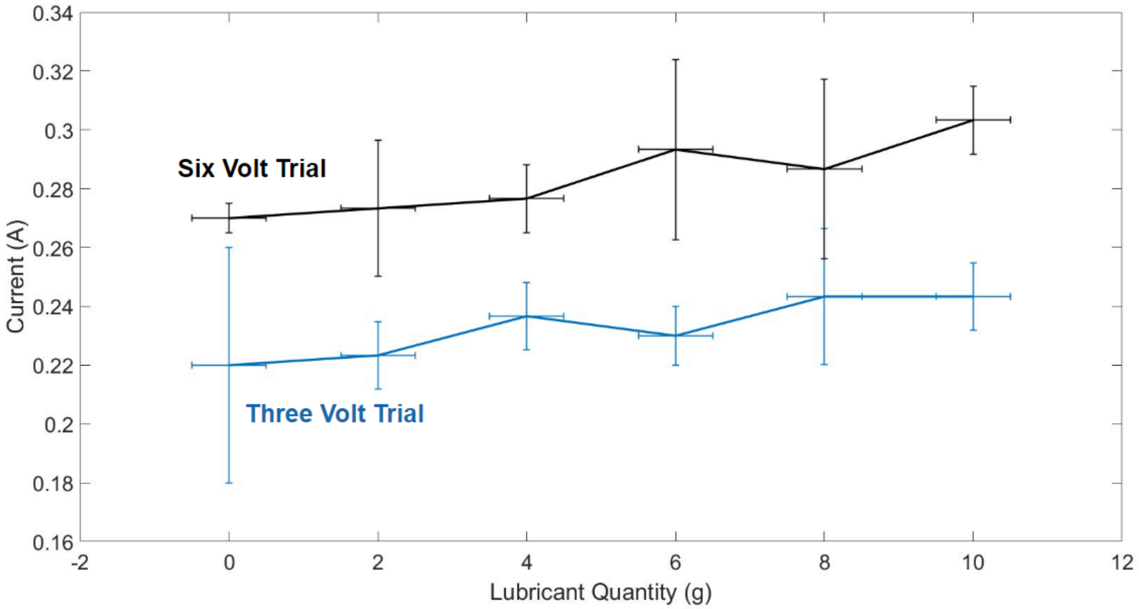


Figure 27. Results chain lubrication test. The lubricant was added in increments of 2 grams, and each point represents three trials.

On the whole, we saw a slight increase in current as more lubricant was added to the chain, both in the three volt and six volt trials. This was opposite our hypothesis—as previously stated, we expected the current to decrease, which would have indicated that adding Krytox to the chain immediately lowered operating friction. These unexpected results could be attributed to several factors: first, the high viscosity of Krytox lubricant at room temperatures (similar to the viscosity of honey) could cause additional friction in the system. The addition of lubricant also increased the mass of the system, so that could have caused these results. Additionally, this experiment is imprecise; error in the current was as high as ±0.04 Amps, which significantly decreases the validity of the trends we see.

Regardless of what we attribute the unexpected results to, they stand as real world data and we must treat them as such. One significant takeaway from this experiment is that we overestimated the short term effects of the Krytox lubricant. The data suggests that rather than decreasing the load on the chain system immediately, the lubricant serves as a long term protection against wear and seizure. This discourages us from wasting valuable time in the future emphasizing Krytox's ability to serve as a short term solution and refocus on applying the correct quantities for long term chain health. This experiment also encourages us to pursue testing with heat as an additional variable. Heller representatives have told us that the oven's temperature plays an important role in chain wear and lubricant breakdown over time. The lack of strong results at room temperature reaffirms this sentiment, and we have been in conversation with ME machine shop staff about the use of heat guns to introduce high temperatures in our experiments, time permitting. Any experiments conducted with heat will be placed here should they be conducted in the future.

Filter Smoke Wick Test

In order to establish a numerical scale for the qualitative condition of the chain, we have created a scale from the color of the lubricant. The supplier has told us that as time goes on, the lubricant will become a darker color. So, similar to a filter smoke test for vehicles, we identified an old lubricant swab as a #10 on the scale as the old, very poor lubricant and a #1 as a fresh chain with fresh lubricant. We are still working on developing the middle of the scale but will likely suggest that the user needs to reapply lubricant around reaching a color #5, which will be a foggy grey. This scale and the mechanism for swabbing the chain can be seen in **Figure 28** below.

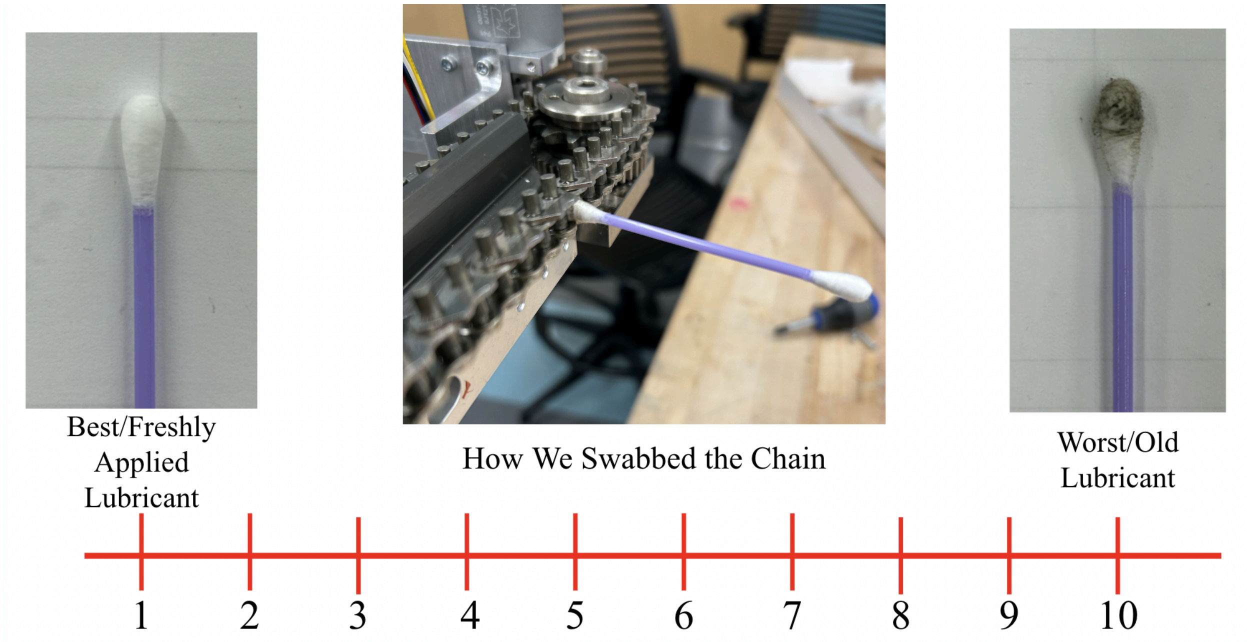


Figure 28.

Ergonomic Analysis and Testing

Our final avenue of testing and analysis comes in the form of optimizing the experience of maintenance staff that handle the lubrication system we create. This ties back to the *Automated* primary requirement as described in **Table 2**. The first method of testing is a physical prototype that will guide the maintenance worker as they push lubricant into the reservoir. The two critical functions of this guide are first that it dispenses the correct volume of lubricant each time, and second that it reliably puts the lubricant inside the reservoir without excessive work required from staff. A concept of the lubricant filler is shown below in **Figure 29**.

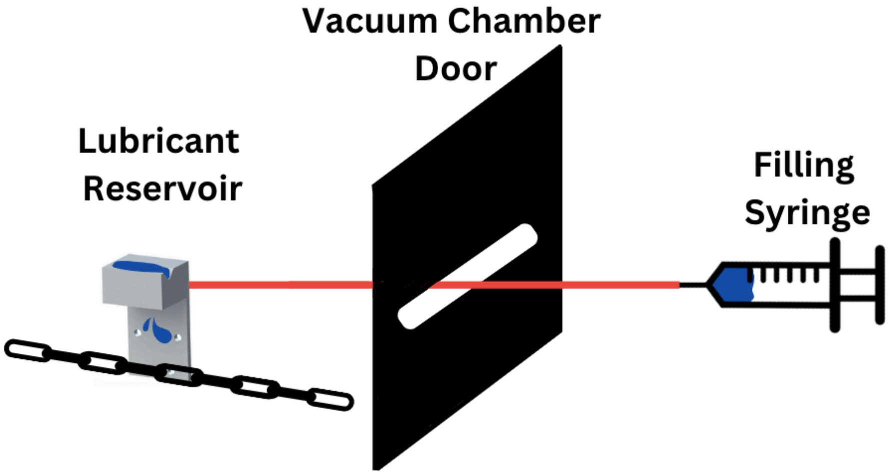


Figure 29. Concept sketch of dispenser for filling the cup reservoir

This prototype will be fabricated using a syringe with an extended nose for guidance. To validate the design, we will repeatedly fill the prototype using a set amount of liquid with a similar viscosity to Krytox -Glycerine-, then push it through a slot identical in dimensions to the reflow oven door. From there, we can measure the amount of liquid that makes it into the reservoir, and repeat the process with different people to determine average time for filling and any additional ergonomic considerations.

In addition to minimizing the time and effort needed to apply lubricant to the chain, we plan on creating a time study to quantify the difference in time and motions from the previous solution to the current one. This would involve shadowing maintenance technicians at a Heller customer's facility. As mentioned previously, we are hoping to visit Saline Lectronics to complete this step, but have had issues communicating with the site. As such, we will plan on conducting the study if we are able to access the site, and if not we will continue to estimate the current time taken as 2 hours, a time provided to us by Heller representatives.

Build Design

Below is the product which our group will be creating for our build design. We will be presenting this as our final prototype to meet the requirements of our project through the semester.

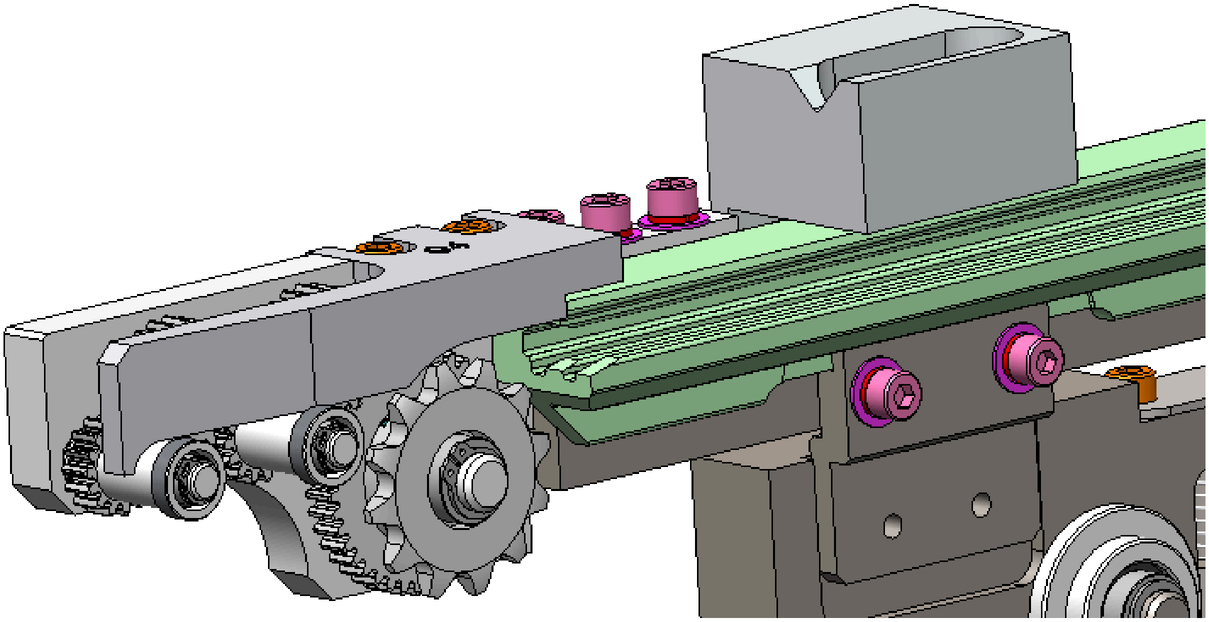


Figure 30. Build design CAD

The design consists of a trough with a drip system that will be screwed into the rail assembly of the conveyor belt. This trough has an orifice at the bottom that allows the lubricant to drip through. The bottom of the trough will be rounded to try to limit the amount of lubricant that gets left behind as residue. The whole top of the container is open in order to avoid creating a pressure vessel when the vacuum is pulled.

Tasks of Build Design

Upon considering the composition of the build design, we wanted to consider the results of the experiments we conducted as well as the requirements and specifications of the customer. The importance of the build design is to make sure that the final design can actually accomplish the tasks it is set out to do. This means that the build design must be able to accomplish all of the specifications and requirements mentioned in that section. In terms of the experimental results, while the motor was deemed inconclusive and the filter test is directed at lubricant reapplication, the wick drip test told us that a wick was not the most practical method of lubrication. The length of time that it took for the lubricant to completely flow out was unreasonably long for a maintenance cycle, while the drip feed through an orifice was quick (approximately 12 minutes) and efficient. Using the orifice was actually the only way to lessen the time of the current maintenance process, which was one of the requirements of our goal.

Aside from accomplishing the tasks of the specifications and requirements of the user, the product also must meet the needs of the manufacturers. The client has told us that they likely will not be making more than 500 of this product per year and therefore are looking at only the use of mills, lathes, band saws, and hand tools for production.

Materials and Parts

A strong attribute of our design is the simplicity of design and implementation. Our part will only consist of a singular piece and the bolts to screw it in and the method of filling, which is an ordered part. We decided to make the build design out of aluminum also to best reflect the final design model, however some of our tests may be run with a 3D printed model—this distinction will be made when describing the procedure for any future experiments. A list of our materials and anticipated costs can be seen below in our **Bill of Materials**:

Table 5. Bill of Materials

Part Number	Part Name	Material	Quantity	Total Cost
1	Reservoir	Aluminum 6061	1	$7.81
N/A	Shipping	-	-	$30.00
N/A	Labor (Machinist)		$21.47/hr x 2hrs	$42.94
			TOTAL COST	**$80.75**

To estimate the labor cost of a machinist, if hand machining was chosen as the manufacturing method, we took the median salary for a Machinist in Michigan. This came to $21.47/ hour and we estimated that it would take 2 hours to machine, being quite liberal as to avoid under-estimating the cost. We also estimated shipping costs of Aluminum 6061 plates based on values given by the United States Postal Service and United Parcel Service. All together, this cost is significantly less than the budget limit for our product. This means that Heller Industries will not only have an opportunity to profit on the production and distribution of our mechanism, but they also will likely have more freedom in where they decide to source the materials we do use.

Manufacturing Challenges

On top of design simplicity, the production of the device is not dependent on exceptional precision. It is important to ensure that the holes on the part's back line up with the screw holes and that the top hole lines up with the drip hole on the rail. The importance of tolerance lies within the fact that there are two surfaces that need precision, however, neither surface is more important than the other or to be considered a critical surface. Tolerances are listed in each respective manufacturing plan.

Safety Aspect of the Build and Manufacturing

Since we are going to hand-manufacture the part on site at the University of Michigan, we will have to implement a safety plan. As a baseline, we will make sure to follow our shop protocol, in which we will submit our manufacturing plan and engineering drawing, wear safety goggles and appropriate attire for the shop, and follow the guidelines of proper machine usage (appropriate speeds, no climb milling, plunging and centerdrilling where necessary etc.). In addition to the engineering drawing below, the manufacturing plans and drawings for all the included components can be seen in the appendix.

Engineering Drawings

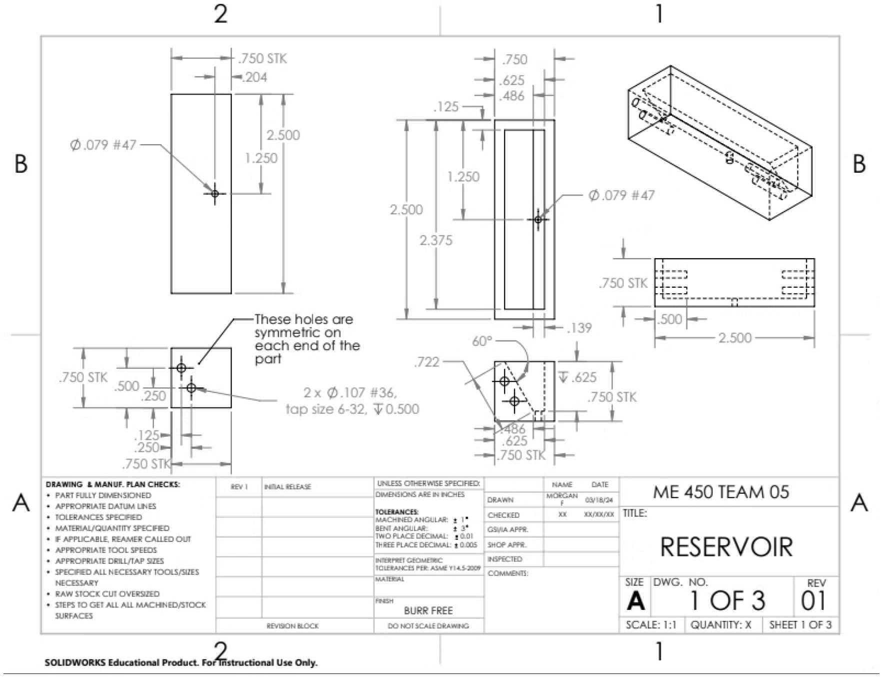


Figure 31. Engineering Drawing of Reservoir with Manufacturing plan

Safety Aspect and Failure Avoidance

We will also need to follow a safety protocol when we run our system. This means that the chain must be locked in a vice while in use. Nobody can touch or modify the chain system when it is plugged into power. The gears must be inaccessible and or covered during operation of the chain. The wires of the motor must be organized and set out of reach of the chain. The biggest risk in our case scenario is making sure to manage moving parts in a proper manner when using the chain, following shop protocol, and acting responsibly. Assembly of the product itself is minimally time-consuming and simple and should not pose a significant safety risk.

If our product itself were to fail, it would likely be due to the fluid bottle-necking at the orifice and spilling over, which our calculations have told us is unlikely, and fatigue due to thermal loading. Due to the fact that the product is undergoing repeated thermal loading and a very low pressure, this will likely decrease product lifespan.

Confidence Level in Our Assertions

One area where we lack confidence is exactly how long the product lifespan will be. We anticipate the product lifespan will be ten years from researching other similar products as well as reviewing the documented properties of the material, however we do not have the resources to physically test this induced cyclic loading on the product. We do anticipate running the chain with everything else in place to test how the lubricant flows over the chain and how it spreads. While we feel this will be an effective measure of test functionality, one major limitation is that the chain which we are running the tests on is different from the actual chain in the system. We have been told by Heller Industries that they are similar enough to consider the difference negligible, however the number of sprockets is different, the tension on the chain is different, the load is different, and the method of driving the chain is different (motor setup and location). We will also confirm that the product is able to address our other user specifications in our *Verification and Validation* section below.

Overlap with Final Design

Despite the challenge, we feel that the build design will be a strong, accurate representation of the final design. We are confident that it will demonstrate the feasibility and performance of the final design while accounting for our manufacturing skill level. There is no significant difference in the geometry of the build design versus the final design as far as the lubricant reservoir is concerned. The two designs are largely similar because the reservoir is designed to hold the same amount of lubricant in both cases, any differences are purely due to dimensional conversion. Additionally, both will be machined with the same aluminum alloy, Aluminum 6061.

The build design will not have the same geometry for mounting purposes. The chain system in the 3D CAD model has different positions for mounting than the physical chain system we have. Therefore, the geometry of the reservoir we build cannot be the same as the final design because the layouts are completely different sizes. Additionally, the piece is not intended to support any significant load, so the strength when mounted does not need to be tested.

The manufacturing processes will be different, the build design will be hand-milled where the final design will be CNC milled (computer numerical control). The CNC mill has a higher level of precision due to human error in hand-milling, but otherwise the scale, material, shape, and functionality will all be consistent. This should give the stakeholders confidence that the final design will in fact work and provide scope for their pursuit of the product by demonstrating exactly what it is capable of. The similarities and differences can be seen in a Venn diagram below in **Figure 32:**

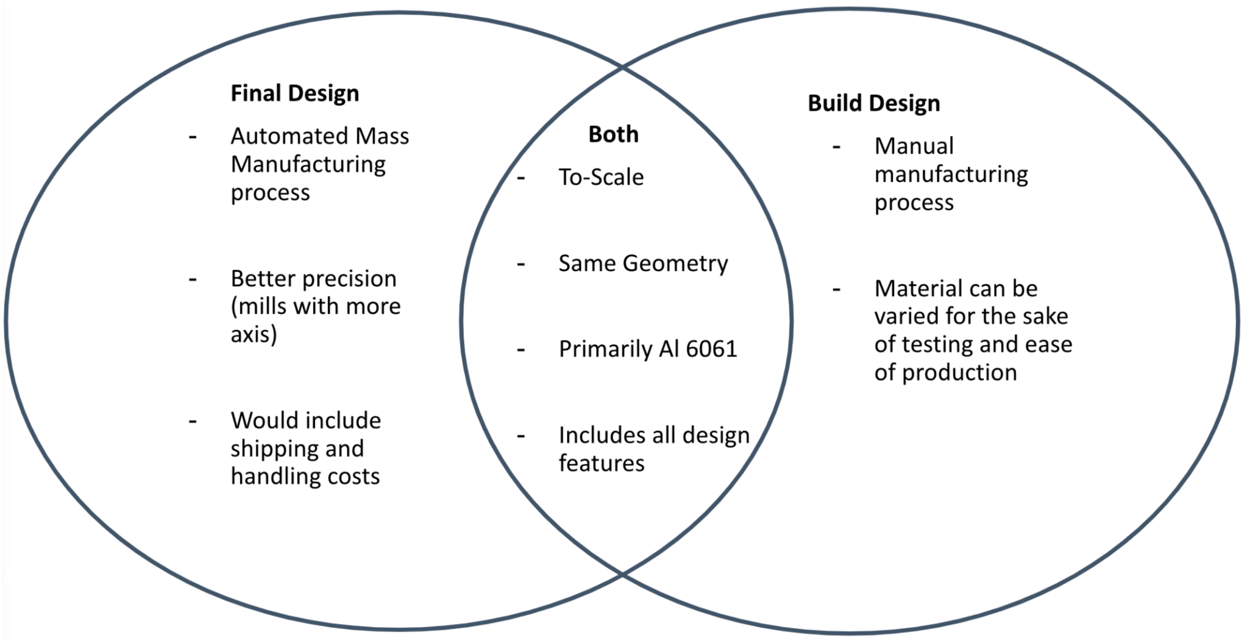


Figure 32. Comparison of Final Design Features Versus Build Design Features

Execution in Metric for manufacturing in China (Per Company Protocol)

Because of all the similarities, most of the description around the build design can be applied to the final design, including the reasoning behind our design decisions as well as verification and validation. However, the final design will actually be sent to China to be manufactured, as that is where Heller Industries has all of their parts manufactured. Therefore, we will need to also make a metric model for our design. The build model will be using all imperial measurements due to the fact that the machines, drill bits, tools, and stock we have easily available in our shop are all imperial. In order to translate, we will simply assume the nearest metric standards that have a corresponding drill size and can even out to easily manufacturable numbers. In addition, this model contains a flange with through holes for mounting inside of the vacuum chamber, which is not present in the build design due to the physical setup available to us not having mounting holes in the same location. In order to verify the practicality of our design, we intend to give Heller an engineering drawing of our final design to get an appraisal from their manufacturer.

Reason for Manufacturing in this Fashion

Another note to make is that the reason we are proposing that the company that they mill the part is because they informed us they will not be making more than 500 or so of the part and that it is not worth it for them to pursue a mass manufacturing method such as casting: they prefer it to be made on a mill. This does not affect the stakeholders because our group will have verified and validated both the functionality of the design and the manufacturing and assembly process, which will be elaborated on more later in the report in the *Verification and Validation* section.

Lessons Learned from Unsuccessful Outcomes and Recommendations

Something that we would likely do differently when reflecting on the experiments we conducted and the conclusions we came to would be to try to find a different method of conducting the motor experiment. The purpose of the motor experiment was to validate the volume of lubricant needed as well as provide a point of fault detection for the motor current. But, the experiment was flawed and the data was inconclusive, thus it did not provide any useful insight. In hindsight, we would try to create a situation that better reflected the circumstances under which the actual machine operated by trying to simulate the load and temperature conditions better. We also think that having a CAD that matched our system would allow us to choose a method of gear engagement and gear itself that would work better for driving the chain. And lastly for that experiment, we would also try to find a more accurate way to measure and apply lubricant, as well as measure the current. Our measurement imprecision was likely a big contributor to not outputting useful data.

Verification and Validation Approach

It is important to our team that our design not only meets the requirements we have set, but improves the problem we set out to solve. To verify our design's performance in regards to meeting our requirements and specifications, we have generated a test case for each of them. In general, we used existing documentation, experiments, and theoretical analysis to verify our design. Below, **Table 6** highlights our primary requirements and specifications, including a plan of verification and the status of that plan at this time. Three of the primary requirements somewhat 'bypass' the verification step simply by their definition and our design considerations.

Table 6. Primary Requirements with verification methods

Primary Requirement	Engineering Specification	Verification Method	Priority	Status
Robust against heat	Withstand temperatures up to 350˚C	Materials - Analyze ceramic (2000˚C), mild steel (1450˚C), and aluminum (650˚C) behavior in high temperatures. Thermal expansion, etc.	**Critical**	**Passed**
Interface with vacuum	Withstand Pressure (10 torr - ATM)	Pressure Analysis - Zero Pressure difference	**Critical**	**Passed**
Accommodate movement	Move 50-350 mm laterally	Statics - Analyze chain's lateral movement for vibrations	**High**	**Passed**
Semi Automated	5 minute Preventative Maintenance Cycle active time - 10 minutes total	Fluids - Analyze wick/drip feed to ensure cup can empty within time Mechanics - Research and implement method of safely filling cup	**High**	**In Progress**
Cost	$5000 limit on Material, labor, and production costs	Materials - Research low cost materials, bring to Sponsor for approval	**High**	**Passed**

The 'Robust against heat' requirement is met because we are only considering materials that are well above our specification temperature of 350˚C, so no real verification test is necessary. We have researched the melting/deformation temperature of ceramic (2000˚C), mild steel (1450˚C), and aluminum 6061 (650˚C), and are using these accepted values as verification that this requirement is satisfied. We determined that using documented values was the best choice because we do not have the capacity to physically test the strength of these materials, and these are widely accepted values. We, therefore, are also confident in the strength of our materials under high temperatures. The 'Interface with vacuum' requirement was tested by a simple pressure analysis: there is no pressure difference between the inside of the reservoir and the outside of the reservoir, so it is not a pressure vessel. This analysis also 'bypasses' a true test because of the design's geometry. We believe that this theoretical analysis is sufficient because the reservoir simply has to survive in the chamber, so as long as it does not implode or explode it will be successful. Next, the ‘Movement Accommodation’ requirement is again met by the design itself. Each chain conveyor would have its own lubrication system mounted on it, so when the chain is moved laterally so is the reservoir. The “Automation’ requirement is verified using a time analysis of how long it takes an 5 mL reservoir of lubricant to empty through a wick versus how long it takes to empty through an orifice, or a drip feed. This verifies the semi automation requirement because it minimizes the amount of time that maintenance will have to spend actively lubricating the chain. The team has done a detailed analysis of the time taken with and without a wick, and determined that using a drip feed is more efficient and will allow the reservoir to empty within the specified maintenance time. The “Cost” requirement is considered in progress because we are still perfecting our final design, but we do not anticipate going over our budget at this time.

We will be conducting or have already conducted tests as verification for the requirements in the following table, which includes a detailed test/analysis plan. These include a test to find the best lubricant amount to avoid dripping, a wick draining test, an orifice draining analysis, and a swab test. These have been discussed in greater detail above, but they can serve as verification tests for these specifications.

Table 7. Verification tests the team will be or has already conducted.

Test	**Specification**	**Verification/ Testing Method**	**Status**
Lubricant Amount	Must determine lubricant amount to the nearest mL	Hand paint lubricant onto chain conveyor system, 1 mL at a time up to 10 total mL on the chain. Run the chain for 5 minutes in between each application. Observe at what lubricant amount the chain begins to drip. The amount before this happens is the ideal lubricant amount.	Complete - 5mL
Wick Test	Determine continuous flow rate through the wick to determine time taken for reservoir to completely empty	Large reservoir of water that we only allowed to flow through the wick. We waited 30 minutes and measured the water released from the wick. We used this information to determine the continuous flow rate.	Complete
Orifice Analysis	Analyze flow rate through a small hole	Use a Samson Flow model to estimate the flow through a small opening. Plug in selected lubricant amount and determine time taken to theoretically empty the reservoir through an orifice.	Complete
Swab Test	Develop a metric to determine when to apply more lubricant to the chain.	Properly lubricate the chain with 5 mL and run a clean cotton swab along the chain and document appearance. Run the chain in 15 minute increments and re-swab in between	Incomplete

The team has also considered if we are effectively solving the initial lubrication problem, or if our design has moved out of scope throughout the design process. To do this we have created a matrix of validation that defines a ‘successful’ design with deliverables. Validation is out of reach for this semester-long project, but it is important to consider this facet of the design process. The following **Table 8** holds our major validation methods, but a more exhaustive list can be found in Appendix C.

Table 8. Validation Matrix

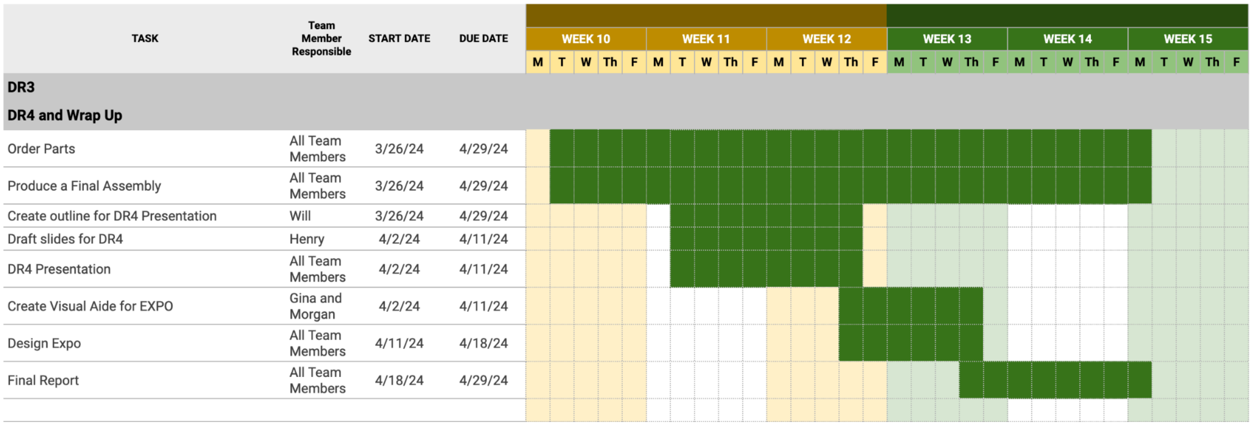
Assumption	**Validation Method**	**Testing Plan**	**Metric**
Makes Process Faster	Trial system	Time Study: Create time breakdown of the hand-painting process and compare to time breakdown of our process	- Number of steps - Time taken - % of active time
Survival in typical chamber environment	Experimental trial	Place system in oven and observe results of cyclic heating at (350 ˚C), cooling (return to ambient), and vacuum pressure (10 torr)	10,000 cycles, No Plastic Deformation, no macroscopic cracks
Survival in edge-case chamber environment	Experimental Trial	Place system in oven and observe results of cyclic heating (480˚C), cooling (to ambient), and vacuum (10 Torr)	1,000 cycles, No Plastic Deformation, No macroscopic cracks

We plan to validate using a series of trials and experiments, including those highlighted above. First, we want to ensure that our system is faster for maintenance personnel than the alternative of hand painting the chain. To prove this, we would conduct a time study of the time required for the current maintenance cycle and break it down step by step into the total number of movements, parts needed, steps taken, etc. Then we would conduct a similar study for time taken in our system and compare. To validate our process, we would want to see a significantly lower number of steps, arts, and movements needed using our system. Next, we would test the survival of the empty reservoir in the vacuum chamber. First, we would run it on a typical cycle (350 ˚C) for 10,000 cycles and observe the results. A ‘success’ is determined when there is no plastic deformation and no macroscopic cracks. Next, we would conduct the same experiment for edge-case scenarios (480 ˚C), but with only 1,000 cycles due to the low amount of time the system spends in those temperatures. This would utilize the same metric for success as the typical environment. We would hope to see no crack propagation or plastic deformation from the cyclic loading of pressure and temperature.

These validation methods are a starting point to go through a systematic redesign cycle until the design is fully verified and validated. It is likely that the requirements and specifications would shift in this time, which would also shift the verification and validation steps. It is important to note that going through several iterations of the process is normal for any design, and is a good way to be certain that the design is effective and accomplishes the goal. Our stakeholders should be confident in our design because we have done extensive research and are undergoing experiments to prove the efficacy of our system. Additionally, our design is currently meeting a majority of its specifications. This being said, our stakeholders cannot possibly be entirely confident in the success of our design because we have only done one iteration of the design process, and it is likely things would change throughout the iterations.

Project Plan Update

In the immediate future, the team is preparing for the Design Expo on April 18th, 2024. This includes fabricating or manufacturing a model, running verification tests, and creating an interesting presentation to show what we have done this semester. With the end of the semester quickly approaching, the team is working tirelessly to deliver a strong and functional design to Heller Industries. Below in **Figure 33** is the team's upcoming project plan with personal and group tasks to complete.



TASK	Team Member Responsible	START DATE	DUE DATE	WEEK 10					WEEK 11					WEEK 12					WEEK 13					WEEK 14					WEEK 15				
				M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
DR3																																	
DR4 and Wrap Up																																	
Order Parts	All Team Members	3/26/24	4/29/24		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Produce a Final Assembly	All Team Members	3/26/24	4/29/24		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Create outline for DR4 Presentation	Will	3/26/24	4/29/24							■	■	■	■	■	■	■	■																
Draft slides for DR4	Henry	4/2/24	4/11/24							■	■	■	■	■	■	■	■																
DR4 Presentation	All Team Members	4/2/24	4/11/24							■	■	■	■	■	■	■	■																
Create Visual Aide for EXPO	Gina and Morgan	4/2/24	4/11/24														■	■	■	■	■	■											
Design Expo	All Team Members	4/11/24	4/18/24														■	■	■	■	■	■											
Final Report	All Team Members	4/18/24	4/29/24																			■	■	■	■	■	■	■	■				

Figure 33. Updated Team Project Plan

Discussion

If we had more time and resources to collect data and better define the problem, there are several areas of our project that we would pursue further.

First, we would likely try to produce a build design that exactly matched our final design. Our current build design is made of 3D printed filament, while the final design for our sponsor is made of 6061 aluminum with an anodized finish. Creating an exact model of the final design would allow for more accurate testing; this is due to machining allowing for tighter tolerances than 3D printing, and the ability to test with the actual vacuum chamber lubricant at higher temperatures (rather than with glycerin as a substitute). Additionally, the 3D printed model was mounted to the system using double sided tape, while the final design would be screwed in, offering better stability and closer contact with the rail. We could not attach the build design in the same fashion because the physical model of the chain and rail that was provided to us is different from the model that is implemented into their system; specifically, the mounting holes present in the 3D model are not present in the physical model, and so the use of an adhesive was necessary.

As mentioned prior, there are also material limitations with our build design. The 3D print filament is not able to withstand the necessary temperature for testing in the true oven environment as opposed to our simulated environment. Creating a model out of aluminum would mean that, with access to an oven capable of heating the lubricant to around 40 °C, we could test the system in a representative environment; in addition, the model could be tested in the precise high temperature and low pressure environment of the vacuum chamber, though the vacuum should have little to no effect on the part.

Despite the benefits of producing an aluminum model, the final model could not be manufactured on campus because it requires a ball end mill and a 5-axis CNC mill, both of which we did not have access to. We also had to modify the 3D printed part due to the differences between the physical chain and rail system that our sponsor provided and the CAD model of the system inside the vacuum chamber. As a result of these limitations, 3D printing the prototype and simulating the lubricant with glycerine was the most feasible in terms of time and cost. Additionally our model accurately captured the functionality of the design, and allied for data collection for our sponsor.

If we were to repeat our testing and design, we would also focus on better simulating the environmental conditions. We used vegetable glycerin to run lubricant flow tests because its viscosity at room temperature is a good approximation of the lubricant's viscosity at 40 °C. Matching the viscosity of the vacuum chamber lubricant, Krytox, allows for a good model of how the lubricant will behave, though it is not perfect. The surface tension of glycerin is higher than that of the vacuum chamber lubricant [36], which suggests that the glycerin drains slightly faster. Being able to test the design with the lubricant at the proper temperature would eliminate this discrepancy between the model and application, and would allow for more accurate data to be collected in regards to how the lubricant drips over time.

In addition to improving the tests' environmental conditions, we would also improve the mechanical conditions if we had more time. The chain provided to us is not the same length as the system we designed for, is not under load by a PCB, and is not at the correct tension. These factors influence how the chain moves through the system and affect how much the chain deteriorates over time, something that lubricant aims to mitigate.

More generally, our experimental procedures would be more accurate with more resources available, such as testing with more accurate and precise instruments and setups. Our method of measuring mass, for example, in some experiments that we conducted depended on a scale that had 1 gram precision. Having more precise and accurate measurements and setups would allow for better design choices to be made, especially if any of the tests we conducted are to be redone in the proper environment.

Design Critique

There are several strengths with the final design, including its simple manufacturing process, the minimal changes required to implement the system, and the ease of use for users. In terms of manufacturing, the part can be easily made with standard or readily available tools using a CNC mill; the part was quoted by Heller as costing $12.03 per unit for a batch of 100 [37], and the simple manufacturing process is reflected in this low price. Additionally, the part can be installed into existing systems with minimal changes, namely drilling a hole in the chain's guide rail to accommodate the lubricant dripping. The system also achieves the intended outcome of being simple to use and making the lubrication process faster and less tedious. By only requiring human input to fill the reservoir, the design is able to lubricate the chain with less manual intervention and significantly faster than would otherwise be possible.

Despite all of these strengths, the design does still have some notable drawbacks. One of these drawbacks is the potential for the user to miss the cutout for the reservoir filler. There are several potential options for solving this issue, many of which were considered. A guide could be attached to the reservoir to aid in maneuvering the filler; this would make it simpler to find the cutout, but would make manufacturing the reservoir more complicated and potentially more expensive. Alternatively, a fitting and pipe or tube could be used to more easily access the reservoir. This poses potential problems with both the temperature and pressure requirements; both the fitting and the piping would need to withstand the vacuum chamber's high temperatures, and it would be necessary to ensure that no pressure difference is created between the tubing (as well as the fitting) and the vacuum chamber. Such tubing and fittings have the potential to make the filling process easier and more consistent, and with more time to research them could provide an economical improvement to the filling process.

Additionally, the system does require user intervention during a preventative maintenance cycle. Ideally, the design would be capable of either self-priming, or could be run continuously with only intermittent maintenance. Beyond this, being able to exert more control over the flowrate would give the system more flexibility, and this could be achieved if the system were self-filling. Thus, with more time available looking into a method of having the reservoir be self-filling would allow for less labor-intensive process of lubricating the chain, and would allow for greater flexibility in the amount of lubricant the chain receives.

Risks

Many of the challenges we encountered revolved around simplicity of design. The more moving parts there are and steps in a process, the more susceptible the project is to be dangerous for the manufacturer, the user and the observer. In terms of safety for the manufacturers, we made sure that every time we worked in the shop or applied the lubricant, we wore safety goggles, closed toed shoes, pants, and our hair pulled back.We also made sure to unplug the power supply each time we need to touch our system or adjust anything. In terms of the safety of the user, we made sure to create a part that was one piece, easy to use, and had a clear installation point. It also is capable of withstanding the max temperatures and pressures and will not interfere with any of the moving parts. Lastly, for the observers at the design display, we put up a plexiglass barricade so that no one would accidentally touch the gears or electrical system while in use. All in all, our safety precautions have minimized risks to anyone interacting with the system.

Reflection

This section contains our thoughts on the impacts beyond the requirements and specifications, such as cultural, social, ethical, and overall stakeholder impacts. These are our own opinions and do not necessarily reflect the beliefs of University of Michigan or Heller staff, although we have consulted with each group throughout the project to better understand their perspectives on such impacts.

Social, Economic, and Environmental Impacts

Beyond simply solving the problem of vacuum chain lubrication, our final design has a potential to impact the public through social, environmental, and safety factors. The first of these factors is public safety; we are fortunate to be using a highly unreactive lubricant (Krytox) with an unreactive metal (Aluminum 6061), which is extremely unlikely to cause health hazards to workers or environmental waste that affects the health of the general public. The heat of the oven poses a burn threat, but Heller has already taken measures to ensure that its workers are not hurt by this, and our solution will make burns less likely, as workers will be spending less time interfacing with the vacuum chamber.

Next, the global impacts of this design are anticipated to be negligible. Heller estimates a production volume of roughly 600 parts per year [35], which would have a very small impact on global aluminum demand. However, our solution's impact has the potential to be outsized—implementing our lubrication system on vacuum reflow ovens would theoretically increase the production of printed circuit boards, which are currently in high demand with a lagging supply chain. We view this increase in PCB supply as a positive and do not have concerns about the ethics of its impact.

We are also considering the social and economic impacts of the manufacturing, use, and disposal of our reservoir system. Manufacturing can be done with standard CNC milling and no extraneous tooling, which minimizes unnecessary social impact. A quote obtained by Heller representatives estimates the cost for manufacturing to be $12.03 for a batch size of 100 parts [37]. Parts will be shipped globally for use, and during use life no additional waste will be produced nor will any maintenance on our reservoir need to be taken, which makes economic and social impact negligible during this stage. Aluminum is a recyclable material, so at end of life the reservoir can be recycled to reduce the overall social and economic impact of the design. A summary of CO_2 footprint and energy consumption is given below in **Figure 34**.

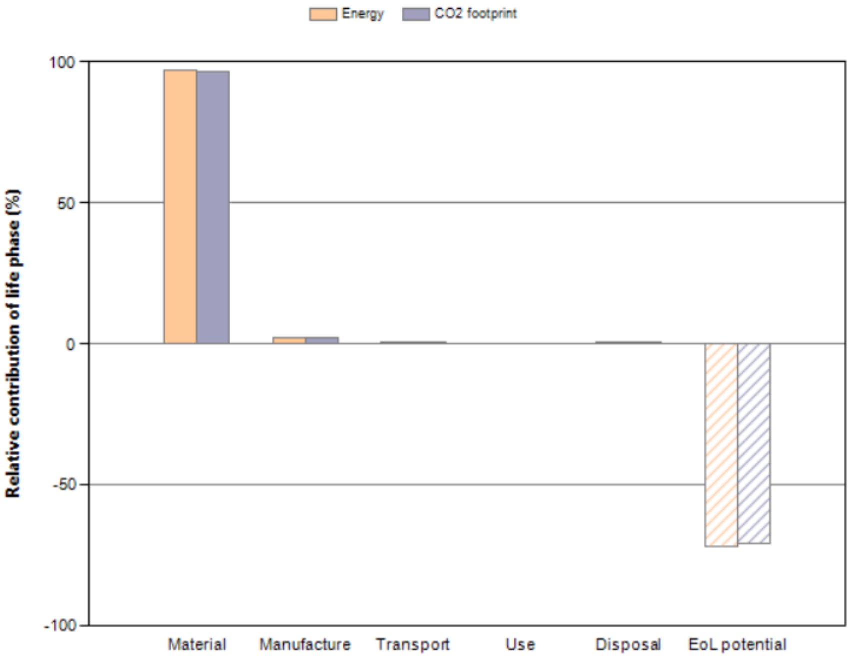


Figure 34: Energy and CO_2 impacts of the proposed reservoir solution over its lifetime.

We used several tools to determine the impacts of our solution for the various factors above. First was a stakeholder analysis (see **Figure 10** and **Table 2**) to determine who we would be affecting with our solution. We also used the GRANTA software to conduct an audit on our part seen above in **Figure 34**. These basic tools allowed us to piece together an idea of how our solution would have an impact outside of completing its basic function, which we believe to be an important facet of engineering.

Cultural Impacts

Our team's performance as a group was bolstered by each individual's unique identity and background. By allowing each team member to voice their own thoughts, we were able to create dozens of automatic and semi-automatic solutions during concept generation, and had productive discussion on narrowing down solutions to obtain what we viewed as the optimal design given our constraints. Had all of us thought the same or not given space for individual differences, we wouldn't have been able to achieve the success we did throughout the design process.

We would like to acknowledge the staff of Heller Industries for respecting our individual opinions and unique backgrounds, and allowing us to voice our thoughts without judgment throughout the course of this project. The power dynamic between us caused us to weigh heavily on Heller's opinions, but at no point did they force us in a certain direction with our project, which led to a final design that satisfied their needs while still being fully our own. Although there may have been cultural and identity differences between us and our sponsor, we did not feel that it impacted our design process or final design in a negative way. On the contrary, their age and experience in industry allowed us to make more informed decisions when designing our reservoir.

Inclusion and Equity

Our sponsor and primary stakeholder, Heller Industries, had more power in our dynamic because they financially supported the project. Additionally our team wanted to meet the sponsor's expectations and deliver a successful project that would be useful for Heller Industries. Our team never interacted with the end users, reflow oven maintenance staff, but we still had power over the design and usability. This creates an uneven power dynamic over the design route because there was no overlap of communication between the two groups. If we were to re-do this project we would prioritize interacting with maintenance personnel and getting their perspectives, to minimize the power dynamic that naturally exists. Our team, as students, does not have the experience with the vacuum reflow ovens necessary to fully understand the design problem. Thus there is definitely a disconnect between our comprehension of the issue and the understanding of those who interface with the machines regularly as a career.

This being said, our team committed a large quantity of time to analyzing the design problem to best assess and solve it. Our group members are all very different, but these differences generally benefited the success of our project. For example, some of the group members are more detail oriented but others were better with zooming out to the big picture which gave our presentations and reports a good perspective of how the audience would receive them. To include several diverse viewpoints in our work, our team practiced consistent and open communication when members disagreed. We also had consistent communication with our primary stakeholders to include their perspectives, which added another layer of diversified thinking and experiences.

We respected our sponsor's opinion in our project, and they were very open to all of our ideas. Our sponsor primarily offered insight as to improve our ideas rather than to change them entirely, so balance was achieved naturally. There were times when our contacts at Heller Industries did express doubts in our approach, and we took them into consideration without much vetting because we respect their expertise in their machines. In general, we did not have to consciously balance the impact on the project because both sides were open to the input of the other. Our team's differences manifested primarily in communication style, some being very communicative and others less so. This most likely skewed our choices towards the more communicative team member's preferences, but we did prioritize communicating opinions to each other throughout the semester.

Ethics

In addition to yielding valuable experience on design and manufacturing beyond academia, our project presented us with real ethical dilemmas. One example of which occurred late in the design process for our reservoir system. The vacuum chamber model we have access to contains three rails—two side rails and a center board support (CBS) rail. As we were mounting the reservoir within the model, we discovered that the rightmost rail had an additional obstruction in the form of a long sensing rod (see **Figure 35**), which would prevent us from mounting the reservoir in the same way as we had on the other rails.

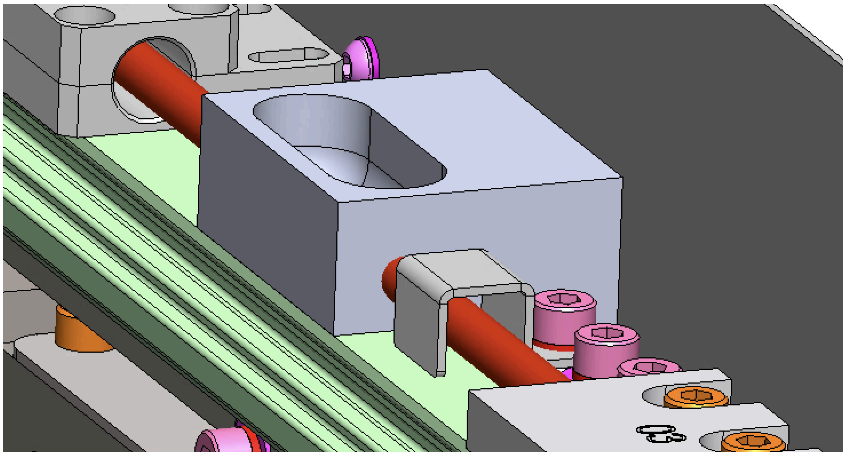


Figure 35: The reservoir (center) with the sensing rod (red cylinder) running through it.

This discovery was an oversight on our end; we should have noticed the asymmetry and accounted for it as soon as we received the CAD from Heller Industries. The ethical dilemma we faced was therefore one of deciding if we should acknowledge our oversight or pretend not to see it and allow Heller Industries to inherit the problem at the semester's end. We chose to immediately talk to our section instructor, who helped us brainstorm for possible solutions in reservoir design. Armed with new solutions, we brought up the issue at our next meeting with our sponsor and explained our fault in its entirety, along with the solutions we had come up with to correct the problem. At the meeting, we learned that the sensing rod is a rare feature in Heller's reflow ovens, and our solution would work for the majority of vacuum chamber chains. As such, Heller staff advised us to focus on our current design. We feel that divulging what we knew to Heller as soon as possible was the ethical decision to make, and it allowed us to focus fully on creating the best design possible.

Our head-on approach to dilemmas emerging throughout the semester showcased above was effective for our team, but we also want to consider those that may occur after our product hits the market. Some such dilemmas may include rushing to implement our product without proper testing, overpromising on product lifetime without guaranteeing lifetime experimentally, and improper training for maintenance people, leading to injury. The first two of these dilemmas fall to the decisions of Heller Industries. Our action items to make testing and verification easier for them is to be very specific on what we have tested and what still needs to be verified on our handoff documentation. Additionally, we will specifically emphasize during meetings that our solution needs to be put into a vacuum and run at temperature to validate that it survives. For the final dilemma of improperly training maintenance personnel, we have already informed Heller Industries of a use guide that will be given during handoff. This will specify exactly how to fill the cup, with what tooling, and under what temperature conditions. The guide is attached to this report in full under *Appendix E*.

Holistically, we see many parallels between our personal ethics and the professional ethics upheld by the University of Michigan as well as potential future employers. We exercised honesty and hard work towards a solution that was beneficial to stakeholders with considerations towards society and the environment, which are key ethical pillars in a professional environment. We recognize that we are not perfect, and will continue to consider and improve on utilizing the ASME ethical standards in our future work as professional engineers.

Conclusion

In closing, our team has addressed Heller Industries' chain conveyor lubrication issue in their vacuum reflow soldering ovens. In the past, a maintenance technician had to manually paint lubricant onto the chain, and Heller Industries sought after an automatic or semi-automatic solution that could lubricate the chain within the vacuum chamber. Our team researched Heller Industries' specific technology and other technology in the application of a vacuum chamber, as well as methods of chain lubrication to establish a foundation of background knowledge on the system. We produced many possible solutions for the lubrication problem in large ranges of feasibility, size, and automacy and ultimately chose an aluminum, open-top reservoir with an orifice to drip lubricant onto the chain moving below. The open-top feature allows the reservoir to remain in the vacuum chamber while the reflow oven is pressurized, and using Aluminum 6061 allows the reservoir to withstand the high temperatures when the chamber is heated. To verify the efficacy of our design's orifice, we did several fluid dynamics physical tests and theoretical analysis of our system. Additionally our sponsor produced a quote for manufacturing our design, and it was significantly under our budget. Ultimately, our design expedites a tedious process with a simple solution that is feasible economically.

Acknowledgements

We would like to thank and acknowledge all who made this project possible, provided guidance, and contributed to the success of our semester. We would like to thank the University of Michigan Mechanical Engineering Department and Heller Industries for providing mentorship and financial support for this project. We are grateful to the Heller Industries Staff for their support, including David Heller and Jim Neville, who provided their guidance with their extensive knowledge and expertise throughout this project. We would also like to acknowledge Professor Brian Kish and Professor Randy Schwemmin from the mechanical engineering department for providing an abundance of support throughout the evolution and development of our project.

Appendix A - Concept Generation

Rapid Idea Generation Notes

The first method of a rapid-ideation round table group discussion generated the following quick list of notes of ideas we thought had potential. The notes are mildly haphazard due to the spontaneity and fast-pace of this process, but they served as simply a launch pad to pursue more careful brainstorming. These notes are linked here in the Docs file we used:

Rapid Ideation Brainstorming ideas

Individual Brainstorming Notes

A sample of what one of our individual brainstorming notes documents looked like can be seen below. These were created before moving onto group discussion and analysis.

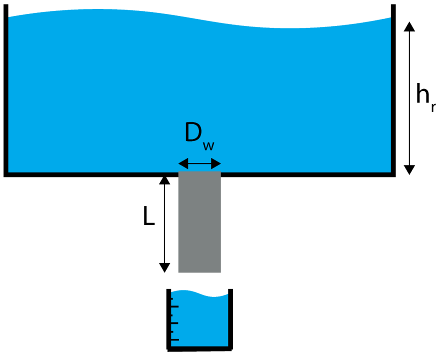
Individual Brainstorming ideas

Appendix B -Experiments

We have five experiments planned and they are described as followed, but are subject to change or development.

Experiment 1 - Wick Porosity Testing

1. Fill the large reservoir with water, measuring the amount of water added (see **Figure 22**)
2. The height of the water must be measured at the start, and ideally at the end to take an average height
3. Allow the wick to saturate, and once the fluid reaches the bottom end of the wick, start the timer
4. Allow the fluid to flow through the wick uninterrupted for 30 minutes into the secondary reservoir, ensuring nothing is leaking from the large reservoir into it
5. Make sure that the free end of the wick is not submerged in the secondary reservoir
6. Measure the volume of fluid in the secondary reservoir
7. Measure the final height or volume in the large reservoir



$$\underbrace{Q}_{(1)} = \underbrace{k}_{(2)} \cdot \underbrace{\frac{\pi D_w^2}{4L}}_{(3)} \cdot \underbrace{\frac{g h_r}{\nu}}_{(4)}$$

Figure 22. Wick testing experimental setup (left) and equation for volumetric flow rate (right) [32]

Experiment 2 - Lubricant Spreading

1. Label the chain provided with 2 inch increments (sticky notes or something)
2. Apply a specified quantity of lubricant (mixed with red food coloring) to the first specified inch mark
3. Run the chain in three full cycles around the sprocket until the chain returns to the initial starting point.
4. First, observe how the red has been spread across the chain
5. Swab a q-tip at each of the 1 inch increments and assign the q-tip an opacity rating (like a filter smoke test)
6. Repeat Experiment with several different specified quantities, washing the chain in between experiments
7. Choose the options with the most uniform dispersion of lubricant throughout the chain

Experiment 3 - Chain Load Current

1. Set up chain and sprocket system by attaching a motor to a gear which drives one of the sprockets (we will only apply a drive force to one side at a time)
2. Beginning with 5 mL of lubricant and increasing by 1 mL up to 10 mL, apply lubricant as thoroughly as possible across the chain
3. Record all conditions: Pressure, Temperature, Length of Chain, Motor type, shaft type, Motor Constant, etc.
4. Turn on devices (wavegen and Labview) and apply a constant motor voltage (likely around 6V. Make sure sure sprocket will spin even with low lubricant quantity) and record the motor current at each lubricant volume
5. Wash off lubricant from chain using Dawn dish soap between tests
6. Graph lubricant volume applied (mL) vs. motor current (mA) to find the optimal volume of lubricant and the minimum current that it occurs at.

Experiment 4 - Wick Fatigue and Failure Consequences

1. Fatigue Test: Drag the wick along the chain 100 times manually with similar force and speed application, record any deformations and types of fatigue.
2. Stiffness Test: Observe the stiffness of the wick, completely saturate the wick with water and then reobserve (bending, loading bearing, strain) and compare results. Let the wick try out fully and repeat with the same wick. Compare results.
3. Consequences of Different Types of Failure: Take a new wick, observe how water flows through it. Take several comparison wicks and damage them in different ways (shorten one, lengthen one, poke a hole in one, cut a tear in one, etc.) and compare how water flows through the wick after these damages occur.

Experiment 5 - Mounting Techniques

1. Create a prototype (or something that resembles the prototype) so several different types of mounting techniques can be done.
2. Attempt to mount the product via several different ways: magnets, screws, rollers, friction, etc.).
3. Gently shake the rail manually. Continue to jostle the rail until the product falls off.

4. Observe how much movement it takes to get each product to be shook off as well as any damage that occurred to the rail when it fell off.

Appendix C - Requirements and Specifications

Requirement	**Specification (Numerical)**	Verification: math-y: How does it meet the specification? Evidence the design meets the requirement (testing or analysis)	Validation: does it actually solve the problem? Client response. How does this help us accomplish our task? Is the customer satisfied with the solution? Customer Satisfaction means it accomplishes the why
Features: supplement product's basic functions			
Consistency in timing of oil application/quantity of lubricant	Must be able to apply the same amount of lubricant everytime the machine is used within 10% error	Using a consistent amount of lubricant every time, fill up the system and allow it to empty for a fixed amount of time (dependent on design); measure the amount expelled, and repeat for several trials	- settings are flexible to not over or under lubricate in different environments (altitude, humidity, climate, etc.)
Corrosion Resistant	Must not oxidize when in contact with the lubricant at 350 C	Lubricant is non-reactive. To verify corrosion resistance, utilize existing knowledge on corrosion resistant materials and coatings in 350 C enviornment	- avoids corrosion to promote device longevity
Cost	Cost of production (including sourcing materials and manufacturing) must not exceed $5000		- it is economical compared to the current cost of maintenance to maintain marketability
Reliability: probability of product failing			
Knowledge of Lubrication frequency	Must have a fault prevention system that can detect system stoppage within one week	Induce sitatuions which consitute failure of the system, and check if it was detected; repeat several times	- it indicates if a lubrication is delayed, early, or missed that it will not shut down the whole system
Yield Strength	Any oil vessel within the vacuum will have a yield strength with a factor of safety ≥ 3.5	Not a pressure vessel, so automatically passes	- it can survive a sudden pressure drop or if the product was struck
Limited complexity	Design should not contain more than 30 pieces	Count the number of (major feature) pieces in the design, ensuring they are below 30	- solution is simple and easily operable
Ease of use	Should be able to operated with minimal supervision by a factory worker within two weeks of training	Gather a group of workers unfamiliar with the new system, and have them trained on how to use it. Observe each of them using the system, and record how long it took for them to set up the system, and how many mistakes were made	- the new solution is easier and faster to use than painting on lubricant by hand
Durability: measure of product life			
Product Lifespan	This product should last at least 10 years	Using an estimate for the number of cycles per year based on downtime and the number of cycles during normal use, find the number of cycles expected within 10 years. In a test envrionment capable of reaching a vacuum of 10 torr and 350 C, expose the system to the calculated number of cycles; regularly check if the system is operational, and repeat for multiple different instances of the system	- the product has long expected lifetime
Shipping Survival	The product should be able to be dropped on the ground from 6 ft in standard shipping protection and slide in a standard cardboard box 6ft laterally without cracks or breakage	Perform a drop test on the package with standard protection, dropping from 6 feet. Check for any non-superficial damage, and repeat several times	-the product is able to be dropped on the ground from 6 ft in standard shipping protection and slide in a standard cardboard box 6ft laterally without cracks or breakage
Serviceability: ease and time to repair after breakdown			
Accessibility of system	The system must be able to fit in the current machine in use.	Verify using the CAD model that the system does not interfere with normal operation	- the system fits in the current machine in use.
Tool Requirement	Must be able to be maintained with the tools listed in the "Required Equipment" category in the user manual (page 144)	Ensure that all components which require specific tooling use tools listed in the "Required Equipment" category of the manual	- can be maintained with the tools listed in the "Required Equipment" category in the user manual (page 144)
System Drawings	There will be a CAD model of the whole system to-scale with correct material properties and dimensioning	Ensure that drawing has correct dimensions and is complete, including the material used	- has accessible CAD and diagrams for ease of manufacturer and customer maintenace
Electrical Schematic Drawings	There will be a machine-to-machine electrical interface that includes electrical connections, grounding, and inter-machine control (per SMEMA standards)	Ensure that such a machine-to-machine electrical interface adheres to the SMEMA standars	- there is a machine-to-machine electrical interface that includes electrical connections, grounding, and inter-machine control (per SMEMA standards)

Durability: measure of product life			
Product Lifespan	This product should last at least 10 years	Using an estimate for the number of cycles per year based on downtime and the number of cycles during normal use, find the number of cycles expected within 10 years. In a test envrionment capable of reaching a vacuum of 10 torr and 350 C, expose the system to the calculated number of cycles; regularly check if the system is operational, and repeat for multiple different instances of the system	- the product has long expected lifetime
Shipping Survival	The product should be able to be dropped on the ground from 6 ft in standard shipping protection and slide in a standard cardboard box 6ft laterally without cracks or breakage	Perform a drop test on the package with standard protection, dropping from 6 feet. Check for any non-superficial damage, and repeat several times	-the product is able to be dropped on the ground from 6 ft in standard shipping protection and slide in a standard cardboard box 6ft laterally without cracks or breakage
Serviceability: ease and time to repair after breakdown			
Accessibility of system	The system must be able to fit in the current machine in use.	Verify using the CAD model that the system does not interfere with normal operation	- the system fits in the current machine in use.
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System Drawings	There will be a CAD model of the whole system to-scale with correct material properties and dimensioning	Ensure that drawing has correct dimensions and is complete, including the material used	- has accessible CAD and diagrams for ease of manufacturer and customer maintenace
Electrical Schematic Drawings	There will be a machine-to-machine electrical interface that includes electrical connections, grounding, and inter-machine control (per SMEMA standards)	Ensure that such a machine-to-machine electrical interface adheres to the SMEMA standars	- there is a machine-to-machine electrical interface that includes electrical connections, grounding, and inter-machine control (per SMEMA standards)

Safety			
Device Temperature Control	The device must either not get to a temperature high enough to melt surrounding materials and it must be able to cool down to ambient temperature within 20 minutes (design dependent)	Ensure that all materials used in the system can withstand 350 C OR Heat up the system to 350 C, and measure the amount of time for the surface to cool to ambient temperature. Ensure this is within 20 min, and repeat several times	-the device does not get to a temperature high enough to melt surrounding materials and icancool down to ambient temperature within 20 minutes
Shields	Any section of the device that poses a risk of expelling material or lubricant must contain a viable shield on it. Viability means protecting the potentially affected surroundings with 100% accuracy.	Ensure such a shield is in place, and can withstand 350 C using relevant documentation on material	- the device contains all necessary shields for safety
Notification of Issues	If the device reads an irregularity in the motor current for chain drive for more than one system cycle (one complete pass-through of a PCB), the user must conduct a swab test to check the status of the lubricant	Induce an irregular motor current for at least one full system cycle, and ensure the system detected it. Repeat several times	- there is an identified mark that indicates an irregularity in the motor current , such that the user will know to conduct a swab test to check the status of the lubricant
In-House Safety Standards	The device must follow all In-House and Industry-Wide safety protocols.	Ensure that all safety standards are 100% followed by referencing relevant documents	- the device follows all In-House and Industry-Wide safety protocols.

Lubrication Standards			
Swab Test	The lubricant must be swabbed with a q-tip once a week, or upon motor irregularities, if the q-tip is anything but clear, a lubrication cycle must be run	Compare the lubricant color range that has been assigned a numerical scale to the point at which the chain stops running smoothly	- prevents machine or chain failure and maitenance requirements
Amount of Lubricant Required per Cycle	There must be ~5 mL of lubricant applied for every lubrication cycle ran	Measure the maximum amount of lubricant that can be placed into the reservoir while the system is installed in the vacuum chamber, and allow to fully drain. Measure the volume expelled, and ensure that it is at least 5 mL	- facilitates maintenance procedure
Load Requirement to Lubricate the chain	The motor current required to move the chain must not read irregularity for more than one cycle.	Allow the system to operate without lubrication until a consistent increase in current greater than the measurement error is read, and note the number of cycles. Allow the machine to run for the same number of cycles using the design to lubricate the chain, and ensure that no such consistent increase in current is observed.	- there is an identified mark that indicates an irregularity in the motor current , such that the user will know to conduct a swab test to check the status of the lubricant
Conditions Requirement	The chosen lubrication process must be underwent during maintenance designated times, where the machine has cooled to ambient conditions	Ensure that the design can cool to ambient temperature within 20 minutes to ensure that it is not operated at too high a temperature	- our system has an effective lubrication and ensures the safety of the workers
Cost			
System Price	The price of the lubrication system must not exceed 2.5% of the price of the entire machine.	Run a cost analysis on the design, including (but not necessarily limited to) material cost, manufacturing cost, and shipping cost. Ensure that this is below $4,000 (20% margin)	- allows reproducability of our design at the company
System Cost	The cost of the lubrication system must not exceed 2.5% of the price of the entire machine.	Run a cost analysis on the design, including (but not necessarily limited to) material cost, manufacturing cost, and shipping cost. Ensure that this is below $5,000	- design allows for profit for the company because it is relatively cheap to make
Manufacturability			
Manufacturing Process	- must be able to be manufactured using only a mill, lathe, band saw and hand tools	- the build design will be produced in the mechanical engineering shop in GGB	- will prove that it can be done by creating the build model
Ease of Manufacturability	- the part needs to be able to made without any additional experience or an excessive amount of time	- the build design will be produced by our group	- a skilled machinist will surely be more efficient than us
Time of Manufacturing	- the part must be able to be made in under 3 hours by a tyical machinist	- the build design will be produced in under 5 hours by our group	- a skilled machinist will surely be quicker than us

Appendix D - About the Team

Gina - I'm Gina Schmidt and I am from Royal Oak, Michigan. I love living in Michigan and plan to stay after graduation, and for a while into my professional career. I love doing hands-on work and tinkering with things until I figure out what isn't working and how to fix it, specifically with car repairs. I worked on cars for years with my father, so I have a strong history with automotive vehicles, and this ties into my post-graduation plans. I hope to work in the Automotive industry, potentially in the controls sector. I do not have a specific job title in mind, I just hope to find something that makes me happy and challenges me. I will be returning to UofM next year to complete a Master of Engineering in Automotive Engineering to specialize my knowledge in engineering for a career working with vehicles. I love cooking and forcing my friends and family to try my food, as well as baking. Additionally, I like to play songs on piano and guitar in my free time as a creative outlet.

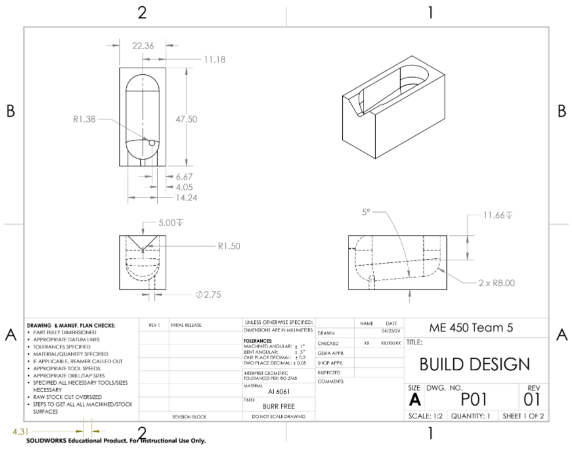
Morgan - My name is Morgan Flynn and I am from Orange County California. My interest in mechanical engineering stems from having an interest in the entirety of a process. I like being able to see idea generation all the way through product development and then presentation, and knowing how systems work. I like being able to fix and maintain all of my systems at home by myself through the knowledge and/or critical thinking skills that engineering provides. It gives me a sense of self-sufficiency and helps me save money. In terms of my future plans, I am hoping to get a job back in Southern California where I plan to work for a while and pay off loans and then I hope to do some traveling through Europe and Southeast Asia. I anticipate later on traveling and maybe working in some different countries for a while and eating good food. I am a major foodie and love trying new foods and learning about cultures through food. In my time back in California before traveling, I hope to adopt a dog from a shelter and get better at surfing in my free time.

Will - Hi, my name is William Scott and I'm from Chelsea, Michigan. Growing up, I spent a lot of time playing with LEGOs and building shelters in the woods near my home. I took my interests in design into high school, where I learned AutoDesk Inventor, got into woodworking with my mom, and became employed as a contractor's assistant where I learned to design in the real world. At the University of Michigan, I quickly decided to go into mechanical engineering because of my previous interests. As a freshman here, I did a stint in the Michigan Aeronautical Science Association (MASA) working with pressure vessels as a part of the Structures subteam. Since sophomore year, I've been designing arms for the mechanical subteam of Michigan Neuroprosthetics (MNP), a club that makes 3d-printed prosthetics for children. After graduation, I'll be moving to Indianapolis to work at Eli Lilly as a manufacturing engineer. Outside of engineering, I enjoy running, watersports, and doing masonry/landscaping projects for my family and neighbors.

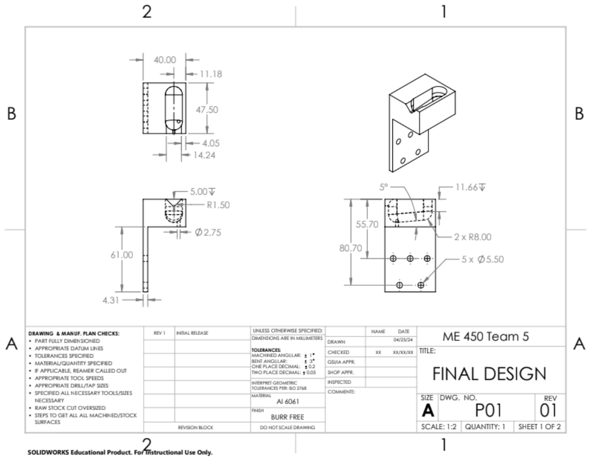
Henry - I am Henry Tukel and I am from West Bloomfield, Michigan. Growing up I always had a fascination with understanding how technology functioned, and would regularly disassemble toys to try and learn how they worked. In particular, mechanisms and other mechanical systems have always fascinated me, and wanting to learn about how they work and how to model them is what originally led me to pursue mechanical engineering. For my future plans, I intend to pursue a Master's degree in mechanical engineering, and potentially a PhD. Beyond this, I am still trying to figure out exactly what I would like to do for work and where, and I am open to several possibilities. In my free time, I enjoy biking as well as playing video games with my friends.

Appendix E - Manufacturing and Assembly

Upon reflecting on the final design and build design for the project, the engineering drawings can be seen below:



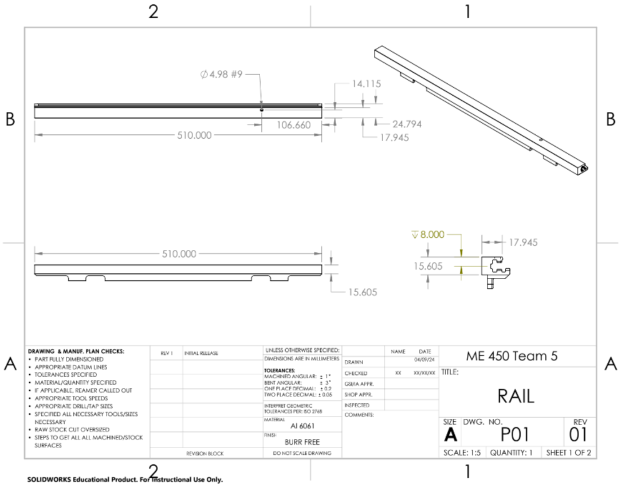
Build Design

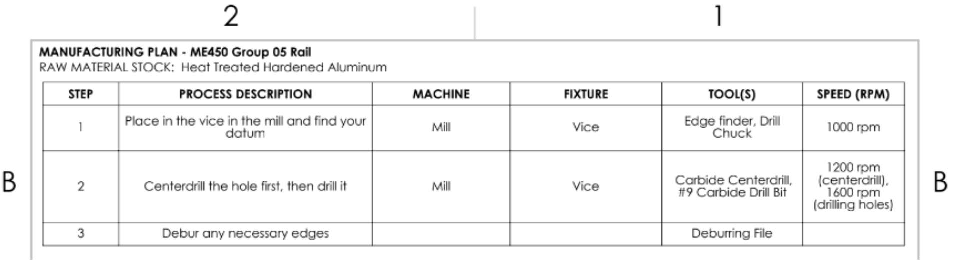


Final Design

The build design was made using a 3D printer by converting the CAD file into an STL file and inputting into an Ultimaker 3D printer. The final design would be manufactured using a 5-axis CNC mill. After receiving the G-code file converted from the Solidworks part, the CNC mill would pursue creating the part by cutting it to length, removing the extruded cut section, ball end milling the reservoir shape, drilling the holes, and finally passing a drill bit along the reservoir edge to create the triangular outcropping. A reference of why the build design and the final design are different can be seen in the report above.

Both the build design and the rail design were installed on their current rail, however, the user needs to add an additional hole for the lubricant to drip through. The engineering drawing and manufacturing plan for this rail can be seen in the images below:



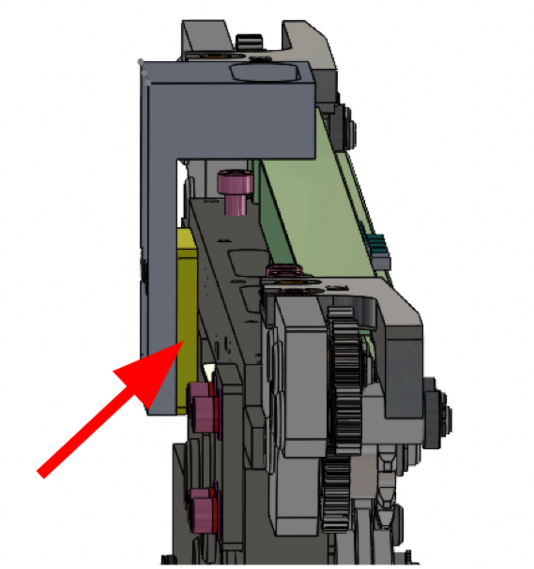


MANUFACTURING PLAN - ME450 Group 05 Rail

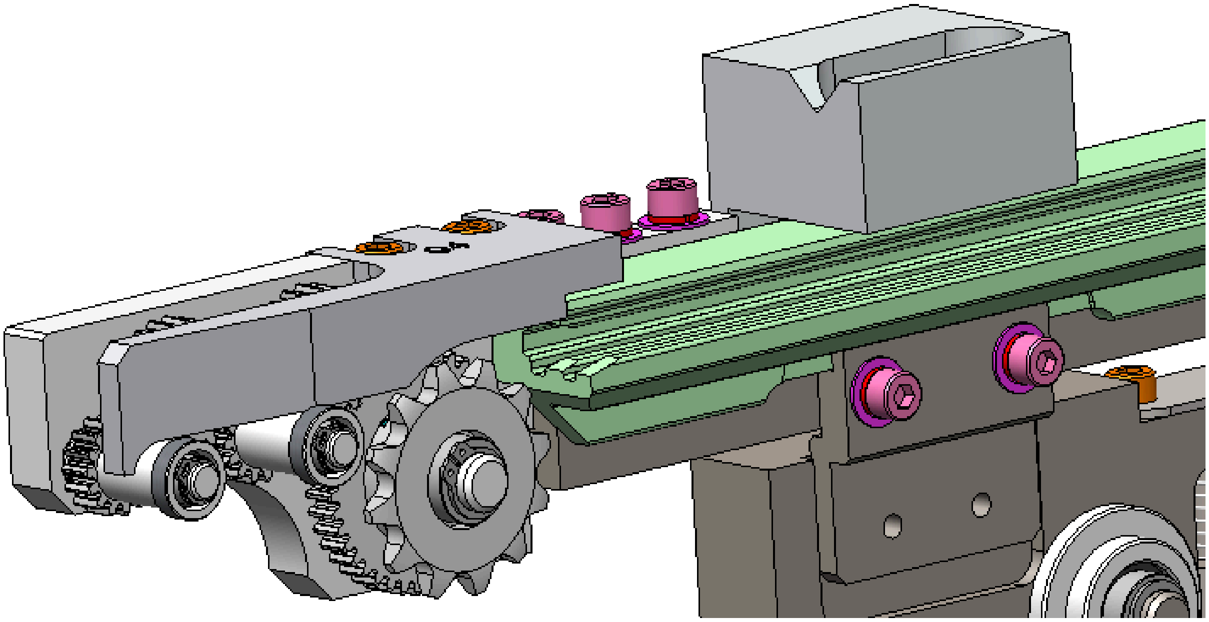
RAW MATERIAL STOCK: Heat Treated Hardened Aluminum

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Place in the vice in the mill and find your datum	Mill	Vice	Edge finder, Drill Chuck	1000 rpm
2	Centerdrill the hole first, then drill it	Mill	Vice	Carbide Centerdrill, #9 Carbide Drill Bit	1200 rpm (centerdrill), 1600 rpm (drilling holes)
3	Debur any necessary edges			Deburring File	

Assembly would be simple for both the build and the final design because there is only one piece. The build design was applied to the system by simply aligning the hole on the rail and using two-sided tape to attach them. This was simply for simplicity of testing and demonstration. The final design would be assembled by removing the five screws that exist on the back of the rail system, removing the spacer that is held on by the screws, and replacing the spacer with the cup via those same screws. The image below shows what the rail would look like if the spacer (yellow part) was not removed. This would leave the cup out of alignment and would limit the thread engagement of the screws in use.



When correctly installed, the system will look like the image below, with the triangular cutout pointed towards the chamber door and sprockets.

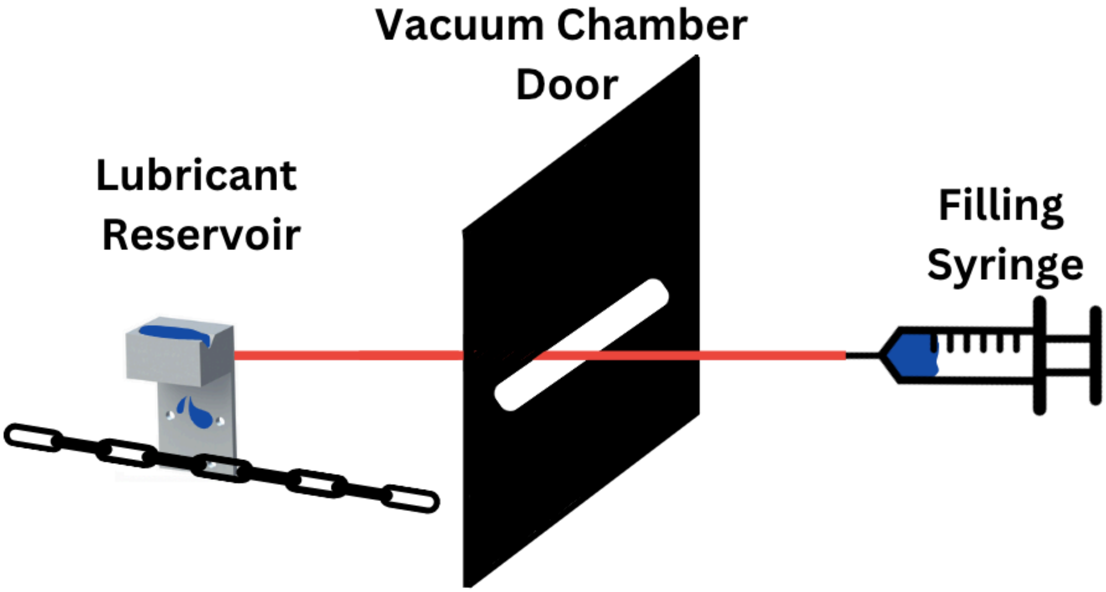


Reservoir Filling Guide

The following is an unabridged copy of the document that Heller Industries requested for the education of maintenance personnel.

HELLER INDUSTRIES

Document Name	Vacuum Chamber Lubrication System Use Guide
Date	25 April 2024
Authors	Henry Tukel, Gina Schmidt, Morgan Flynn, William Scott



Required Conditions for Use

In order to operate this system safely and effectively, there are several steps to complete before lubricating the chain:

- **Shut off the vacuum oven**—this process should be completed during a preventative maintenance (PM) cycle

- Ensure that the ambient temperature inside the oven is **NO GREATER than 40ºC**
- Open the vacuum doors such that the chain and reservoir are exposed

Steps for Using the Chain Lubrication System

1. Fill Syringe with Lubricant
   Begin by filling a syringe (minimum 175mm length needle, 5mm maximum outer diameter, and 10mL fill size) with **5mL of lubricant**.

2. Transfer to Reservoir
   Insert the needle of the syringe into the tapered edge of the reservoir. Once inside, carefully void the contents into the reservoir.

3. Run Chain
   Once humans are clear of the vacuum, start the chain at a speed of **30cm/min**, or any integer multiple (60, 90, 120cm/min, etc) to ensure that the chain is evenly coated with lubricant.

4. Clean Up and Preparation
   Wait for **10.5 minutes** with the chain running, after which the lubricant should be dispersed along the chain. At this point, maintenance may choose to leave the chain running or stop it to perform other PM tasks. If desired, rinse the needle in water or replace if the needle is damaged.

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