Beginner Friendly Vertical Hydroponic System

ENME472: Section 0101

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Executive Summary

Our goal has been to design a cost effective, low maintenance, and high yield hydroponics system for inexperienced farmers and hobbyists. This would help improve access to fresh produce in urban areas, where many people are considered food insecure due to lack of supermarkets. Homegrown hydroponics can also reduce strain on the food supply chain and provide access to produce grown without pesticides and other harmful chemicals. Our final design is a modular and vertical system that can typically house 70 plants for $250 with a footprint of about 6 sqft. By our calculations, this would provide the user with 2.5 salads worth of lettuce per day, which they could eat, sell, or trade with other farmers in order to get more variety in their produce.

We used PVC piping to hold the plants and to allow for the water and nutrients to flow through the piping. We had to determine a suitable size for our system that allowed for a proper amount of water. By performing calculations such as beam bending analysis, we were able to finalize some dimensions. Our PVC piping is 2.375” wide for the outer diameter and the inner diameter is 2.067”. Horizontally, the tube is 27 inches long. Our system is stackable to the height will be different depending on how many layers the consumer decided on keeping. Our prototype stands at about 3 feet tall. Our pumps are connected and with flexible tubing to re-circulate the water back to the top of the system. Through research and calculations, we determined which pump would be most effective for our hydroponics system. After putting together our prototype, we have determined that our design is safe to use and is watertight. We can leave our system running without endangering anyone or the environment around it.

The Raspberry Pi has been set up with an internet connection and we wrote code that controls the main pump, nutrient pump, and lights at the proper rate. We have set up an ultrasonic sensor to measure water height and a conductivity sensor to measure nutrient concentration, as well as a camera to monitor plants. Data from the measurements are shown on the user interface with updates every time new measurements are taken. The data remains even when the system is shut down for maintenance, and when it is turned back on it is loaded into the system. Through the use of these controls, we have successfully automated the critical functions of a home hydroponics system. While our prototype uses a Raspberry Pi, the final design requires a custom microcontroller.

After completing our prototype and final analysis of our design, we have been able to draw conclusions about our product. It was able to deliver on the most important customer requirements such as being low cost, high yield, and low maintenance, but there is room for improvement. Functions can be further automated with detailed control algorithms and machine learning. Efficiency of water and nutrient usage can also be improved with better measurements, and durability and reliability can be improved with redundancy in the system. Further development in these areas and the custom parts needed for these improvements would need to be fabricated before going to market, however, this project has served as a proof of concept for the idea.

Final Design

Populations have been suffering with food insecurity for a long time, whether it's because of a lack of infrastructure or racial disparities in urban areas. In recent years issues like global warming and limits on the food supply chain during the pandemic have worsened this concern for many. Hydroponics is a new method of farming that can improve food security while reducing environmental impact of food production and stress on the food supply chain. However, it still takes time and effort to maintain a personal hydroponics system. The problem our group has chosen to tackle is designing a hydroponics system that is affordable to marginalized groups while still being low maintenance so that it is easy for anyone to use.

Our final design consists of the planter itself and a controls subsystem which is controlled by a Raspberry Pi 4 on the prototype. The planter has a vertical and modular design that allows the user flexibility in how many plants they grow, while maximizing the yield compared to the footprint of the system. Water enters the PVC pipes at the top and trickles down through each layer until it reaches the reservoir where it is collected. A pump recirculates water back up through tubing. The pump and all other electronics are controlled by the Raspberry Pi on our prototype. The Pi runs the main pump at a constant speed, runs the nutrient pump as necessary based on measurements it takes from the conductivity sensor, measures water height with an ultrasonic sensor, turns on (or off) lights, takes pictures of the plants, updates the user interface, and sends text alerts as necessary. Each second, the Pi checks all the states of the system (it reads the water height and nutrient levels), and then responds with the necessary actions (turning the pump on, taking a picture, changing the state of the lights, updating the interface, sending a text, etc.). The two subsystems work together to maintain the proper living environment for the plants. The automated controls complete the critical functions of hydroponics farming so that the user doesn't have to. These critical functions are providing nutrients, water, and light to the plants at the proper rate.

Completing our prototype has informed some design changes for the final design since our original thoughts prior to Report 3. The main pitfall of our prototype was our conductivity sensor, which was essentially a bare wire lead. This helped us accomplish our goal of keeping the system price down, but it does not do a good job of measuring conductivity and is not a long term solution due to corrosion. Due to this we have made the decision to include a better (and more expensive) sensor in the final design. Even though it is a bit more expensive, it will provide a much better quality reading, and the nutrient level will be more stable. While low cost is an important objective for us, the most critical is keeping the plants healthy so we have to prioritize that. Another design change has been with the diameter of the PVC. The PVC we used in the prototype was chosen simply out of convenience, but for the final design we have done further research and decided on a thinner PVC product with the same outer diameter but less material overall. This is simply because it will be cheaper and equally as functional, while also reducing the environmental impact that PVC has. This design decision is justified by the fact that it aligns with the goals of our design to be low cost and environmentally friendly.

Prototype & Testing

Prototype

The main goal of our prototype hydroponic system was to see if we could successfully grow a variety of plants from seeds. Thus the questions we answered were finding out if the system actually works and if the system does work, and if the plants would grow properly and flourish in the hydroponic environment when compared and contrasted to the standard, dirt grown plants.

We chose to focus on all of the system critical functions including the nutrient delivery, fluid circulation, automated system monitoring, and grow lights timing and mounting. The nutrient and fluid circulation is a critical function as if the plants do not receive nutrients and water, they will die very fast. A main feature of our system that we advertised to potential users is low maintenance, which can be accomplished through the use of an automated system monitoring. Lastly, we ensured that the grow lights we chose could be programmed to automatically turn on and off at the desired intervals and that the lights fit properly in our frame. Some functions that we deemed less important were the modularity of the frame, maximizing the number of plants in the system, and overall system aesthetics. For the frame, we had limited time, materials, funds, and equipment. Having a modular frame is not critical to answering our overall question of determining if the system functions, as it is more of an optimization of the users ability to use the product. Similarly, maximizing the number of plates grown by the system is something that is an option available to the user but not necessary for proper operation. Finally, we decided that aesthetics was a secondary concern to ensuring the system functions. Once we know the design works, further iterations can improve how it looks.

The prototype is a simple wood frame layout with 2 layers of PVC pipes angled downward to aid in water and nutrient solution flow. Seven 1.25 inch holes were drilled on each layer of the PVC piping to create spots for growing plants. The holes were drilled to house the net cups, which will allow the coconut coir to stay in place. Another critical function that was prototyped is the pump system. There are 2 pumps in total, one for circulating the nutrient mix and one for circulating the water and nutrient solution through the entire system. Both pumps were purchased and installed to test the automation of the final system.

We put grow lights on a timer using Raspberry Pi's GPIOs to turn the lights off for 8 hours during the night. For the user interface, we used Tkinter which is a common library used for interfaces with Python, and especially on Raspberry Pi's. We also used the after() method to pause for 1 second and then run the system again before updating the interface with new information. Twilio was used with the corresponding Python library to rent a phone number using a free trial and send messages to the user when they need to change the water. We output an image of the plant, current water and nutrient levels, and graphs in matplotlib of water and nutrient usage. These data points are used to analyze the condition of the plant and decide whether the system needs attention from the user. For the pump system, we used Raspberry Pi's GPIO to control them via a L298N motor driver board. This board uses the L298N chip and some supporting hardware to control up to two motors at 5-35V with a maximum continuous current of 2A each. The motors are powered by a separate DC supply and controlled via PWM inputs from the Raspberry Pi. The main circulation pump runs continuously and the nutrient pump is actuated periodically according to our control algorithm.

For the nutrient adjustment, we used a feedback loop to turn the pump on for 0.5 seconds if the nutrient level was too low, then waited 2 minutes to adjust again in order to give the solution time to become well mixed and provide an accurate result. We used a wire lead to measure this coupled with a Adafruit MCP3008 analog input chip for the Raspberry Pi (which only has digital pins) to read the voltage. We mapped the measured value to a ppm after testing voltages for full strength solution and water. We used an ultrasonic sensor to measure water level using a simple trigger and echo routine. If the water level dropped rapidly, we sent a text to the user. Since the livelihood of the system depends on continuously monitoring it and obtaining data for analysis, countermeasures were taken into account. When the system is turned off, it is possible for data to be lost. We combatted this by storing data in a SQLite database. This stores data in a file on the Raspberry Pi and quickly reads from it while the program runs. If the program stops, the file remains. This could easily be changed to a SQL database on the internet so that data could be accessed from anywhere in the world, and not just the user's Raspberry Pi. This is how the actual product would work, since we would be using a custom chip rather than the Raspberry Pi and instead of having a dedicated monitor, we would connect the chip to the internet and store data there, so that it could be accessed on a website or mobile app.

Using wood for the frame created a different look than what the final product would be and reduces the reproducibility of the system. Additionally, we did not create a housing unit for the electronic components and opted to have them sit out and be fully visible. The final design will hide the controls to improve the aesthetics of the system. The remaining materials are the same or similar enough to the final product that they have no effect on the fidelity of the prototype. The only alternative material we considered for the final system was using a thinner PVC product as it would reduce cost without affecting functionality.

Testing

After the frame and grow trays were constructed, the coconut coir was added to the net cups to act as a growing medium for the seeds. Since plants depend on sunlight for photosynthesis, grow lights were also added to each layer of the frame with an appropriate timer. Once the basic setup was finished, the system ran without human input for 30 days. The only input was adding more water to the system. The main water circulating pump was implemented at the beginning, and the nutrient pump was added a week after to aid in the healthy growth of the plants. In addition, the team created a user interface that collects live data of the water level, nutrient level, and images of the plants. In order to ensure the system works on multiple species of plants, the prototype grew 6 lettuce, 4 spinach, and 4 basil plants. During the germination stage, 4 seeds were added into each cup net to create a higher chance of germination. Once the seeds are sprouted, only the healthiest one remains in the spot.

In the testing of our prototype, we kept as many aspects as possible consistent throughout the system. The timing of the grow lights were coded to be the same on all the plants. The same nutrient solution flowed through the PVC to reach all of the plants with a consistent flow rate. We were able to acquire data on the water consumption of the system, the nutrient consumption of the system, and the growth rate of a variety of plants. We grew basil, lettuce, and spinach from seeds in our system. Please note that as we are not very experienced gardeners, our produce may be different compared to a professionally grown plant. We continued to improve and automate the hydroponic system throughout the plant growth which may have accidentally shocked and damaged the plants.

Figure 1: Basil grown in our system (left) and professionally grown basil (right) (🌱 *Growing Basil Time*

Lapse - 40 Days in 1 Minute, 2020)

Both of the basil plants shown in figure 1 have been growing for approximately the same amount of days.

Figure 2: Leaf lettuce grown in our system (left) and professionally fully grown leaf lettuce (right) (*H-E-B | No Store Does More*)

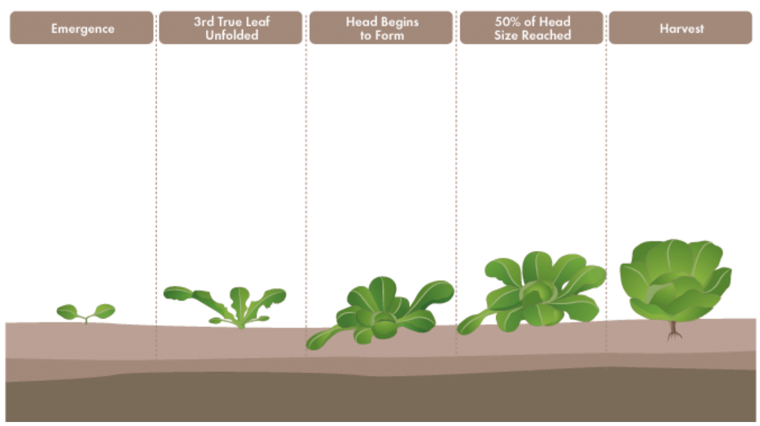

Figure 3: Stages in the Lifecycle of Lettuce (*ResearchGate*)

Figure 2 shows a comparison of our partially grown lettuce plant next to a fully grown plant that is sold in stores. When comparing these images to figure 3, you can see that our plant is at the third stage, head begins to form, while the professional plant is at the harvest stage.

Figure 4: Spinach grown in our system (left) and professionally grown spinach (right) (*Growing Spinach Time Lapse. 2020*).

In these images, our spinach plant had a few more days to grow compared to the professional.

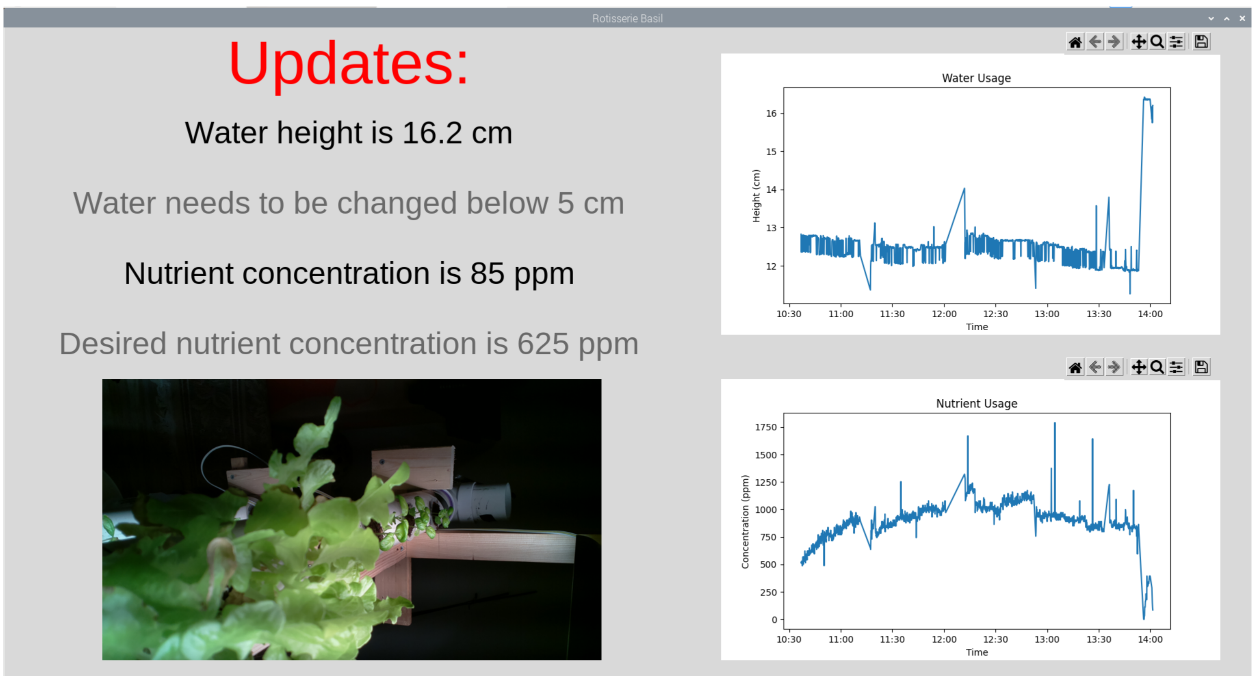

Figure 5: Screenshot of the user interface screen taken at the end of Design Day.

Throughout design day we had our automated system monitoring program running. This system collects data on the water height in the bucket, the concentration of nutrient mix in the solution, and captures images of the plant to monitor its health. The water height is found via an ultrasonic sensor attached to the top of the bucket holding the water. The sensor is aimed downward and measures the distance from the top of the bucket to the top of the water to calculate the water height. The nutrient concentration is found by measuring the conductivity of the solution. The more nutrient mix there is in the solution, the higher the conductivity will be. Due to time and budget constraints, our conductivity sensor was somewhat inaccurate as shown in the random jumps in the graph. As the overall trend is stable, we concluded that we can continue to use conductivity to measure concentration conditional on the final product having a higher quality sensor. Unfortunately, due to the poor quality sensor, it is difficult to draw conclusions from the nutrient usage chart. In the water usage chart, there is a clear downward trend throughout the data. The larger peaks can be attributed to people bumping into the system and jostling the water skewing the height measurement. The final 15 minutes on both charts can be ignored as this was when we were shutting down the system and preparing it for transportation.

Shown in the top left of figure 5 are the desired water height and nutrient concentration. Figure 6 demonstrates the text alert system that will notify the user if the measured values are not within the desired range.

Figure 6: Screenshot of text alert from system

Overall, our system did meet all of the Design Specifications that we listed in the DSM. The first design specification was to keep the cost around $200. Our starter kit is $250, and expansions are $40 which means that cost per plant for the starter kit with one additional layer (two layers total, with two sets of 7 plants per layer) is $10.36. A full system with 5 layers is $410 at $5.86 per plant. The cost per plant for our competitor AeroGarden is currently $21.67, which is about 2.1 times our price for a 28-plant system.

While a full system costs more than $200, we still beat the AeroGarden with a >50% reduction in price with just one expansion pack. It would be even more cost-effective for the customer if they decide to purchase more expansion packs and increase the size of the system to the maximum of 5 layers. Since the design is modular, additional tiers of grow trays are available for sale as needed. The next design specification is to design the system to not break or malfunction for reliability measures. The system held up well without any leaks, blockages, or malfunctions during the 45 day growth cycle.

Efficiency was not measured and calculated. However, based on the local Pepco electricity pay rate of $0.14/kWh, grow light consumption of 31 Wh/plant/day and pump of 12 Wh/plant/day, the total cost for a 45-day growth cycle is $2.94. This seems very reasonable for growing 14 plants in a 45-day period of time. Durability was also one of the parameters. The frame proved to be durable with surviving the transportation to and from Design Day and multiple people bumping into the frame at Design Day. The next design specification is automated/low maintenance. The Raspberry Pi and other electrical components ran smoothly without loud sounds and the user only had to add water to the system as needed. Lastly, improving production was also met with the modular design that allows the user to plant more than the competitor AeroGarden and horizontal systems.

Since the team started testing early, we were able to experience what a user would if they had the full system. Some changes that needed to be made are creating a housing unit for the electronics, making the system look more aesthetically pleasing, and hooking up the water line to the water reservoir to eliminate all necessary human interaction. For the prototype, the wiring and electronics components were exposed, which could lead to possible water damage and malfunction. Therefore, a housing unit is essential for the final implementation. The final system must also look well-made and for prospective buyers to consider purchasing it for use in their homes, as the aesthetics of the machine could be the most alluring part for certain customers, and for other customers aesthetics might only change their decision if our product is deemed an unwanted addition to their living space. Finally, having a water line connected to the system will increase the low maintenance and automated aspect of the system. Beginners will be more attracted to this feature than others because of their lack of experience and time.

There are very few human factor considerations that were not addressed in designing the system. As the hydroponic system is on wheels, everyone should be able to easily move it. Someone with limited arm mobility may have difficulty harvesting plants from the top layers of the full, 5 layer system, but if this is an issue, they can choose to reduce the number of layers to a height that is optimal for them. The other main user interaction aspect is adding water to the bucket as needed. The automated system will inform the user when this is necessary. Adding water is no more strenuous than watering normal plants thus it should not be an issue. Additionally, our product's intended users are young adults to middle aged people, most of whom do not have physical disabilities.

Finalized Human Factors Analysis & Testing

As stated previously, our hydroponic system was designed with low maintenance as a priority resulting in minimal user interaction. No design changes have been made since report 3 as we already took into account the fully loaded system with 5 double sided tiers. Assembly instructions will be provided with the kit which will include step by step instructions for the frame assembly, laying the PVC onto the frame, and attaching the various layers with the flexible PVC connector. This last step of attaching the flexible connector carries the greatest risk for human error as it is a mechanical connection. If the connection is not tight enough, the system will leak. To address this issue, the final step in the assembly instructions will be to test the system with just water before adding plants to ensure a watertight seal.

Our product was designed to have as little user interaction as possible, limited to only adding water when directed to, thus all users in our end user population are able to properly utilize our system. To confirm this, we had our friends and roommates interact with the system without issue. Assuming the users properly follow all set up directions, the system will function on its own with no issues as shown through our prototype.

Manufacturing Plans

Material Selection

The material selection for our project took a lot of time and consideration. There were many mechanical properties that we had to compare, but we had limitations. The design criteria and considerations that the materials had to conform to that may not be exactly mechanical properties included watertight, non-toxic, and sustainable. However, a large factor for us was the expense of the material since we were trying to create a low-cost system. For our prototype, we decided to use a wooden frame and PVC piping for the channels to hold the plants and to deliver water to the plants. These materials were easily accessible to us and affordable. Overall, the seven design criteria that we had to compare were: function, environment, shape, manufacturing, cost, aesthetics, and sustainability.

PVC (polyvinyl chloride) is a high strength thermoplastic. Below are figures that show the different mechanical properties of PVC piping and how it compares to other materials.

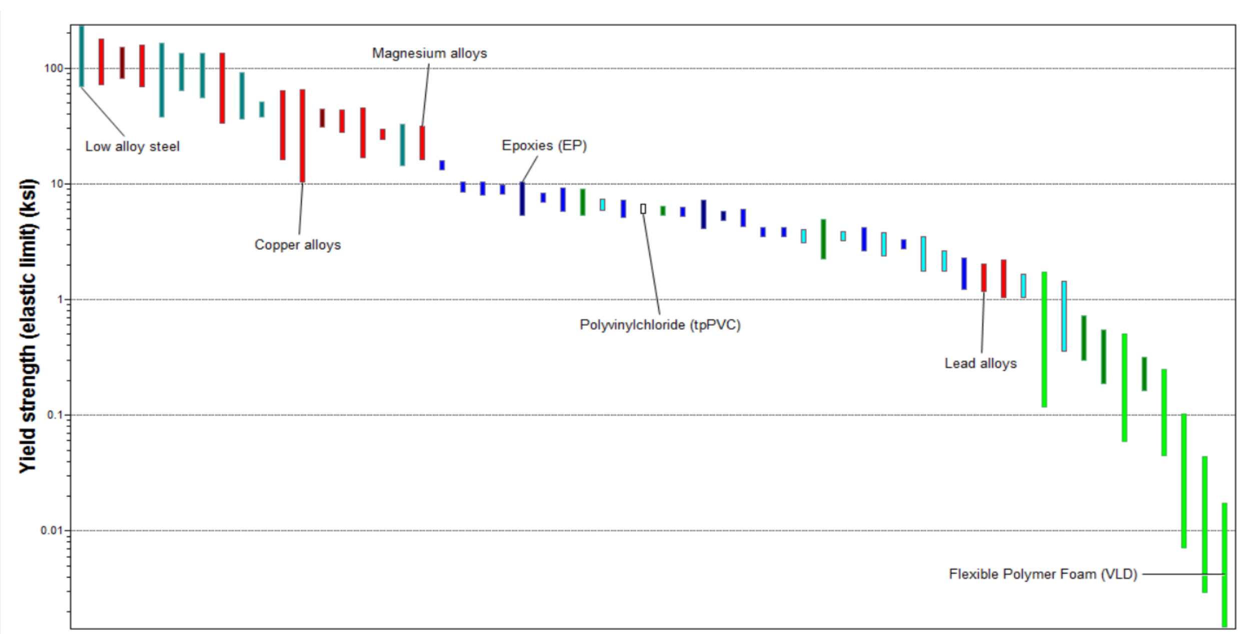

Figure 7: Yield Strength of different materials compared to PVC

The first mechanical property that we had to assess was the yield strength. The yield strength is important in representing how much of a load can be applied to an object. Yield strength is a significant property to consider because when the stress is greater than the yield strength, then deformation of the object would be the result. For our project, this property is important because we needed the channels that the water flowed through to be able to sustain the force of gravity without deforming. Since PVC has a yield strength of 8.0 KSI, we knew that the piping would not bend with the amount of water in the pipes and the weight of the plants in the soilless mixture.

A trade off that we had to consider with this property was the fact that when yield strength increases, the N-value decreases. This means that the increase in the hardening modulus cannot increase at the same rate as the yield strength.

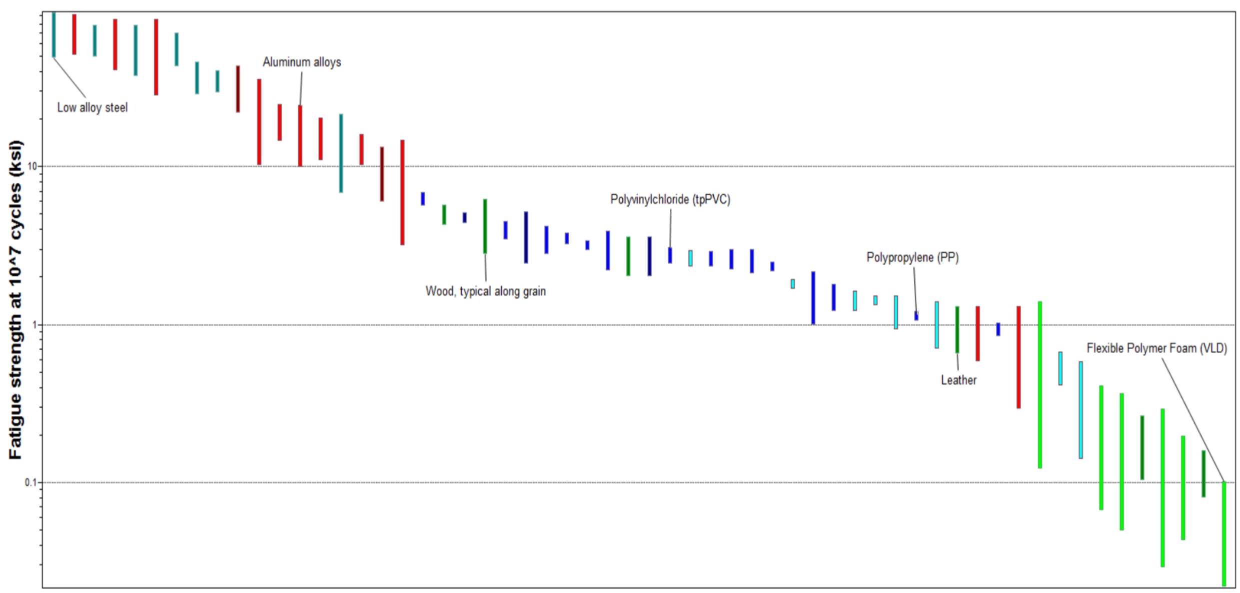

Figure 8: Fatigue strength of different materials compared to PVC

The next property that we had to assess for our project was the fatigue strength of the material. Fatigue strength is measured as the greatest amount of stress that a material can withstand for a given number of cycles without breaking. If the fatigue strength of a material is not large enough to sustain itself for the anticipated cycles that the product would have to endure, then the product would break. Since our system would have to be running constantly with the water cycling over and over, we knew this was an important property for the channels of PVC piping. PVC has a fatigue strength at 10^7 cycles of 7.0 KSI. This value is more than enough to withstand the forces that the water will exert on the system for 24 hours a day.

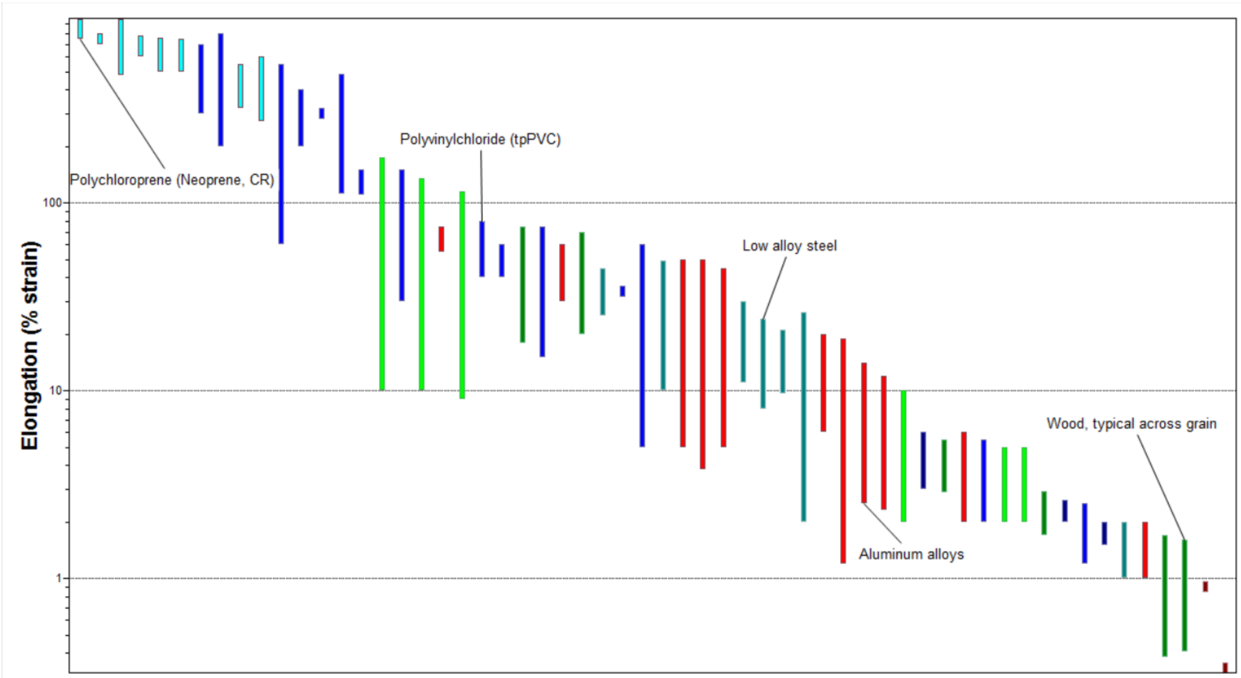

Figure 9: Elongation of different materials compared to PVC

Elongation is the measurement of how much a part is stretched while strain is the ratio between the deformed length to the starting length. In other words, this value quantifies how much a material will plastically and elastically deform up to a fracture. Materials with low elongation are brittle and will break in tensile testing since they tend not to plastically deform. Materials that are more ductile tend to have greater elongation and will deform before breaking which makes this more suitable for our product needs. We needed this value to be high enough to prevent any breakage in our pipes even if there was deformation. PVC piping provides us with enough tensile strength to support the forces exerted and has a great enough elongation value to withstand additional forces to be able to bend before fracturing.

A tradeoff to having this have a high value, means that the material may deform which would certainly impact the functionality of the apparatus.

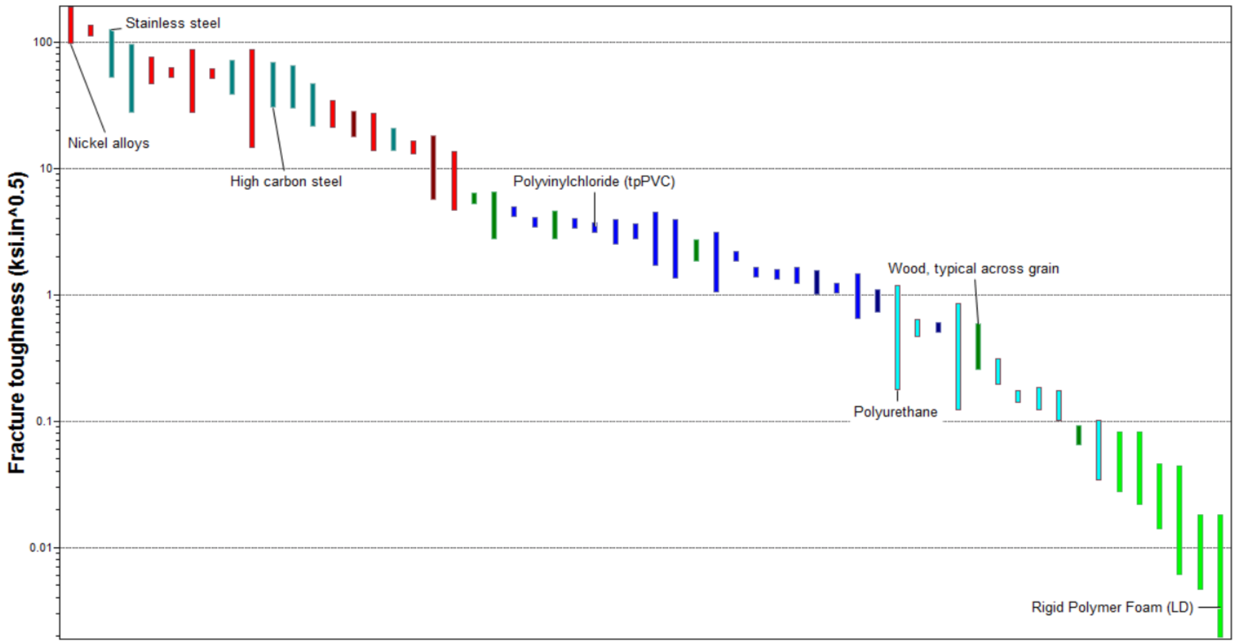

Figure 10: Fracture toughness of different materials compared to PVC

Fracture toughness is a measurement that quantifies the materials capacity to resist fracture when there is a flaw in the material. During the processing and fabrication of the material, it is nearly impossible to create a material without any flaws. It will be inevitable that there will be cracks, voids, and defects in the tubes that we plan to purchase. We have to analyze the fracture toughness to determine if the material we choose, flaws included, will be able to withstand the forces if there's a deformity in our material. This is a property that actually includes the flaws of the material while the other values do not account for that. By referencing the table above, PVC has a relatively high fracture toughness so we knew that the flaws in the PVC piping would likely not cause a problem for our prototype.

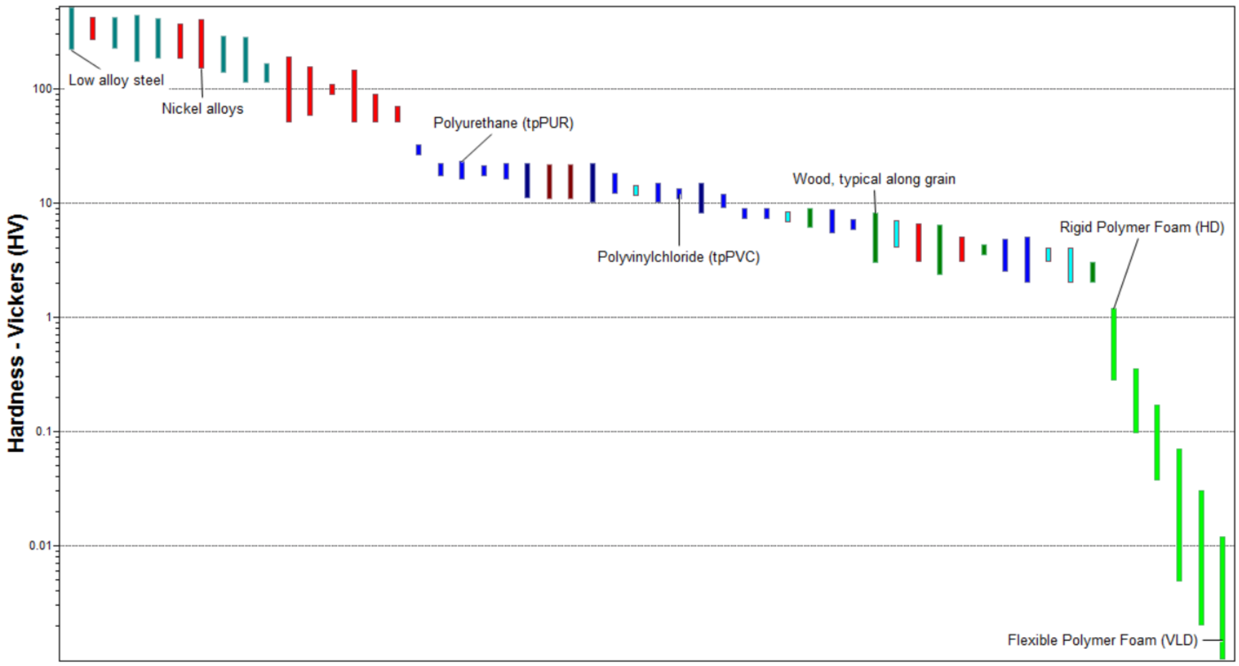

Figure 11: Hardness of different materials compared to PVC

Hardness is the value that quantifies the resistance of a material to deform. For our project, we needed all components to keep their form to maintain the functionality of the prototype. Even though as discussed above, that we need a material that would deform over fracturing was an important property, the ability for our prototype to maintain its shape is just as significant. By looking at the figure 11 above, PVC has a hardness level greater than 10 HV. Notice that this chart is logarithmic so the values are more spaced out as opposed to the scale being linear. However, PVC has a hardness level that is hard enough to maintain its shape for the amount of force that our prototype would endure.

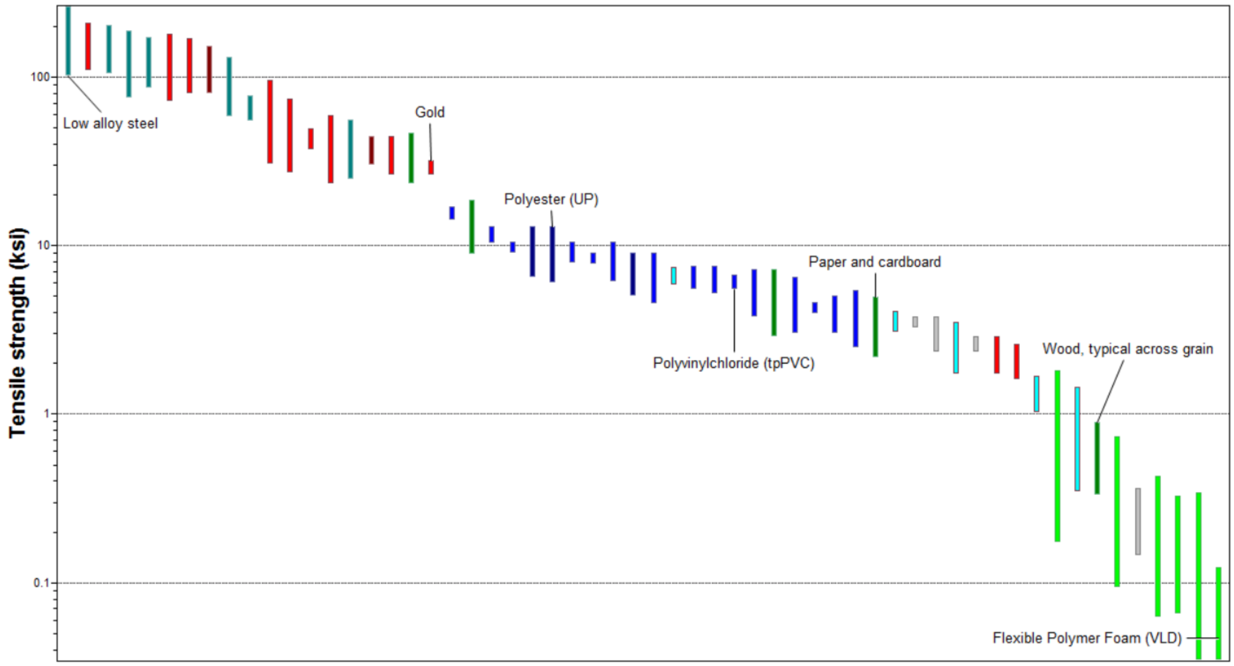

Figure 12: Tensile Strength of different materials compared to PVC

Tensile strength is the maximum load that a material can support without fracture when being stretched and divided by the original cross-sectional area of the material. In other words, this value represents the minimum tensile stress needed to split apart the material. Tensile strength is also an important property to determine mechanical performance. We needed to know this value to determine if our components would break during testing or not. Since the tensile strength of PVC is about 7 KSI, we knew we would be able to have our prototype running without the tubes failing.

Figure 13: Young's Modulus of different materials compared to PVC

Young's modulus is the quantity that is the measure of the ability of a material to resist changes in length when under a lengthwise tension or compression. Our prototype had areas where this property was important to analyze. PVC has a large enough Young's Modulus to maintain its shape under compression for our apparatus.

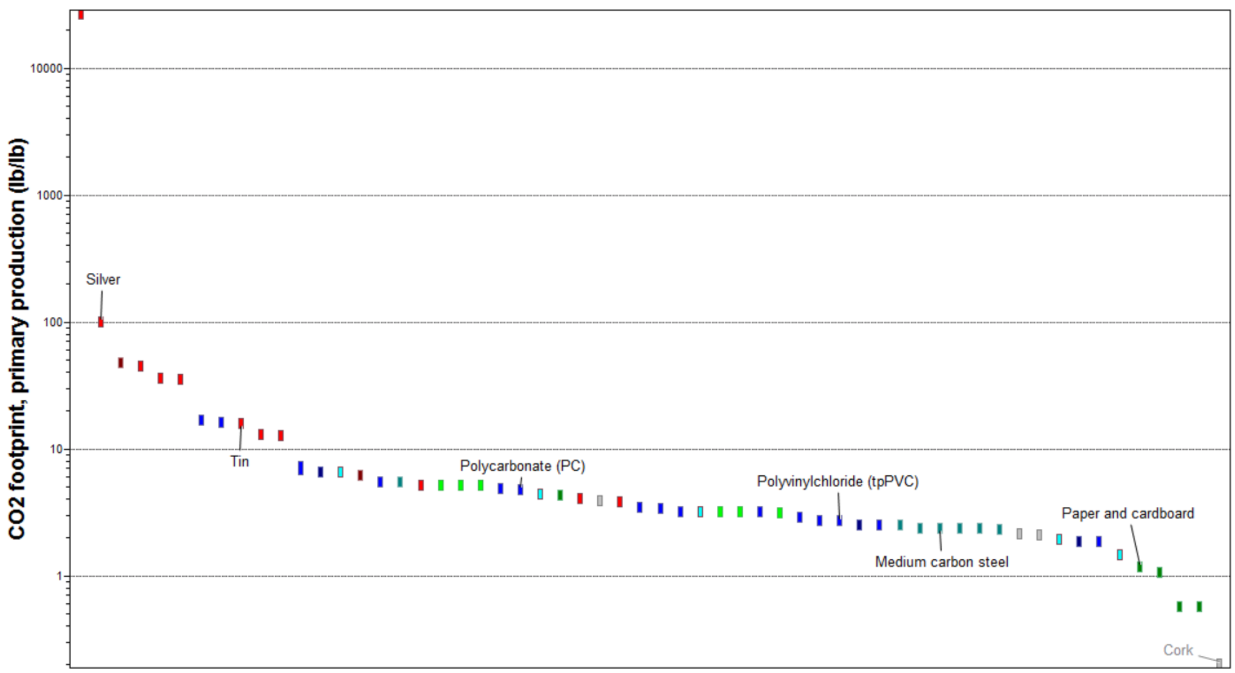

Figure 14: CO2 footprint of different materials compared to PVC

The increasing levels of CO2 in the atmosphere is a global concern and manufactures and businesses need to do their part in protecting the environment. The buildup of greenhouse gasses have disproportionately tipped the Earth's energy balance which has resulted in trapping additional heat and increasing the Earth's average temperature. The changing temperatures are increasing at a rate too rapid for the ecosystems to adapt so the impact has created adverse effects.

In figure 14, the CO2 footprint for the production of the materials is charted. PVC is on the lower end of the CO2 output so this made this material more eco-friendly. A goal of our product was to help us figure out a way to propagate as many vegetables as possible to combat food scarcity. With this goal in mind, we wanted to create the most eco-friendly and sustainable project possible. We looked into buying used PVC pipes to reduce our carbon footprint. There are companies that do sell used PVC piping so this could be a way that we could take advantage of to reduce our carbon footprint, and on a large scale would ultimately protect the environment.

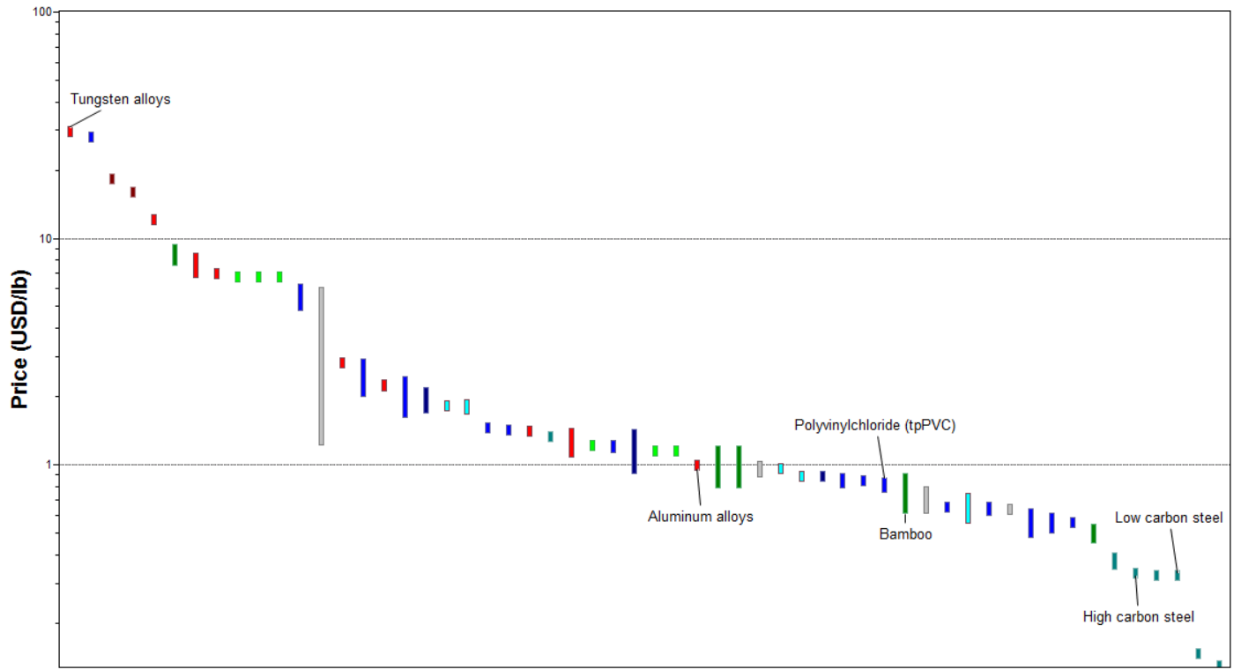

Figure 15: Price of different materials compared to PVC

The price of the material was one of the most significant limitations when choosing a material. Since we were trying our best to create an affordable hydroponic system, we had to keep the costs down wherever we could. Our PVC pipes that were the largest and most expensive were $8.97. Even though the components added up quickly, this was a reasonable enough quantity for us to be able to afford and construct a prototype.

Materials can be classified into four main groups: metals, polymers, ceramics, and composites. Ceramics are too brittle so any advantage that these materials would have is a tradeoff to the obvious fact that it might shatter with an outside force exerted onto it. Since we already looked at a polymer, let's look at a metal. Another material that we could have selected for our prototype was stainless steel. Stainless steel is an iron alloy. Below is a table with some of the most important mechanical properties that we compared.

Mechanical Property	English Units
Hardness, Vickers	129
Yield Strength	312 KSI
Elongation (% strain)	70 %
Tensile Strength	732 KSI
Modulus of Elasticity	28000 KSI

Mechanically, using stainless steel would have been a viable option, however, a tradeoff to using a material stronger is that being able to customize the components would have been significantly more difficult. We were able to cut the PVC pipes with a saw to customize them. This flexibility allowed us to easily adjust the pieces that were too long. We would have had less flexibility using a stronger alloy such as stainless steel. Even though the material is stronger and more durable, this does not offset the fact that we would have limited in the customizability with steel. This is where the shape of the design and the material selection of our prototype mattered. We wanted to work with a material that we could adjust relatively easily without having to use expensive or dangerous machinery to customize our parts. PVC piping worked perfectly for this target.

Another design consideration that cannot be found by looking at the mechanical properties is how the prototype interacts with the environment. This goes back to the customer requirements and the engineering characteristics. As we have discussed in previous reports, the hydroponic system should not have an impact on the outside environment. This function encompasses the environment in a sustainability sense and also the surrounding environment of the system. In the sustainability sense, the system should not produce large amounts of nutrient-contaminated wastewater. In terms of the room the system is set up in, it should not cause noticeable changes or issues. Our system has to be water tight and not allow water to get all over the inside of someone's house/apartment. Properly assembled PVC pipes are watertight so we were effectively able to carry out this criteria.

The manufacturing process will be discussed later in this report, but the process of manufacturing PVC is quite difficult. PVC polymer is made by taking a chemical called vinyl chloride monomer (VCM) and it is then polymerized. This means that in the manufacturing process, the VCM reacts with itself repeatedly. The result is a long molecular chain which is the polymer or plastic.

Making VCM is complicated. By reacting ethylene and chlorine together, ethylene dichloride (EDC) is produced in a process called chlorination. The ethylene is then pumped into a reactor where the temperature must be below freezing.

The second part of the process is called oxychlorination. By having the two processes, chlorination and oxychlorination, there is very little material lost through the process. The EDC must then be converted into vinyl chloride (BCM). Cracking EDC in the furnace involves heating the EDC in a furnace. The EDC is split into VC and hydrochloric acid. The VCM can decompose further. Quenching must be done to ensure that the heat does not degrade the VCM. The VCM coming out of the furnace is quickly removed. Water is used for cooling during quenching and during the cooling process. Chlorination requires large quantities of water. Water is held in cooling units and then recirculated into the process. Purification is the step where the VCM is purified in distillation columns and then piped for storage in large metal containers.

Polymerization of the VCM is carried out in a reactor called an autoclave. The autoclave is filled with VCM and water then heated. This is where the VCM reacts to turn into a polymer. The contents of the autoclave then undergoes stripping. The usable product is separated from the unusable parts. The usable part then continues through the manufacturing process to a step called centrifuging. The PVC is a slurry. It must be dried which is done next. Once the drying is complete, it is a white powder. The powder is sent to a giant, shaving sieve and the quality of the material is assessed. The white power is then cleaned with water to ensure there is no waste. Once the water is removed, the PVC is ready to be made into pipes.

Since the manufacturing of PVC is so difficult, if we were to bring this product to market, we would not manufacture the pipes in house. It would be far easier to just buy the pipes. Overall, the PVC piping provides all the functionality that we need from the channels and is an aesthetically pleasing part of our prototype that makes it look clean and crisp.

Manufacturing Process Selection

For our custom steel frame, multiple metal manufacturing processes are potential candidates including but not limited to: casting processes such as permanent mold casting or powder metallurgy, material removal processes such as machining (milling), deformation processes such as sheet metalworking (bending, drawing, shearing), and joining processes such as welding (MIG, TIG, and stick welding). We selected MIG Welding (spray transfer) as the manufacturing process for the custom metal frame.

MIG Welding Spray Transfer

Metal Inert Gas Welding is a simple and inexpensive process for middling production needs, with relatively low initial costs, making it ideal for the product. In the process, a metal electrode (fed through wire) and workpiece create a heat generating arc between them that consumes the electrode. When applied to the metal the heat forms a weld pool in the region heated above the steel's melting point into which the melted electrode fuses and welds the metal together. The selected transfer mode, which is the method by which the electrode metal gets to the weld pool is spray transfer, when the molten steel is sprayed, within the metal wire's diameter, into the weld pool in droplets ("What is Gas…", 2022).

Based on the volume of manufacture expected, we should utilize multiple MIG welding stations in an assembly line, with multiple welders working on different stages of the frame at a time. Other equipment for this stage of the manufacturing process (welding) includes heat/eye protection equipment for welders, metal wire to feed through the MIGs, and quality testing machines (stress etc).

Design Guidelines include, but are not limited to:

1. Metal Thickness: Our design thicknesses of 0.125 in and 0.0625 in are well within the required thickness recommendations for MIG welding (Holdheide, 2020).
2. Threshold Current/Voltage for Spray Transfer: Spray transfer requires a minimum current of 150-175 amperes, and a minimum voltage of 24 volts to properly set the welds (Nguyen, 2021).

3. Fillet Radius: Overwelding occurs when the fillet radius is improperly gauged with the metal thickness, and too much metal is deposited into the weld pool. This can cause distortion and potential failure. For our design thicknesses, a fillet radius of no more than ¼ in should be used (Kapindula, 2020).

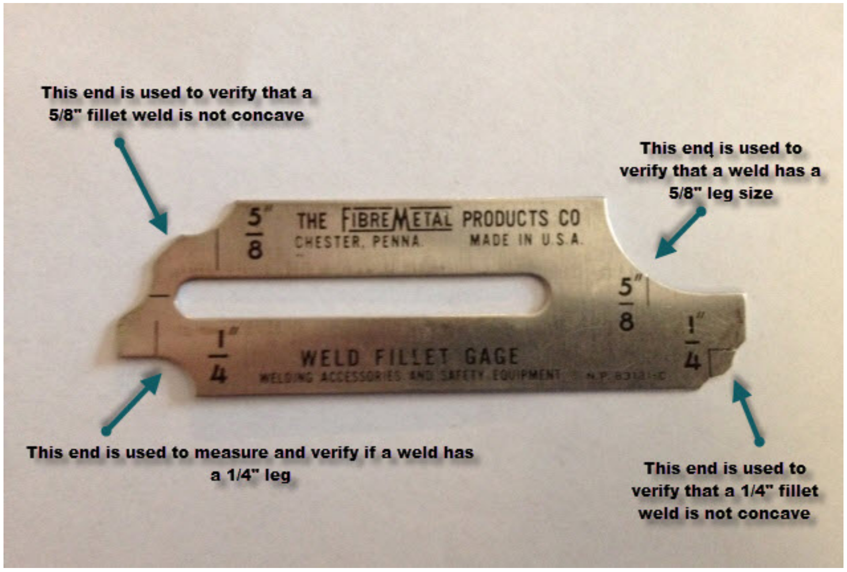

Figure 16: Weld Gauge used to prevent overwelding

4. Wire Size: The wire size is equivalent to the diameter of the spray transfer, and is proportional to the fillet radius, but also requires a certain amperage when scaled up. Our desired wire size can be selected as 0.030 in to ensure sturdy welds given the thin steel we will be welding. Based on that thickness our operating amperage is within range, with an upper cushion to accommodate for increased amperage during use (amperage changes alongside the wire feed speed) (Nguyen, 2021).

Wire Size	Amperage Range
0.023 inch	30 – 130 amps
0.030 inch	40 – 145 amps
0.035 inch	50 – 180 amps
0.045 inch	75 – 250 amps

Figure 17: Wire Size and Amperage (Nguyen, 2021)

In our design, 1/8 in thick steel caps are welded to 1/16 in thick steel tubes. Both steel thicknesses satisfy the minimum constraints for MIG welding with spray transfer. In addition to design constraints for the manufacturing process being satisfied, the rectangular cross sectional structure of our design would also allow the implementation of minimized welding, where the weld is not continuous, but used in a few stress concentrated locations, which will result in an even more inexpensive process.

Assembly Procedure

The hydroponics system will be shipped in various parts to be assembled by the user. These include parts of the steel support frame, PVC tubes, electronics, pumps, and housing components. The steel frame will come in pieces that need to be assembled and bolted together. The bolts come with the set and are inserted into pre-drilled holes and tightened into attached weld nuts with an allen wrench. The light bars will also be bolted to the frame, specifically the underside of each crossbar. Once the frame is fully assembled, the user can start adding the PVC piping that will house the plants. The user will receive a few different types of PVC components. All cemented joints will already be assembled and the user will be able to put the system together using only the flexible collars. There are two different versions of the main PVC grow tube. Each grow tube will have holes for the plants pre-drilled. There is the standard version with two elbows and two vertical risers, and the version for just the bottom tier, which will have the additional elbows and downspout to safely drain the water into the reservoir. Both versions of the tubes will function as one side of one tier of the system, and will have an elbow connected on each side, one angled upward and one angled downward. The vertical riser will be attached to the other end of the elbow. Flexible connectors, included in the kit, are used to connect two verticals and will be tightened via an included socket key. The PVC module rests on the arms of the support frame. Vegetables are planted into a substrate of the user's choice (coconut coir is recommended and supplied with the system), which is added into the net cups provided. The long plastic tubing included connects to the large pump, and is used to transport the water from the reservoir to the top of the system. The top of the tubing is attached to and goes through a PVC end cap, which the user will place on top of the uppermost vertical riser, preventing it from falling out and spilling the circulation water. The water reservoir included sits below the PVC downspout at the bottom of the base grow tube. The electrical box is attached to the base of the system next to the water reservoir. The large pump is plugged into the electrical box, which plugs directly into a wall outlet. The lights will be attached to the light bars and plugged into the electrical box. Water can now be added to the reservoir, filled to the line. If the user wishes to add nutrients, they can connect one end of one of the small plastic tubes to one end of the small pump included. The second small plastic tube connects to the other end of the small pump and is inserted into a nutrient solution. The small pump's electrical wire connects to a second port on the electrical box. The concentration of nutrients will be determined by the system after the user enters in the type of seeds planted and the planting date. It is recommended that the user test the system to ensure everything is working properly. To do this, the user should turn all of the electrical components (lights, pumps, etc) on and cycle some water through the system to make sure the water is flowing smoothly and there are no leaks before leaving the system alone. These steps will be listed in more detail along with graphics illustrating each step in the user manual included in the package.

Product Cost

An individual unit cost of a product can be determined by the equipment cost (negligible here), the tooling cost, the material cost, the labor cost, and assembly cost (negligible too due to the assembly being the responsibility of the user). We based our cost analysis on expected sales revenue over the first five years, to ensure that money spent on initial manufacturing set ups will not be tied to lower production than is occurring after the product has been on the market and grows in popularity and demand.

The startup costs of putting our product on the market will be the largest obstacle and will be the most expensive. Some of the expenditures that we would have to consider include:

- Location for manufacturing
- Hiring an engineering team
- Hiring a business team
- Buying all the materials needed
- Setting up a software/website
- Buying all he machinery
- Marketing and advertising
- Insurance
- Licences for starting a business

Once we establish our business and the startup costs are covered, we can start looking at the product and how much we could sell it for. Based on a standard of 40% reduction in cost for bulked ordering, the material cost of producing 10,000 units (sales estimate) would be 10,000*(250*0.60) which equals $1,500,000. The $250 per unit cost is estimated by adding a 20 dollar adjustment to the prototype cost to adjust for the metal frame.

The tooling cost can be estimated as the price of each welder needed. This makes the total tooling cost 850*10 which equals $8,500 ("Unlimited…", Harbour Freight Tools).

The labor cost (assuming a lack of engineering interns available) should be gauged alongside the sales revenue, averaging around 20-35% of total revenue (20% is assumed here) (Osman, 2021).

10,000 units sold at a product cost per unit of $250 yields a total revenue of $2,500,000, which can be used to inform a total labor cost of $500,000. Summing the costs $1,500,000 + $8,500 + $500,000 leaves a total expenditure of $2,008,500 and profits of $491,500.

As the company becomes more successful and we establish ourselves as a reputable hydroponics company with a quality product, the need to keep up with the market would arise and we would be able to sell more products. With this we would also have to hire on more engineers to continue to improve our products and propel our ideas into a growing market, increasing the percentage of revenue utilized on labor. Our goals would be to increase production rates of the hydroponic system, lower the cost of the system, and to be more interactive with the user.

With these tactics, we will be able to see our sales increase each year. With a starting point of 1000 the first year, we optimistically hope to see an increase to 1500 the following year and then 2,000 the next. At this rate, 5,500 more units would need to be sold in the combined fourth and fifth year to match the cost analysis done above, which is reasonable if 2000 a year is hit in year three. With the startup costs covered, the business would be able to see revenue grow in the long term as it diversifies.

Quality Plan

This quality plan is intended to verify the quality of the frame components throughout the manufacturing process. Incoming stock will be verified for dimensional accuracy and expected minimum strength requirements. Specific components will be randomly selected during the manufacturing process as well, to check for dimensional accuracy and weld integrity. After manufacturing is complete, there will be another round of testing to again ensure dimensional accuracy and weld integrity. Randomized testing will also be performed on the finished products, including assembly to verify that the individual components fit together properly. Lastly, lifecycle testing will be performed using accelerated weathering followed by strength testing.

Incoming stock inspections will be conducted on 100% of incoming raw materials by quality control personnel. Due to the modest production quantities we expect and the safety-critical importance of the material meeting specifications, this intensive testing was deemed necessary. Dimensions will be checked against the specifications and corrective actions will be taken with the supplier to resolve any out-of-spec stock. Obviously, the out-of-spec stock will not be used to build frame components. Additionally, test sections of a portion of incoming stock will be tested for mechanical properties in a standard series of destructive bending and tensile tests. Failure to meet minimum specifications for strength will again result in corrective actions being taken with the supplier of the stock.

During the manufacturing process, the dimensions of the cut pieces of stock will be checked by automated vision systems before the component parts are welded together. Things such as overall length and location and sizing of holes will be verified, and any out of spec components will be discarded. The cutting and drilling operations will be performed by machines, so a high failure rate will result in that particular machine being taken out of service temporarily for recalibration.

After the manufacturing process, all parts will be checked again using an automated visual inspection system to ensure dimensional accuracy of the final welded parts is within specifications, allowing the parts to properly fit together when assembled. Out of spec parts will be discarded. Welding will be performed manually, and a small portion (1%) of each fabricator's parts will be destructively tested during each shift to ensure weld integrity. These parts will be randomly selected with a greater frequency occurring in the beginning and end of the shift. Testing will be performed by quality control personnel, and any parts that fail the testing will result in all the parts produced by that fabricator during that shift being discarded.

Final product inspections will be conducted on a small percentage each lot of assembled kits of parts awaiting final packaging. The kits will be fully assembled by technicians to verify that the parts fit together as expected and will not cause any issues for the end used. The kits will also be checked for the correct amounts of each of the components, including the extra hardware that will be included in each kit. Any parts that don't fit together will result in all the parts in that lot being set aside, and they will all be assembled to identify all the faulty units. The defective components will be swapped out if possible, and the repaired kits will be disassembled and packed back up before being shipped out to customers.

Accelerated life cycle testing will be conducted on a small portion of outgoing units. The units will be assembled, then subjected to enhanced aging with the use of a salty, high moisture environment. The weathered units will be tested with load testing at 4 times the expected design loads. The critical frame components have safety factors of 6.6, so failure 4 times the expected load will result in examination of that lot of finished parts to identify and scrap units with defects that may have caused the failure seen in the test unit.

This quality plan will ensure that customers receive a safe, functional, and durable product, and minimize warranty claims, customer complaints, and missing or replacement part requests.

Engineering Documentation

Parts List & Bill of Materials

Part Name	Standard/Custom	Model #	Supplier	Material(s)	Manufacturing Technique
Straight PVC Pipe (2in)	Standard	531137	Home Depot	N/A	N/A
PVC 90 Degree Elbow (2in)	Standard	4807VHD2	Home Depot	N/A	N/A
PVC 90 degree street elbow (2 in)	Standard	PVC003021000HD	Home Depot	N/A	N/A
Rubber PVC Coupling	Standard	159-22	Home Depot	N/A	N/A
PVC 90+ degree connector	Standard	C4807VHD2	Home Depot	N/A	N/A
Flexible PVC Connector	Standard	P1056-22	Home Depot	N/A	N/A
Water Circulating Pump w/ 1/2" ID x 5/8" OD Clear Vinyl Tubing	Standard	03-01-1249	HiLetgo	N/A	N/A
Nutrient Pump	Standard	LYSB01IUVHB8E-ELECTRNCS	Esooho	N/A	N/A
Water Resevoir	Standard	AX-AY-ABHI-76585	Ropak USA	N/A	N/A
Arducam 5MP Camera for Raspberry Pi	Standard	B0033	Arducam	N/A	N/A
Flex Ribbon Extension Cable for Raspberry Pi Camera	Standard	B07J57LQQS	A1 FFCs	N/A	N/A
Raspberry Pi 4	Standard	4	Raspberry Pi	N/A	N/A
Coconut Husk	Standard	13126	Burpee	N/A	N/A
Net Cups	Standard	B096RYD71Y	Siyan	N/A	N/A
Conductivity Sensor	Standard	KUIDAMOSbxwehk62zy	KUIDAMOS	N/A	N/A
Ultrasonic Sensor	Standard	B07B94C7KT	XiaoR Geek	N/A	N/A
High Voltage Relay	Standard	B00E0NTPP4	SunFounder	N/A	N/A
L298N Motor Driver	Standard	CECOMINOD012186	Qunqi	N/A	N/A
Grow Lights	Standard	INWT504014650Dc	Barrina	N/A	N/A
3" x 1.25" Red Swivel Caster Wheels	Standard	LDPPS3X125RG	CasterHQ	N/A	N/A
Frame	Custom	N/A	N/A	Steel	Purchase hollow, rectangular steel tubing Weld on tabs with pre-drilled holes User assembles the frame with provided bolts

Bill of Materials: Starter Kit

Part Name	Quantity	Standard/Custom
Base PVC Section	2	Custom
2 in PVC Cap	2	Standard
Water Circulating Pump w/ Tubing	1	Standard
Nutrient Pump	1	Standard
Water Reservoir	1	Standard

Arducam 5MP Camera	1	Standard
Flex Ribbon Cable Extension	1	Standard
Raspberry Pi 4	1	Standard
Ultrasonic Sensor	1	Standard
Conductivity Sensor	1	Standard
High Voltage Relay	1	Standard
L298N Motor Driver	1	Standard
LED Grow Light	1	Standard
Net Cups	14	Standard
Coconut Husk Pellets	42	Standard
Concentrated Nutrient Solution	1	Standard
Floor Bar	2	Custom
Floor Crossbar	1	Custom
Short Vertical Base	1	Custom
Long Vertical Base	1	Custom
Short Vertical Top	1	Custom
Long Vertical Top	1	Custom
Light Bar	1	Custom
Tube Hanger	2	Custom

Bill of Materials: Expansion Pack (One Extra Layer)

Part Name	**Quantity**	**Standard/Custom**
Normal PVC Section	2	Custom
2 in Flexible Rubber Coupling	2	Standard

LED Grow Light	1	Standard
Light Bar	1	Custom
Short Vertical	1	Custom
Long Vertical	1	Custom
Tube Hanger	2	Custom
Net Cups	14	Standard
Coconut Husk Pellets	42	Standard

Engineering Drawings

Engineering drawings for the standard components were deemed unnecessary, as they will not be manufactured or modified in any way. Models and drawings were created for the ten custom frame components and two different pieces of PVC pipe required. The PVC pipe sections will be made from standard 2 inch Schedule 40 PVC. The steel frame components will be made from five different standard profiles of hollow rectangular steel tubing, all with 1/16 in. wall thickness. The profiles required are 1.5 x 0.75 in., 1.25 x 0.75 in., 0.5 x 0.75 in., and 0.5 x 1.25 in, and 1.125 x 0.625 in. These pieces will be shipped disassembled and put together by the user with 0.25 in. machine screws of appropriate lengths, using welded tabs of 0.125 in. thick sheet steel and 0.25 in. weld nuts that will be attached at the fabrication facility.

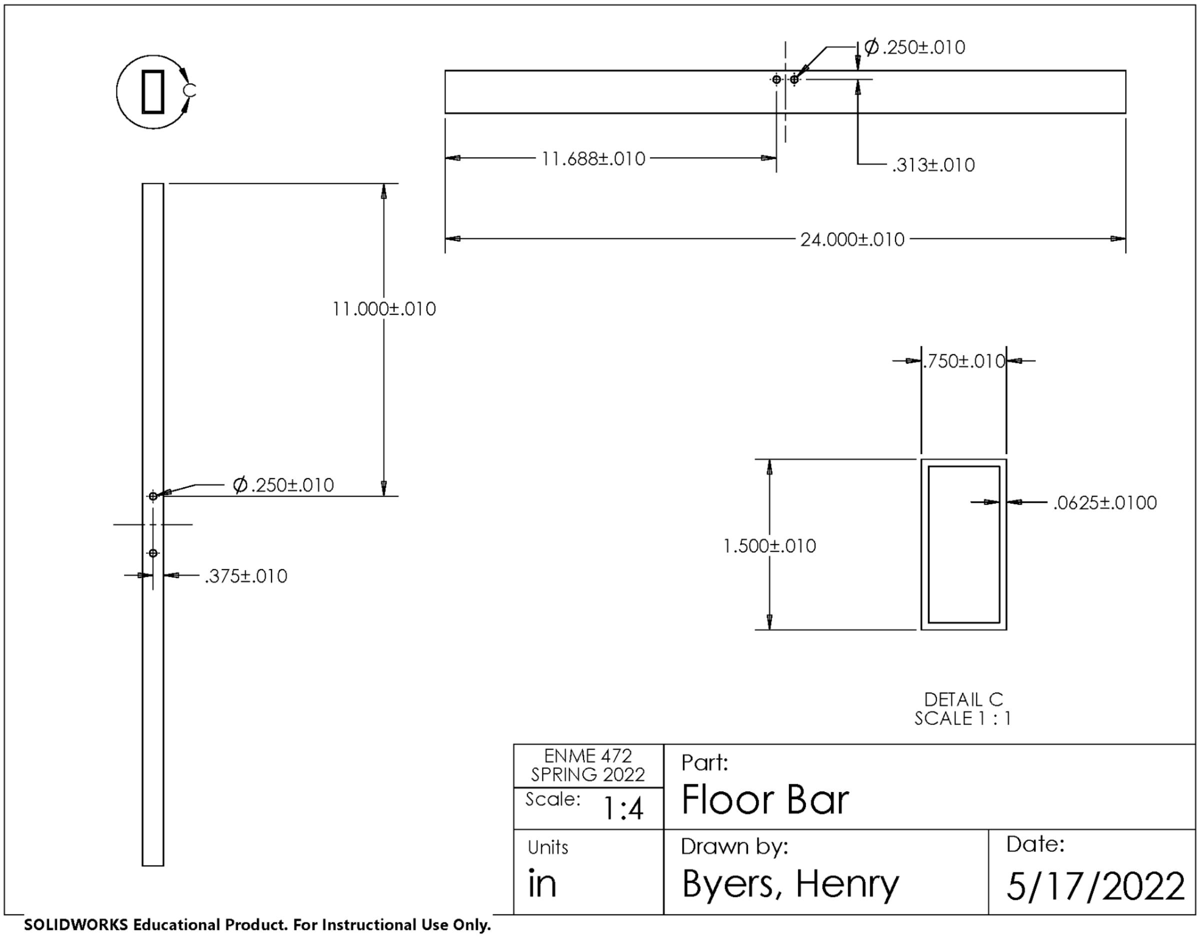

Figure 18: Engineering drawing for the floor bar component

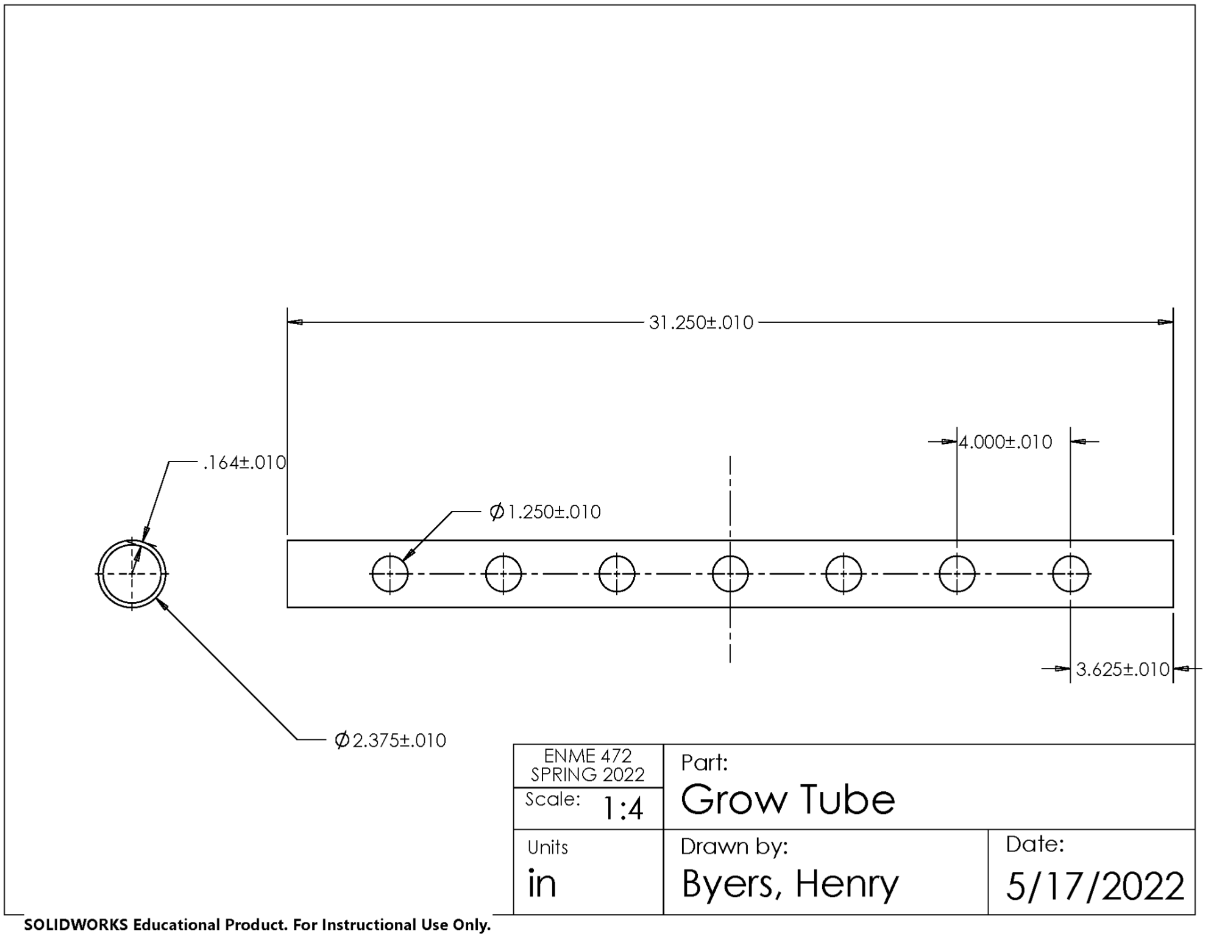

Figure 19: Engineering drawing for the PVC grow tube component

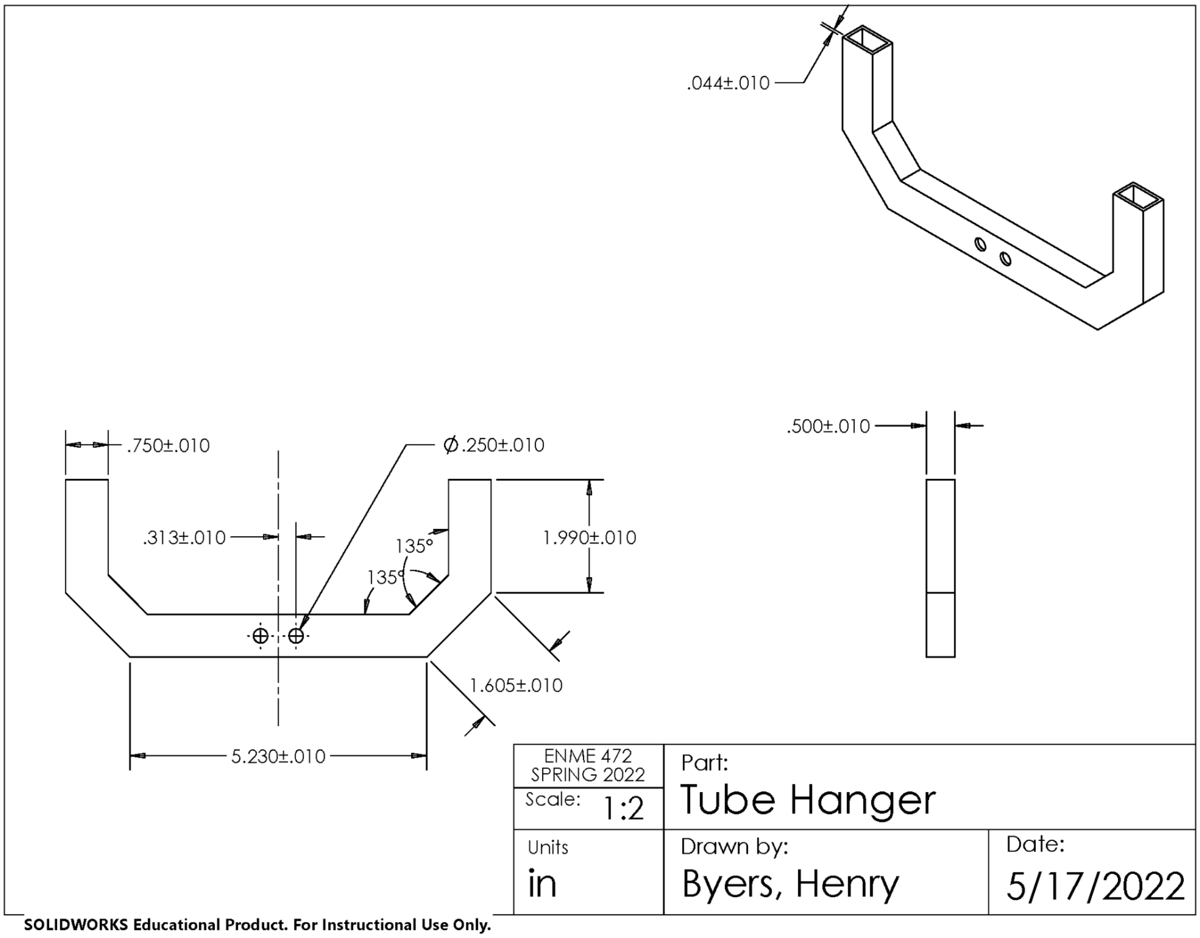

Figure 20: Engineering drawing for the PVC grow tube hanger component

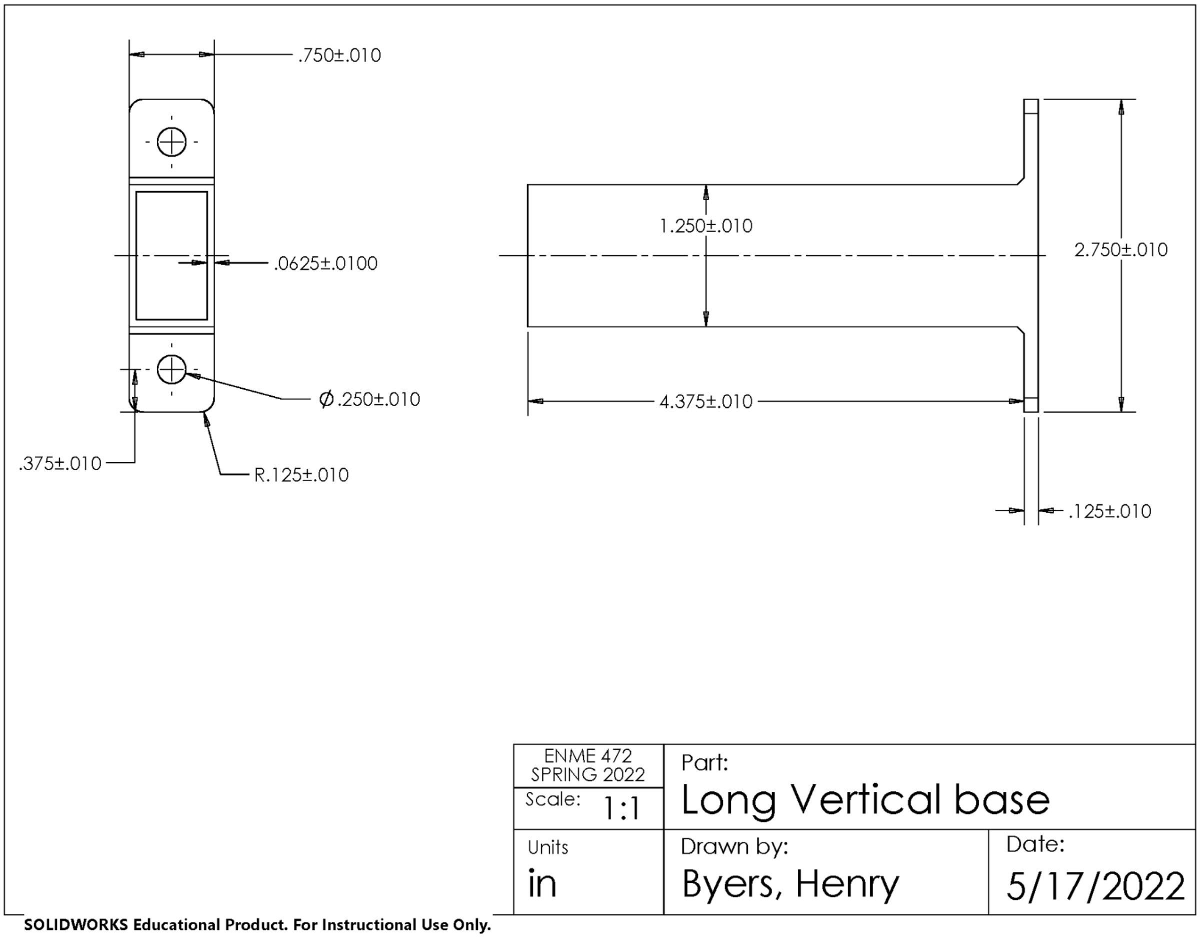

Figure 21: Engineering drawing for the long vertical base frame component

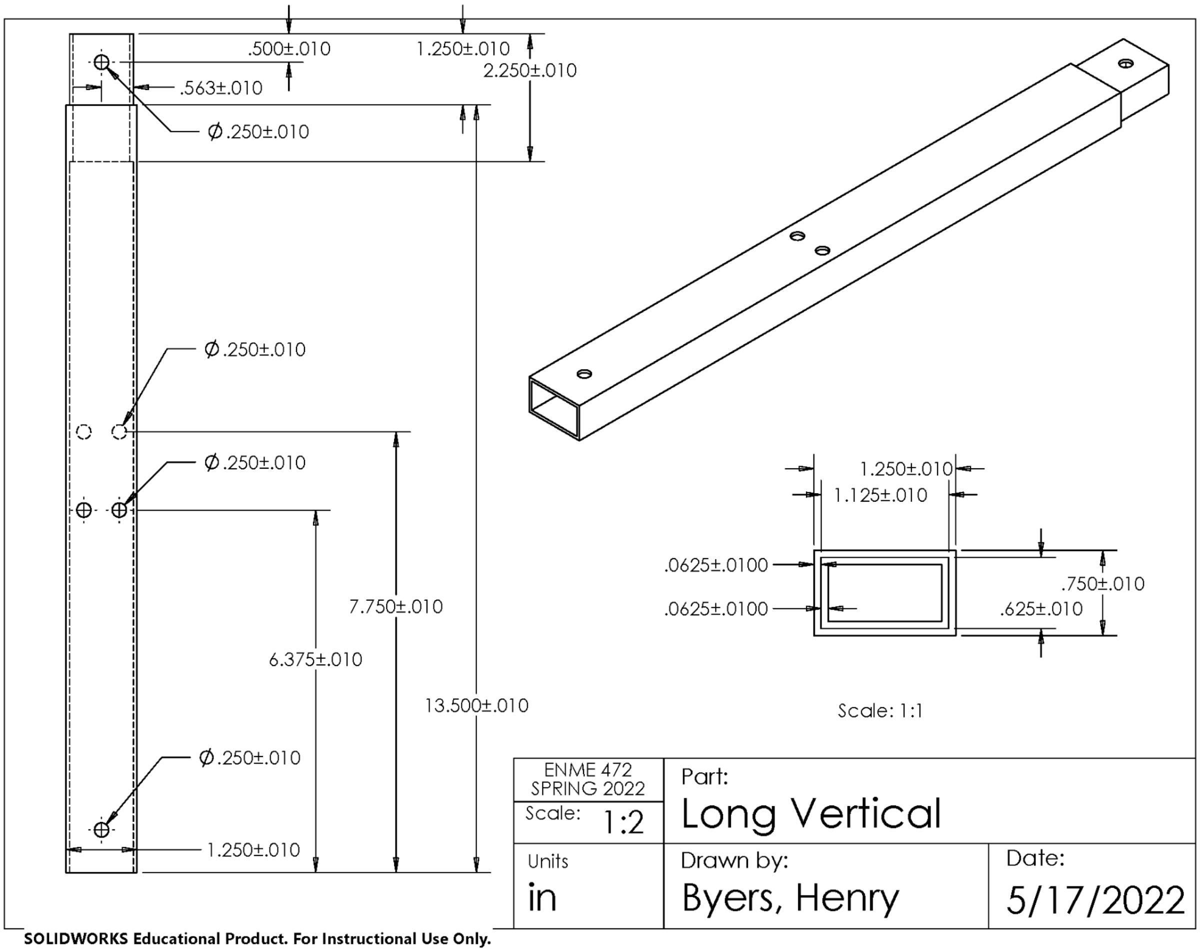

Figure 22: Engineering drawing for the long vertical frame component

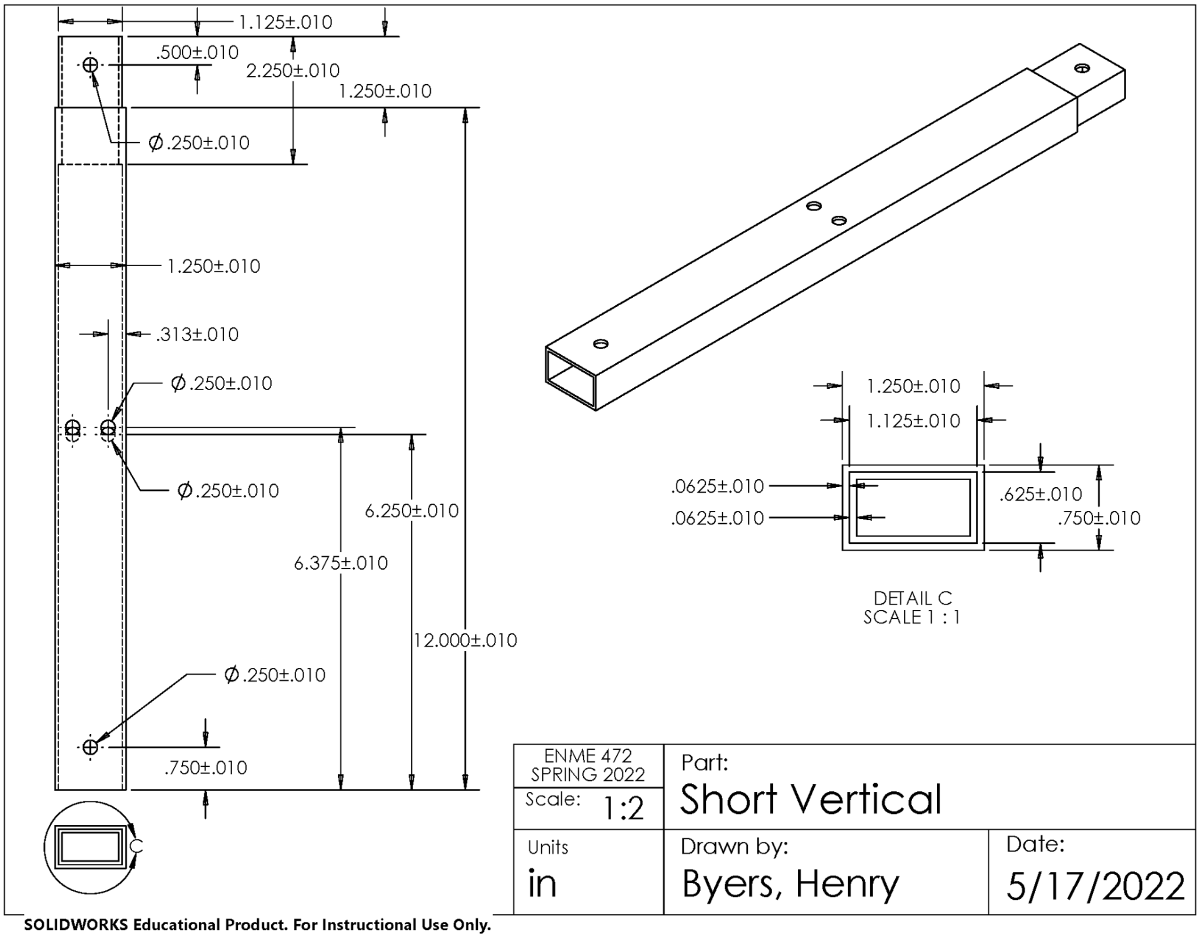

Figure 23: Engineering drawing for the short vertical frame component

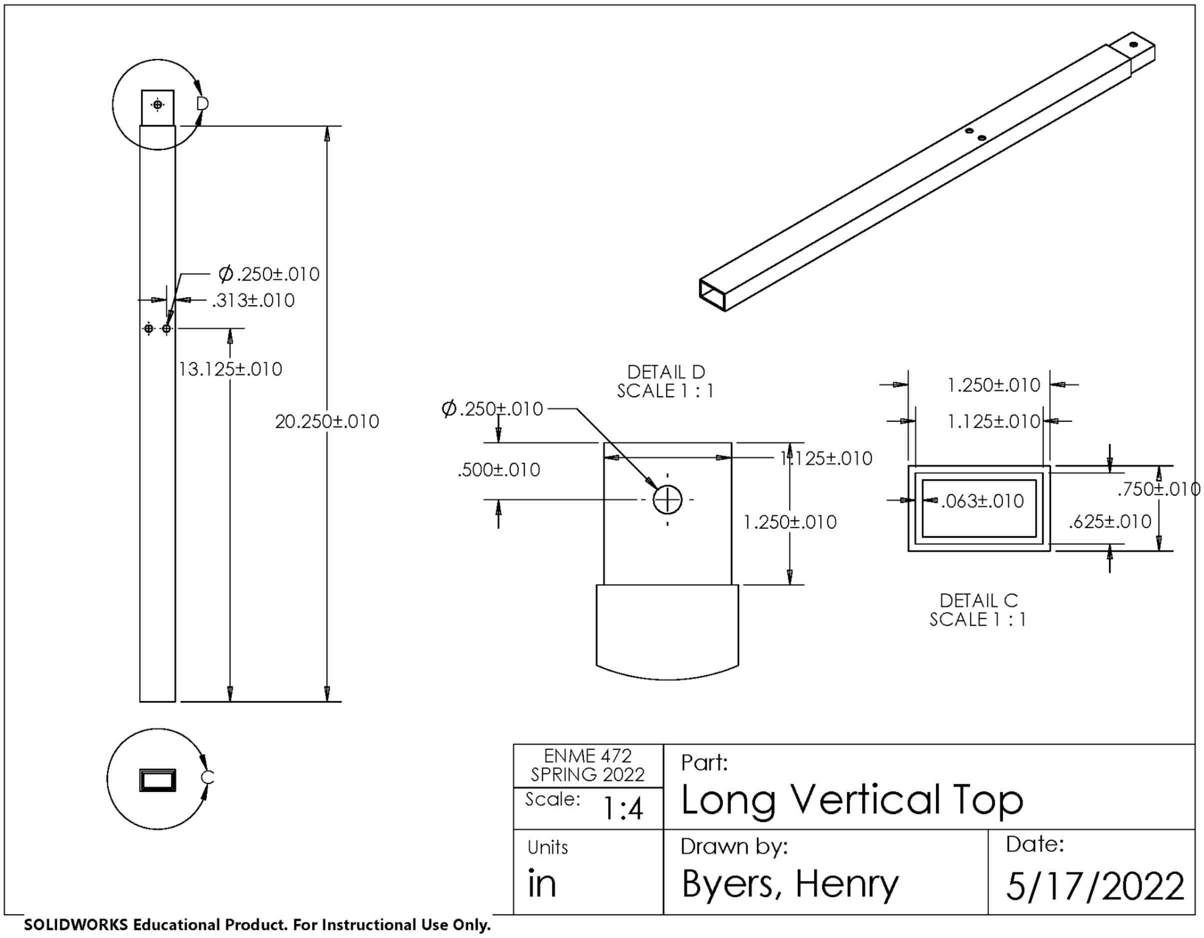

Figure 24: Engineering drawing for the long vertical top frame component

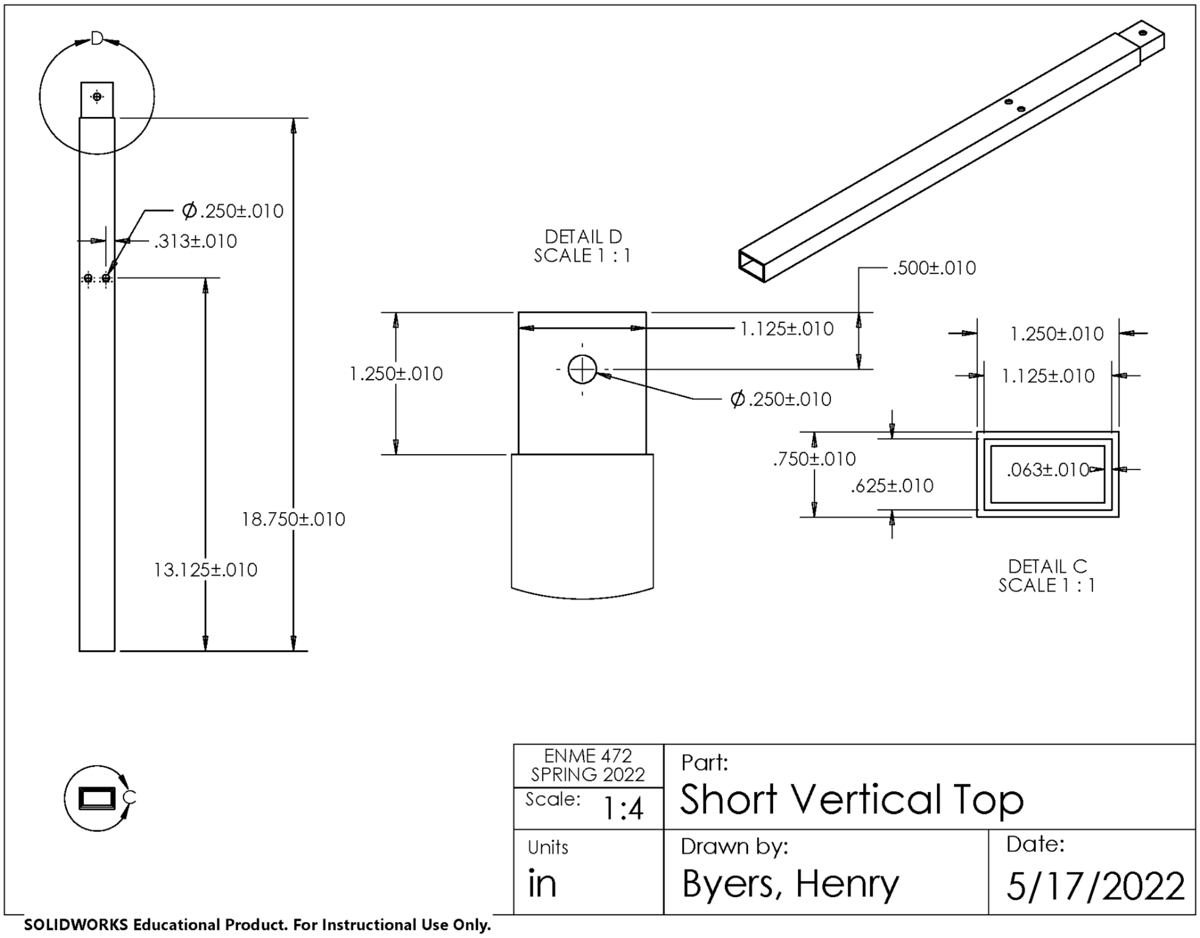

Figure 25: Engineering drawing for the short vertical top frame component

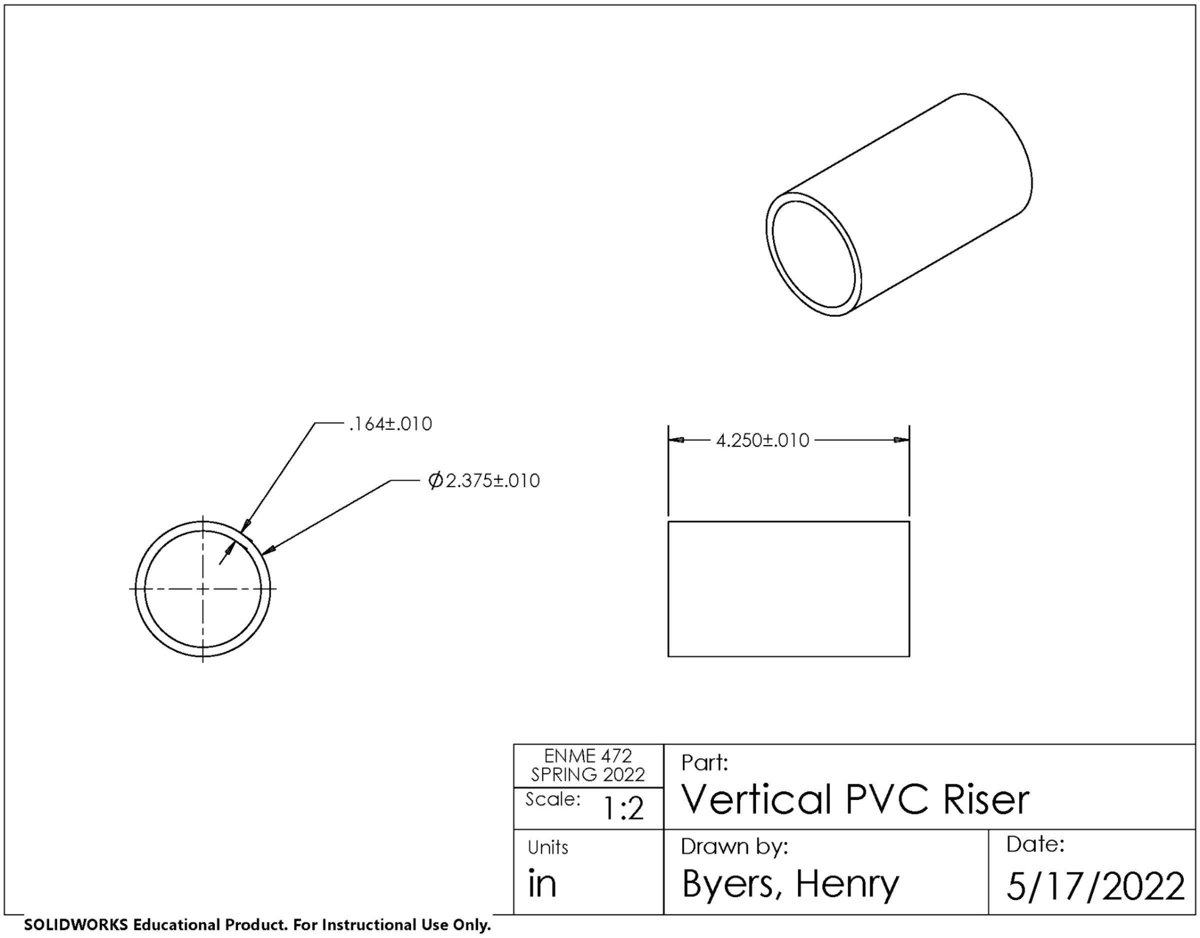

Figure 26: Engineering drawing for the vertical PVC riser component

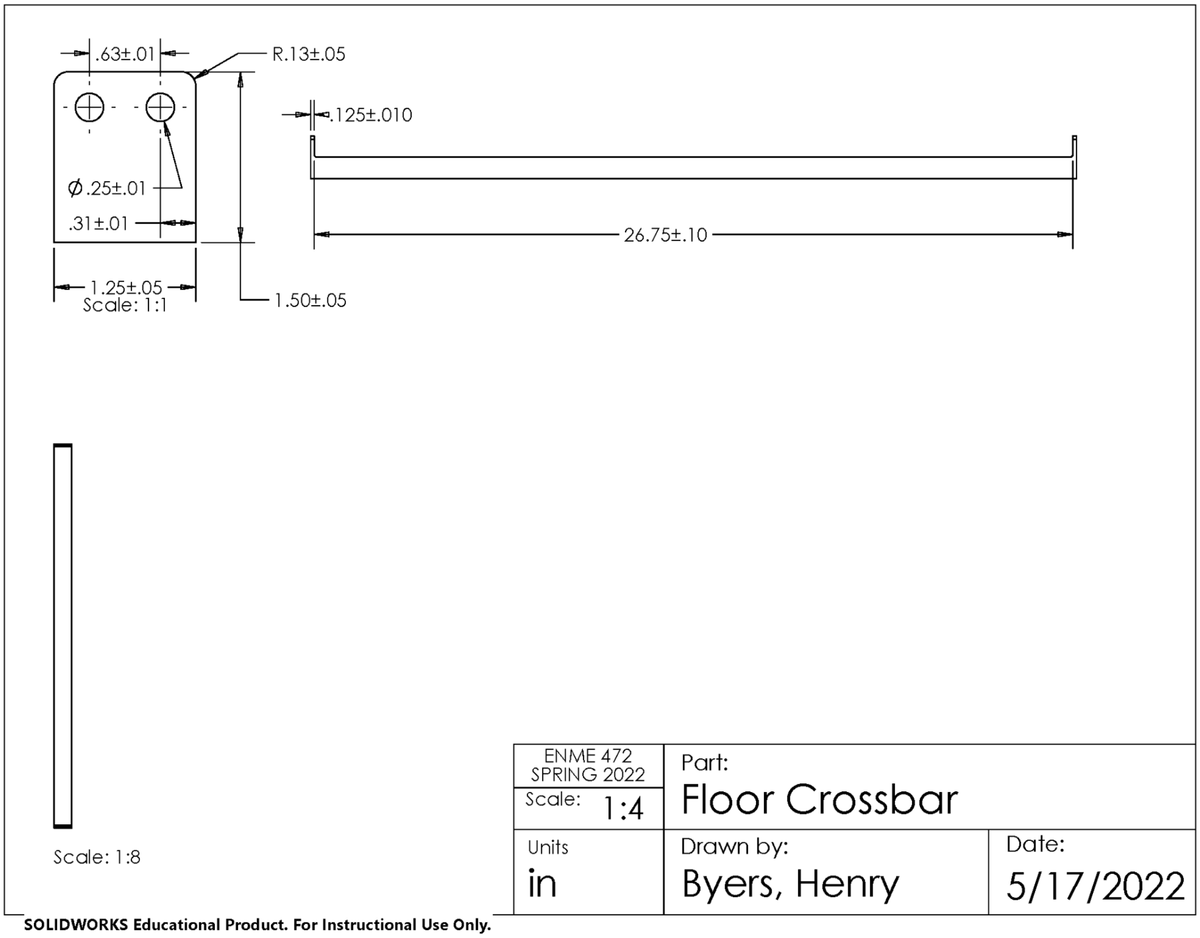

Figure 27: Engineering drawing for the floor crossbar frame component

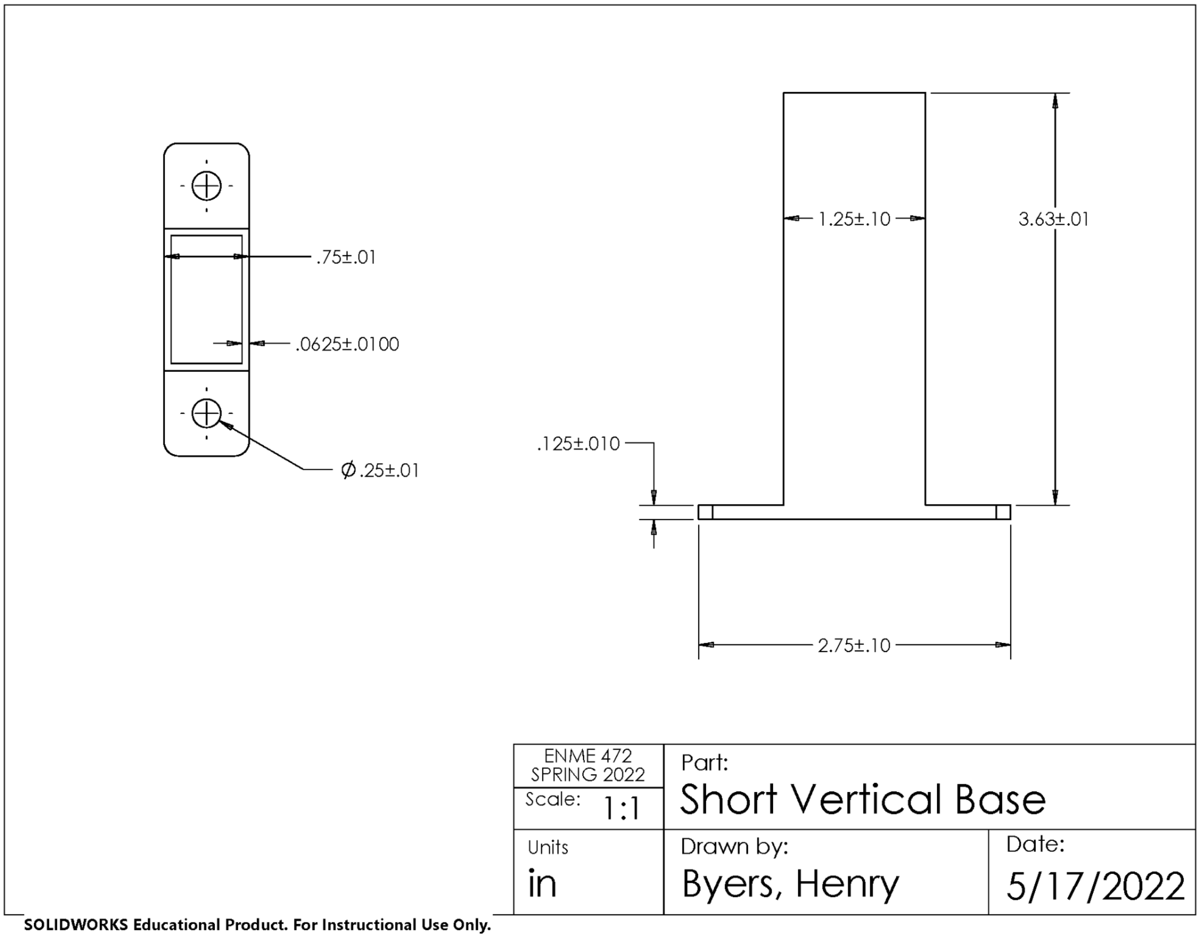

Figure 28: Engineering drawing for the short vertical base frame component

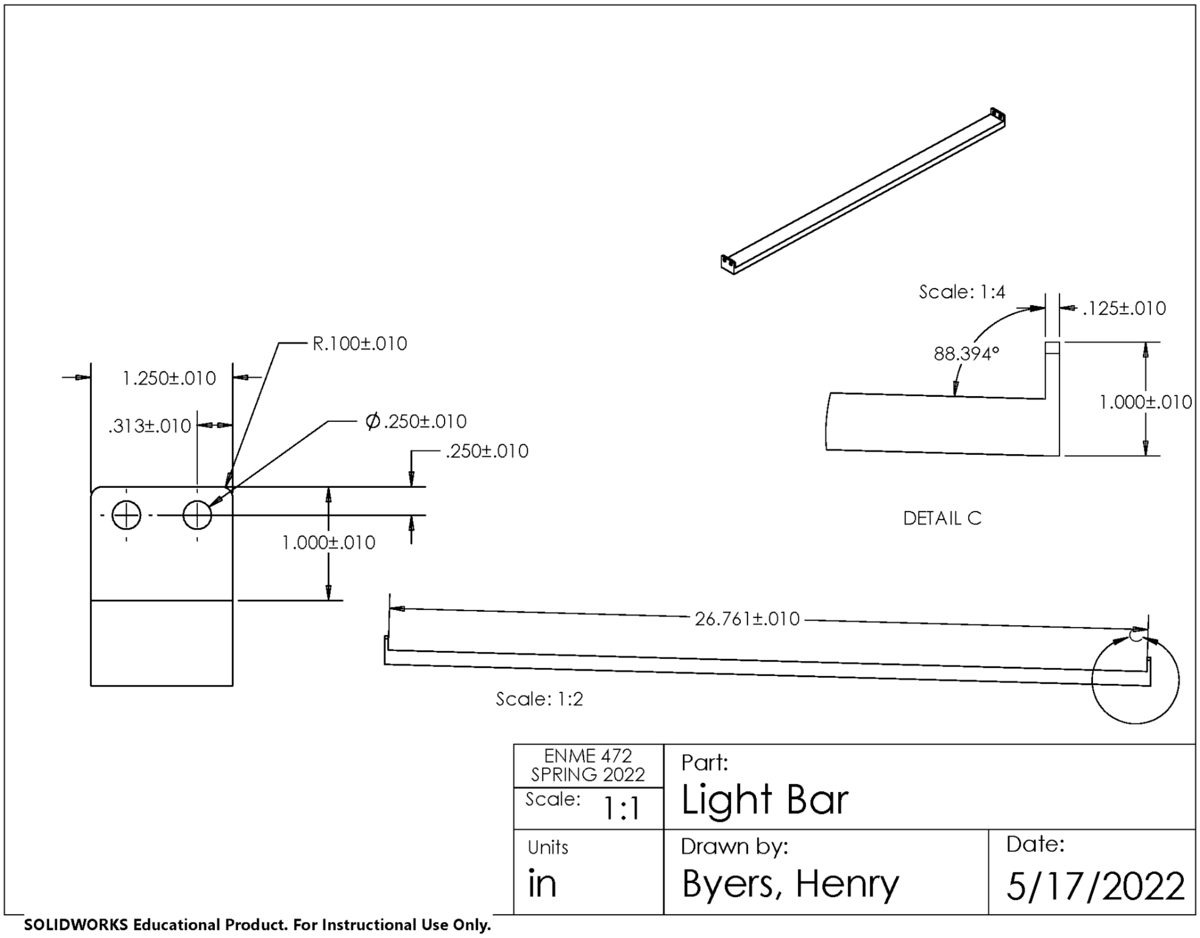

Figure 29: Engineering drawing for the light bar component

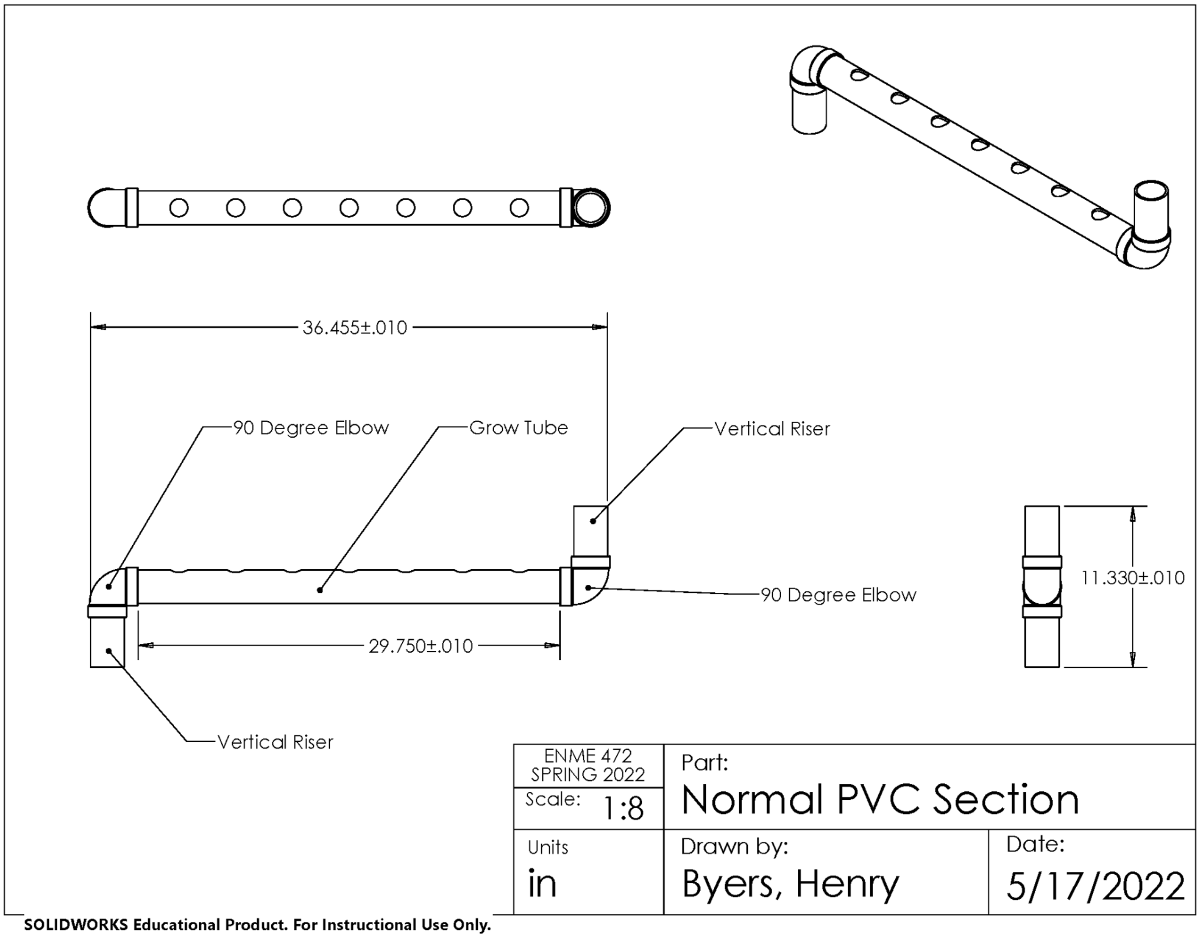

Figure 30: Engineering drawing for the normal (non-base layer) PVC tube subassembly

The length of the grow tube was identified as a critical subassembly dimension. It has to be long enough to allow the two elbow connectors to clear the frame and the tube hangers, and excess length will add material, weight, and cost to the system. A stackup analysis was performed based upon the dimensions of the frame and the 90 degree elbow fittings, accounting for the maximum possible depth into the fitting that the PVC pipe could be assembled too. The required length of the grow tube was then rounded up slightly to 31.25” long.

This subassembly, the “Normal PVC Section”, will be assembled at the factory using PVC cement. This creates a reliably watertight joint, but is very messy and can be tricky for anyone without experience using it. To dramatically increase the ease of assembly, all of the cemented PVC joints will be put together at the factory, and the users will just attach the flexible collars, which create a watertight seal without any glue or cement.

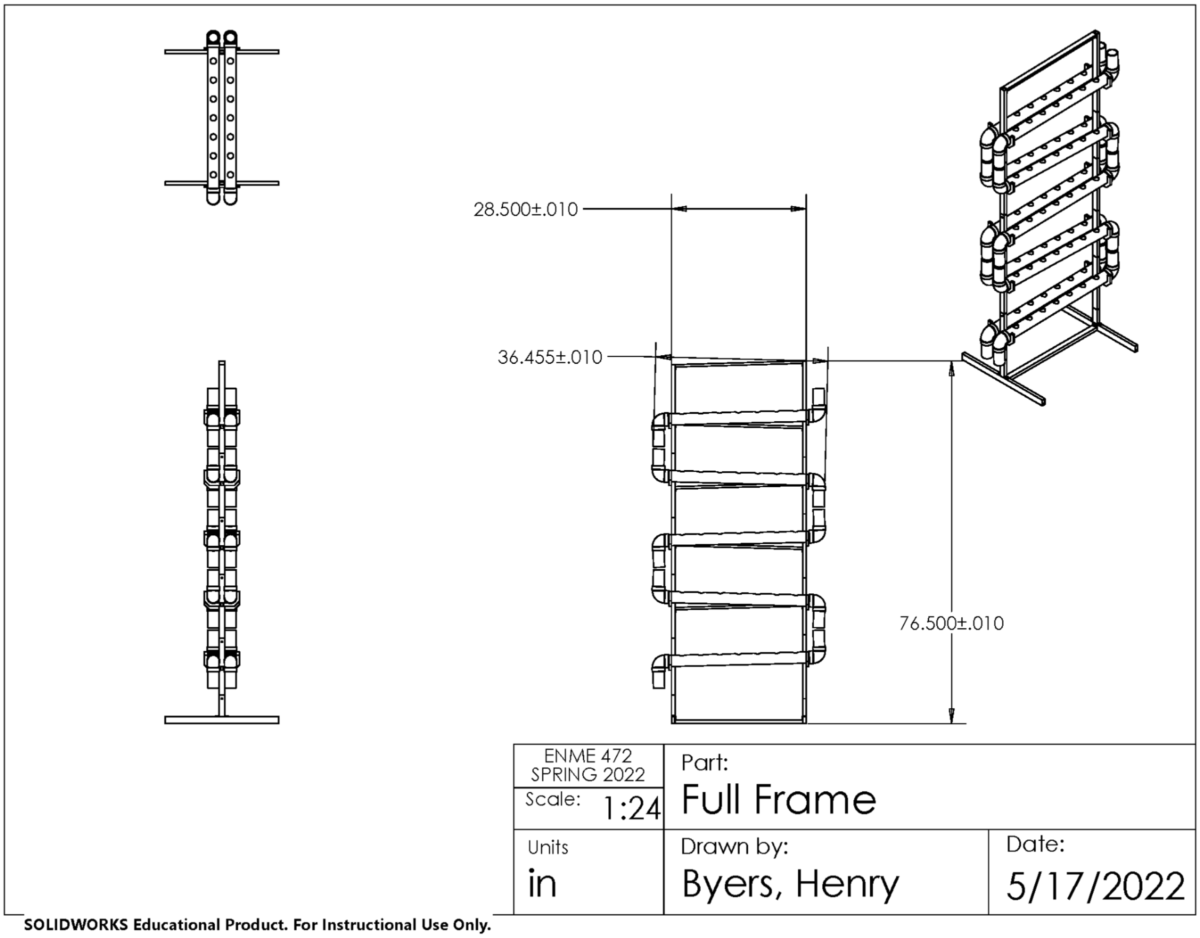

Figure 31: Engineering drawing for the fully assembled frame and grow tubes

Conclusions and Reflections

Summarize Project Results

Our final design is a vertical and modular hydroponics system with automated critical functions. Our customer requirements are low maintenance, automated, improve production, reliability, durability, cost effective, less space required, adjustable for different plants, and efficiency in power and water. We have been able to deliver on most of these requirements. Being that the system does critical functions on its own, it can be considered low maintenance, automated, and able to improve production. It is certainly cost effective, considering the yield our system provides compared to comparatively priced models like the Aerogarden that only provides space for typically less than 10 plants. Similarly, its vertical design takes up much less space than the same number of plants growing in the Aerogarden would occupy. It also provides efficiency in water and power by minimizing use of extra resources, but this can always be improved on. Our system does provide some reliability and durability, but there is definitely room for improvement. A backup pump could be included to make the system more reliable, but this would take away from our goal of cost effectiveness. Similarly, a backup power source could be added. However, our system does improve reliability for the hydroponics farming process as a whole considering that it reduces user error. In terms of durability, we can always improve. We have chosen materials that are certainly durable enough to complete the necessary processes, but due to the modular nature of the system, the connections are not the most durable choice. Since improved yield is prioritized over durability, this is a choice we had to make. Finally, adaptability to different plants is the customer requirement that we have least been able to address. Our system works well for leafy plants that don't need much vertical space to grow, but fruiting plants would not fit. In order to fix this we could create modular attachments that allow for levels with more vertical space, or potentially "tilt" the system so that it is still mostly vertical, but plants aren't directly on top of each other. These solutions reduce the yield or take up more space, which were bigger priorities for us, so we did not make this design change.

The most critical design decisions that have led us to be able to deliver on almost every customer requirement has been our choice to use a vertical design. Other design options in earlier stages did not maximize space nearly as well. Secondarily, our choice in electronics components has allowed us to deliver on maintenance related goals as well as cost goals because they are able to deliver on the critical functions of hydroponics without being expensive, and they are not more sophisticated than necessary for the level of precision needed to grow plants.

Reflection on The Product Development Process

The product development process has helped us to deliver on our customer requirements. The other designs we have considered were not able to deliver nearly as well on our most important requirements of high yield and low cost. This is because they simply cannot accommodate as many plants in the same space. It also helped us to think through what the most critical functions of the system were, and not add unnecessary ones that would not help us achieve our goals. Since cost is such a priority, adding any extra functions or using equipment that is overly sophisticated would have been detrimental to our goal.

While the final design of our product definitely benefited from the design process in some ways, there are some drawbacks. Since we spent so much time using “the process,” we spent less time prototyping. Early stage prototyping would have allowed us to perform more testing, which would have given us better data to prove that our solution is as good as we believe. It also would have allowed us to refine the control systems to be even more efficient, or improve our user interface. Adding functions to the controls system and interface is an upfront cost that would deliver higher value to the customer without making the physical components of the system cost more.

We can’t know whether “trusting the process” or “failing fast” with prototyping would have been a better method for achieving our goal, but it was an important learning lesson either way. In any project there is a balance between planning and doing. For us, planning a lot worked pretty well.

The most beneficial aspects of the process to us were in the customer discovery phase. We were able to reach many potential customers through our research on Reddit, and we also talked to an expert in the field. This allowed us to set priorities that were aligned with what customers are actually looking for, and understand the true value of our product. Had we skipped these steps, we may have designed a much different product, which may not have been as appealing.

Recommendations for Future Work

Weaknesses of our project include lack of reliability, durability, and adaptability to different plants. These weaknesses directly oppose the strengths of our project, which is that it is low cost and has a high yield compared to other systems. We can improve on these by adding more options to users for different types of plants, or introducing redundancy into our systems. Of course, any steps we take would increase the price of the system, but with further testing we could determine if it would pay off. Another weakness in our project is that even though it completes critical functions of hydroponics, it does so only on the most basic level. Our recommendations surround making improvements to these functions.

We recommend that before going to market, improvements be made to the software. This includes but is not limited to an improved feedback loop for nutrients. This includes testing and potentially upgrading the conductivity sensor so that it is more accurate, adding something to stir the nutrients so that readings are more accurate, and doing testing to determine what the most efficient interval to add nutrients is. Additionally, we recommend improving water circulation by adding a direct connection to a water source and drain so that water can automatically be added and emptied, and the controls system can be updated to reflect this. More sophisticated controls can also be added to better detect leakages and blockages as well. Multiple ultrasonic sensors could be added to measure water level at different locations and pinpoint the problem. Users could then receive more detailed alerts, and have less problem solving to do on their own. We also recommend that the camera be improved to detect the health of the plants. Machine learning algorithms could be implemented to determine whether the plants are beginning to brown better than the human eye. This technology could be incorporated to adjust nutrient levels as well. All of these functions would need to be incorporated into a custom microcontroller. Another aspect that we could improve on is recyclability. PVC is harmful to the environment, so finding an alternative material that is still cheap enough could be a way to mitigate this impact.

The next step in the development process would be to begin manufacturing prototypes of the final design, and do further testing. We would also recommend further research be done of controls algorithms and machine learning algorithms to improve the controls, and that that be added to the interface. Given that our product meets customers requirements, we believe that it is an idea that is ready for the market, however, because our prototype was only a rough mock up of the design, we would need to do further testing before it could be manufactured for sale.

Our research has shown that there is definitely a need for a product like ours in the market, considering that there are no cost effective options with a similar yield. Our system has the potential to be successful in the market, but needs testing to make sure it can meet customer requirements in the long term.

Professionalism

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Appendix

All code can be found at https://github.com/katherinekemp/enme472.

Task Tracking

Tasks	**Completed by**
Executive Summary	Katie
Final Design	Katie
Prototype & Testing	
Prototype	Ashley and Ly
Testing	Ashley and Ly
Finalized Human Factors Analysis & Testing	Ashley and Ly
Manufacturing Plans	
Material Selection	Heather
Manufacturing Process Selection	Atticus
Assembly Procedure	Adam
Product Cost	Atticus
Quality Plan	Henry
Engineering Documentation	
Parts List & Bill of Materials	Ly and Ashley
Engineering Drawings	Henry
Conclusions and Reflections	
Summarize Project Results	Katie
Reflection on The Product Development	Katie

Process	
Recommendations for Future Work	Katie