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Frugal Urban Greenhouse

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UNDER MY SUPERVISION BY

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ENTITLED

Frugal Urban Greenhouse

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Abstract

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This project collaborates with Valley Verde, a San Jose nonprofit organization, to build a greenhouse as a prototype for their Super Jardinero urban gardening program. This project also partners with the Frugal Innovation Hub, and has the goal to be affordable, rugged, and simple. The group created a design that ultimately met the desired metrics for weight, cost, and ergonomics. The design style makes hardening-off easier and specializes this greenhouse for seedlings, while structures currently on the market are built for larger plants. It is cheaper than any alternatives on the market and effectively meets Valley Verde's needs.

Table of Contents

List of Figures

List of Tables

1 Introduction

Many people throughout the San Jose area struggle from a lack of food sovereignty. Food sovereignty, as defined by the partner organization Valley Verde is “where local communities form a just and participatory food system that honors the relationship between the people and the land, builds generational knowledge and skills, recognizes food as sacred and a right for all.” It is an essential part of people’s daily life and many steps should be taken to protect this right. Because of the importance of food sovereignty, the engineering senior design team, also known as team “ACE,” partnered with the Frugal Innovation Hub (FIH) and local nonprofit 501(c)(3) Valley Verde (VV) to create a frugal urban greenhouse design. The purpose of this greenhouse is to be used in the spring and winter seasons to help seedlings become mature. The vision of this project is to benefit an existing humanitarian cause that supports the local community while also developing and improving engineering skills. Team ACE is guided by the core values of active learning, engagement with others, and awareness of local needs. The engineering goals include designing a preliminary model using CAD and FEA, creating a build guide, and testing and finalizing a working prototype of an urban greenhouse that is cheaper, lighter, and more suited to the needs of the partner organization than the existing design. The team is composed of mechanical engineers who used knowledge learned throughout undergraduate study (i.e. from Heat Transfer, Machine Design, and Fluid Dynamics) to create a unique and appropriate solution to the problem.

1.1 Problem Definition

The problem, as defined by VV and its users, is to create a greenhouse that is cheaper, lighter, and more effective than the previous design. In the terms of this project, “effective” means that the greenhouse can yield 500 or more seedlings per growing season. The team goal is to create a greenhouse design for $500 or less and meets the space and functionality requirements needed by Valley Verde. The team also looked to create a greenhouse that is durable, easily repaired, and is customized to meet needs specific to Valley Verde’s needs (hardening off (will be explained later), automatic watering). Although there are many commercial greenhouses on the market, the team attempted to make a cheaper greenhouse that is more specifically suited to the needs of Valley Verde.

1.2 Literature Review

There are few projects similar to the frugal urban greenhouse that exist in the university Scholar Commons, but the most relevant is “The Seedling Sanctuary: Automated Cold Frame for Gardner Elementary” under the supervision of Dr. Hohyun Lee. The team hopes to incorporate the project’s successes with the fully-automated seedling box (Bell 2019) into the heating and cooling of the greenhouse. However, the budget and small-scale growing of the cold frame seedling box make this reference more of a guide. The VV participants participate in the program to learn gardening skills and develop greater food sovereignty. Providing them with a fully automated box would undermine the purpose of the program and take away from educational opportunities.

The critical portions of this design will be its structure, configuration, and control systems for heating and ventilation. In an article for the journal *Energy Conversion and Management*, Coomans (2013) proposed energy-saving techniques during spring growing seasons using a mechanical ventilation system for controlled dehumidification. This was an efficient way to control interior conditions for an urban greenhouse during the February season, where a temperature of 75 to 85 degrees Fahrenheit is desired. While this method may not be entirely "frugal" based on the more complex systems used, it may be modified to be utilized in the final design.

A large obstacle with controlling the interior conditions of the greenhouse is the user schedule. VV's participants commonly work full-time jobs and cannot attend to ventilation and heating. For this reason, the Team investigated intelligent control systems for greenhouses. The article "Greenhouse Intelligent Control System Based on Indoor and Outdoor Environmental Data Fusion" provides schematics on a system for this, detailing its environmental monitoring module and its data processing module (Sun 2020). The Team scaled this to an appropriate level for the design and implemented a watering system based on moisture data collected using an Arduino.

The next two sources cover engineering analysis. Firstly, Team ACE prioritizes a fatigue analysis as its baseline for durability; an article from the journal *Applied Science* gives detail on how to perform this analysis for greenhouses (Hur & Kwon 2017). While fatigue was not found to be the primary mode of failure, this method ensured that all modes of failure were properly accounted for and maximum durability could be achieved. Additionally, in normal greenhouse use, many features bear repeated action so failure due to fatigue is not unrealistic. The roof, for example, must withstand frequent "loading" and "unloading" from multiple shade cloths, wind, and rain. These small, yet repetitive, actions contribute to fatigue and possible failure. The standard analysis is done in static conditions, but the presence of wind makes it necessary to normalize the wind speed and consider its effects as a dynamic load. Secondly, the structure must be analyzed for its effect on airflow. In "Computational Fluid Dynamics Modeling to Improve Natural Flow Rate and Sweet Pepper Productivity in Greenhouse," researchers determined that a two-step roof was superior to a traditional arch in a simulation environment (Limtrakarn 2012). The physical two-step roof validated the simulation once it was built. When constructing and testing the greenhouse, these analysis methods were kept in mind to better understand how to best build a greenhouse that meets the customers' needs.

1.3 Thesis Overview

This thesis will discuss the entire design process for the Frugal Urban Greenhouse from creation to final execution in detail. There are six main chapters being the conceptual design overview, subsystems, CAD (computer aided design) modelling, constructions, construction guide, and cost analysis. Each chapter delves deeply into each topic and has supporting subchapters for each topic. These chapters are generally organized in the order that they were addressed throughout the project and give a fairly detailed look into why design decisions were made, what difficulties the team encountered, and how those problems were fixed. It gives a complete and comprehensive overview of the entire FUG design project.

2 Preliminary Conceptual Design

In this chapter, the design problem will be more concretely defined and conceptual design choices will be justified. This chapter first defines the important subsystems in a greenhouse, explores customer needs, and identifies many of the factors and challenges that were anticipated in building the greenhouse. It also explains how and why the team made specific design decisions and builds a basis in previous engineering work through patent and standard reviews. Overall, it is a comprehensive view of the research and preparation that led to the creation of the final conceptual design.

2.1 Subsystem Definition

The purpose of this chapter is to outline the various systems employed within the greenhouse design. As part of this, the team first conducted surveys and interviews to fully understand customer needs. From there, Team ACE was able to generate system-level requirements and criteria. After extensive market research, customer interviews, and literature reviews, the most relevant systems and subsystems were determined as outlined in Figures 1 and 2.

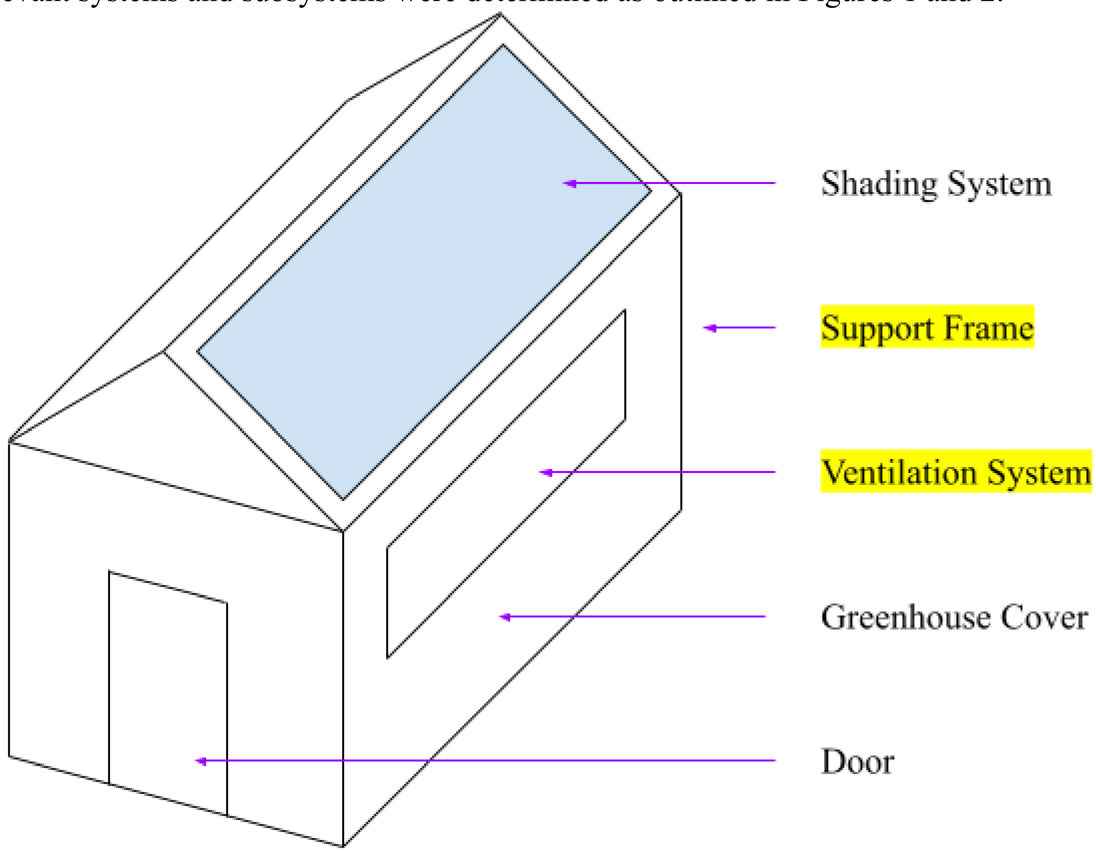

Figure 2.1: Basic Greenhouse Sketch with Major Subsystems Highlighted

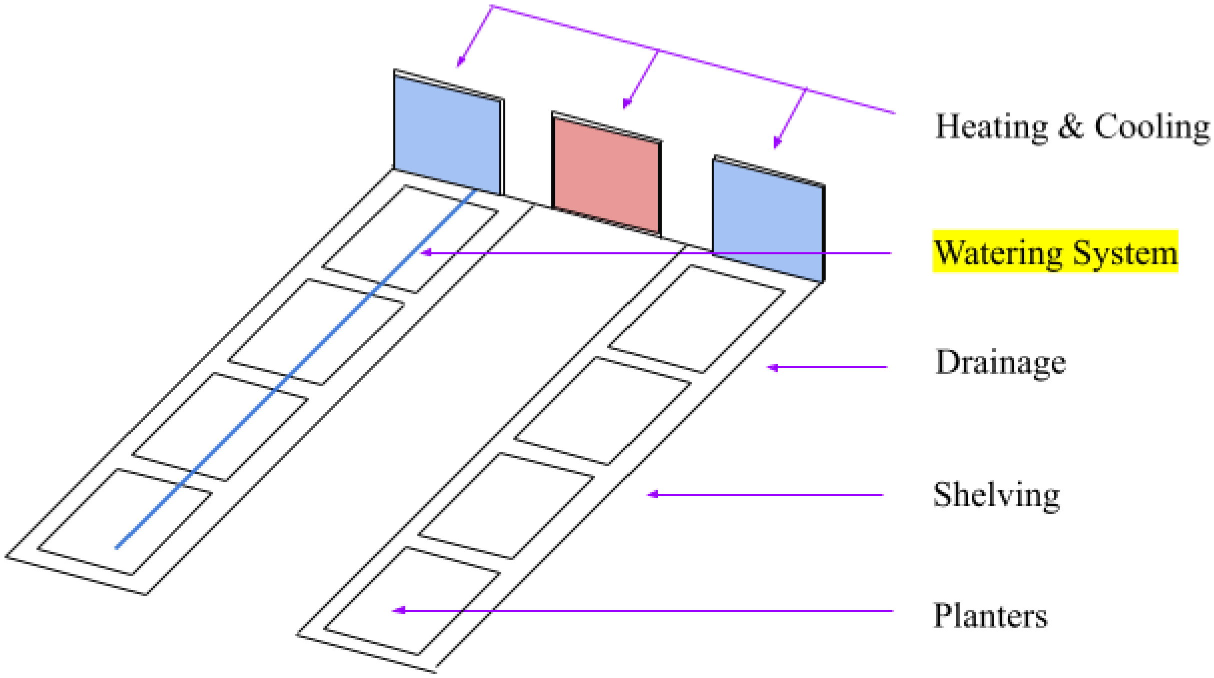

Figure 2.2: Sketch of Greenhouse Interior with Major Subsystems Highlighted

Based on the customer needs and research, as well as the technical knowledge, the team decided to mainly focus on improving the greenhouse support system in conjunction with the ventilation system as well as the watering/irrigation system. Although all of the subsystems defined in the Figures above are important, addressing the structure and irrigation subsystems would be the most effective given the time and resources allotted. While there is something to be gained by addressing other subsystems in the future, they were outside of the scope of this senior design project.

2.2 Customer Needs

These sketches show the main components involved in building any greenhouse; however, specific customer inputs were needed to understand how each of these systems should look. Although certain features may be helpful in different contexts, the team wanted to ensure that the design was specifically tailored to Valley Verde's needs. To begin this process, the team first tried to understand greenhouse user needs as a whole. By conducting market research and interviewing partner contacts and individual greenhouse users, the team developed a preliminary list of customer needs for greenhouses in general. This list was then organized as shown in Table 2.1, which summarizes the most common and important needs as shown across all sources. To better differentiate between and understand these needs, they were divided into four main categories and ranked them roughly in order of importance between each category.

Table 2.1: Initial Customer Needs Survey Results

1. Performance	**2. Ease of Use (Ergonomics)**	**3. Frugality**	**4. Monitoring/ Miscellaneous**
1.1 Produces 500 seedlings per growing season	2.1 Lightweight and easy to assemble	3.1 Is low cost to build	4.1 Has effective ventilation
1.2 Has high crop yield rates	2.2 Eliminates redundant lifting/movement	3.2 Is low cost to maintain	4.2 Can heat or cool plants
1.3 Can be used year-round	2.3 Is low-tech and easy to operate	3.3 Keeps water and energy prices low (efficient)	4.3 Plants can be watered remotely
1.4 Can withstand wind/rain/snow etc.	2.4 Areas are at an appropriate height	3.4 Able to be repaired with local materials	4.4 Monitors temperature/humidity
1.5 Keeps out pests	2.5 Shelves are appropriate sizes for planters	3.5 Works easily with things available in peoples backyards	4.5 Is aesthetically pleasing
1.6 Made from inorganic materials	2.6 Door sizes make carrying plants/tools easier	3.6 Rainwater harvesting	
	2.7 Reduces effort for hardening off* plants		
	2.8 Has a storage area		

*Hardening off is a very important process of acclimatizing seedlings grown in a greenhouse to outside conditions so they can be more resilient when they are planted. However, in a traditional greenhouse, hardening-off is typically a fairly arduous process, as one has to move each tray from the inside and outside, potentially multiple times a day based on the seedling, for anywhere from a few days to two weeks.

Moving forward, an extensive criteria matrix was made to determine the most important criteria. As shown in Figure 2.3, this matrix shows all important criteria, as well as their weight against all other criteria.

Criteria	Weight	Cost	Manufac	Temp R	Automat	Water E	Energy I	Modular	Planting	Durabilit	Repaira	Moisture	Hardeni	Storage	Work sp	Safety	Air Circu	Ease of	Shading	Aestheti	Space U	Ergonor	Material	Monitori	Total Weight	Percent Weight
Weight		0	0	0	1	0.5	1	1	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0.5	1	9	3.3
Cost	1		0	0	1	1	1	1	0	0	0	0	1	1	1	0	0	0	0.5	1	0	0	1	1	11.5	4.2
Manufacturability	1	1		0	1	1	1	1	0	0	0	0	1	1	1	0	0	0	1	1	0	0	1	1	13	4.7
Temp Regulation	1	1	1		1	1	1	1	0.5	0.5	1	0.5	1	1	1	0	0.5	1	0.5	1	1	1	1	1	19.5	7.1
Automation	0	0	0	0		1	1	1	0	0	0	0.5	1	1	1	0	0	0	0	1	0	0	1	0.5	9	3.3
Water Efficient	0.5	0	0	0	0		1	1	0	0	0	0	1	1	1	0	0	0	0	1	0	0	1	1	8.5	3.1
Energy Efficient	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0.4
Modularity	0	0	0	0	0	0	1		0	0	0	0	0	0.5	1	0	0	0	0	1	0	0	0.5	0	4	1.5
Planting Capacity	1	1	1	0.5	1	1	1	1		1	0.5	0.5	1	1	1	0	0.5	1	0	1	0.5	1	1	1	18.5	6.7
Durability	1	1	1	0.5	1	1	1	1	0		1	0.5	1	1	1	0	0.5	1	0.5	1	1	1	1	1	19	6.9
Repairability	1	1	1	0	1	1	1	1	0.5	0		0	1	1	1	0	0	0	0	1	1	0	1	1	14.5	5.3
Moisture Regulation	1	1	1	0.5	0.5	1	1	1	0.5	0.5	1		1	1	1	0	0.5	0	0.5	1	1	1	1	1	18	6.5
Hardening Off	0	0	0	0	0	0	1	1	0	0	0	0		1	1	0	0	0	0	1	0	0	1	0.5	6.5	2.4
Storage space (insid	0	0	0	0	0	0	1	0.5	0	0	0	0	0		1	0	0	0	0	1	0	0	0	0	3.5	1.3
Work space (Outside	0	0	0	0	0	0	1	0	0	0	0	0	0	0		0	0	0	0	1	0	0	0	0	2	0.7
Safety	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	23	8.4
Air Circulation	1	1	1	0.5	1	1	1	1	0.5	0.5	1	0.5	1	1	1	0		1	0.5	1	1	1	1	1	19.5	7.1
Ease of use	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0		0	1	1	0.5	1	1	15.5	5.6
Shading	1	0.5	0	0.5	1	1	1	1	1	0.5	1	0.5	1	1	1	0	0.5	1		1	1	0.5	1	1	18	6.5
Aesthetic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0.0
Space Utilization	1	1	1	0	1	1	1	1	0.5	0	0	0	1	1	1	0	0	0	0	1		0	1	1	13.5	4.9
Ergonomics	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0	0.5	0.5	1	1		1	1	16	5.8
Material Frugality	0.5	0	0	0	0	0	1	0.5	0	0	0	0	0	1	1	0	0	0	0	1	0	0		0	5	1.8
Monitoring	0	0	0	0	0.5	0	1	1	0	0	0	0	0.5	1	1	0	0	0	0	1	0	0	1		7	2.5
																									275	**100.0**

Figure 2.3: Design Matrix

This helped the team create weight values to use in assessing each design. For example, though the criterion of "pleasing aesthetic" was still used to evaluate the designs, it carries no weight in the final score of a design because it did not seem more important than any other criteria (at the time of creating the criteria weight matrix). Note the highlighted criteria, such as

- Temperature regulation
- Soil moisture regulation, and
- Air circulation

These criteria, along with natural sunlight, are *essential* for successful seedling production.

After pushing multiple design ideas for different subsystems into the matrix, weighting them appropriately for each criterion, the following design emerged:

- Ventilation Subsystem: Integrated Side Wall Vents and Clamp Fans
- Structural Subsystem: PVC Pipe Frame with Dome Roof
- Watering Subsystem: Hose-Attachable Sprinkler System

See the following sketches for the whole design.

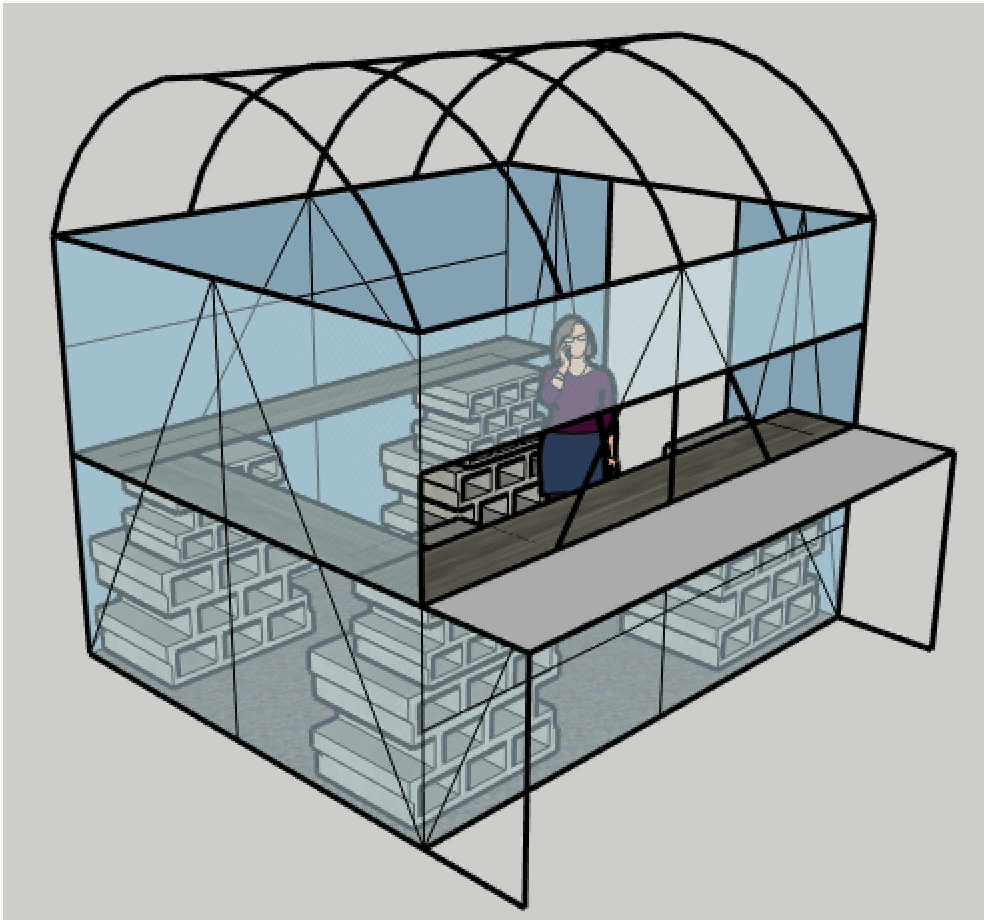
Figure 2.4: Preliminary Overall Design, Isometric View

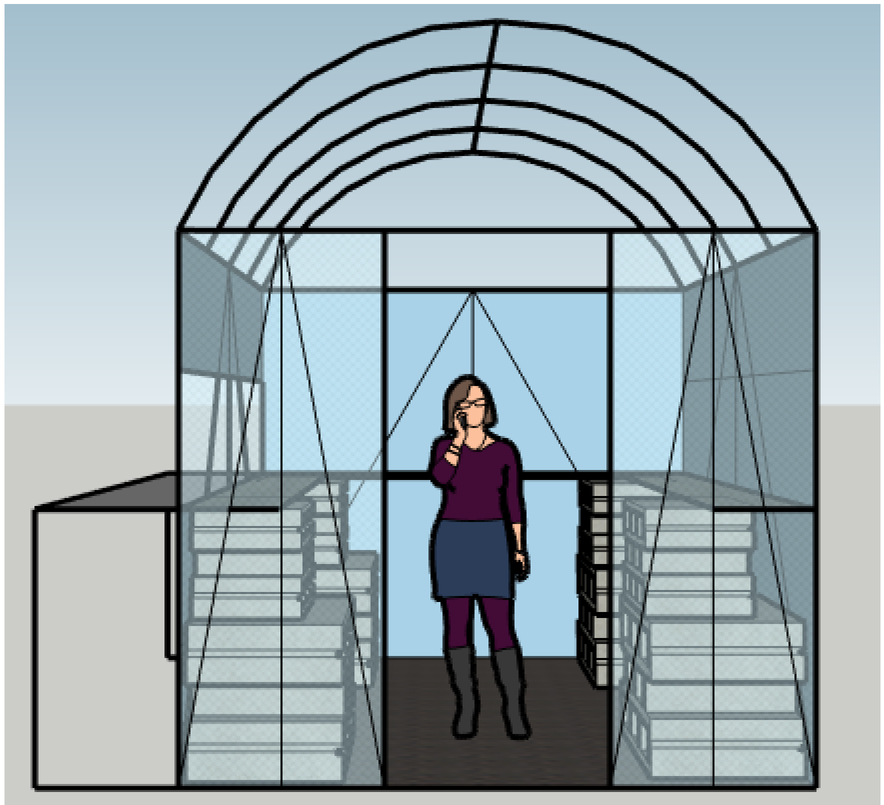

Figure 2.5: Preliminary Overall Design, displaying shape and fold-out shelves/vents

Drawings of each specific subsystem will be provided and described later in the report.

2.3 Functional Analysis

The main function of the greenhouse is to create a suitable environment for growing seedlings. To be able to do this, it must be able to perform necessary sub-functions including but not limited to regulating soil moisture, temperature, air circulation, and shading. Based on the customer's needs, the team wanted to accomplish these functions while also making the greenhouse cheap, durable, ergonomic, and easy to use. While these come after the main functions and subfunctions in order of importance, they will influence how the greenhouse is designed.

2.4 Inputs, Outputs, and Constraints

The inputs to the greenhouse that the user provides include water, energy, labor, time, and materials. The goal of the greenhouse is to essentially reduce these user inputs as much as possible without sacrificing plant yield. There are also inputs from the environment to consider, such as rain, organic debris, wind, humidity, and temperature. These inputs cannot be altered by the design of the greenhouse, so steps will be taken to ensure that the greenhouse reacts to and controls these inputs appropriately.

The main output of the greenhouse is properly grown seedlings. The greenhouse design is intended to optimize this output with minimal inputs from people. While there may be some other unintentional outputs such as excess water or materials from manufacturing, the intention was to minimize these unnecessary outputs for the design.

For a more specific list of constraints and goals for the design, please refer to the Product Design Specifications in Appendix C.

2.5 Benchmarking Results

Preliminary market research for the greenhouse design can be found in Appendix I. For this research, the team intentionally looked at a variety of greenhouses with different styles, designs, and price points. Based on these designs, as well as customer specifications (such as cost and allowable space), components from many different designs were taken to create one that will be cheaper and more effective at meeting Valley Verde's needs than a commercial greenhouse. Valley Verde's old greenhouse design can be seen in Appendix G. While greenhouse structures tend to be fairly basic and standardized, a large need that commercial greenhouses do not address is the need for controlled and efficient watering. The Super Jardineros, who are the families that utilize the greenhouses, typically work full-time which makes managing and watering plants throughout the day difficult. Because of this need, as well as the general gap in market solutions, the greenhouse will seek to address this need and improve on current methods for watering. While some changes to the design structure were made to better fit Valley Verde's needs, a lot of the design and analysis for this greenhouse will be devoted to making an effective and efficient watering system to fill the gap in the market.

2.6 Issues, Options, Trade-offs, and Rationale

Weighted criteria and selection matrix can be found in Appendix D. To create weighted criteria, a list of every customer need or specification was created. The team then rated these criteria against each other. A specific criterion was rated against each other criteria and was assigned a 1 if it was deemed more important, a 0.5 if it was deemed equally important, and a 0 if it was less important than the criteria it was being compared against. After each criterion was assessed against all other criteria, the point values of each criterion became their "weight," which determined how important they should be to the final design.

With the weighted criteria created, the team then rated the different ideas based on these criteria. Design ideas were rated by subsystem, as comparing a structural criterion to a watering design criterion, for example, did not make a lot of sense. There were four main subsystems in this design criteria, being structure, watering, shading, and ventilation. For each idea, it was rated a 1 (a single point) if it effectively met criteria, a 0 if it performed at a baseline or did not have an effect on the criteria, and a -1 if it worsened the criteria. Then each weight was multiplied by the score to determine which subsystem ideas were most effective.

The final design best meets the most important needs. While the final design does not address all of the potential needs of Valley Verde, it does address the most important ones and will result in an effective greenhouse design.

2.7 Team and Project Management

The team revolves around a potluck style for achieving goals in which all of the team members do the same prep/work for the sequential assignments and tasks. Rather than having a select emphasis within the group and more specific roles, the team operates as a united front of general knowledge. This would only present productivity issues as the project goes further and in the manufacturing phase. Ensuring that there are not too many cooks in the kitchen for a given task and that every member knows their strengths and weaknesses will prove to be quite helpful in the future aspects of work after design.

2.8 Project Challenges, Constraints, and Current Solutions

Most of the challenges within this project lay in the allocation of space and efficiency. A multitude of market greenhouses already exists to produce as much produce as possible given the lack of spatial and financial constraints. This exists for the cheapest market greenhouse and those that take up the least amount of space. The team's objective is to build a greenhouse that fills these requirements whilst remaining easily repairable to those who are unfamiliar with structures. The caretakers are low-income families in Santa Clara County who are generally tied to extensive work hours so the greenhouse must be self-sufficient in the absence of constant monitoring. The desired measurements of the greenhouse steer the design towards a smaller greenhouse with lighter materials that will ultimately allow for easier use. Affordability becomes more certain as the structure is aimed to be made of local materials for easy repair and lower prices. The implementation of an Arduino will open the door to automated monitoring and easier instrumentation use within the greenhouse. The water for these structures will be provided by the families; it is every intention of the project to supply a method of watering the produce in the most efficient manner with a timer.

2.9 Budget

While the detailed preliminary budget can be seen in Appendix E, the original estimated cost was $2000, which was provided by the School of Engineering. While this budget includes the original estimates, actual needs turned out to be much different than originally planned for. For example, a large portion of the budget was allocated to items that were never actually necessary, such as solar panels, fans, and metal shelving. When the budget was created, the understanding of the project was much different than what the customer actually expected and what was realistically possible for the team to design in the given time. Also, the team did not allow an adequate amount of money for prototyping and testing; however, this was accounted for by the unnecessary items from the scope. Although the preliminary budget did not turn out to be very representative of actual costs, it served as a launching point and allowed the team to better understand exactly what building a greenhouse would entail, and gave a reasonable estimate of material properties, prices, and options.

2.10 Timeline

A complete timeline can be seen in a Gantt chart as shown in Appendix J. COVID-19 limited the ability to complete these events in the time predicted; however, the team was able to effectively pivot throughout the project to adapt to the current conditions. Also, the team had not had any experience manufacturing greenhouses so these timetables were estimated and changed as necessary throughout the design process. Design challenges also added roadblocks to this timeline, but the large buffer allowed the project to be completed on time. While many changes needed to be made throughout the design process, this timeline served as an effective preliminary roadmap and got the project started on the correct footing.

2.11 Design Process

The design process for this greenhouse included even participation from all team members in generating the initial ideas, creating criteria, and rating designs. To begin creating preliminary design ideas, each team member created around 20 sketches. This ensured that there were a variety of ideas to consider, and stretched the group to explore more creative solutions to issues. When the sketches were compiled, each design was then critiqued and evaluated based on the perceived efficacy (based on market research, customer interviews, and literature review). Afterward, the team separated ideas into appropriate subsystems and determined criteria relevant to each grouping. These criteria were then weighted, as described earlier. Then, these designs were ranked using the weighted criteria and best scoring ideas for each subsystem were integrated into the final conceptual design.

2.12 Safety Risks and Mitigations

A complete safety review can be found in Appendix I. As a whole, the main hazards in the project generally involve the cutting and securing of PVC with power tools, which can be mitigated by receiving proper training, wearing appropriate PPE, and remaining focussed throughout these processes. While other hazards are noted in the safety review, these are generally inconsequential to the overall safety of the project.

2.13 Review of Existing Patents

Although the Frugal Urban Greenhouse is not meant to be commercially sold, to get an idea for design ideas, the team also looked at existing patents that may be similar to the greenhouse design to further refine and understand the components essential for greenhouse creation. This was a helpful exercise as it showed the team what was possible and gave ideas for the design. The six most compelling patents are reviewed below:

1. Twin section greenhouse of polycarbonate sheets with lateral ventilation

This greenhouse design has many similarities to the existing design, the main one being the venting scheme. It has a claim to "lateral ventilation," where the vents "transoms on hinges, and the height of the windows is half the height of the vertical wall." This is very similar to the final design, which has lateral ventilation with vent sizes similar to half the height of the structure. The main difference between these ventilation systems is that the vents are load-bearing and can be opened to be used as shelves, while the vents in the other design do not serve a similar purpose. However, the design would likely not infringe on this patent because of the specificity of the claim. Although it does have similar features to this project's design, this patent also specifically covers a structure that is domed on one side and flat on the other, which is not included in the team's final design. It is also created from "fiberglass arcs" which is different from the PVC structure utilized.

Although the design does use a similar ventilation system, the claim is very specific to the ventilation system and structure as a whole and thus would likely not be infringed upon by the current design. However, the hybrid dome/flat design is an interesting solution for when there are crops that require two unique conditions and could be further investigated in future iterations.

2. Greenhouse monitoring system

This patent is for a greenhouse monitoring system and is very similar to what was used to test the greenhouse, but is unique from the system ultimately implemented. The main claim for this patent is "A greenhouse monitoring system, comprising: a controller, a sensor, a communication assembly and a greenhouse regulation device." The sensor specifically includes a soil humidity and temperature sensor, a greenhouse temperature and humidity sensor, and a gas and illumination sensor in conjunction with a "crop irrigation device, an air heating and humidifying device, a light supplementing device, a roller shutter device and a ventilation device". This is very similar to the team's prototype control system, which utilized a soil humidity and temperature sensor in conjunction with an irrigation system to test soil moisture and water it appropriately. This design did not test the air humidity, air temperature, or light levels; however, it could make the greenhouse more effective in further iterations. As a whole, this controller sensor design, as patented, seems very effective for more high-tech growing applications but may be more difficult to implement in a frugal/low-tech way. Also, although the testing system utilized similar ideas, the final design does not use a sensor/controller method and thus would not infringe upon this patent. However, it shows more important variables that would be important to test in future iterations and gives a high-level overview of how greenhouse conditions could be effectively regulated. Other ideas that the patent claims that were not utilized include a soil nutrient sensor with a fertilizing device, or a video camera to watch/view the crops remotely. While these are all ideas that could be used in the greenhouse (as it is not being used for a commercial purpose and thus would not infringe upon this patent) they are outside of the scope of the particular project but could be interesting ideas to investigate.

3. System for cultivating plants

The main subject of this patent is an (ideally) automated shelving system that allows for the rotation of shelves and, consequently, a more equal amount of light distribution to plants and in turn increasing the overall productive volume of a greenhouse. The reasoning for this is that while stacked shelving easily adds greater productive volume, plants on lower levels have limited access to light and will not survive. Additionally, creating a dynamic shelving system reduces the need for human labor. Specifically, this patent states that "the supporting structure of the greenhouse is formed by the shelf system," (Peng 2020). This is relevant to the FUG in that the shelves are built into the greenhouse as vents. However, the greenhouse would be stable and supported without the addition of the shelves and therefore they do not technically provide any actual support to the roof of the greenhouse. Another claim from this patent states that "a work area is provided in the greenhouse, with seed stock from the shelves of the 15 shelf system being able to be transported to and from said work area with the help of at least one shelf system"

(Peng 2020). Within the context of the FUG, an additional work area is provided through the fold-out vents and the original seed trays can be easily transported to and from this additional shelving by the act of pushing or pulling the trays through the opening. So this brings up a question, does the presence of these vents and their use count as the "help of at least one shelf system?" Looking back at the main purpose of the patent, this IP is specifically related to a system that rotates seedlings between "an arrangement of shelves with a plurality of planes" (Peng 2020). For this reason, transportation to and from the work area is automated and works among multiple planes, not just one plane back and forth as in the context of the FUG.

4. Vertically integrated greenhouse

This next patent looks at the vertical integration of suspended trays in a greenhouse for maximizing crop yield, energy savings, and space. This idea is similar to earlier sketches for the FUG, which included the use of multi-level hooks to create storage space or allow placement of various elements (watering rods, cooling rods). The system includes a unique tray configuration, a suspension system, and water distribution via a reservoir and pump.

The main concern with the Valley Verde client was the use of shelving that would block light to lower levels. This patent design is novel because it allows for the capability of diurnal and seasonal dynamic tracking--in other words, the shelves are adjustable via the suspension system and could be programmed to move throughout the day and over a season, following sunlight patterns. For example, the patent writers determined that the solar angle at one time of day is 45 degrees, whereas the solar angle, later on, may be much lower at 25 degrees. This takes the plant shelving to a new level and could be considered in future designs.

5. Greenhouse and method for cooling same

This patent specifically looks at a combined roof-ventilation system for a greenhouse. This roof is composed of three separate parts, two arcs branching inwards that overlap but are separated at the greenhouse's center point. At their separation, the two arcs are joined by a third plane that actively circulates air and utilizes nozzles to spray mist, further cooling the air within the greenhouse (Lefsrud, 2013).

While this greenhouse utilizes an arched roof like the FUG, this patent specifically identifies the roof as containing a separation at its middle point. Additionally, the arcs in this roof are described as containing unequal arc lengths and angles while the FUG has a completely symmetrical roof. The other aspect of this patent that relates to the FUG is the combined ventilation/misting system. While the FUG ventilation system does not have nozzles locally integrated, the misters which are used for watering the seedlings in the greenhouse will be positioned in parallel with and not far from the main opening of the vents. The air cooling benefits of the misting system are well recognized within the context of the FUG, but it is not their main purpose and their correlation with venting placement is convenient for the design of the greenhouse but not entirely necessary. Additionally, this patent specifically defines the ventilation system as existing between two overlapping planes of the roof, and this specificity separates any possible infringement of the FUG design on this patent. However, with the knowledge that hot air will rise to the roof of the greenhouse, a roof-oriented ventilation system is likely more effective than the FUG ventilation system and would be an interesting, and likely much more effective, consideration for a future design.

2.14 Engineering Standards

2016 California Building Code 1605/1606/1607: This engineering code defines what acceptable live loads should be used for different loading scenarios in California. Section 1605 defines how loading situations should be combined, and sections 1606 and 1607 define how dead and live load should be defined for structures, respectively. According to section 1605, loads should be combined to include a factor of safety.

For the sake of simplicity, the project looked at Equation 16-1 from the Building Standards Commission (2016):

$$1.4(D + F)$$

Here, the variables are defined where D is the dead load and F is the live load. Specifically helpful, this equation accounts for supporting both the dead and live loads while also including a factor of safety.

Section 1606 defines dead loads as "the actual weights of materials of construction and fixed service equipment" (Building Standards Commission, 2016). Because there was no need for special construction equipment, one can define the dead load as the weight of the load-bearing member itself. In the context of the greenhouse, this would be the weight of the roof, which is roughly 20 lbs.

Section 1607 defines live loads as temporary loads and describes them as either uniform or concentrated loads. The standard provides a table of different loading conditions along with different loading conditions for each. Based on the conditions, the most relevant loading condition for the greenhouse roof is an "ordinary flat, pitched, and curved roof (that is not occupiable)" (Building Standards Commission, 2016). For this specific loading situation, there is no concentrated load expected and a 20 psf distributed load. These loads were considered in the original FEA and design of the greenhouse, however, they led to a structure that was over designed and was too costly given the constraints of the problem. Based on the area of the roof, a 20 psf pressure would account for 1600 lbs of force, and once applied to Equations 16-1 (assuming the dead load is negligible) would be 2240 lbs total. Although the team did try to design with this number in mind, it was ultimately unrealistic and did not make a lot of sense in the context of this greenhouse. Firstly, the greenhouse is a very low-risk structure. Section 1604.5 defines agricultural structures as a type 1 risk, meaning that they are "Buildings and other structures that represent a low hazard to human life in the event of failure" (Building Standards Commission, 2016). However, the loading condition as applied in section 1605 does not account for this risk, and thus it is reasonable to assume that the factor of safety in Equation 16-1 may be reduced to account for lesser risk. Secondly, the strength of the greenhouse roof is mainly limited by the strength of the greenhouse plastic. Even if the structure can withstand these loading conditions, if they are applied to the plastic the structure will still fail. With these factors in mind, but still using the standards as a reference, the team decided to design the greenhouse to support 10 psf (which realistically still seems more than the plastic would be able to support) at a factor of safety of 1.2. The 10 psf value is also following the International Building Code for greenhouses. With all of this data in mind, along with the assumptions made, the greenhouse created can withstand a 1000 pound distributed load. After considering the standard, as well as specific applications, this is a fairly reasonable and realistic load that will not lead to overdesign--while still protecting against failure.

ASME Y14.5: This engineering standard defines a clear and standard way for geometric dimensioning and tolerancing. It defines a set of symbols, practices, and definitions for drawings to ensure that drawings can be viewed and understood by all people that can use the drawings (The American Society of Mechanical Engineers [ASME], 2019). This can help improve quality, lower costs, and save time for manufacturing applications. While these standards do make a lot of sense for most engineering applications, they do not translate as well to the application for many reasons. The first and most important reason that the team does not specifically adhere to this standard is because the manufacturing process is communicated to a non-technical audience. While these standards can make communication between parties that understand the standards much easier, they can be very difficult to understand at first glance. Also, the tolerancing standards do not make sense in the context of the greenhouse. The only actual situation where tolerances are applicable is in the cutting of PVC; however, the tolerance is limited by the tools used and provided to the partner organization, and does not need to be very specific. Although the design could include a tolerance of about a quarter-inch to each cut, this very broad tolerance is intuitively followed and would mainly serve to confuse and complicate the drawings rovided. With all of these factors considered, it was decided to communicate the drawings in a way that makes more sense for the project and does not follow these well-defined standards. Instructions are given using an IKEA-style manual. This format has proven to be clear for a non-technical audience, can be easily used without the need for software or internet connection, and can be used by people who speak many different languages. Although these tolerancing standards work well when communicated to people who understand them, they are difficult to learn and would only add further complexity for the partner organization. However, some difficulties are anticipated with communication and the team will iterate drawings based on the feedback of the partner organization.

OSHA 1926.51: According to OSHA (Occupational Safety and Health Administration), this standard requires consideration of fall risk within the context of construction. OSHA states that there is a duty to provide fall protection for surfaces that lie six feet or more above a lower level (Occupational Safety and Health Administration [OSHA], n.d.). This greenhouse was specifically designed to eliminate risks such as this one. The height of the greenhouse was reduced to make higher elements more accessible during construction and to underscore the stability of the greenhouse. Additionally, the lightweight nature of the greenhouse allows it to be easily turned on its side by two able-bodied individuals. Because of this, there are zero instances where an individual will be required to stand on a surface above six feet to complete the construction of the greenhouse. That said, the construction of this greenhouse does require the use of a step-ladder and therefore should reference OSHA standard 1926.1053 which requires ladders to have stable, evenly spaced, horizontal rungs (OSHA, n.d.). This project's main deliverable will be a construction manual where the materials required for construction will be listed. In this section, warnings and a reference to standard 1926.1053 can be mentioned to ensure communication of possible risks to the people performing construction (OSHA, n.d.). It is important to note that for this project, it will be appropriate to provide the warning in both Spanish and English, ensuring accessibility to all possible parties.

OSHA Ergonomic Guidelines: Within the context of a workplace environment, prioritizing ergonomics prevents the development of musculoskeletal disorders that affect muscles, nerves, blood vessels, ligaments, and tendons. The practice of ergonomics means that the job is fit to the specifications of the person and OSHA provides seven considerations for ensuring the incorporation of ergonomic practices into the design and development of new products (OSHA, n.d.):

1. Provide Management Support
2. **Involve Workers**
3. Provide Training
4. **Identify Problems**
5. Encourage Early Reporting of MSD Symptoms
6. **Implement Solutions to Control Hazards**
7. **Evaluate Progress**

Of the seven considerations above, 2, 4, 6, and 7 are relevant to the scope of this project and crucial to its long-term success. From its inception, this project involved the "workers," in this case Super Jardineros and Valley Verde greenhouse workers, to gain a better understanding of current problems and opportunities for ergonomic improvement within the context of a new greenhouse design. From various interviews, discussions, and information sessions, there were three main ergonomic concerns:

- The height of the greenhouse shelves and seedling trays
- The daily movement of heavy seedling trays for the hardening-off process over the last few weeks of seedling growth
- The ease of construction

Implementing solutions to these problems is the main focus of this project. The first concern was relatively simple to address. Based on data of the average height of Super Jardineros and recommendations by Valley Verde, shelf height was set to around 2.5 feet. However, because each participant in the Super Jardineros program receives their greenhouse, shelf height can easily be adjusted on a case-by-case basis. This is made possible by the use of simple fittings and connectors specific to PVC piping. The second concern was addressed through the design of shelf-level vents that double as tables for hardening off. Consequently, rather than having to carry trays from the inside of the greenhouse to a separate table outside, trays can simply be pushed (the ergonomic preference, according to OSHA) from the inside, out, or vice-versa (OSHA, n.d.). The third concern was addressed by consideration of greenhouse materials, dimensions, and the required tools and strength for the construction of the greenhouse. Using PVC piping and fittings as the main structural material allows for the greenhouse to be built by unskilled workers with little to no training in construction. There are only four tools required to build this greenhouse, only one of which is a power tool. Even so, this power tool is a drill that requires no formal training for operation and is relatively accessible and familiar to most people. Additionally, the PVC is extremely lightweight, meaning that the greenhouse can be lifted in parts, or even in its entirety, relatively easily. The height of the greenhouse reaches only eight feet so it can be built with the use of a simple step ladder.

It would have been easy to simply develop solutions to these ergonomic concerns, but to evaluate progress and ensure that they are being appropriately addressed, the greenhouse was built twice by the team and once again by Valley Verde to receive feedback on how easy it is to build and how effectively the customer needs were met. These multiple iterations of building leave room for the solutions to be further improved upon if necessary or possible.

NGMA: The National Greenhouse Manufacturers Association (NGMA) defines greenhouses in two ways: for production, or commercial (*National Greenhouse Manufacturers Association* [NGMA], 2004). This greenhouse is not available for public use, and used primarily to grow seedlings for resale back to Valley Verde--thus, it is not commercial. The NGMA notes that their standards comply with the International Building Code and its referenced standards (e.g. ASCE 7 Category 7 of IBC Category IV). The IBC codes provide lower importance factors to greenhouses, as they pose less of a risk to occupants than other buildings. As previously mentioned, following strict codes for load estimation on the greenhouse led to an overbuilt, expensive structure. Most importantly, the IBC exempts greenhouses from withstanding earthquake (seismic) loads (NGMA, 2004).

Chapter 2 of the manual notes that "structures and their components shall have adequate stiffness to limit vertical and transverse deflections, vibrations or any other deformation that may adversely affect their serviceability." In the earlier analysis, FEA showed that areas of significant deformation existed in the horizontal members, on the roof. Rebar support and 45-degree angle PVC supports were added into the structure, so that overall deflection is within no more than a few inches. Section 2.3 suggests the Allowable Stress Design method for designing the greenhouse, but the deflection was a better metric in the end. The NGMA also gives guidance for collateral interior loadings such as hanging loads, at a minimum of 2 psf in the applicable areas, but the greenhouse has no consideration for hanging plants (this was resolved in conversation with the partner organization) (NGMA, 2004).

Chapter 3 of this design manual from NGMA makes additional notes on connections, such as with screws. This design relies on self-tapping screws that comply with SAE standards. The unbranded purchase makes it difficult to trace whether the screws have Building Code Evaluation Reports associated, as suggested by NGMA. However, a building official (or in this case, the design team) is allowed to waive this requirement on a project-by-project basis. The rest of the NGMA manual gives common-sense advice, such as "connections for all bracing elements shall be adequate to convey the required loads" or "wall members shall be capable of conveying all required vertical and lateral loads" (NGMA, 2004). These standards are building-specific and were addressed in earlier FEA.

2.15 Social, Environmental and Economic Considerations

Background Information
The most obvious impact of this greenhouse is its social implications. Valley Verde's Super Jardinero program allows those who generally would not have the access, knowledge, or resources to garden at their homes the means and education to do so. This has the social benefit

of giving families valuable experience, as well as providing them and the surrounding community fresh, organic, and culturally relevant foods (some types of vegetables may be considered niche and expensive at traditional grocers). Although it is difficult to quantify the social impact, this greenhouse will facilitate the growth of a healthier and more sustainable food system in San Jose. Politically, there are few implications. This project is run by a nonprofit organization on a small scale--any permissions given by the local government or petitions made would have existed before this Frugal Urban Greenhouse design.

There are many economic considerations in this greenhouse, both in its cost to produce as well as the economic effect it will have on the Super Jardineros and their community. Firstly and most simply, the cost of the greenhouse is cheaper than other commercially available models, which will have an obvious economic impact. Secondly, the greenhouse will allow the Super Jardineros to sell seedlings back to Valley Verde, which will help to provide a supplemental income. This will allow lower-income families to have more disposable income, which will serve to improve their standard of living and sense of agency.

Manufacturability was a very important factor that was considered throughout the project and many steps were taken to improve the manufacturability and repairability of the greenhouse as much as possible. The number of suppliers for greenhouse parts was minimal so the greenhouse could be easily repaired. The suppliers are also either local to California or part of national chains that have numerous branch locations in the Bay Area. Lastly, a construction manual with accompanying video instructions was created to improve the ease of manufacturing for the greenhouse. These decisions led to many manufacturability improvements and created a design that is very easy and accessible to build.

Sustainability was also essential in the design of this project. One of the main goals of the greenhouse is to improve sustainability by promoting organic farming and reduce greenhouse gas emissions from processes like transporting or processing foods. While the Super Jardinero program is likely not large enough to have a significant impact on the environment, it is a step in the right direction and serves as a model of how urban agriculture can be successful. However, there is also an environmental toll due to the greenhouses, as the plastic and PVC can take hundreds of years to degrade and can release harmful chemicals like chlorine, carbon dioxide, and nitrogen oxides into the atmosphere. While the greenhouse will mostly serve to improve sustainability practices, it is also important to acknowledge that it may have some downsides.

Finally, the product does facilitate ethical behavior. Food production is a significant contributor to climate change and the FUG promotes ethically defensible practices such as organic farming that will help to mitigate this problem. Ethics is a question of right or moral action, so the Frugal Urban Greenhouse needed to avoid creating a situation where the gardeners are left in a moral quandary, as well. Food theft, providing poor sources of nourishment to the family, and engaging in illegal business are all eliminated by the greenhouse. The Super Jardineros, who were trustworthy and productive members of society before joining the program, can be supported by the Frugal Urban Greenhouse to continue their morally upright aways.

Assumptions

Use of project

1. Backyard, family use
2. May prioritize inexpensive plastics over more costly, sustainable materials due to small production quantities (only 4 greenhouses over the next year will be built)
3. Supported with education by Valley Verde
4. Production on a small scale (500) relative to commercial greenhouses
5. Three-year minimum usage
6. Supplements household income but is not the primary income
7. May be subject to relocation

Scope of interest

1. Not for commercial use
2. The primary focus is educational gardening
3. Organic and sustainable gardening, with cultural relevance
4. Not for plant nurseries or plants heavier than seedlings
5. Not for hanging or climbing plants

Quantitative results

Quantitatively, manufacturing time has been improved by three hours. The previous greenhouse took 9 hours total to construct, while the FUG design can be built in six hours. This build time includes preparation (cutting many PVC pipes to length in a standardized way, reducing the amount of unusable/wasted lengths) and setup. The client ran through an initial build with 5 super jardineros on the weekend of May 8th, 2021. Valley Verde expressed some trouble with the roof construction but was able to overcome the issue using the instructional videos. Their final build time was 5 hours, which the design team hopes will be shorter in future builds now that VV is familiar with the design.

Table 2.2: Breakdown of Impact

Economic Impact	**Sustainable Impact**	**Social Impact**
1. Savings of $300-$500 (greenhouse manager Claudia Damiana reported that similarly sized greenhouses have cost the organization $800-$1000 in the past). 2. The greenhouse provides income of around $2000 annually or $2 per plant per growing season. The client indicated that for some jardineros, this income comprised as much as 13% of a gardener's income. The annual report notes that half of all home garden families (a group that includes the super jardineros) earn less than 25k a year, and about a quarter earn between 25 and 45k. 3. In the future, Valley Verde hopes that the greenhouse will continue providing income for the families as they reduce their grocery bills, sell excess plants, and expand the greenhouse use (for example, using the under-shelf space to grow mushrooms, which thrive in heat and darkness). The economic potential of mushrooms should be explored in future reports	1. Uses 175 lbs of PVC and PVC fittings & 20 lbs of plastic (x4-5). 2. Studies indicate that 1 metric ton of PVC (not produced from alternative sources) has a carbon dioxide equivalent of 1.97E3 to 4.03E3 kg, depending on the process. The greenhouse's environmental impact due to PVC is minimal, but in the future recycled PVC might be a worthwhile replacement. This carbon dioxide equivalent for one Frugal Urban Greenhouse would thus range from 156.35 to 319.84 kg, although this metric is not the most appropriate considering that the plastics must be produced at a scale minimum much higher than 175 pounds. 3. Produces 500 organic seedlings per season per greenhouse, transported locally to the Valley Verde facility.	1. Gives 4-5 families professional gardening experience. 2. From 2020, 659 individuals served and 2108 encounters. 3. Supports 113 home gardening families in their program to develop seedlings into mature plants. 4. In 2020, produced 260 seedlings from super jardineros, 10,293 seedlings from the organization as a whole, and distributed 12,673.

This project's social and environmental impacts have been evident from the beginning and inspired the team to join the project. Valley Verde's mission to improve the health outcomes of its participants and increase their earning potential is aided by a successful Frugal Urban

Greenhouse design. The main assumptions for this project were the greenhouse's personal, not commercial use, and a need to make cost-effective choices over sustainable choices. Moving forward, using recycled PVC over regular PVC may reduce the project's carbon dioxide equivalent footprint. The social, short-term impacts are also highly considered, where the $2000 annual income may contribute as much as 13% of their annual income for some growers. The Frugal Urban Greenhouse also supports the efforts to distribute for free (to CalFresh users) or sell seedlings, improving community health outcomes and access to fresh food.

3 Conceptual Subsystem Design

This chapter will explain in detail the three subsystems within the greenhouse, being the structure, watering system, and ventilation system. Each subchapter explains each component in detail including sketches, features, and design rationale. This helps show what the greenhouse will look like at a smaller scale and elucidates the most essential parts of the FUG.

3.1 Greenhouse Structure

The role of the structure subsystem is to provide a stable and suitable environment for the plant to grow. Although it does not directly address many of the key criteria like temperature regulation, moisture regulation, and air circulation, it does impact the ability of other subsystems to complete those functions. The structure is a critical subsystem because its shape impacts all other subsystems. A structure was chosen as shown in Figure 3.1, utilizing a traditional greenhouse shape with a domed roof.

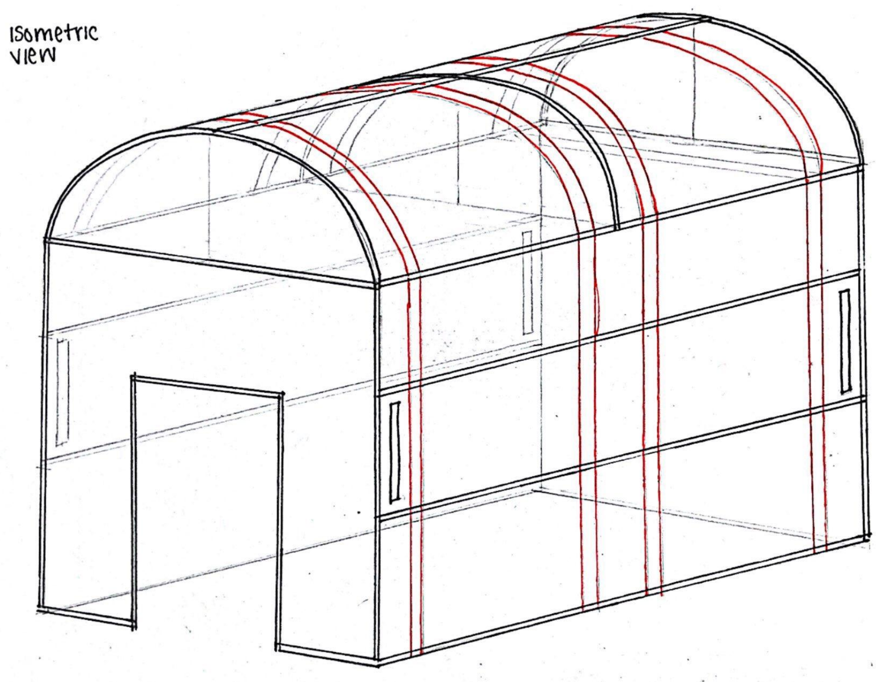

Figure 3.1: Structure/Shading Subsystem

This rectangular greenhouse floor plan with a domed roof far exceeded the score for any other style of greenhouse conceived in the brainstorming phase of this project. This design received a lower score in manufacturability than the standard pentagon-shaped greenhouse currently in use because its roof requires more complicated construction techniques. However, the increased air circulation allowed by the domed roof readily compensates for the difficult construction.

Repairability is an important design criterion when aiming for frugality. Because this design is more basic, it will face fewer problems and need fewer repairs. Additionally, any repairs it does need don't require disassembly of the entire greenhouse and they wouldn't significantly impact the use of the greenhouse. The closet-inspired design, for example, could potentially have issues with the sliding doors making the plants difficult or impossible to access.

Most importantly, compared to other conceived designs, this greenhouse has the benefit of being safer. Safety is the number-one-rated design criterion and so any design's score in this area holds a lot of weight. The closet-inspired design, because of its narrow nature, possesses a risk of toppling over in high-speed winds and so received a poor score in safety. Safety, however, is not a concern held for the more traditional greenhouses with a wider floor plan.

3.2 Ventilation

The ventilation system in a greenhouse helps maintain a temperature critical to successful plant growth. Temperatures that are too warm or too cold can damage a crop, so having a way to regulate greenhouse temperature through air circulation is very important. Two main ways to control air circulation were explored, being either active or passive ventilation. Active ventilation is where the air is forced through the greenhouse, typically using a fan or pump, while passive ventilation occurs due to the natural movement of air through vents or openings. Based on the theme of frugality, it was decided that utilizing passive ventilation would be most appropriate. While active ventilation is typically more effective than passive ventilation, it is more expensive, uses energy, and is more complicated than passive ventilation, which is why it is not utilized in the design. Based on that, the team created a ventilation system like the one shown in Figure 3.2.

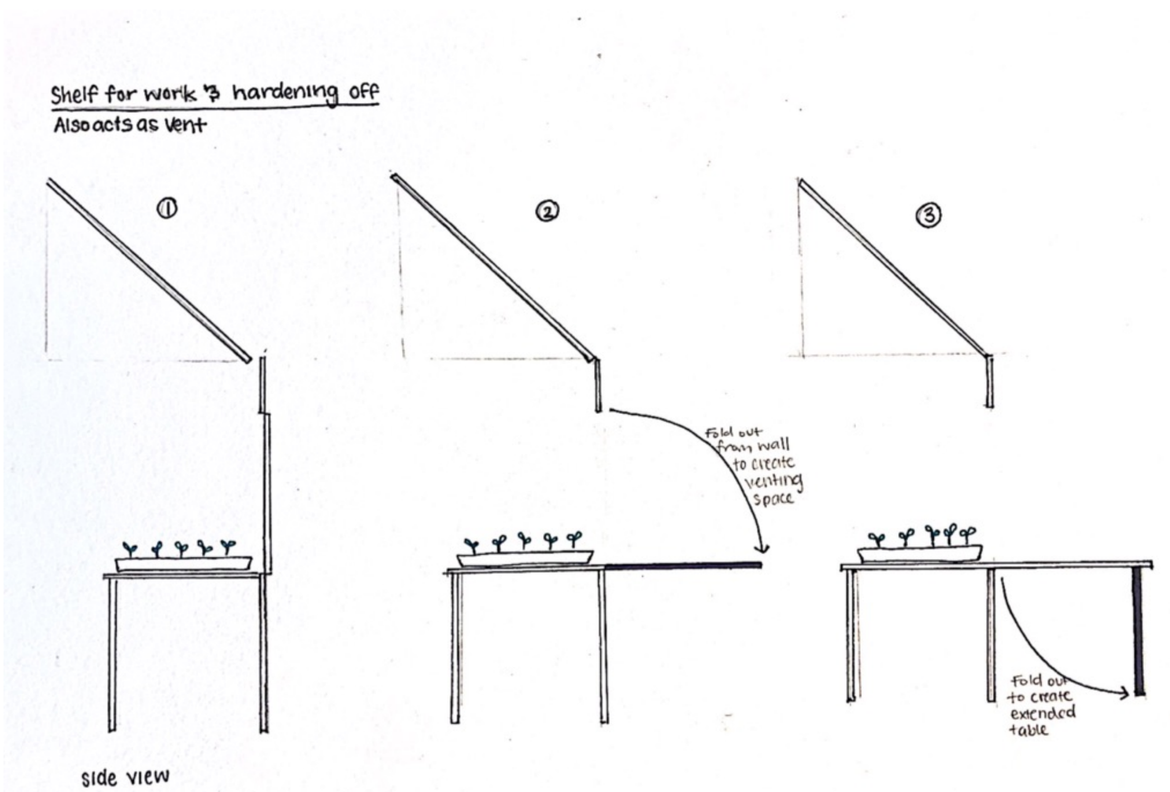

Figure 3.2: Ventilation Subsystem

The design in Figure 6, above, displays a vent along the length of the greenhouse. These vents would be on both sides and can be folded down in increments using hooks and notches (mechanism not shown in the Figure). If folded down to 90º, fold-out legs can be used to create additional table space. The vent panels will likely be made out of a rigid wire mesh, similar to the main benches. A plastic sheet over the panel will be able to be removed or rolled up when the panel is converted to a table, allowing for water drainage.

Other ventilation designs accomplished a single purpose: providing sufficient air circulation to moderate the temperature of the greenhouse. This design was preferable because not only does it provide lots of ventilation space at controllable increments, but it also satisfies the customer's need for a workspace (used for repotting) and an easier way to transfer the plants outside for hardening-off (incrementally exposing plants to natural elements). Previously, plants were carried in and out of the greenhouse every day during the hardening-off process. This process can be laborious and time-consuming. The above design allows for the trays to be simply pushed into the unprotected environment.

Unfortunately, despite its other functional advantages, this ventilation design does contain some trade-offs. To achieve the most efficient ventilation of the greenhouse, it would make sense to put the vents on the roof where hot air will rise and amass. However, these vents will be covered by any relatively simple shade cloth design. Because of this, and their difficult accessibility, these vents are not preferable. Additionally, as mentioned before, any forced ventilation methods require additional energy input into the system. With frugality as one of the goals, and with vents along the entire length of the greenhouse, ventilation will be sufficient and more financially efficient without the use of more expensive electrical components.

3.3 Moisture Regulation

The main role of the watering system is to water the greenhouse plants appropriately and efficiently. It must be compatible with a garden hose and be adjustable and adaptable to water plants in a variety of different configurations. Also, because many of the super jardineros are not able to water their plants throughout the day, Valley Verde had requested that the system be automated. They also wanted the system to be fairly easy to implement and learn for new gardeners. Automatic watering is generally not included in greenhouse designs, so this was a good opportunity to explore creating a new solution to a generally unexplored problem.

To accomplish this, the team decided to use a misting system. This is helpful because it can be done automatically, will be effective for all plants that will be grown within the greenhouse (according to contacts at Valley Verde), and is more efficient than a sprinkler system. This system will work in tandem with hooks that will hold the misting system, as well as things like fans and miscellaneous tools. Also, a misting system can be implemented relatively cheaply and provides a large benefit to the entire system. This system ideally would be controlled with a timer system. At the moment, the plan was to use an off-the-shelf timer that would connect a hose to the misting system.

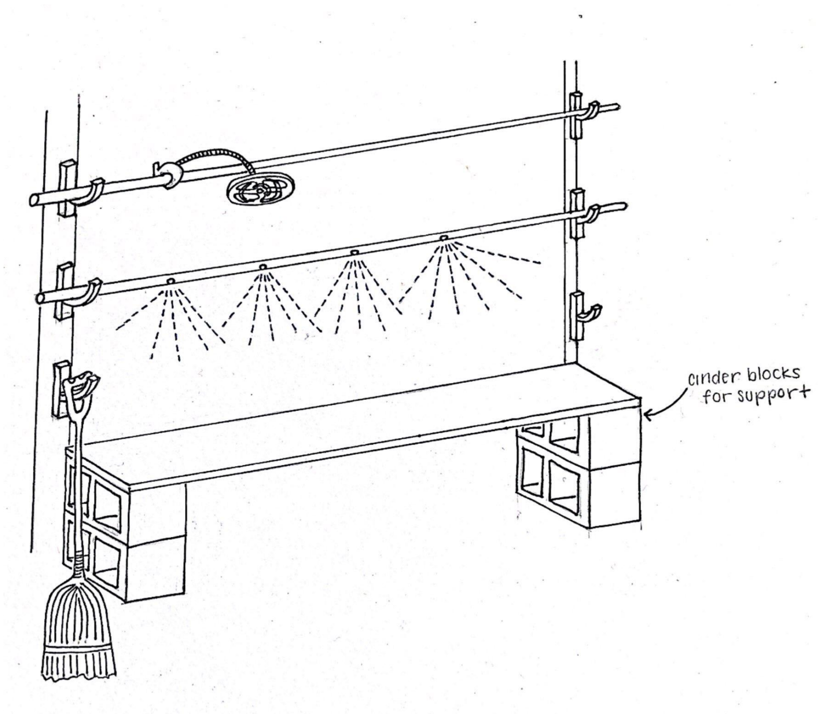

Figure 3.3: Watering Subsystem

The main options chosen were hose watering, gravity watering, sprinkler watering, drip irrigation, and misting. There were also options of using either a timer system or an Arduino control system for automatic watering. Based on the decision matrix, which can be found here, a timer system most closely met design criteria. Although the misting system did not perform the best under design criteria, it was the most compatible with the timer system (along with the sprinkler system) and it came recommended by the partner organization Valley Verde.

One major trade-off with misting is that it adds a lot of complication to the system. It is much more complicated than the current system, which is hand/hose watering. However, based on the customer's need to water the plants during the day without human input, it was a worthwhile trade. Another trade-off made is efficiency. A misting system will be less water-efficient than a hand-watered system and does not minimize water loss. Because of this, prototyping work was attempted on the misting system to make it as efficient as possible. Looking at factors like flow rate, nozzle types, distance from the plants, and duration, would maximize the efficiency of the system and make the losses (compared to hand watering) minimal.

4 Computer-Aided Modelling

During the CAD/FEA (computer-aided design & finite element analysis) phase of this project, the team modeled the structural frame of the greenhouse. This ensures that the greenhouse can withstand expected loads but also more precisely determines a list of required materials and the greenhouse's total cost.

Due to PVC's large range of elastic deformation, deflection analysis, rather than a failure analysis, is an appropriate indicator of how well the greenhouse will withstand the expected loads (outlined in the assessment criteria section). In modeling and analyzing the greenhouse, the team noticed many potential critical points in the greenhouse and made appropriate design iterations to make the greenhouse frame structure as effective as possible. Using FEA helped troubleshoot this design and meet structural requirements and customer needs while remaining frugal and effective.

4.1 Assessment Criteria

In the greenhouse, a primary concern is an excessive displacement in the PVC frame. Because PVC is fairly elastic, none of the members are expected to break or fail, but excess deflection could make the greenhouse not function properly. To determine that the design is successful, the greenhouse is examined in three different conditions:

1. No external loads applied: Only gravity and other weight forces applied. In this loading condition, the maximum acceptable deformation is 1 inch. The greenhouse should be able to carry its weight with minimal deflection.
2. Expected daily loading: Wind and live loads are assigned based upon expected daily circumstances faced by the greenhouse. This will include 100lbf of force from live load applied on the roof, as well as a wind load force equivalent to a 20mph wind. The 100 lbf is meant to simulate things like the greenhouse cover material, shade cloth, or organic debris. For this condition, the maximum acceptable deformation is 2 inches. Because this is expected to be the daily use case for the greenhouse, the deflection should also remain fairly minimal.
3. Maximum loading: This is meant to model the most extreme loading conditions on the greenhouse. This will include 1000 lbs of live load applied to the roof, as well as a wind load force equivalent to a 50 mph wind. For this loading condition, the maximum acceptable deflection is 8 inches. While this deflection is fairly large, it is still within 10% of the minimum greenhouse dimension (8ft) and would likely not cause the structure to fail (this will be later tested and verified in the construction and testing process). The team will also ensure that the factor of safety in this loading condition is greater than 1, so no plastic deformation will occur.

If the greenhouse can meet the criteria for all three conditions, it is a successful preliminary design.

4.2 Assumptions

The assumptions made during the FEA of the greenhouse iterations are as follows:

- The bottom posts of the greenhouse use a roller/bearing fixture where they cannot move in the y-direction. This is to simulate the interaction between the beams and the floor.
- The left beam was fixed in the horizontal x-direction. This is to simulate resistance to movement in that direction due to forces like friction and was necessary to see deformation from horizontal forces.
- Wind and live load on the roof are considered to be the only external forces.
- The weights of the vents and door are simulated using vertical and horizontal forces. The vents were assumed to be 15 lbs each and the door was assumed to be 20 lbs.
- All parts are considered bonded at touching faces. This is the largest assumption that is made. However, the partner organization has yet to guide the team on the best fixture method. This issue will be reexamined and solved during the construction and testing phases.
- Materials properties are as described in Appendix K
- The wind force was calculated as described in Appendix N

4.3 Final Structural CAD Design

The final structural CAD design after numerous iterations (which can be referenced in Appendix L) can be seen below.

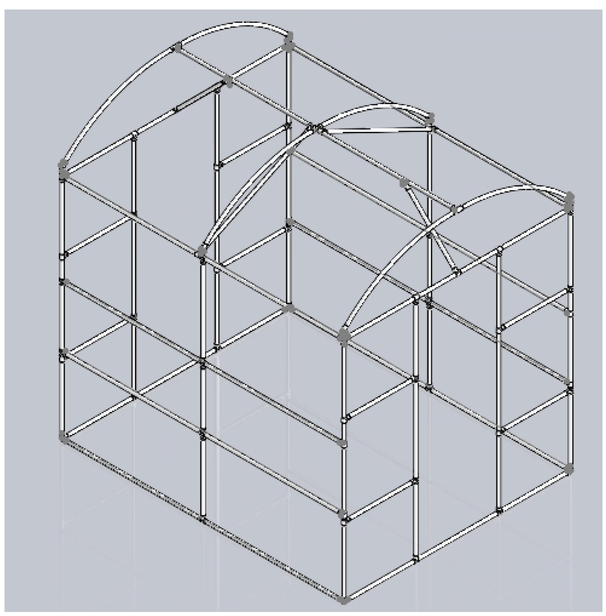

Figure 4.1: Final structural CAD Design

Other views of the final design can be seen in Appendix M.

According to the Solidworks analysis, this greenhouse will weigh approximately 135 lbs (215lbs with estimated door and vent loads) and will be approximately 8’ x 10’ x 10’ (L x W x H).

To verify it met the criteria that were outlined above, FEA was performed with each of the three conditions. This model was analyzed with a very coarse mesh to improve processing time because none of the geometry used in this model was very complex.

Condition 1: Weight loading and no external forces

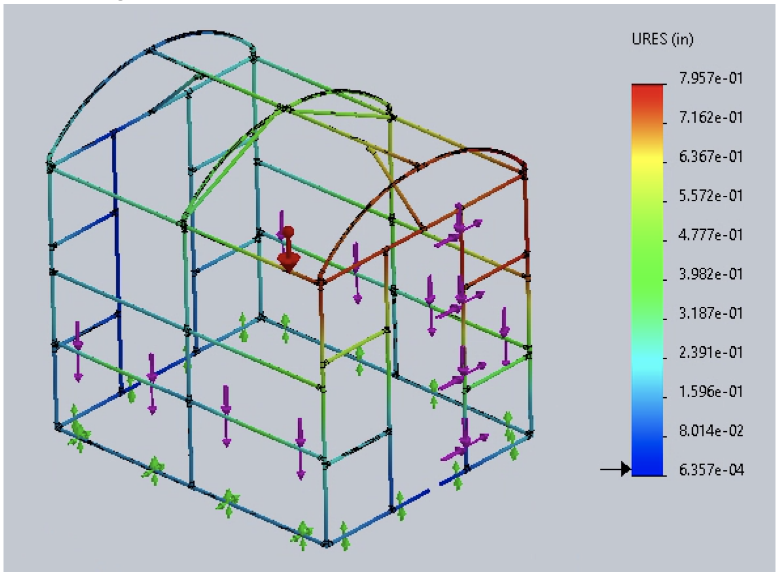

Figure 4.2: FEA with weight loads

As shown in the Figure, the maximum deflection due to the no-loading situation is 0.796 inches. This is acceptable as it is less than one inch, which was the criteria for the first condition.

Condition 2: Expected daily loading

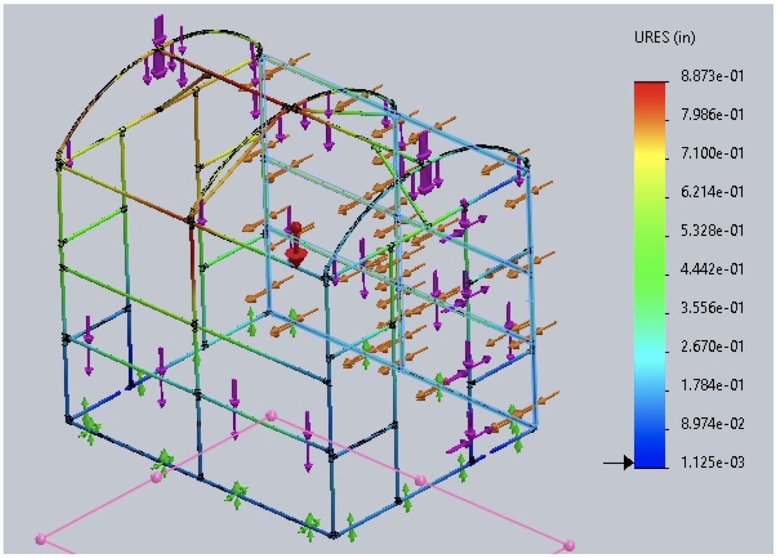

Figure 4.3: FEA with expected daily loads

As shown in Figure 4.4, the maximum deflection is 0.8873 inches given the expected loading condition. The maximum deformation on the greenhouse is less than 2 inches, which means it is acceptable based on the criteria for condition 2.

Condition 3: Maximum loading conditions

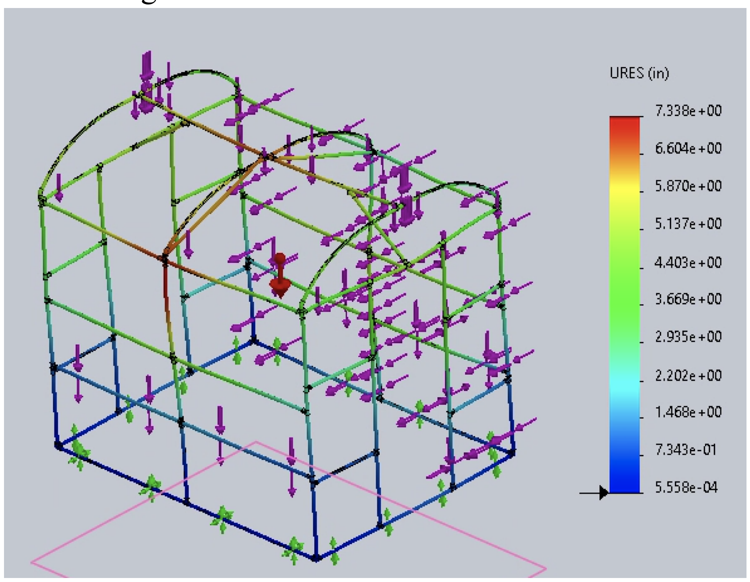

Figure 4.4: FEA with maximum loading

As shown in Figure 4.4, under maximum loading conditions, the deformation on the greenhouse is 7.338 inches. Although this is a considerable amount, it is reasonable to assume that with proper connections the greenhouse would not fail under these circumstances. While it is possible to make a greenhouse with smaller deformation, based on budget, customer needs, and original conceptual idea, the Team believes that this design will be effective. Also, most of the deformation comes due to the bending of the PVC, and there is very little actual strain on any of the components within the greenhouse. The minimum factor of safety for plastic deformation under this loading is also 1.2, which means even under this extreme loading condition the materials will not plastically deform and fail. These loading conditions are much higher than would be reasonably expected at any point for the greenhouse, so although these deflections are large, it shows that the greenhouse structure can withstand these large loading conditions without failing.

4.4 Hand Calculations

As engineers, it is important to have some intuition about whether the modeled results regarding failure seem appropriate. To gain this intuition, one can use some generalized hand calculations. See Appendix P for typed calculations of the critical pipe lengths: the horizontal, centered roof pipe and the generalized vertical column. The horizontal, central pipe reinforced with rebar was shown to have a deflection downward of less than 1.2 inches (more conservative than FEA analysis shows, but still an appropriate order of magnitude). The vertical column is demonstrated to buckle but not yield, which is obvious given the material properties.

4.5 Materials and Costs

Based on the refined model, a more specific list was made of what will be used in the construction of the greenhouse. Those parts, along with required quantities and prices are shown below. The Grand Total of $398.30 is well below the goal budget of $500. Materials like a watering timer, misting tubes, a rebar cutter, or a PVC pipe cutter have not been factored into this calculation. Instead, the Team is only considering that which is essential to the greenhouse structure in the $500 goal.

Looking forward, the team plans to increase the number of cinder blocks, instead of building actual legs for the fold-out shelves of the greenhouse. Additionally, it is desirable to add a specific value for fasteners, but at this point, one may estimate their cost to be around $10 to $15.

Table 4.1: Bill of materials and costs

Description	Quantity	Cost	Cost/Unit (Dollars)	Total (Dollars)
4-way fitting	4	10.71 (4 pack)	2.6775	10.71
90 Degree socket elbow	4	2.8	2.8	11.2
45-degree elbow	8	1.19	1.19	9.52
10 ft PVC pipe	30	4.12	4.12	123.6
Slip Tee fitting	40	62 (100 pack)	0.62	24.8
Snap Clamps	30	45 (100 pack)	0.45	13.5
Cattle Gate	3	16	16	48
Slip Cross	7	22.25 (25 pack)	0.89	6.23
Rebar	2	5.74	5.74	11.48
PVC hinge	6	21.48 (4 pack)	5.37	32.22
Cover Material	1	47.66	47.66	47.66
Cinder block	**30**	1.9	1.9	57
T-Fitting	2	1.19	1.19	2.38
Grand Total				398.30

4.6 Computer-Aided Modeling Conclusions

Using Solidworks modeling and FEA, in conjunction with hand calculations, the Team was able to solidify and greatly improve the greenhouse design. Although the conceptual greenhouse idea before this goal was a good start, by actually modeling the design the Team was able to verify that it is viable, improve it, and determine material costs and quantities. It also makes creating a construction plan much simpler and helps provide a visual representation of the project. Although the team will have to verify that many of the assumptions made were reasonable, the completion of this goal gave a much more solid understanding of the design, as well as how it should be built.

5 Construction

The construction can be broken up into five main steps. The progression of the construction manual is incorporated into these steps but more detailed descriptions of the construction manual's development can be found in Chapter 6.

1. All of the parts for the main structure were ordered.
2. The PVC and rebar were cut to size.
3. Initial construction took place with documentation on what worked well, what made construction more difficult, and any unforeseen structural challenges that were encountered throughout the process. This step of construction was used to inform the construction manual that is being completed simultaneously.
4. This fourth stage of construction consisted of another build by team ACE, following the construction manual very closely. This ensured the instructions were clear and thorough. This stage included filming a timelapse and other specialized videos as supplementary materials to the construction manual.
5. The construction manual and greenhouse materials were sent to the partner organization Valley Verde. VV will provide feedback for the manual once they have completed construction. It should also be noted that updates will be sent to VV throughout this construction process to receive continual feedback. The team must check in with them regularly during this phase to ensure that the physical greenhouse continues to match their expectations and needs.

Due to restrictions of COVID-19, some of these steps overlapped slightly due to ordering or communication delays.

5.1 Material Purchasing

To make purchasing as streamlined as possible, materials were sourced from three main vendors. It was a priority to make sure that any materials used were easily accessible, and replaceable when necessary. Home Depot, with its many locations around the South Bay and relatively low prices compared to competitors such as Lowe's, was chosen as the source for PVC. A local hardware store was preferable to a bulk supplier because lead times are more predictable -- the PVC can be bought as needed and driven home same-day. With bulk suppliers, shipping can be expensive and can sometimes take weeks to complete. A company called Circo Innovations from Central California was chosen as the source for PVC fittings because of their wide range of fitting options, low prices, and incredibly short lead time -- only three to four days maximum. Lastly, Amazon was chosen as the main supplier of greenhouse plastic. For such large rolls of plastic, shipping is often pricey and Amazon can keep costs low, quality high, and lead times relatively fast.

5.2 Greenhouse Height

Once constructed in its first iteration, it became apparent that the greenhouse was too tall. This made it difficult to perform certain tasks required for construction. For the second round of construction, the greenhouse was shortened from eight feet to six and a half feet. This benefitted the design of the greenhouse threefold:

1. With shorter pieces of PVC and less greenhouse plastic, it decreased the cost of materials and consequently the cost of the greenhouse.
2. Flipping the greenhouse on its side and other construction activities became more accessible.
3. The shorter stature made the greenhouse more stable and less likely to be affected by strong winds.

The door height of the greenhouse was important to consider in this change because it would be counterproductive to make a door that is outside of regulation. According to OSHA guidelines, a door must be at least 78 inches, or 6.5 feet, high which is exactly the height of the new greenhouse design. It is also important to note that Valley Verde self-reported the Super Jardineros to be no more than 5.5 feet, leaving plenty of clearance between their heads and the door frame.

5.3 The Roof: An Unforeseen Spring Force

The semicircular roof of this greenhouse is made of a single piece of 117” PVC which is bent into place. In FEA, this PVC was assumed to be plastically deformed. However, in actual construction it was found that its *elastic* deformation created a spring force, causing the walls to bow slightly outwards, by about five to six inches on either side. This can be seen in Figure 5.1a, below. To temporarily solve this problem, a string was added to compress the walls of the greenhouse until further construction could be completed and a more permanent solution could be found, as seen in Figure 5.1b.

Figure 5.1a: Horizontal Deflection

Figure 5.1b: String-fix for deflection

In considering more permanent solutions, the Team experimented with adding rebar to the lengths of PVC where the bowing occurred. This did not solve the problem and added significant amounts of weight to the roof of the greenhouse, furthering the concern that it may be more likely to tip over in strong winds. With further construction, the diagonal roof supports were completed and they acted as constraints on the horizontal deflection of the greenhouse, solving the horizontal deflection. These completed diagonal roof supports can be seen in Figure 5.2, below.

Figure 5.2: Close up of diagonal roof supports

Unexpectedly, the spring force provided a significant amount of support to the roof of the greenhouse. In the end, the rebar that was initially deemed necessary through FEA became redundant. Not only was its contribution to the roof's strength now unnecessary, but the addition of rebar also made the greenhouse more top-heavy and for these reasons, it was removed from the final design and budget.

5.4 Greenhouse Plastic Iterations

For initial construction, a roll of 5' wide greenhouse plastic was used to cover the greenhouse. While seemingly a perfect fit for a 10' long greenhouse, it turns out that a small amount of plastic, about 1.5-2," was necessary on each side for the snap clamps to effectively hold the plastic in place. This first iteration can be seen in Figure 5.3 below. Notably, on the rear wall of this image, the greenhouse visibly overlaps which made it difficult to create an air-tight seal.

Figure 5.3: Greenhouse with Five Foot Wide Plastic

For these reasons, the length of the greenhouse was shortened by three inches in the second construction, allowing for the 1.5” lee-way on either side for snap clamp attachments. Additionally, a 10’ wide roll of greenhouse plastic was ordered. With the benefit of the 10’ length and extra room on the sides, the new plastic worked phenomenally and made construction significantly easier. Once all the plastic was attached, cuts could be made along the openings of the vents and doors and extra snap clamps added to hold any loose plastic in place. The greenhouse with 10’ plastic is shown in Figure 5.4.

Figure 5.4: Greenhouse with Ten Foot Plastic

The 10’ plastic was an improvement to the previous design in three ways. First, it was cheaper per square foot than the five foot plastic, which was a much needed improvement for the greenhouse’s tight $500 budget. Second, a single 10’ role of plastic can easily cover two greenhouses which simplifies material ordering and cheapens the cost of shipping per greenhouse. Finally, the 10’ plastic also fulfilled the previously defined frugal criteria that the greenhouse should be both simple and rugged: not only was the greenhouse plastic easier to attach in its 10’ width, but the single pieces are less likely to come loose due to wind or pressure.

5.5 Vents and Hardening-Off Shelves

The successful application of hardening-off shelves was perhaps the most original aspect of this project. This process, which had previously required the Super Jardineros to carry each tray in and out of the greenhouse, now allows them to simply push the trays onto the vents and pull the trays back in when necessary. These shelves are entirely novel, unused in any design currently on the market, and unrivaled by any patent currently in existence. The vents, folded out into their shelf form can be seen in Figure 5.5 below. The legs for the vents were designed to be removable and their easy set-up makes conversion from vent to shelf seamless. Figure 5.6 shows a close-up of the vent legs.

Figure 5.5: Vents Folded out as Hardening-Off Shelves

Figure 5.6: Vent Leg

5.6 Shelving Iterations

A major goal for this greenhouse was to achieve a more ergonomic set-up for greenhouse users. Mainly, this plays a role in the shelving. While the previous design had two levels of shelving, neither level at an ergonomic height, this design was able to achieve the desired capacity for seed growth while also maintaining ergonomically placed shelves and workspaces. The final design for the single row of shelves is seen in Figure 5.7 below. The height of the single row of shelves, about 2.5 feet, was chosen based on Valley Verde's request and experience.

Figure 5.7: Shelving

Previous iterations had included the use of cinder blocks and wire mesh for the permanent interior tables in the greenhouse, such as those shown in Figure 2.3. However, these shelves are significantly more expensive than the final PVC, by about $60 or 12% of the $500 budget goal. Additionally, the PVC shelves easily outperform the cinder block and wire shelves. Where all of the seed trays weigh about 55 lbs in total, the shelves can easily hold at least 150 lbs, leaving a Factor of Safety of about 2.7.

5.7 Valley Verde Build

Once the materials and the construction manual (Chapter 7) were sent to Valley Verde, they were able to complete a single construction of the greenhouse. Participants ran into some issues with the roof as the curved beams were difficult to bend and it took five people to do so. As a result, Valley Verde has decided that they will organize all five Super Jardineros to build each greenhouse. As an unforeseen consequence of this arrangement, the cooperative build will also provide an opportunity for connection between the Super Jardineros which Valley Verde sees as desirable for cultivating community. They also experienced some difficulties that resulted in breaking some PVC fittings. However, breakage occurred in The Team build, as well, and is expected to be minimal in future builds as the Super Jardineros become more familiar with the build process. With everyone working together, it took Valley Verde 5 hours to build the greenhouse, not accounting for about 1.5-2 hours worth of PVC cutting. This timing was expected and acceptable. The only feedback Valley Verde had with regards to structural design was that the greenhouse's footprint was larger than they had originally pictured, despite the originally communicated dimensions. For this reason, the construction manual will be altered to accommodate a slightly smaller floor plan while maintaining the required seedling capacity. Photos of Valley Verde's initial build can be seen in Figures 5.8-5.10, below.

Figure 5.8: Super Jardineros collaborating to construct the first two walls of the greenhouse

Figure 5.9: A Super Jardinero standing next to the partially completed greenhouse

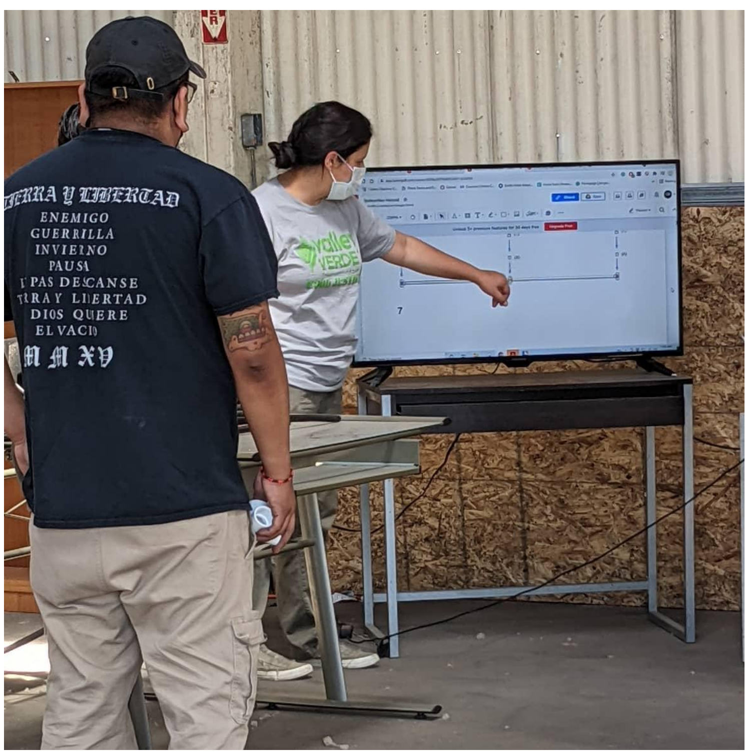

Figure 5.10: Claudia Damiana Referencing the construction Manual

6 Moisture Regulation System

The moisture regulation test plan was created to implement the most effective possible misting system for the greenhouse. In this context, an "effective" moisture regulation system entails one which is easy to use, reliable, completely waters plants, and is water efficient.

To begin this process, it first was necessary to figure out the best materials to use for the watering system. While choices of piping and misting nozzles were fairly limited based on the available water pressure provided by city water, there were a wide variety of timers and moisture sensors to choose from. To ensure thorough and thoughtful material selection, the team looked at a variety of different sensors and timers with different functions, prices, and manufacturers. Important specifications and pros/cons for each item are listed, to help develop as clear of an idea as possible. These results can be seen summarized below.

6.1 Materials

For this system, the Team decided to use an Arduino system to measure soil moisture in conjunction with a misting system. Ideally, the misting system could be controlled either directly by the Arduino, or by a hose timer, which would be reserved for use in the final design (for simplicity). Tables 6.1 and 6.2 show the results of research and comparison for various materials.

Table 6.1: Moisture Sensors

Item	Cost	Specifications	Pros/Cons	Notes
STEMMA Soil Sensor	$7.50	Ranges from 200-2000 capacitance Measure temp ± 2C	Pro: Can measure humidity fairly precisely, measures temp Cons: Would have to manually correlate capacitance to humidity %, need a specific cable to work	Needs a special 4-port cable (JST PH 4-Pin to Male Header Cable - I2C STEMMA Cable - 200mm)
KeeYees 5 Pcs High Sensitivity Soil Moisture Sensor Module	$7.48	Can set soil moisture by adjusting potentiometer	Pros: Cheap, comes with cable involved Cons: Not clear how the sensor works from the website	
LGDehome 6PCS	$12.99	Uses capacitive	Pros: Customer receives 6 units and their cable, can measure	

Capacitive Soil Moisture		sensing	moisture in multiple areas Cons: Very little info or documentation about the sensor (no reviews)	
I2C Soil Moisture Sensor	$13.00	Operates 0-85C Moisture reading <10% variation	Pros: Has a wide temp range. It is well documented with instructions on how to use it. Cons: slightly more costly	
Waveshare moisture detection sensor module	$2.99		Pros: Cheap, Arduino code already supplied Cons: Can oxidize and break very quickly, no specs	https://create.arduino.cc/projecthub/electropeak/complete-guide-to-use-soil-moisture-sensor-w-examples-756b1f

Table 6.2: Timers

Item	Cost	Specifications	Pros/Cons	Notes
Raindrip 1-station Irrigation timer	$29.98	Period: 1, 2, 3, 4, 6, 8, 12, 24, 48, or 72 hours Duration: 3, 5, 10, 15, 20, 30, 45, 60, 75, 90, 120 minutes	Pros: Wide variety of period and duration options, compatible with hose, fairly well-reviewed Cons - On the expensive side, has many settings that would not be used	
Mechanical water timer	$13.98	Duration: 0-120 mins (analog with 15 min breaks)	Pros: Analog (no need for batteries/electronics), cheap Cons: Would need to be manually set daily, coarse	

			precision	
Gilmour single outlet electronic water timer	$24.36	Period: 6, 12 hours, 1-7 days Duration: 1-360 mins	Pros: Programmable clock (can water at specific times of the day), highly customizable durations Cons: Needs AA batteries, periods aren't super flexible	

Miscellaneous necessary electronics include the Arduino breadboard, jumper cables, a power supply, a breadboard, batteries, etc. It may be noted that the Waveshare moisture detection sensor module and the LGDehome 6PCS Capacitive Soil Moisture were chosen moving forward, based on the pros, cons, and cost.

Because the misting system would run off a typical garden hose, it would have to be a low-pressure system. This limits the misting nozzles; however, it restricts the design to larger nozzles which would be more effective for watering plants. While some evaporative cooling is desired, overall, the misting system is intended for watering use rather than cooling the greenhouse. This also means that the inside of the greenhouse may become wet, but organic material in the design was omitted for this reason.

Due to constraints on cost, as well as pressure as outlined above, it was most beneficial to use plastic nozzles in conjunction with traditional misting tubing. These can be referenced in the table below.

Table 6.3: Misting Materials

Item	Cost	Notes
Sprinkler Nozzle, 20pcs Plastic	$4.29 (20 nozzles)	1.2-1.8 m spray diameter, compatible with ¼ inch tubing
50ft 1/4 inch Blank Distribution Tubing	$8.99	
Orbit DripMaster 69432 Faucet to 1/4-Inch Drip Tube Adapter	$5.64	Also are some bulk prices

After the material selection was completed, general parameters that would be important to know for the moisture regulation system are described. For example, the team first had to research how much moisture was needed for plants to grow most effectively. From there, using parameters like the soil volume, the team calculated approximately how much water each planter would need. This will be helpful because it will help determine the efficiency of the system by comparing the expected value to the amount of water used. Then, other specs such as the nozzle spray diameter were used to determine a potential configuration for the misting nozzle. Finally, details for testing were determined. These included information on the scope of the testing, criteria for success, objectives, and deliverables. As a whole, it describes how tests should run and what constitutes a successful test.

6.2 Setup and Initial Calculations

It was assumed that the following factors are outside greenhouse user control:

- Wind (although the wind that enters the greenhouse may be adjusted via ventilation)
- External temperature (the greenhouse plastic insulates, and the shade cloth prevents excess heat from entering)
- Seedling & soil type (Valley Verde will dictate the seedlings to be grown, and provide soil)

The testable variables in this scenario include:

- Distance and configuration of watering system
- The flow rate of misters (nozzle type)
- Watering duration
- Watering period
- Time of day

By combining all testable requirements, the Team intended to create a system that effectively waters seedlings while being as water-efficient and user friendly as possible--this ensures that the entirety of the tray is watered evenly without wasting excess water. It should be noted that the client did not request such a system, as hand-watering has worked in the past. The goal was to measure moisture content in individual soil plugs, report that to the Arduino as either sufficiently moist or needing watering, and mist appropriately.

Analysis

Initial assumptions assume uniform water distribution from the misting system and neglected evaporation rate. To understand how the seedlings should be watered, it is important to understand the needs of the seedlings to minimize the time and effort spent testing. Firstly, it is important to know the crops Valley Verde grows, which include: okra, eggplant, cucumber, peppers, summer squash, tomato, winter squash, and various herbs.

Because these are all vegetables, they require 41-80% of the fully saturated soil moisture ("Guide: Soil Moisture", 2020) to grow most effectively. Based on this metric, one can get a reasonable estimate of how much water needed, to better understand the types of trays configurations. All values will be rounded up to the whole inch, to provide a slight overestimate. There are 3 basic configurations of soil trays used at various stages of the growing process:

1. Plug flats
   a. Volume (72 cells) = 3.6 in^3 * 72 = 260 in^3 per tray
   b. Volume (98 cells) = 2.26 in^3 * 98 = 222 in^3 per tray
2. 10" x 20" Trays

    a. Volume = 10.94” * 21.44” *2.44” = 573 in^3
3. 3” diameter by 3” height daisy pots with germination trays
    a. Volume (per pot) = $\pi * 3^2/4 * 3 = 22$ in^3
    b. Volume (germination tray) = 10.8” * 21.25” * 1.29” = 297 in^3
    c. Volume (Total) = 22 * 18 + 297 = 693 in^3 per tray

Because the 3 of these configurations have different volumes, watering will have to be adjusted for each accordingly. The tray types of interest are mainly the plug flats, where individual seedlings grow.

Soil moisture is defined as

$$\frac{V_{wet} - V_{dry}}{V_{dry}} * 100$$

Given this equation, and that 1 gallon is equivalent to 231 cubic inches, each tray should receive the following amounts of water to reach and stay within the 41-80% soil humidity.

Table 6.4: Predicted water per tray

Tray Type	Water to 80% (gallons)	Water from 41-80% (gallons)
Plug Flat (72 cells)	.900	.461
Plug Flat (98 cells)	.769	.394
10” * 20” Tray	1.98	1.02
Daisy Pots w/ germination trays	2.40	1.23

Based on the misting diameter outlined by the nozzle manufacturer, one would expect that one nozzle would be able to water 4 trays, as shown in Figure 6.1 below. All trays are approximately 10” by 20” and the configuration would be the same for any tray configuration.

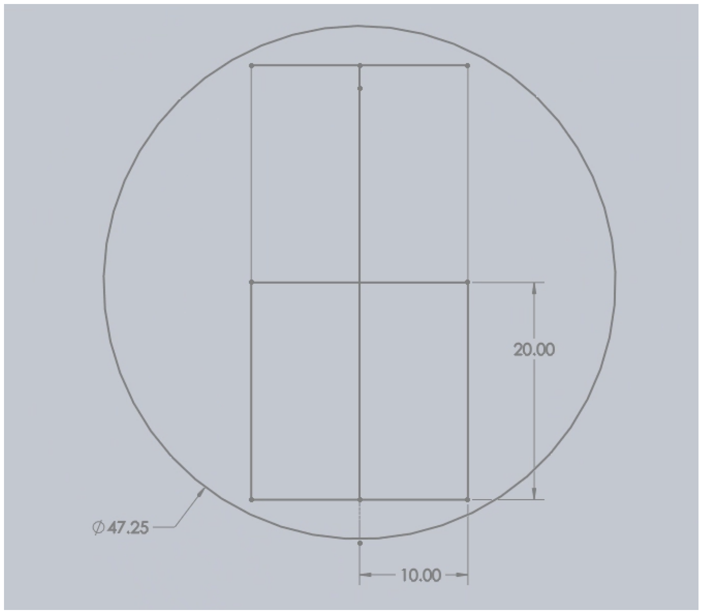

Figure 6.1: Misting Nozzle Diagram (inches)

As a whole, the misting system should look as shown in Figure 6.2 below.

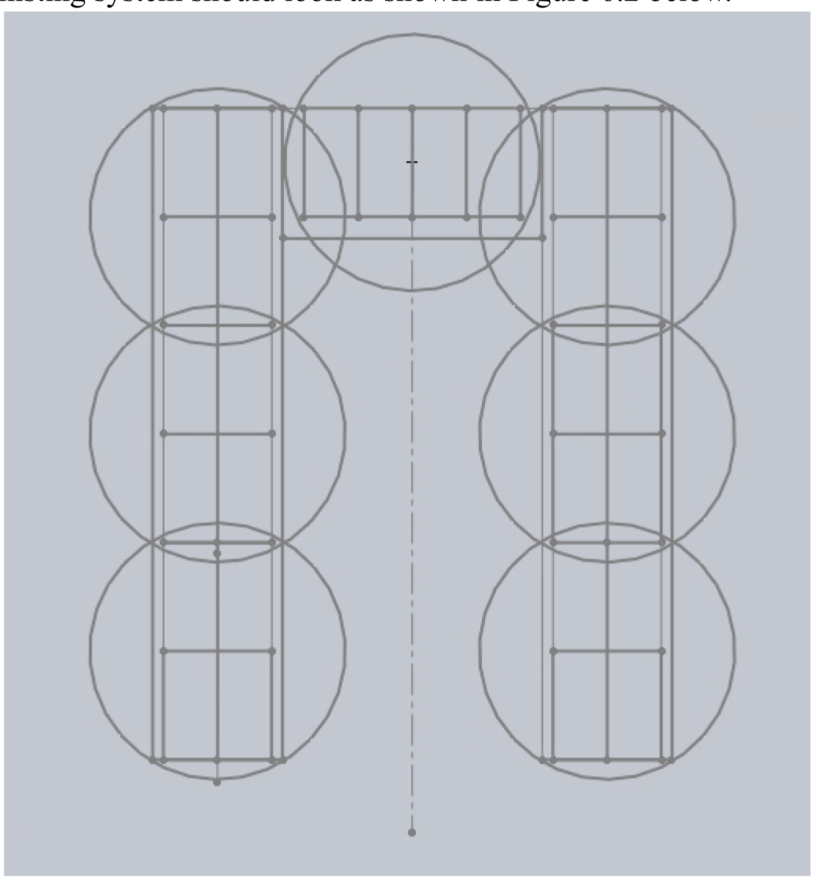
Figure 6.2: Entire greenhouse misting system design

As shown in this Figure 6.2, to effectively mist the entire greenhouse, 7 misting nozzles per greenhouse are needed and about 26 feet of misting tubing (plus whatever it would take to attach the hose), and one hose to the misting tubing adapter. This will work for watering 28 trays, which is well above the stated need. Given this preliminary model, some areas of concern included the areas on the perimeter of the misters and the overlap areas of the misters. The overall setup within the greenhouse was not possible, as responsibilities for testing this water system and building the greenhouse were delegated to team members located in different states. Thus, the idea for testing was only to validate the use of sensors and moisture data feedback.

6.3 Test Plan

1. Initial analysis of the soil moisture sensor test and the system for testing. The following must be recorded and known before any testing:
    a. Duration: the suggested time for watering will be 30 minutes or shorter. The Super Jardineros ideally water their seedlings before work in the morning, and after arriving home. If this automated system proves superior to the hand-watering method, it will save time and resources (San Jose Water, 2020)
    b. Time of day: as this research will be conducted in a different state than the target area, it is desired to run the experiment in an indoor environment, where indoor temperature will be closer to the seedling growing temperature (75-85 degrees).
    c. Average humidity: humidity will be calculated using basic principles from MECH 125 for conditioned buildings.
    d. Soil composition: the partner will provide specific soil suggestions for purchase.
    e. Sensor data: the chosen sensors, based on the above market analysis, are the LGDehome 6PCS Capacitive Soil Moisture (to get multiple measurements) and the Waveshare moisture detection sensor module (to get comfortable with the Arduino system).
2. Scope of testing:
    a. The main risks and issues associated with testing are the internal environment conditions producing results not generalizable to the greenhouse. Otherwise, human error will be reduced by using a pre-coded Waveshare sensor to get familiar with the system and practice code; then, this code will be applied to the 6 sensors from LGDehome.
    b. The client will not use this electronic sensing system, but rather a simplified version that does not require sensors. The test data will be used to generate a watering guide that recommends duration for watering, based on the physical setup, per weather conditions like external temperature.
3. Test objective:
    a. The objective of this system is to simulate a non-ideal moisture environment, with ambient conditions as described above in 1b and 1c, and generate an ideal watering time based on continuous sensor feedback for the moisture content.
    b. A secondary objective is to provide meaningful watering duration data for the three configurations as described in the analysis section earlier.
4. Test criteria:
    a. Suspension criteria--testing will be suspended and restarted when results are not reproducible and accurate. The Waveshare sensor should demonstrate accuracy, and the LGDehome sensors should demonstrate relative reproducibility (with

some variance allowed for the moisture gradient due to different positions relative to the center of the misting hole).

b. Exit criteria--testing will end when suspension criteria are not triggered after three consecutive sessions.
c. Run rate--the run rate will be defined as the total number of tests executed, divided by the total number of tests attempted. The desired run rate is 80% to start, with 8 out of 10 tests finishing successfully. 20% of the tests may be discarded due to various errors, to be determined.
d. Pass rate--the pass rate will be 90%, where 9 out of 10 tests are completed with useful results. As defined in 4b, testing will end after three consecutive successful attempts, but not before 90% of all executed tests are deemed successful. For example, testing may end at the earliest if tests 8-10 are successful, but testing must continue if the last three tests fail the suspension criteria.[1]

5. Sensor setup: the sensors will be calibrated according to the user instructions provided with the product.

6. Test environment: the testing environment, necessarily based in the state of Virginia in teammate Rivera's home, will be controlled to mimic the lower end of the temperature and humidity range for seedling growth. Desired ambient temperature will be close to 75 degrees, and humidity will be calculated as described in 1c.

a. Human labor cannot be divided for this testing design; however, the Team will provide feedback at all stages and have access to relevant details like Arduino code, run rate and pass rates, and watering duration based on the moisture sensor feedback.

7. Proposed Deliverables:

a. Schematic of the sensor placement for the Waveshare (single sensor) design and the LGDehome (6 sensor) designs.
    i. Considering there are three soil configurations, there should be 6 schematics total.
b. Soil moisture reading logs for each design and individual sensor. 6 logs are expected (average values of successful tests will be accepted).
c. Watering time logs, where watering time is collected for each moisture value starting at 41% and ending at 80% moisture. 6 logs are expected (average values of successful tests will be accepted).
d. Verification that the water weight added to the system is appropriate, based on previous ballpark calculations for the three soil configurations. 6 verifications are necessary--water added to the system will be calculated via simplified fluid flow rate based on the misting nozzle diameter and Bernoulli's principle (there should be a single streamline from the water source to its exit at the nozzle).

The most useful part of this plan was ultimately the test criteria. This was used to determine later on that testing should terminate due to issues with reproducibility and accuracy. A preliminary configuration was made to see the feasibility of the sensors standing alone, undesirable wire tangling, and other causes for concern. The sensor outputs are not fully wired here.

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[1] This example assumes as well that there is a 100% run rate for the first ten tests, which may not be true.

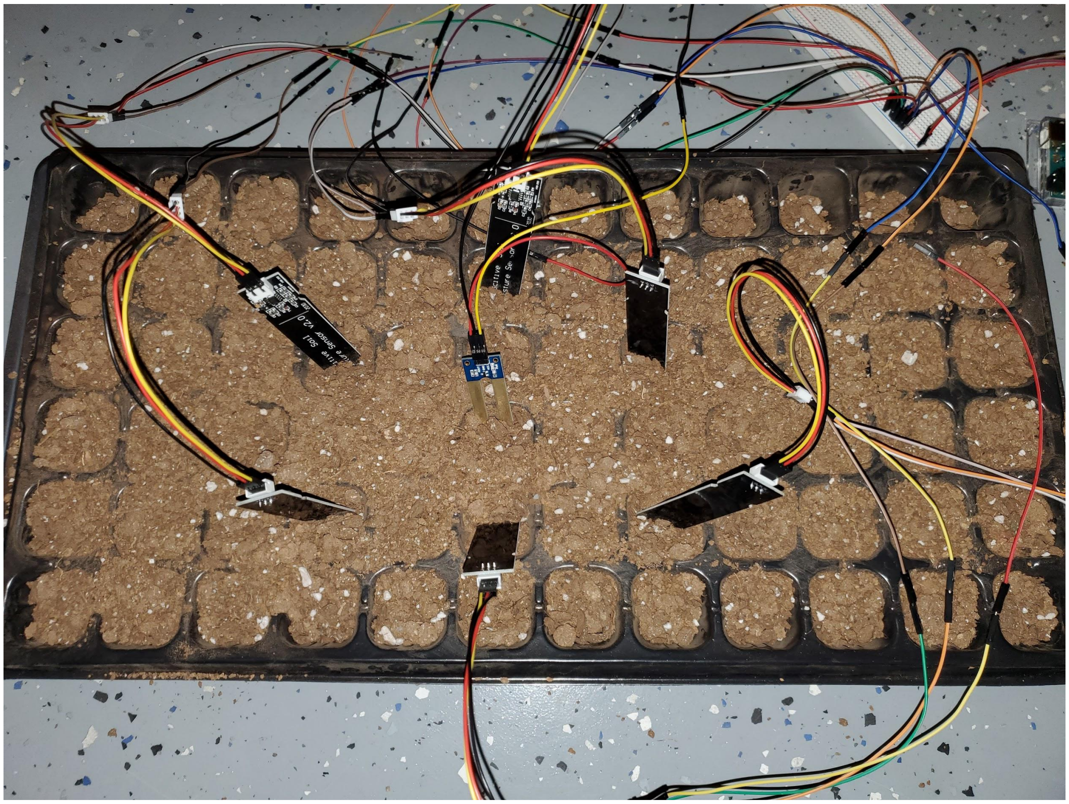

Figure 6.3: Practice set-up

Some primary concerns were jumper wire sensitivity to moisture and weather. The months of March and April had variable local weather, inconsistent with San Jose conditions. To reiterate, the Waveshare sensor was chosen for accuracy and ease of use, and the LGDeHome sensors were chosen for cost and quantity, allowing the team to create a grid of testable plugs with moisture data. The moisture data from the grid should have verified that watering was uniform.

6.4 Sensor Troubleshooting

The following schematic is provided by the manufacturer for the Waveshare moisture sensors.

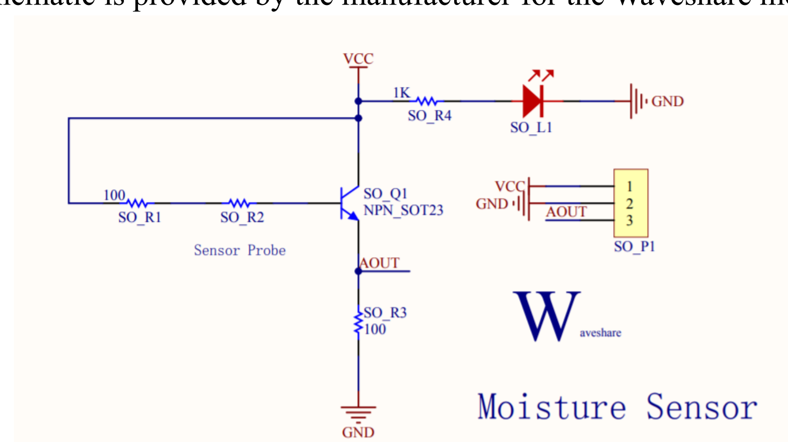

Figure 6.4: Schematic for Waveshare moisture sensor

A useful piece of information on this schematic, also found in online guides, is the output. This sensor provides an analog output; the sensors from LGDeHome provided analog outputs as well, but this was only confirmed upon receipt of the sensors in the mail. Waveshare also provides a sample code that was modified only slightly (adding some LED blinks within the loop for visual cues, and more outputs for the serial monitor such as the unitless analog value) for use in the LGDeHome sensors. See the lines below:

```
int Moisture_ain=A0;
int ad_value;
void setup()
{
 pinMode(Moisture_ain,INPUT);
 Serial.begin(9600);a
}
void loop()
{
 ad_value=analogRead(Moisture_ain);
 if(ad_value>200)
 {
  Serial.println("High-moisture environment");
 }
 else
 {
  Serial.println("Low-moisture environment");
 }
 delay(500);
}
```

Unfortunately, the sensors were not as sensitive as desired and provided, at best, a binary output. The analog outputs would have been ideal for creating benchmark values for no moisture content, full saturation, and the 41-80% range somewhere in between. In the end, the Waveshare sensor could only provide analog values based on wet or dry conditions (defeating the purpose of analog output with many position values), and the LGDeHome sensors were almost useless. Another source of failure could result from the fact that the two sensors used different basic principles. The Waveshare used a transistor and the LGDeHomes were based on capacitors. The Team concluded that the LGDeHome sensors were either too sensitive to the dielectric constant of water to provide consistent benchmark values, or that they were too inexpensive and thus defective.

After discussion with project advisors, it was concluded that quantifiable decision-making would have made the sensor selection process stronger. Whereas for design and subsystem ranking, the Team used weighted criteria and had clear priorities, the sensor selection was made using market research. Using more project time and budget to rectify the situation seemed inadvisable, and the system overall was not implemented into the final design. All the leftover materials, such as misting tubing and nozzles, were gifted to the client--should they choose to rig a simplistic misting system, albeit without a watering guide, in the greenhouse.

7 Construction Manual

Although it was originally planned to help Valley Verde build the greenhouse in person, the COVID-19 pandemic limited the team's ability to physically help with construction. Because of this, the team was forced to pivot and create a way to build the greenhouse design without in-person assistance. Thus, the team created an IKEA-style construction guide to assist Valley Verde. This process was done in Solidworks and is stylized to mimic the black and white wireframe format that IKEA uses, with arrows or pop outs to add further clarification. This style was chosen for a variety of reasons. Firstly, it would be able to communicate the design ideas in a nontechnical way that would be accessible to a wide audience. Although technical engineering drawings are very effective for communicating with an engineering audience, the people who will be using the manual do not come from technical backgrounds, so this style was avoided. The IKEA style is a tried and true format that has proven effective for a variety of audiences, so it seemed like the most effective way to communicate. Secondly, this format utilizes very few words, so it is effective for bridging language barriers. Many of the Super Jardineros at Valley Verde do not speak or read English, so using as few words as possible is very important. Finally, even when the pandemic is over, Valley Verde may still need to construct more greenhouses, so this manual serves as an effective lasting guide to help Valley Verde for as long as they may need it. The construction manual was meant to mirror physical construction as closely as possible and give all steps and sequencing to make construction as easy as possible. This chapter will describe the important components of the construction guide as well as the steps for creating it.

7.1 Material Lists and Diagrams

The first part of the construction manual includes a material list and accompanying pictures of each part. While there was no way to avoid using words for this section, it was necessary to introduce and label each part in a way that was unified and clear. The list gave each item a quantity and label, to show what materials are needed to start greenhouse construction. There is also a graphical representation of each fitting or miscellaneous piece, as shown in Figure 7.1.

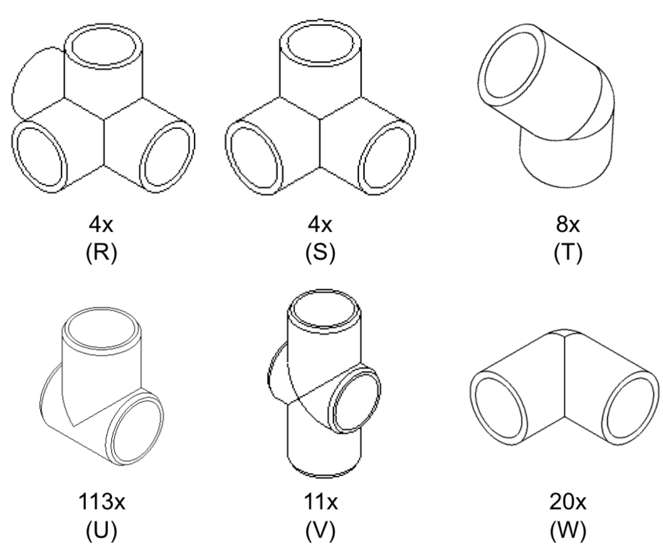

Figure 7.1: Graphical representation of fittings

While this image does not include all of the items, it gives a reasonable idea of how this section is formatted. This is helpful for those who may not be able to read English or just need further clarification, as it shows all of the information from the material list in a graphical representation. While writing may be confusing, this style provides clear images and will give the user adequate guidance for building.

Finally, the team included a PVC cut list, as shown in Figure 7.2. This shows how 10ft pieces should be cut and in which quantity to reduce waste.

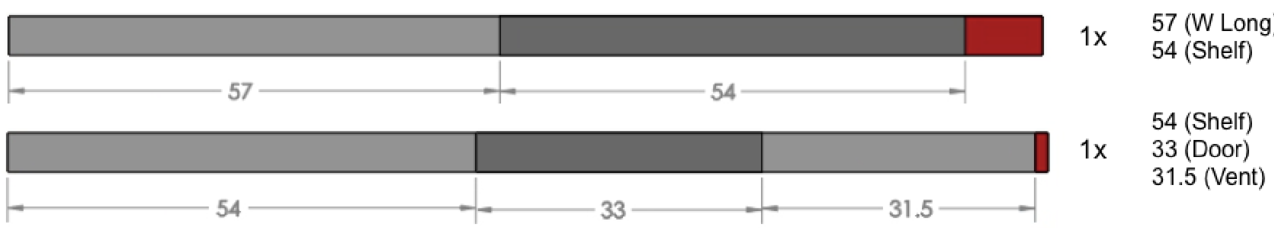

Figure 7.2: PVC cut list

The full PVC cut list can be seen in Appendix R. In this image, the grey sections are the parts of the pipe that are used, and the red section is the part of the 10ft pipe that is scrap. It also notes what each piece should be used for, which makes it easier to separate/label pieces ahead of time to allow construction to go more smoothly. While this graphical cut list may not be perfect, it was created to simplify the process of cutting PVC by creating clear and simple instructions that reduce waste and are easy to follow. It is much easier than trying to Figure out how to cut the PVC based on something like the material list and should be an effective tool for Valley Verde to use.

7.2 Greenhouse Construction Steps

Once all materials have been obtained and cut correctly, steps for construction are provided. The construction is split into six sections, being the long wall, short wall, roof, vents, doors, and shelves. There is also a section included that details how to cover the greenhouse. Each of these sections includes diagrams with part numbers that show how the parts are put together and fastened. This can be seen as shown in Figure 7.3.

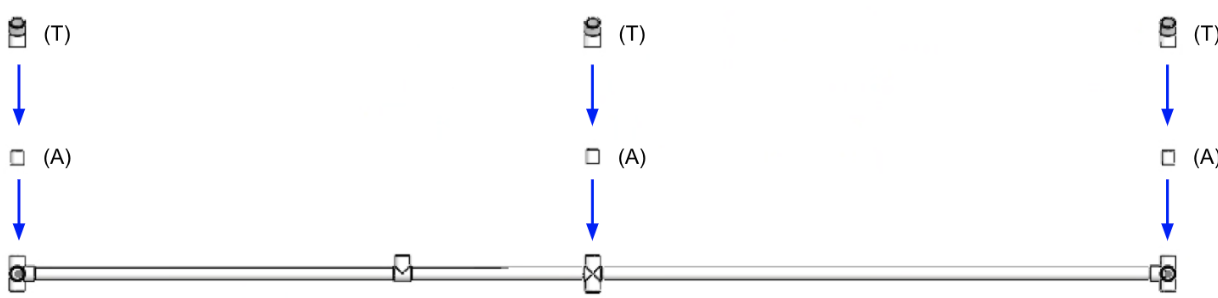

Figure 7.3: Long wall top beam construction step

This Figure details how the top beam of the long wall should be assembled and includes part labels so the correct fitting or PVC length is clear. It avoids the need for any language and provides a clear diagram of how assembly should be done. While this step is not highly orientation-dependentSidewall, the instruction manual also shows how certain parts should be oriented for ease of construction. An example of this can be seen in Figure 7.4.

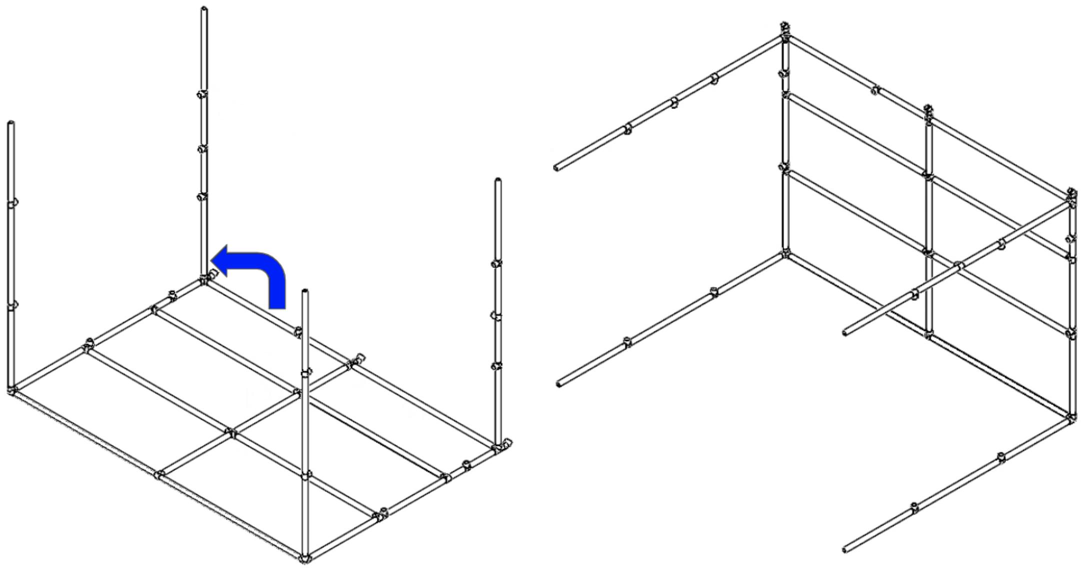

Figure 7.4: Long wall flip

This Figure shows how the greenhouse wall structure should be flipped, so it is easier to attach the second wall. If the subsequent step was completed without this orientation change it would be extremely difficult, and showing the most effective orientation can help save Valley Verde a lot of time and difficulty in construction.

Finally, the construction manual outlined how screws should be inserted into the greenhouse structure, as shown in Figure 7.5.

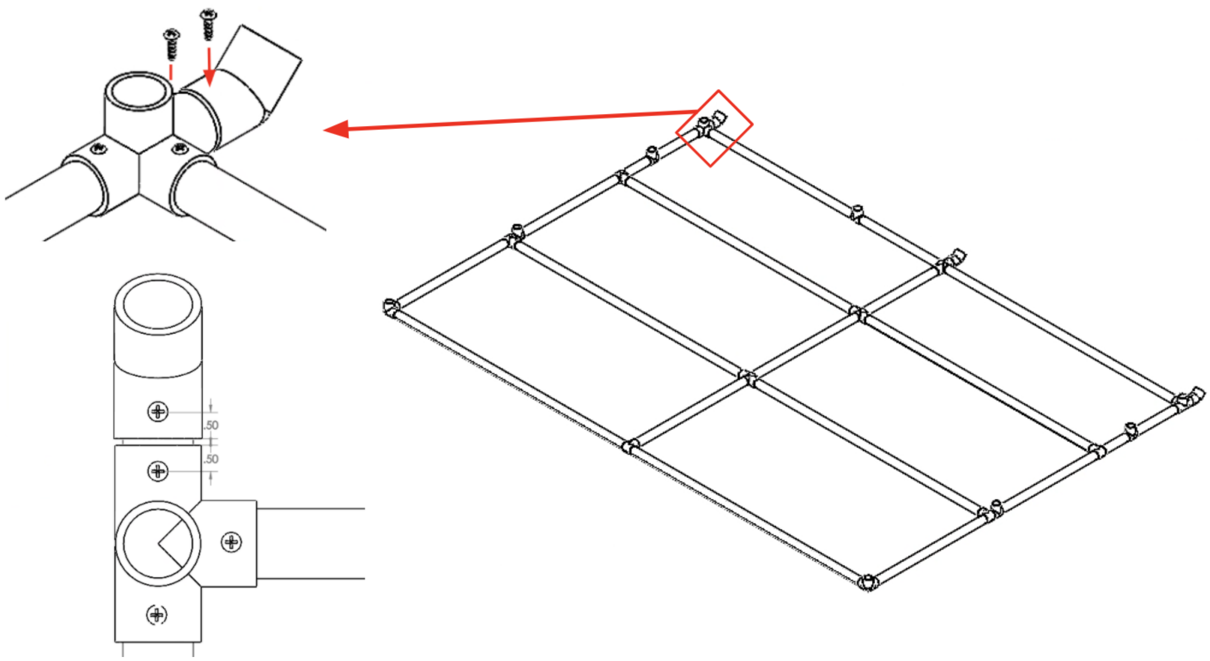

Figure 7.5: Long wall screw configuration

This Figure details how and where screws should be installed in the structure and includes multiple views and measurements to avoid confusion. In this construction manual, red arrows were used to denote putting screws in place, while blue arrows were used for everything else. Like the other steps, it provides a sequence of how screws should be installed in the greenhouse for maximum ease and efficacy.

In addition, diagrams were included for how snap clamps should be applied to attach greenhouse plastic. Less detail was provided in these Figures because each part is the same and precision is much less important when compared to other steps. One of these diagrams can be seen in Figure 7.6.

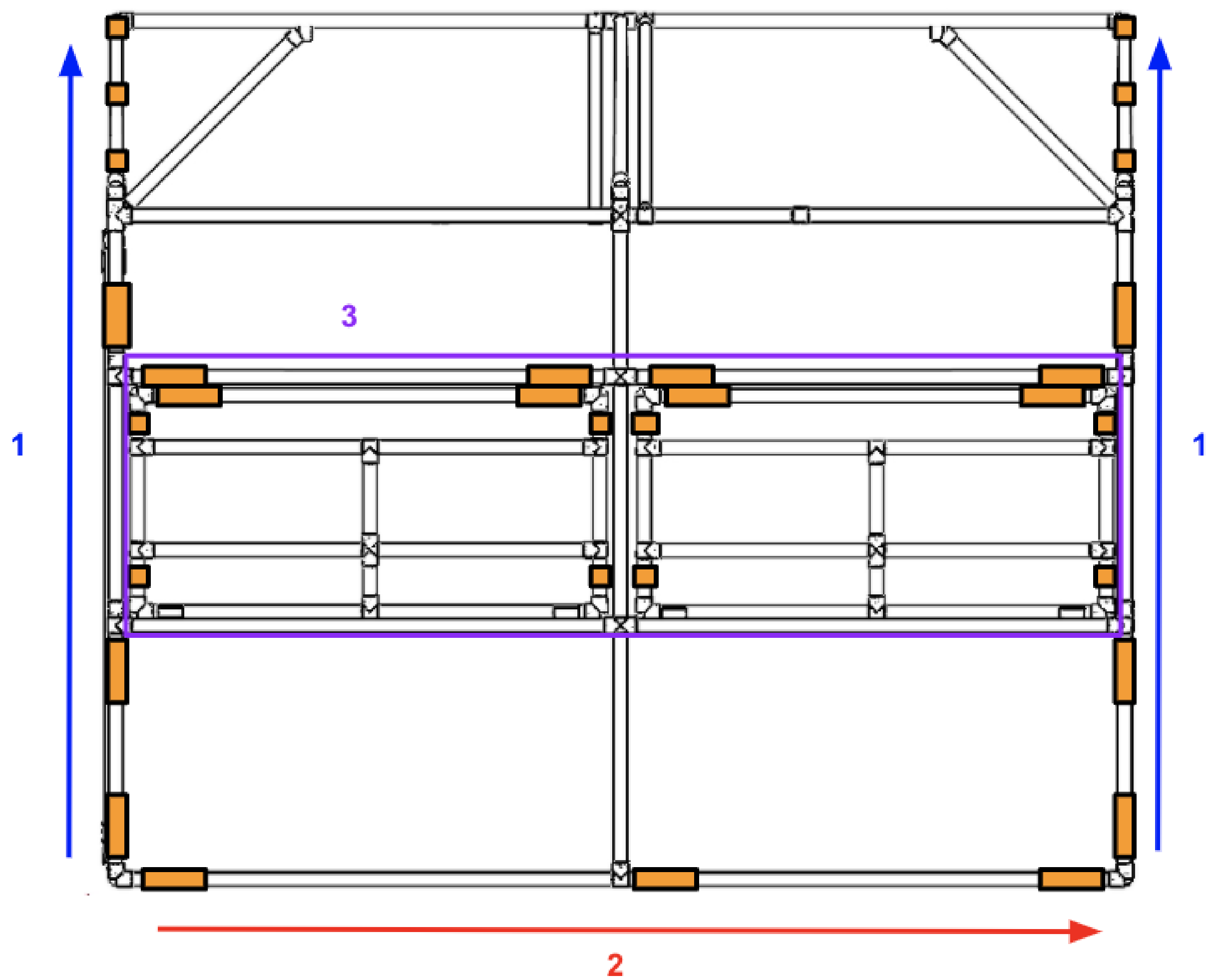

Figure 7.6: Side wall snap clamp installation guide

As shown in the Figure above, these diagrams outline where the snap clamps should go and give a rough sequence for the order that the clamps should be installed (first along the sides, then the bottom, then around the vents). While this step is much less straightforward and clear than the steps before it, the application is much simpler and it is included towards the end of the manual, which should allow those following the manual to understand it more easily.

Finally, videos were included with each major step so that if construction was unclear, there was also a video of the entire process to further clarify how each step was completed. Because it is ultimately likely that there will be some confusion with the steps as they are initially presented, this extra precaution will ensure that Valley Verde can follow the steps that are outlined. While the entire construction guide is not included based on its length, the full process for the vent construction is included in Appendix S.

While in-person construction would have ultimately been preferable, the construction guide will serve as an effective solution to aid with manufacturing during the COVID-19 pandemic. While this format did make it more difficult to communicate more complicated steps, it ultimately did a good job of explaining most steps and should be a useful tool. Based on the feedback from

Valley Verde's preliminary build, the guide was effective and gave Valley Verde most of the tools to be able to build the greenhouse. Although there were some issues, specifically with the arch structure itself, Valley Verde has been able to make the greenhouse based on the original design and the construction manual. They did suggest some adjustments to be made with the overall dimensions of the greenhouse, but generally they liked what had been produced and were very happy to receive the design.

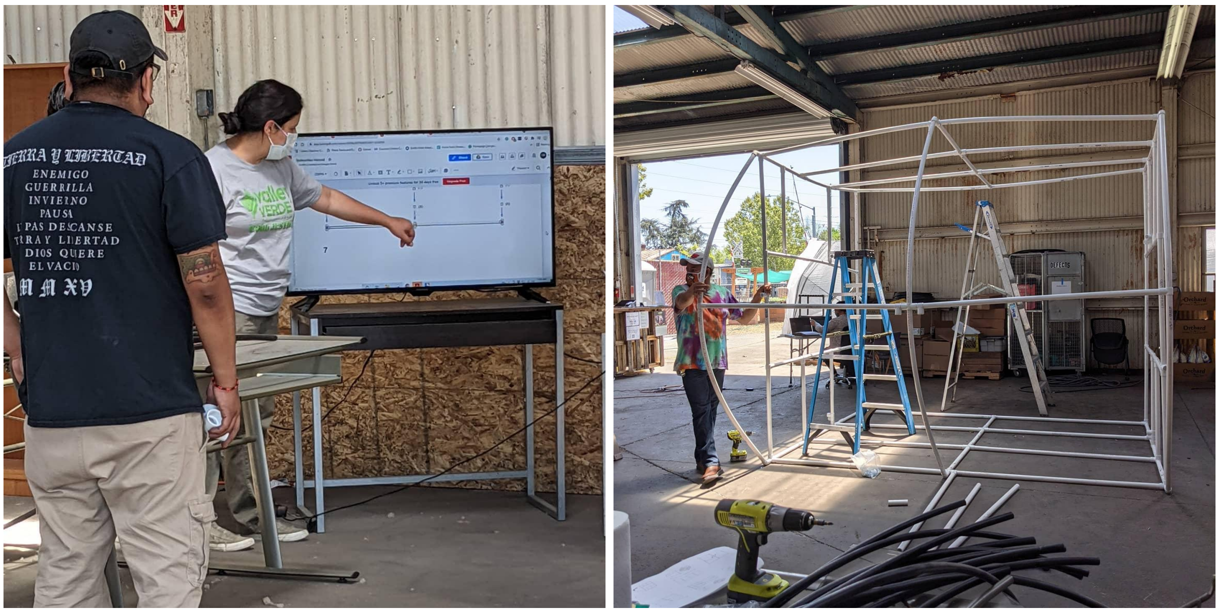

Figure 7.7: Valley Verde Construction

8 Cost Analysis

The cost analysis chapter of the thesis describes how the budget was dealt with throughout the project. It outlines original cost estimates, how money was spent, and the costs of the final product. It also describes issues or challenges that arose throughout construction and describes how these problems were fixed.

8.1 Preliminary Budget

One of the most important goals for the final greenhouse was to meet a budget requirement of around $500 per greenhouse. This is about $300-$500 cheaper than typical greenhouses are sold (based on the inputs from partner organization Valley Verde) and was a difficult design challenge. The project started with an initial budget of $2000 from the School of Engineering and used the majority of that budget on prototyping, while $500 was reserved to give Valley Verde materials to construct one greenhouse. The original estimate of materials and costs for the first iteration can be found in table 8.1 below.

Table 8.1: Budget for Preliminary Greenhouse Design

Description	Quantity	Cost	Cost/Unit	Total
4-way fitting	4	10.71 (4 pack)	2.68	10.71
90 Degree socket elbow	4	2.8	2.8	11.20
45 degree elbow	8	1.19	1.19	9.52
10 ft PVC pipe	27	4.12	4.12	111.24
Slip Tee fitting	28	62 (100 pack)	0.62	17.36
Snap Clamps	30	45 (100 pack)	0.45	13.50
Cattle Gate	3	16	16	48.00
Slip Cross	7	22.25 (25 pack)	0.89	6.23
Rebar	2	5.74	5.74	11.48
PVC hinge	10	21.48 (4 pack)	5.37	53.70
Cover Material	400	142.99 (1200 ft)	0.12	48.00
Cinder block	30	1.9	1.9	57.00
T-Fitting	2	1.19	1.19	2.38
Grand Total				400.32

This budget shows the exact materials and costs that were needed for a preliminary greenhouse. In the documents provided to Valley Verde, these tables were linked with the supplier who provided those materials and the costs. To keep things simple for Valley Verde, the project was limited to three suppliers- a local hardware store (Home Depot, Lowes), Circo Innovations, and Amazon. The local hardware store was used for things like bulk PVC and generic fittings, Circo Innovations was used to buy specialty and cheap bulk fittings, and Amazon was used for more specific items like the watering system and greenhouse cover. It was believed that all of these suppliers would allow Valley Verde to easily build or repair new greenhouses if needed. This allowed products to be purchased with generally small lead times (2 days or less) with the exception of the greenhouse cover (which was heavy and took around a week). Because it is intended to build multiple greenhouses, parts were bought in bulk to reduce the cost per unit, so while the original investment may be slightly larger, the cost per unit of each greenhouse was estimated to be $400. The largest costs in the original estimate were for PVC and the greenhouse cover, which was consistent with the expectations of the project. Based on this estimate, the project was well under budget; however, it did not include the costs of doors or vents, which would increase costs in later iterations. It also did not factor shipping or tax expenses.

8.2 Project Spending

This project was granted a $2000 budget from the School of Engineering. Of that budget, it was planned to set aside $500 for final greenhouse materials for Valley Verde, and the rest was allocated to construction and prototyping. During the project, around $400 was spent on prototyping and testing the watering system, while about $1100 was used for the physical construction of the greenhouse. Although the prototyping budget is much more than the cost to build a single greenhouse, figuring out and changing PVC lengths, cover material, and fittings produced excess costs. However, the project was able to meet its goals within the constraints of the budget, and overall managed to create a successful final project.

8.3 Final Budget

The final budget can be seen in table 8.2. This budget includes all costs for the greenhouse including vents, shelving, and shipping/tax.

Table 8.2: Final Budget

Description	Quantity	Cost (dollars)	Cost/Unit	Total (dollars)
4-way fitting	4	1.95	1.95	7.80
90 Degree socket elbow	4	1.75	1.75	7.00
45 degree elbow	8	15.25 (25 pack)	0.61	4.88
10 ft PVC pipe	49	3.50	3.50	171.50
Slip Tee fitting	113	62 (100 pack)	0.62	70.06
Snap Clamps	100	45 (100 pack)	0.45	45.00
Slip Cross	11	22.25 (25 pack)	0.89	9.79
PVC Hinge	2	21.48 (4 pack)	5.37	10.74
Cover Material	50	196 (100 ft)	1.96	98.00
L-fitting	20	15.25 (25 pack)	0.62	12.40
Chain/Hooks	6	3	0.50	3.00
Screws	360	17	0.017	6.12
Shipping/Tax				57.71

Grand Total	504.00

As can be seen from the table, the final budget was $504, which was right at the design goal of $500 for the project. This is about $100 more than originally estimated, which is due to not including shipping and tax costs, as well as severely underestimating the needed quantity of cover material and snap clamps. This led to issues with the budget, but this was resolved by changing the original shelf design from one that utilized cattle gates and cinder blocks to a more sturdy design that utilized PVC and slip fittings. Cost was also further reduced by replacing the more expensive metal hinges on the vents for snap clamps. Budget was a defining and driving force throughout this project, but based on the original specifications and needs that were given, the project was able to successfully meet the design goals.

One major issue that came up while budgeting was that the price of PVC increased during the duration of this project. Originally, PVC was $3.50 per 10ft pipe, which was what the design choices for the project was based off of. However, a PVC shortage caused the price to rise to $4.40 per unit, which made the project go much over budget. The final budget discussed in section 8.3 uses the original $3.50 estimate because that is what was originally designed, and it is expected that the price should go back down when PVC can be produced as normal. However, if this was a project in industry, ensuring that suppliers maintain consistent prices is important. As this was an uncontrollable issue this project nothing could be done about this problem, but it is definitely important to be aware of when similar problems arise. However, despite this price increase issue, the project was generally able to stay on budget and met the customers’ needs.

9 Conclusion

Overall, this project was able to meet the goals set forth at the beginning of this project and promote food sovereignty, humanitarian efforts, and the local San Jose community while promoting and developing engineering skills. The design process consisted of a preliminary conceptual design based on academic research, customer feedback, and market reviews, a CAD model which utilized FEA to create a clear initial design, and a prototyping and testing phase to build and finalize the design. It was also accompanied with moisture system testing and a construction manual to help Valley Verde build the final product. Although the final design was not perfect, it met the needs of the customer and gave lots of room for the project to improve. The design process taught and emphasized the use of project management, critical thinking, and problem solving and was ultimately a very successful project.

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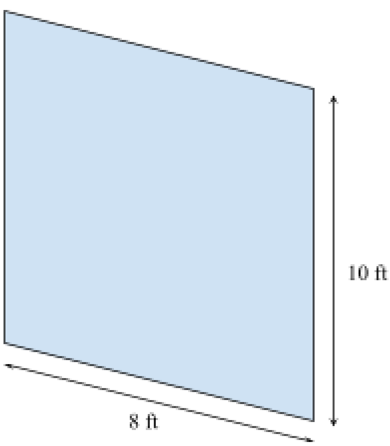
Appendix A - Wind Forcing Hand Calculations

These calculations calculate the force due to wind on the greenhouse and calculate the necessary weight to ensure it does not tip. Based on these calculations, even with a max gust speed of 110 mph, the greenhouse will only need to be 42 pounds to not tip if the weight of the trays is considered. Also, this only considers the dry weight of just the soil in the mass calculation. This calculation shows that based on the dimensions of the greenhouse, the team will not have to be too concerned about weighting the greenhouse to avoid tipping. However, this calculation makes a lot of assumptions so this will be reevaluated with finite element analysis later in the process.

Required weight to avoid toppling by wind

According to the City of Santa Monica Building and Safety Division, the maximum wind speeds in California can reach up to 110 mph = 161.33 ft/s.

The force due to wind is proportional to the area of the greenhouse wall, a relationship shown and calculated here:



$$F = \frac{1}{2}\rho v^2 A$$

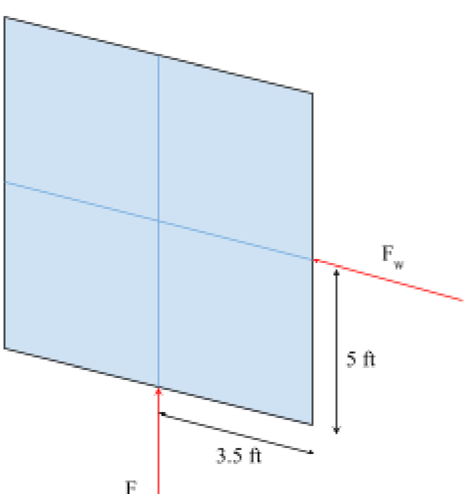
A = 8 ft (wide) x 10 ft (tall) = 80 ft^2

$$\rho_a = 2.3769 \times 10^{-3} \frac{slugs}{ft^3}$$

$$F = \frac{1}{2}(2.3769 \times 10^{-3} \frac{slugs}{ft^3})(161.33 \frac{ft}{s})^2 (80\, ft^2) = 9894\, lbf$$

For the greenhouse to remain stable, the moment from the weight must be more than or equal to the moment applied by the wind.

Assume wind force is applied at the middle of the greenhouse. The weight of the greenhouse will also be applied at the middle so:



$$F_w d_w = mgd_g$$

$$d_w = 5\, ft$$
$$d_g = 4\, ft$$

$(9894\ lbf)(5\ ft)\ =\ m(32.2\ \frac{ft}{s^2})(3.5\ ft)$

m* = 438 *lbm

This is the required *total* mass of the greenhouse and all its connected components to resist the force of wind and stay standing upright.

One of the goals and customer needs is that the main greenhouse structure remains light. For this reason, the team needed to make sure that when it built the greenhouse, it was still meeting or exceeding the minimum mass requirements. To do this, the team needed to know the mass of the structure on its own. Other than the structure, the main contributor to mass is the soil inside the seed trays, which is accounted for in the calculations below:

$Seed\ Tray\ Volume\ =\ 10''\ (Length)\ x\ 20''\ (Width)\ x\ 2''\ (Depth)\ =\ 400\ in^3$

With 22 trays within the greenhouse, the total volume of soil in the greenhouse is:

$$V_{tray} = 22 \times 400\ in^3 = 8800\ in^3 = 5.09\ ft^3$$

The density of the soil, $\rho_{soil} = 78 \frac{lb}{ft^3}$, so the total mass contributed by the soil is:

$$m_{soil} = V_{tray}\rho_{soil} = (5.09\ ft^3)(78 \frac{lb}{ft^3}) = 397.2\ lbm$$

From here, the mass of the greenhouse can be calculated as:

$$m_{house} = 438\ lbm - 397.2\ lbm = 41.8\ lbm$$

This means that for the greenhouse to keep from tipping over, the structure on its own must weigh 41.8 lbm at a minimum. It is predicted that this is an achievable goal.

Appendix B - Product Design Specifications

Design Project: Frugal Urban Greenhouse
Team: ACE
Date: 13 April 2021
Revision: 4
Datum description: Original Greenhouse Blueprints

Table B-1: Greenhouse PDS

Elements		Requirements	
	Units	**Datum**	**Target Range**
Structure	US Customary Length (L x W x H)	10’-1 ½” x 6’-3 ¼” x 8’-¾”	10’ x 8’ x 8’
Weight (Dry)	Pounds	Qualitatively “heavy.”	200
Cost	Dollars	500	500
Seedling Yield	Units	400	500+
Assembly Time	Hours	9 (6 pre-assembly, 3 assembly)	6
Shelves[1]	Units	3	1
Shelf Strength	Pounds (to support)	150	200
Shadecloth	Percentage	80, 60, & 40	80, 60, & 40
Side Vents	Units	0	2
Sprinkler/Misting system	Units	0	1
Water	Liters/day	10	8
Life Span	Years	3	4-5
Indoor Temperature	Degrees Fahrenheit	75	75 ± 10
Ergonomics	N/A	Insufficient[2]	Improved
Repairability[3]	N/A	No	Yes

Peak Wind[4]	MPH	Unknown	110
Safety[5]	N/A	Safe	Safe
Solar Exposure	Hours/day	10-15	10-15
Shading System	N/A	Cloths changed by hand	Strap system
Temperature Range[6]	Degrees Fahrenheit	45 - 80	45-80
Inside Space	Cubic Feet	168	144
Rainfall	Avg. # Inches/year	16	16
Watering	N/A	Hose	Hose/sprinkler

[1]Multiple shelves limited light access for lower shelves in the past.
[2]Cramped spaces and multiple shelves made the greenhouse ineffective from an ergonomic standpoint.
[3]Previous greenhouse was not easily repairable and was dismantled after 3 years. The team desired a greenhouse that can be easily repaired with accessible materials to increase life span.
[4]Is a standard value that Bay Area houses are designed to withstand.
[5]Safety incorporates things like having a durable structure, being resistant to catastrophic failure, and not creating unsafe situations
[6]Minimum and maximum daily average temperatures in the Bay Area

Appendix C - Decision Matrices

Criteria	Criteria	Weight	Cost	Manufacturability	Temp	Automation	Water	Energy	Modularity	Capacity	Durability	Repairability	Moistur	Hardeni	Storage	Work sp	Safety	Air Circ	Ease of	Shading	Aestheti	Space U	Ergonor	Material	Monitori
Weight	Weight		0	0	0	1	0.5	1	1	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0.5	1
Cost	Cost	1		0	0	1	1	1	1	0	0	0	0	1	1	1	0	0	0	0.5	1	0	0	1	1
Manufacturability	Manufacturability	1	1		0	1	1	1	1	0	0	0	0	1	1	1	0	0	0	1	1	0	0	1	1
Temp Regulation	Temp Regulation	1	1	1		1	1	1	1	0.5	0.5	1	0.5	1	1	1	0	0.5	1	0.5	1	1	1	1	1
Automation	Automation	0	0	0	0		1	1	1	0	0	0	0.5	1	1	1	0	0	0	0	1	0	0	1	0.5
Water Efficient	Water Efficient	0.5	0	0	0	0		1	1	0	0	0	0	1	1	1	0	0	0	0	1	0	0	1	1
Energy Efficient	Energy Efficient	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Modularity	Modularity	0	0	0	0	0	0	1		0	0	0	0	0	0.5	1	0	0	0	0	1	0	0	0.5	0
Planting Capacity	Planting Capacity	1	1	1	0.5	1	1	1	1		1	0.5	0.5	1	1	1	0	0.5	1	0	1	0.5	1	1	1
Durability	Durability	1	1	1	0.5	1	1	1	1	0		1	0.5	1	1	1	0	0.5	1	0.5	1	1	1	1	1
Repairability	Repairability	1	1	1	0	1	1	1	1	0.5	0		0	1	1	1	0	0	0	0	1	1	0	1	1
Moisture Regulation	Moisture Regulation	1	1	1	0.5	0.5	1	1	1	0.5	0.5	1		1	1	1	0	0.5	0	0.5	1	1	1	1	1
Hardening Off	Hardening Off	0	0	0	0	0	0	1	1	0	0	0	0		1	1	0	0	0	0	1	0	0	1	0.5
Storage space	Storage space	0	0	0	0	0	0	1	0.5	0	0	0	0	0		1	0	0	0	0	1	0	0	0	0
Work space (Outside	Work space (Outside	0	0	0	0	0	0	1	0	0	0	0	0	0	0		0	0	0	0	1	0	0	0	0
Safety	Safety	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
Air Circulation	Air Circulation	1	1	1	0.5	1	1	1	1	0.5	0.5	1	0.5	1	1	1	0		1	0.5	1	1	1	1	1
Ease of use	Ease of use	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0		0	1	1	0.5	1	1
Shading	Shading	1	0.5	0	0.5	1	1	1	1	1	0.5	1	0.5	1	1	1	0	0.5	1		1	1	0.5	1	1
Aesthetic	Aesthetic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
Space Utilization	Space Utilization	1	1	1	0	1	1	1	1	0.5	0	0	0	1	1	1	0	0	0	0	1		0	1	1
Ergonomics	Ergonomics	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0	0.5	0.5	1	1		1	1
Material Frugality	Material Frugality	0.5	0	0	0	0	0	1	0.5	0	0	0	0	0	1	1	0	0	0	0	1	0	0		0
Monitoring	Monitoring	0	0	0	0	0.5	0	1	1	0	0	0	0	0.5	1	1	0	0	0	0	1	0	0	1	

Figure C-1: Decision Matrix

Appendix D - Idea Sketches

Subsystem: Overall Structure

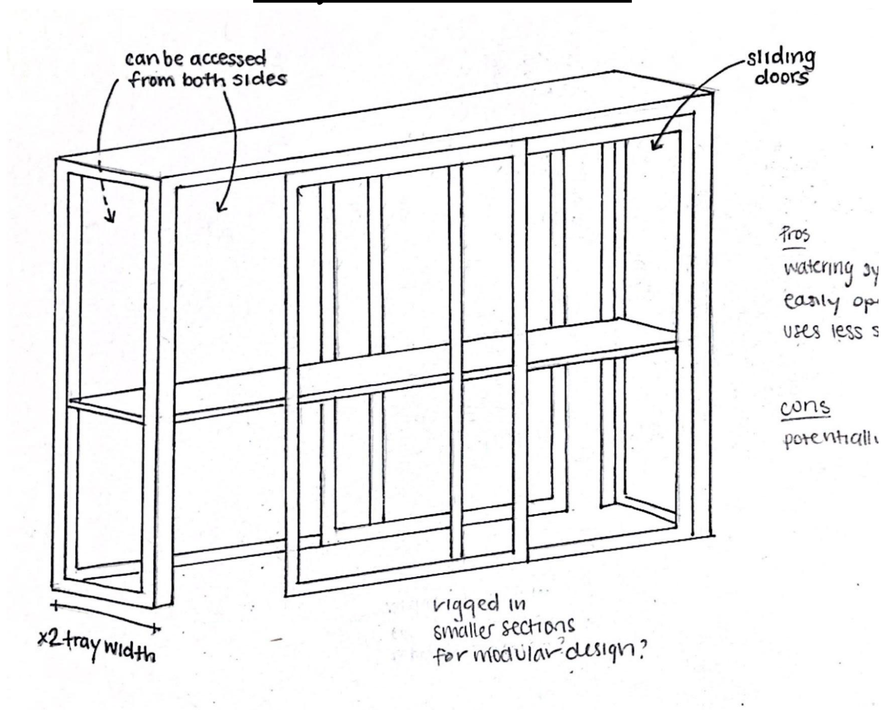


Figure D-1: Full size "closet" greenhouse

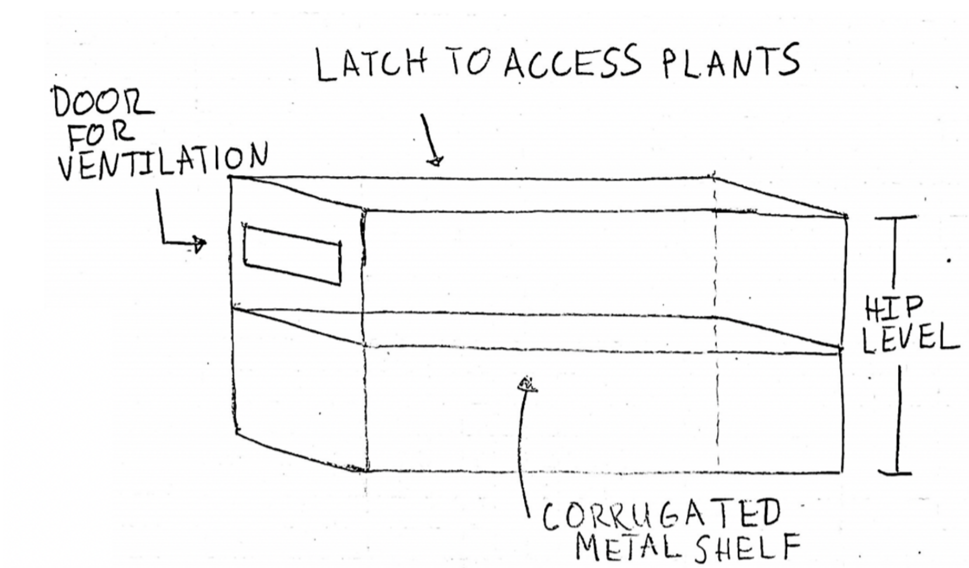


Figure D-2: Full/Oversized Cold Frame

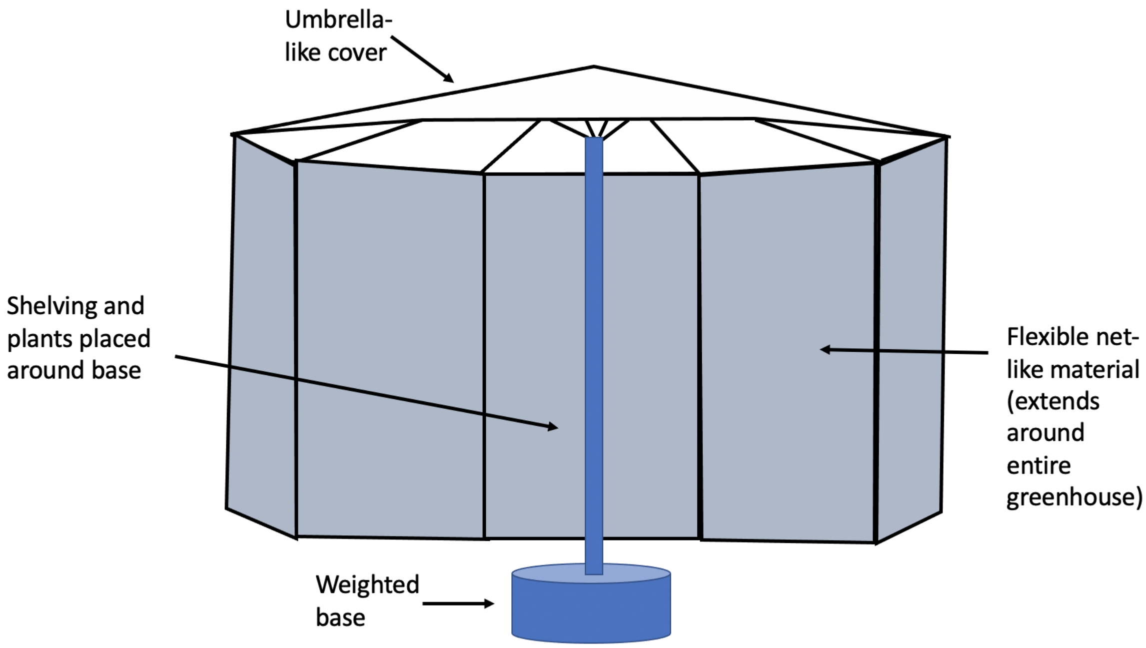


Figure D-3: Umbrella House

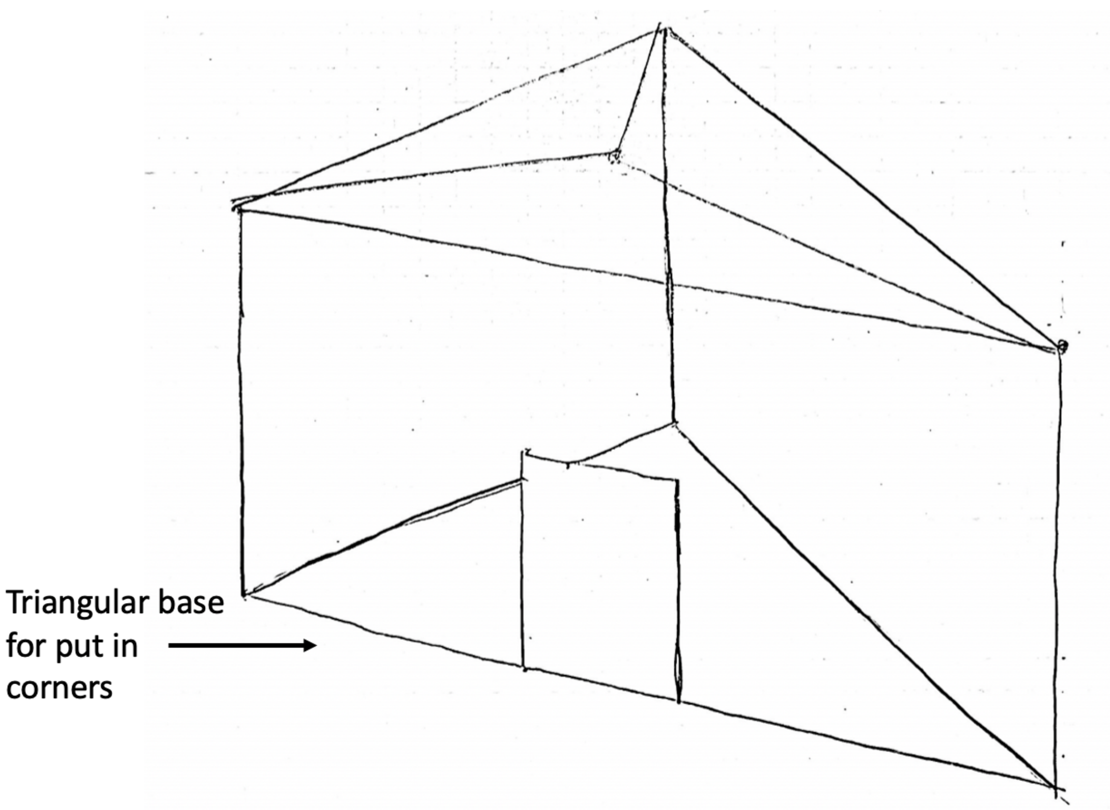


Figure D-4: Maximum Corner Space Design

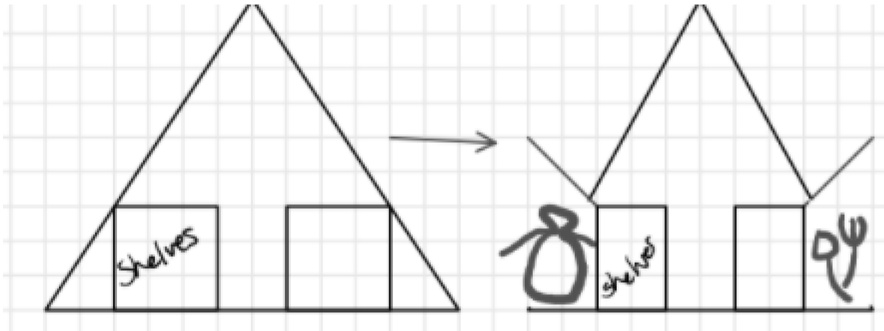


Figure D-5: Triangle House

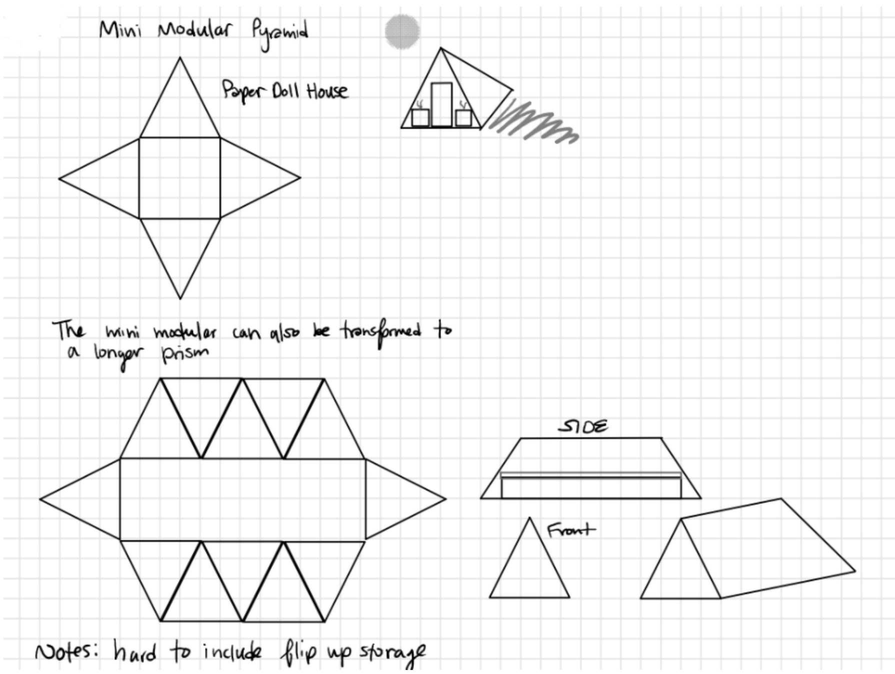


Figure D-6: Modular Paper Doll Design

<u>Subsystem: Ventilation</u>

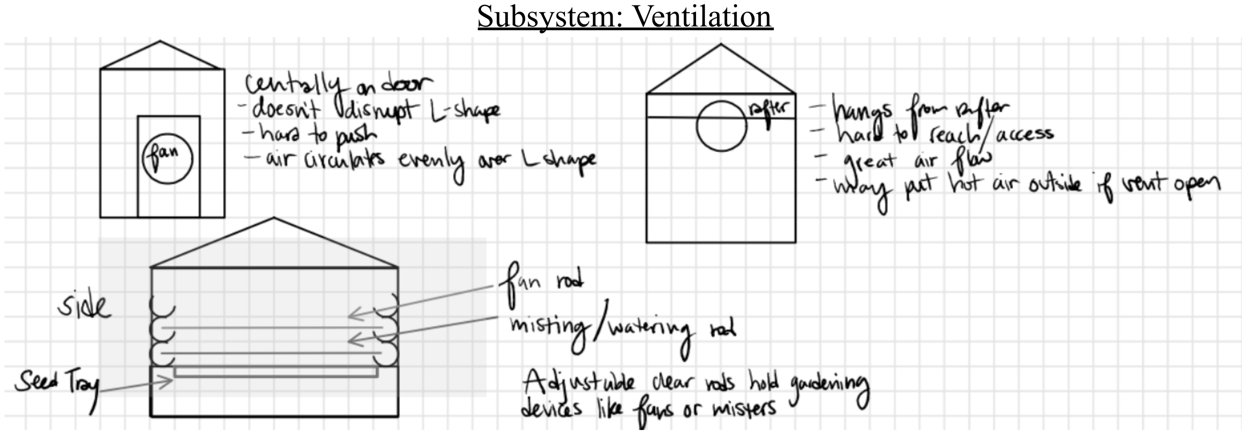


Figure D-7: Adjustable Rod Design

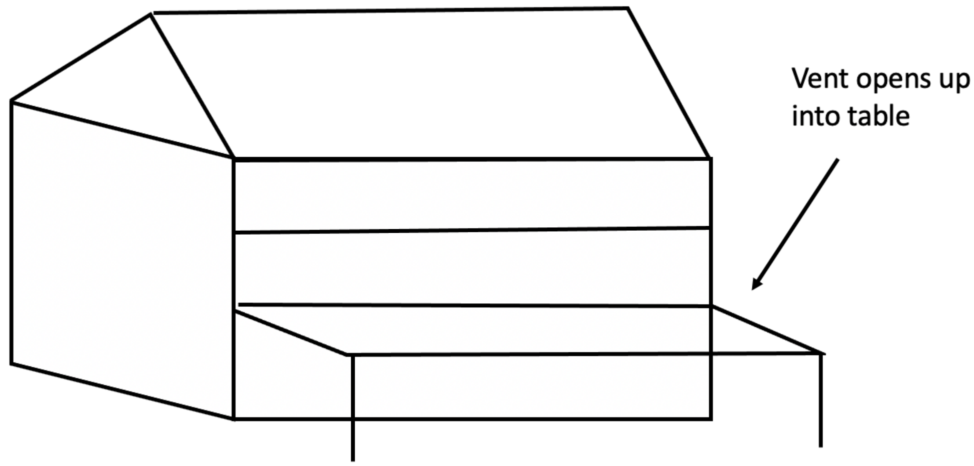


Figure D-8: Side Pocket Ventilation

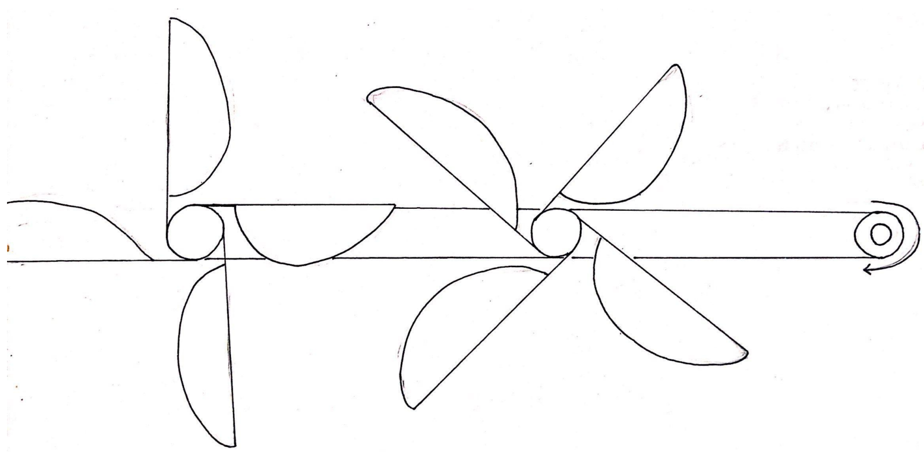


Figure D-9: Belt Fan for Ventilation

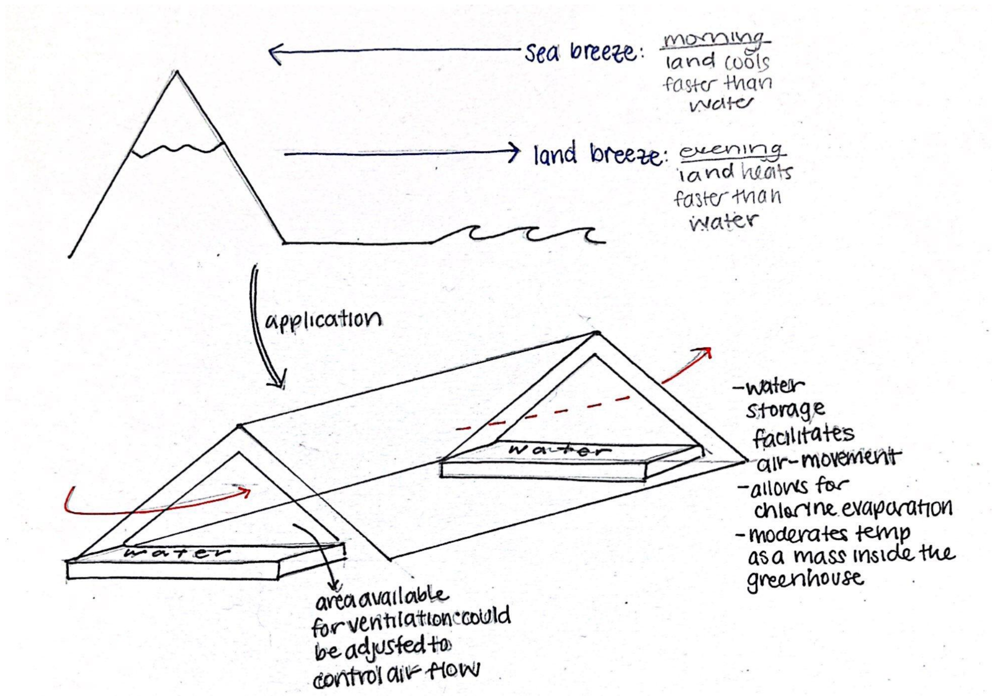


Figure D-10: Sea Breeze Ventilation

Subsystem: Watering

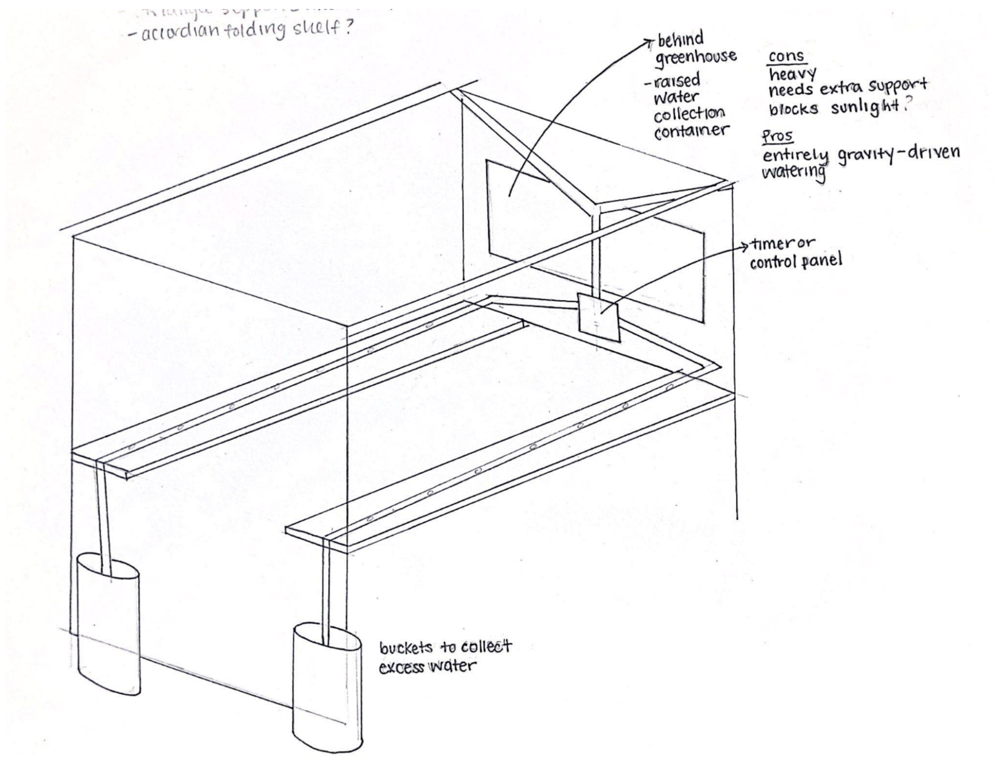


Figure D-11: Gravity Watering

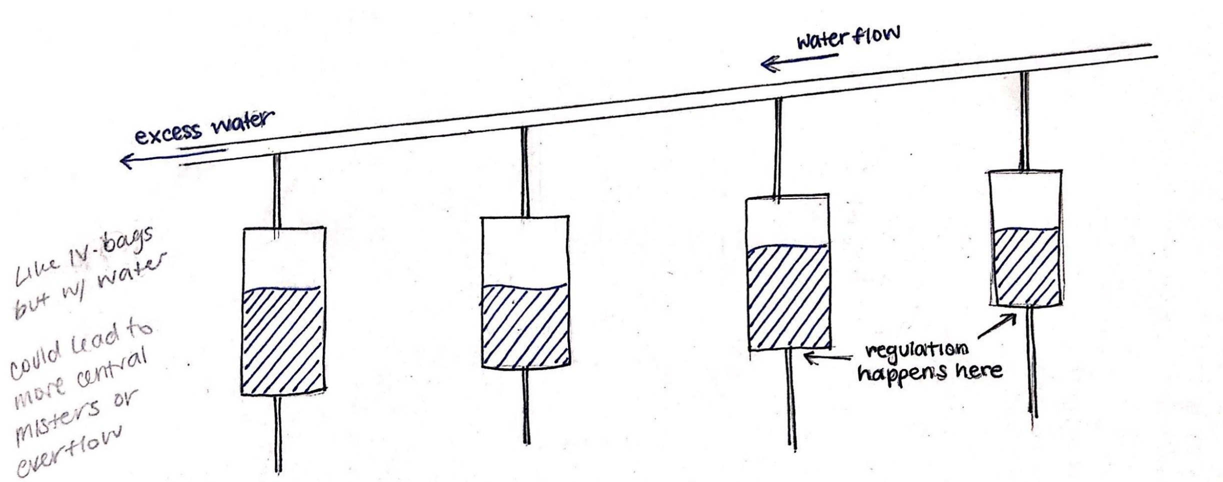


Figure D-12: IV Bag Watering

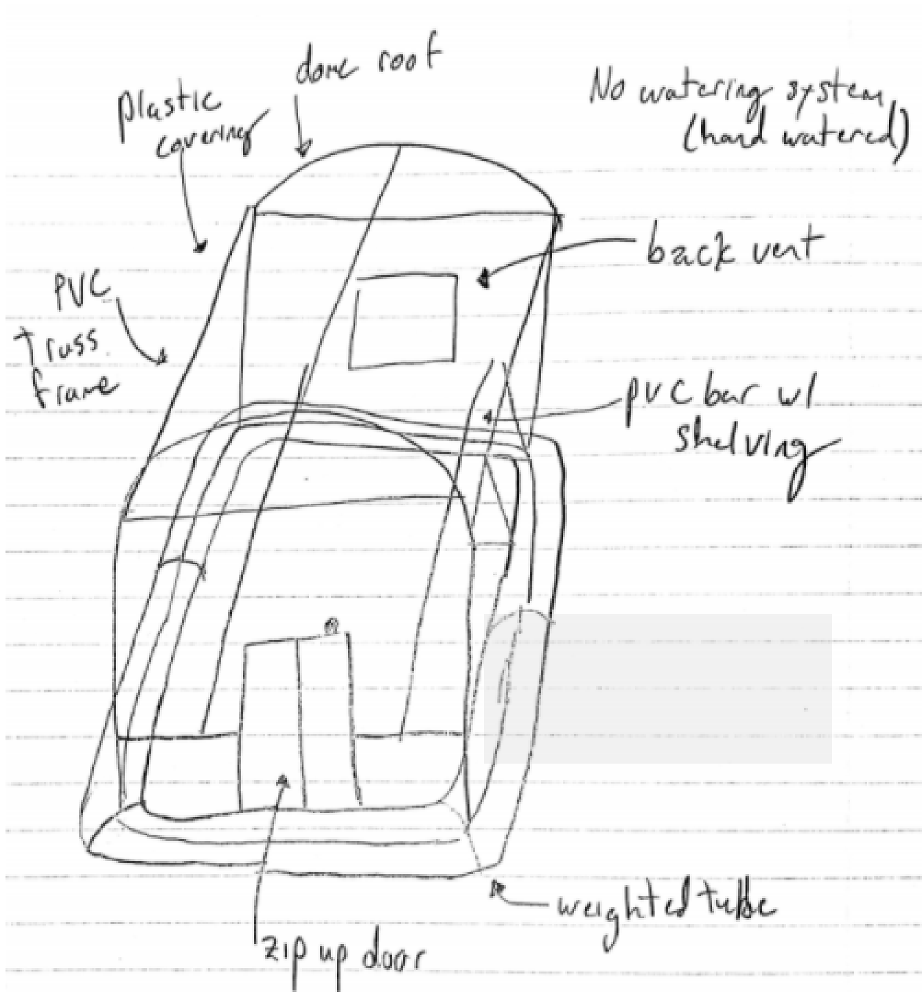


Figure D-13: Weighted Base

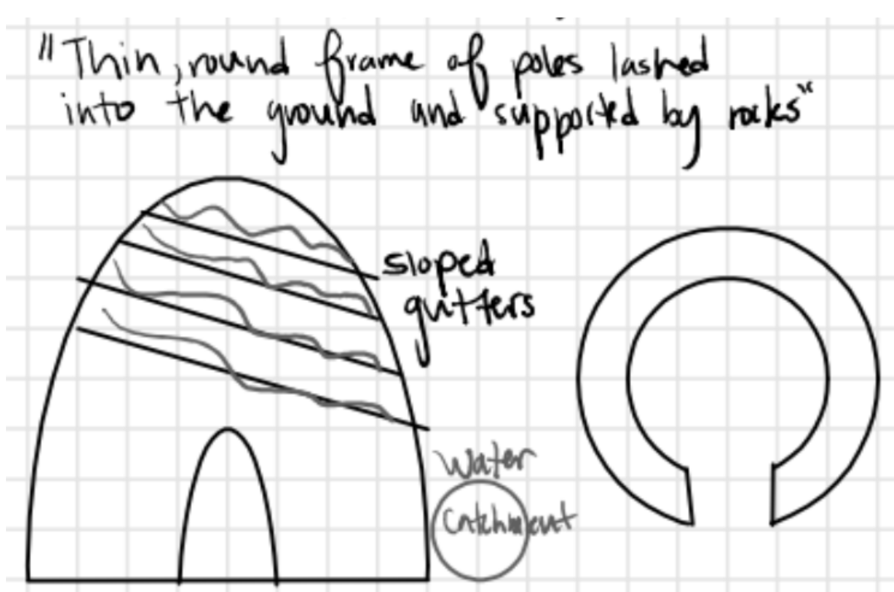


Figure D-14: Sloped Gutter Design

Subsystem: Shading

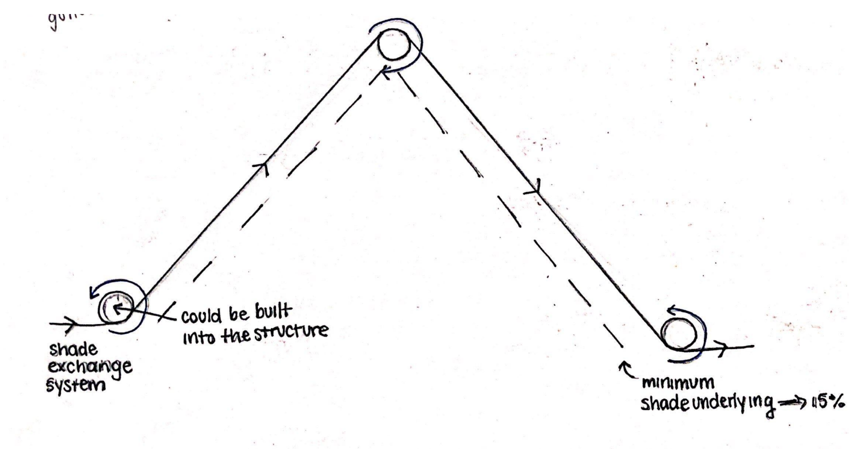


Figure D-15: Conveyor Belt Shading System

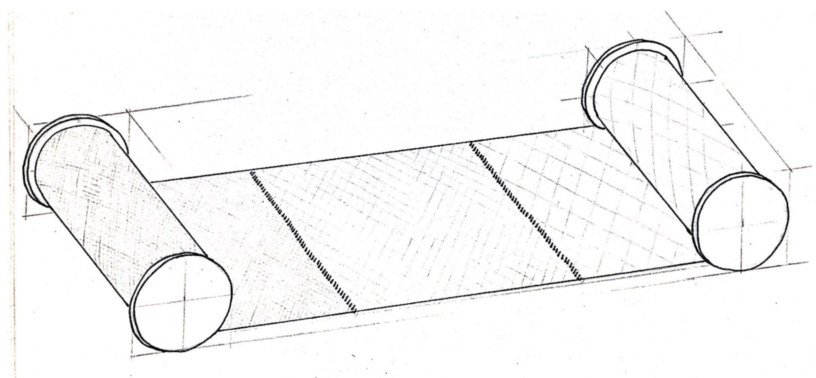


Figure D-16: Spool Shading Design

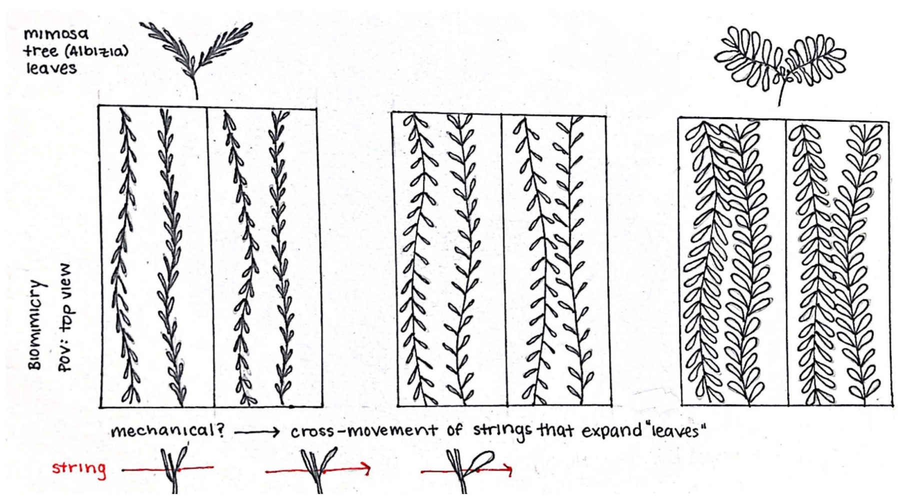


Figure D-17: Biomimicry shade concept

Appendix E - Budget Tables

Table E-1: Tentative Budget

Component	**Justification**	**Cost ($)**
Arduino Environmental Monitor Bundle	Create a baseline for the temperature, humidity, pressure, light, and UV levels.	50
Arduino Starter Kit	Necessary to integrate the Environmental Monitor Bundle into a full system.	92
¾ ” Diameter PVC Pipe	12 column support pipes at 6 feet high.	21
	12 roof support pipes at 4 feet length.	14
Shelf support braces	18 braces to make connections between pipes.	10
Slotted framing struts	4 struts at 10 feet long.	80
	4 struts at 6 feet height.	48
Flexible cover material	Comes in rolls	191
Flat, corrugated metal sheets	Can be used for shelving and treated for rust. Multiple needed to hold minimum of 22 seed trays.	220
Screen material	Necessary for door and any vents, to prevent insect entry.	21
Fans	Small, clip adjustable fans for easy reconfiguration. 1 per two seed trays	153
⅝” Diameter flexible tubing	May be used in the misting system for cooling.	40
Miscellaneous fasteners	Estimated quantity to account for different needs.	100
Seed Trays	A few prototyping sample trays.	50
Soil	1 bag of soil for testing heat/humidity	15
Heating Mats	For regulating plant temperatures	230
Gravel/drainage rock	To stop plants from growing inside the greenhouse and make it easier to walk within (2 ft^3)	120
Cinder Blocks	To support shelves (18)	36
Subtotal		1491
+ *California Sales Tax*	Currently 9%.	135
Total		**1626**
Available Budget	Granted by the School of Engineering	**2000**

Appendix F - Old Greenhouse Design

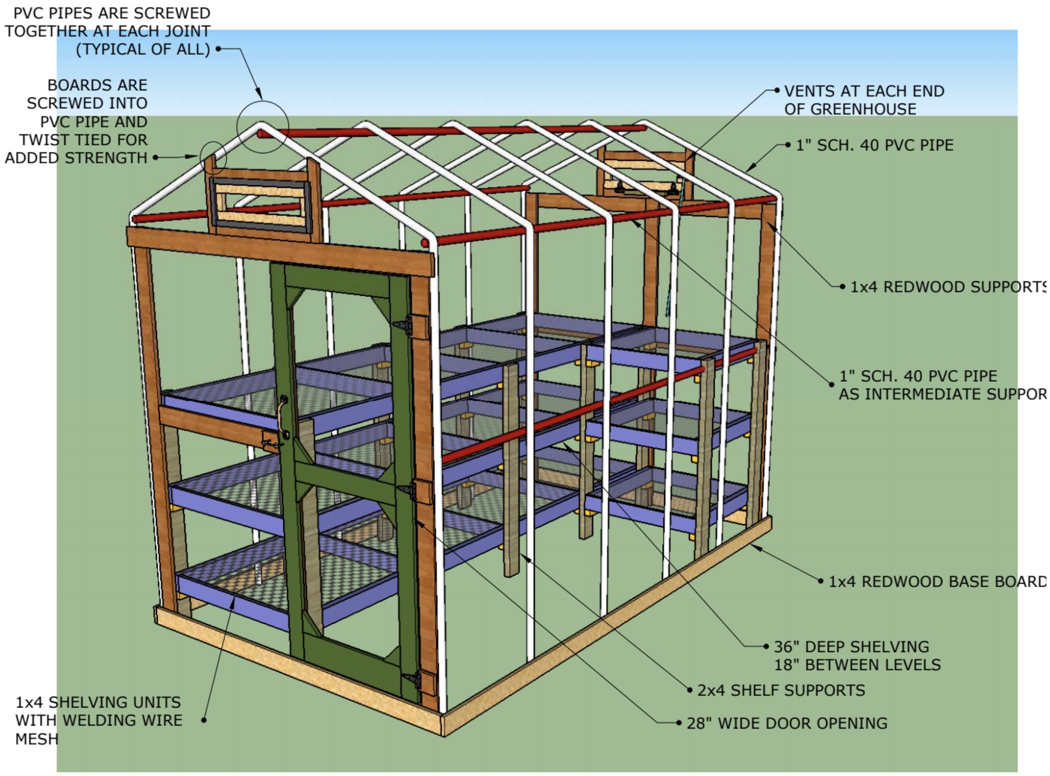
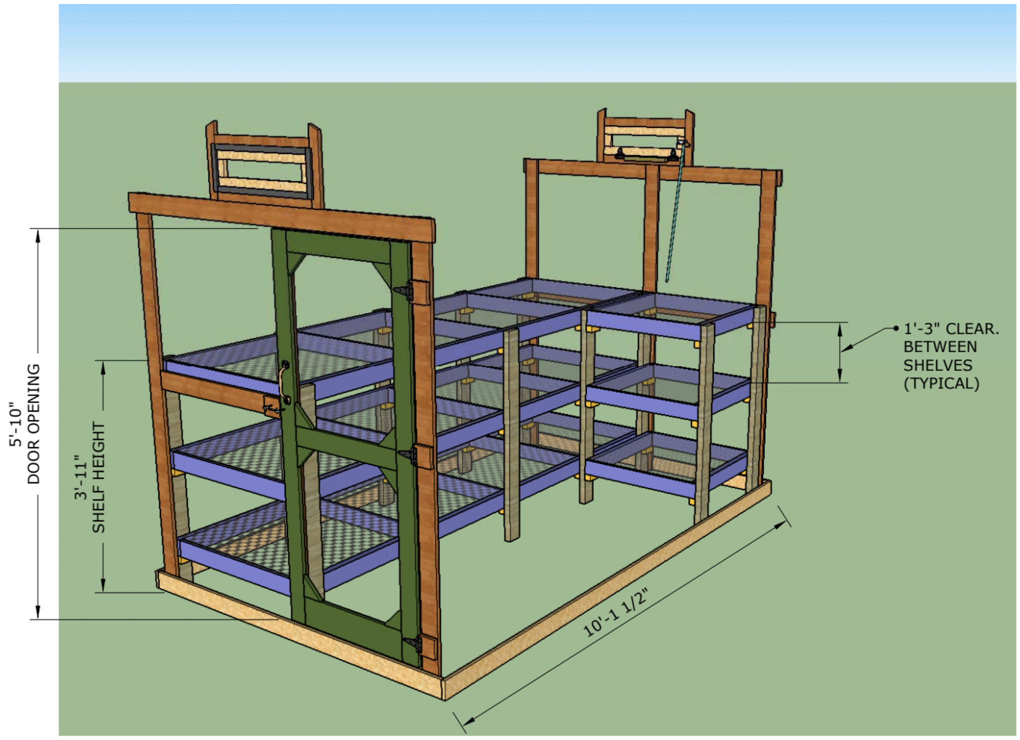


Figure F-1: Old Greenhouse Isometric View



PERSPECTIVE VIEW - PVC PIPING NOT SHOWN

Figure F-2: Old Greenhouse Isometric View - No PVC

Figure F-3: Old greenhouse in use

Appendix G - Market Research

The complete market research for the greenhouse design is summarized below

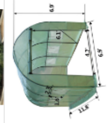
Source	Key Features	Length	Width	Height	Weight	Cost	Cost/Sqft	Images	Link	Efficacy	Potential Improvements
Wayfair	Rollup zippered door, Plastic frame, Not weather resistant, Staked installation, Clear plastic cover, Adjustable shelves, Adjustable window vent	2 ft. 5 in.	4 ft. 8 in.	6 ft. 5 in.	15 lbs.	$64.99	$5.77		https://www.wa	Very cheap - good example of a frugal greenhouse. Likely does not have enough feature to be effective but shows how cheaply they can be made.	Double shelves are not effective. Rollup door also seems like it would add unnecessary time and difficulty. Also not sturdy enough to withstand the elements.
Eartheasy	Aluminum frame, Modular, Rigid plastic UV-protected paneling, Roof vent, Automatic vent operator available, Galvanized potting benches available, Gutters for rainwater collection	8 to 20 ft.	8 ft.	Apex: 8 ft. 6.5 in., Sidewall: 5 ft. 3 in.	146 lbs	$1,500	$23		https://earthea	A high end greenhouse - a good example of a longlasting and durable greenhouse but ultimately way out of our price range.	The all visible walling and roof make this greenhouse diffuicult to cover from heavy heating during the peak summer season. Similarly, the cost of an additonal shade would push this greenhouse well out of
Wayfair	Wood frame, Polycarbonate panels and roofing, Beautiful aesthetic, Safety glass windows, Plywood floring, Door with window and screen, Shelving included, UV-ray resistant	8 ft.	8 ft.	10 ft. 4 in.	1800 lbs.	$5,799.99	$90.62		wayfair.com/L	A very spacious and study green house. It is a good example of a structure that can withstand various weahering conditions.	The heaviness of this greenhouse alone make this a very unlikely option for such small scale application. The targeted applicaton of our greenhouse lies in accessibilty and easy
Wish	Roman or Gothic arch styles available, Steel frame, Rollup door, Rollup windows, Spray-treated surface for rust/corrosion	11 ft. 9.6 in to 14 ft 9.6 in.	6 ft 10.8 in.	6.9 ft.	42.77 lbs. to 47.18 lbs.	$103	$1		https://www.wi	This lightweight greenhouse also dwells in the very accesible price range for most greenhouses. The wider aspect allows for more movement with crops. Rollou doors and windows give users an easier access to ventilation.	Arched roofing makes the structure weaker given any excessive weight or force along the peak of the roofing. Such damage would be nearly impossible for repair for full-time inexperienced agricultural customers.
Wayfair	Lean-to design, Sliding door, Aluminum frame, Frosted polycarbonate panels, Roof and door venting, 100% recycled content	6 ft.	4 ft.	7 ft. 3 in.	33.1 lbs.	$370	$15		https://www.wa	The eco-friendly aspect of this greenhouse makes it one of the most appealing designs for giving back to a community. The small scale aspect leads to greater attention per individual crop. Slanted roofing allows for focused energy and sunlight targeting	The small scale of this greenhouse does not allow for a greater profit as opposed to others. Whereas other greenhouses specialize in outputting an impressive amount of produce per growing season, this
Northern	Peak roof style, 4-tiered shelving, Steel mesh shelves, PVC covers, 15 minute snap assembly, Blocks UV rays, 5/16 in. steel frame, Rollup zippered door	5 ft. (dubious)	1 ft. 11 in.	4 ft. 8.37 in.	11 lbs.	$30	$3		https://www.no	4-tiered shelving and slim aspect of this greenhouse can give way to square footage in a backyard being used more efficiently. The cheaper aspect of this greenhouse allows for mutliple to be purchased in hopes of maximizing output and profit. The quick assembly also makes this easily transportable.	The vertical shelving can result in not as much sunlight reaching the lower levels. Additionally, the flimsy and easy PVC assembly can be harmed by intense enough winds in the valley as well as general usage.

Figure G-1: Market Research. Images produced without permission from Google.

Appendix H - Timeline

The timeline for the rest of the project is defined by the Gantt chart below. The black arrows show dependencies between certain events. This is a fairly general timeline, which will continue to be updated as tasks are completed. All members will try to participate in all tasks, so there is no division to be made there.

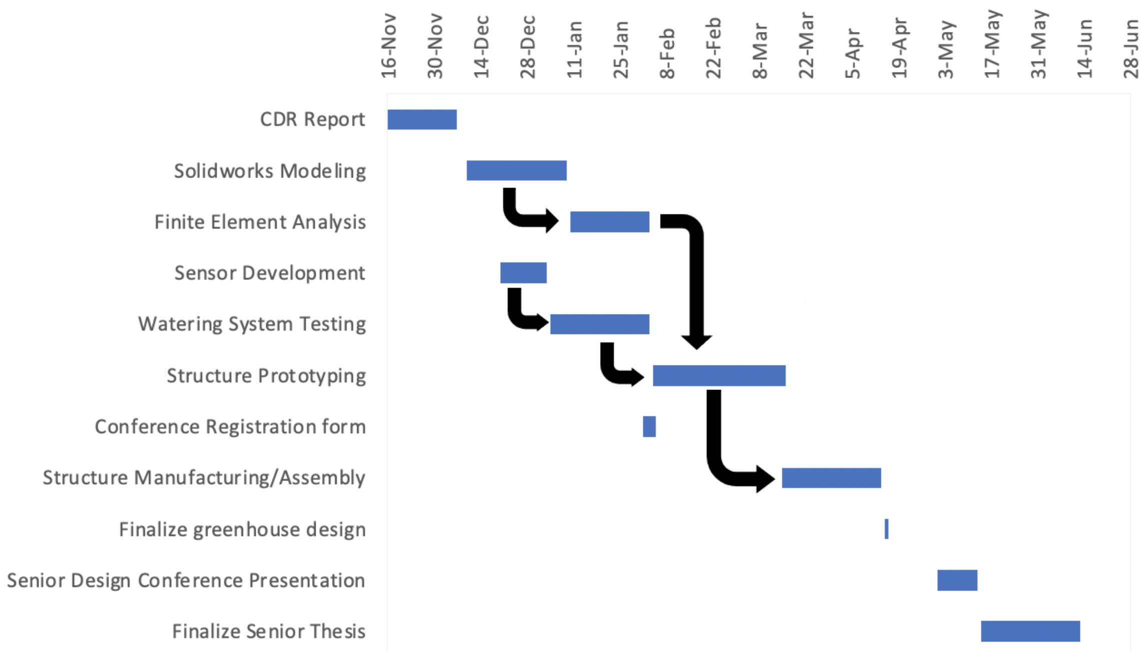


Figure H-1: Gantt chart

Appendix I - Safety Review

The Safety Review can be viewed at the end of this document.

Appendix J - Patent Literature

Note: Any spelling or grammatical errors are faults of the original authors, as published online.

1. Twin section greenhouse of polycarbonate sheets with lateral ventilation

Description

A two-section greenhouse made of polycarbonate sheets with lateral ventilation belongs to the field of cultivation devices for growing seedlings, vegetables, flowers, berries and green crops in early spring, summer and late autumn.

Known garden polycarbonate greenhouses with a semi-cylindrical top, the ends of which are equipped with entry doors and transoms for ventilation, sold by many companies (for example, http://www.teplicino.ru).

In such a greenhouse, plants overheat in the summer, pollen is sterilized due to high temperature and low productivity.

Known polycarbonate-glass-plastic greenhouse made of honeycomb polycarbonate, having the shape of a half cylinder, the frame of which is filled around the perimeter with concrete mortar, the polycarbonate coating is connected to the frame through plastic modules, the doors at the ends of the greenhouse are equipped with a rubber seal (RU 152873 U1, 06/20/2015).

There is no side ventilation to maintain in the greenhouse an optimal microclimate for each culture (temperature, relative humidity, air velocity, soil moisture).

The objective of the utility model is to develop a garden two-section greenhouse made of polycarbonate sheets with side ventilation.

This is achieved by the fact that the two-section garden greenhouse is made of polycarbonate sheets with lateral ventilation, characterized in that the cross section is made on the north side and the top is cylindrical, and on the south side it is flat vertical in the form of a wall with uprights, and the top openings are made along the entire length of the greenhouse windows are transoms on hinges, and the height of the windows is half the height of the vertical wall, and at the ends there are doors. The length of the greenhouse is divided by a movable partition for growing various crops and for hanging them four longitudinal wires for trellises are arranged under the roof, depending on the planting scheme. The greenhouse is fixed in the ground by anchor stakes, curved honeycomb polycarbonate sheets are interconnected by fiberglass arcs to the southern vertical wall. To carry the greenhouse to a new place, there are staples mounted on the frame.

In FIG. 1 shows a general view of a greenhouse in axonometric projection; in FIG. 2 - cross section of the vertical wall of the greenhouse with an open side window - transom.

The frame of the greenhouse is composed of two longitudinal bars 1 and 2, which are connected by transverse beams 3 for rigidity. The north side and the upper part of the greenhouse are made in the form of a cylinder and have arcs 4, which are fixed below on the lower longitudinal beam 1, and the middle longitudinal rail 5, and the upper axle roof rail 6 of the vertical wall 7, the vertical south wall comprises struts 8 connecting the upper roof rail 6 rigidly to the lower longitudinal bar 1. The vertical wall 7 is divided in height by half with a longitudinal rail 9, on top of which mounted windows - transoms 10, connected to the rail 9 by hinges 11 and fixed in the upper closed and lower open positions by the pins 12. For hanging the trellis wires are provided 13. The greenhouse is fixed on the site using anchor stakes 14. The greenhouse is divided in length by a movable partition 15, where a certain microclimate is maintained for each culture. Doors are arranged at the ends of the greenhouse 16. For carrying the greenhouse to a new place in the garden, brackets 17 are arranged. Bars 1 and 2; beams 3, rails 5, 6, 9 can be made of antiseptic wood, galvanized pipes, aluminum or galvanized profiles (corner, channel, section, etc.)

In early spring, greenhouses grow seedlings of vegetables, flowers and vegetables, for example, radishes. Then a partition 15 is made of a thick polyethylene film or of a thin polycarbonate sheet and seedlings are planted. Tomato seedlings are planted to form in one lash. The temperature of the soil and air, as well as the relative humidity of the air, is regulated by opening - closing southward directed windows - transoms 10. Opening windows - transoms half the height of the vertical wall also allows the sun to penetrate the photosynthetic greenhouse, which significantly improves the quality of vegetables. The next year, vegetables are swapped. For example, instead of tomatoes, cucumbers are planted and vice versa. After many years of operation, a pathogenic microflora develops in the greenhouse, so the greenhouse should be moved to a new place, moving it behind staples 17 or changing or sterilizing the soil.

Claims

A two-section garden greenhouse made of polycarbonate sheets with lateral ventilation, characterized in that the cross section is made on the north side and the top is cylindrical, and on the south side it is in the form of a flat vertical wall with racks, in the upper part of which are made windows that open down the entire length of the greenhouse - transoms on hinges, and the height of the windows is half the height of the vertical wall, and at the ends there are doors, the greenhouse is divided in length by a movable partition for growing various crops, for hanging of which four longitudinal wires for trellis are arranged under the roof, depending on the crop planting scheme, the greenhouse is fixed in the ground with anchor rings, curved honeycomb polycarbonate sheets are interconnected by fiberglass arcs to the southern vertical wall, brackets mounted on the frame are provided for moving the greenhouse to a new place.

2. Greenhouse monitoring system

This patent is very long and can be best summarized with the claims section

Claims

1. A greenhouse monitoring system, comprising: a controller, a sensor, a communication assembly and a greenhouse regulation device;
the sensor is connected with the controller through the communication assembly;
the controller is connected with the greenhouse regulating equipment;
the sensor is used for acquiring environmental parameters in the greenhouse;
the controller is used for controlling the greenhouse regulating equipment according to the environmental parameters.
2. The greenhouse monitoring system of claim 1, further comprising: a display;
the display is connected with the controller;
the display is used for displaying the environment parameters so as to be viewed by workers.
3. The greenhouse monitoring system of claim 1, further comprising: an input component;
the input assembly is connected with the controller;

the input assembly is used for acquiring equipment operation information input by workers, so that the controller controls the greenhouse adjusting equipment according to the equipment operation information.

4. Greenhouse monitoring system according to claim 1, wherein the environmental parameters comprise: soil temperature and humidity parameters, indoor temperature and humidity parameters, illumination intensity parameters and gas concentration parameters;

the sensor includes: a soil temperature and humidity sensor for collecting the soil temperature and humidity parameters, a greenhouse temperature and humidity sensor for collecting the indoor temperature and humidity parameters, an illumination sensor for collecting the illumination intensity parameters and a gas sensor for collecting the gas concentration parameters;

the greenhouse regulating apparatus comprises: the device comprises a crop irrigation device, an air heating and humidifying device, a light supplementing device, a roller shutter device and a ventilation device;

the soil temperature and humidity sensor, the greenhouse temperature and humidity sensor, the illumination sensor and the gas sensor are respectively connected with the controller through the communication assembly;

the crop irrigation device, the air heating and humidifying device, the light supplementing device, the roller shutter device and the ventilation device are respectively connected with the controller;

the controller is used for controlling the crop irrigation device to irrigate the crops in the greenhouse according to the soil temperature and humidity parameters; controlling the air heating and humidifying device to work according to the indoor temperature and humidity parameters; controlling the light supplementing device and the roller shutter device to work according to the illumination intensity parameter; and controlling the operation of the ventilation device according to the gas concentration parameter.

5. Greenhouse monitoring system according to claim 4, wherein the crop irrigation device comprises: a switch assembly and an irrigation assembly;

the air heating and humidifying device comprises: the first relay and the indoor temperature and humidity regulator;

the light supplement device comprises: a second relay and a light supplement lamp;

the rolling shutter device includes: the device comprises a roller shutter driving component, a roller shutter stepping motor and a roller shutter;

the ventilation device includes: the ventilation driving assembly, the ventilation motor and the ventilation fan are arranged;

the switch assembly, the first relay, the second relay, the roller shutter driving assembly and the ventilation driving assembly are respectively connected with the controller;

the irrigation assembly is connected with the switch assembly;

the first relay is connected with the indoor temperature and humidity regulator;

the second relay is connected with the light supplementing lamp;

the roller shutter driving component and the roller shutter are respectively connected with the roller shutter stepping motor;

the ventilation driving assembly and the ventilation fan are respectively connected with the ventilation motor.

6. Greenhouse monitoring system according to claim 4, wherein the greenhouse regulating device further comprises: a greenhouse air supply device;

the greenhouse air replenishing device is connected with the controller;
the controller is also used for controlling the greenhouse gas supplementing device to work according to the gas concentration parameter.
7. The greenhouse monitoring system of claim 1, further comprising a terminal device and a server;
and the controller respectively carries out data interaction with the terminal equipment and the server through the communication assembly.
8. The greenhouse monitoring system of claim 7, further comprising a camera device;
the camera shooting equipment is connected with the controller;
the camera shooting equipment is used for shooting crop video information in the greenhouse;
the controller is used for sending the crop video information to the terminal equipment or the server through the communication component.
9. The greenhouse monitoring system of claim 1, further comprising: a soil nutrient detector, a fertilizing device and a guide rail;
the soil nutrient detector is connected with the controller through the communication assembly;
the fertilizing device is connected with the controller;
the guide rail is arranged in the greenhouse;
the fertilizing device moves along the guide rail;
the soil nutrient detector is used for collecting soil nutrient parameters;
and the controller is used for controlling the fertilizing device to fertilize according to the soil nutrient parameters and the prestored fertilizing information.
10. Greenhouse monitoring system according to any of the claims 1-9, wherein the controller is of the Raspberry-Pi type.

3. System for cultivating plants

The key elements of this patent are best described in the claims.

Claims
1. A greenhouse (2) with:
a supporting structure (4) and a translucent roofing (6), wherein the roofing limits the greenhouse to the outside and is supported by the supporting structure; and a shelf system (8) comprising an arrangement of shelves (12) with a plurality of planes (14), wherein the shelves (12) are arranged such that they form shelf aisles (16, 18) in the longitudinal and transverse directions, wherein the supporting structure (6) of the greenhouse (2) is formed by the shelf system (8).
2. The greenhouse according to claim 1, wherein the shelves (12) are arranged such that shelf aisles (16, 18) in the longitudinal direction and the transverse direction are formed, wherein shelves (12) of simple or multiple depths are provided between adjacent shelves (16).
3. The greenhouse according to claim 1 or 2, wherein the shelf system (12) is an automatically operable system and comprises at least one, preferably driverless, shelf vehicle (20) by means of which seed stock may be put into a storage place in the shelf system (12) or fetched therefrom.
4. A greenhouse (2) with:
a supporting structure (4) and a translucent roofing (6), wherein the roofing limits the greenhouse to the outside and is supported by the supporting structure; and an automatically operable shelf system (12) comprising an arrangement of shelves (12) with a plurality of planes (14),

wherein the shelves (12) are arranged such that they form shelf aisles (16, 18) in the longitudinal and transverse directions, wherein the automatically operable shelf system (12) comprises at least one, preferably driverless, longitudinally and transversely movable shelf vehicle (20) by means of which seed stock may be put into a storage place in the shelf system (12) or fetched therefrom.

5. The greenhouse according to claim 4, wherein the shelves (12) are arranged such that shelf aisles (16, 18) in the longitudinal direction and the transverse direction are formed, wherein shelves (12) of simple or multiple depths are provided between adjacent shelf aisles (16).

6. The greenhouse according to any one of claims 3 to 5, wherein further at least one lifting equipment (22) is provided by means of which the at least one shelf vehicle (20) may be transported between different planes (14) of the shelf system (12), or wherein the at least one shelf vehicle (20) is designed to switch from one shelf plane (14) to another plane (14) by itself.

7. The greenhouse according to any one of claims 4 to 6, wherein the supporting structure (4) of the greenhouse (2) is formed by the shelf system (12).

8. The greenhouse according to any one of claims 3 to 7, wherein further a work area (24) is provided in the greenhouse (2), with seed stock from the shelves (12) of the shelf system (8) being able to be transported to and from said work area with the help of the at least one shelf vehicle (20).

9. The greenhouse according to any one of claims 3 to 8, wherein the at least one shelf vehicle (20) is configured such that the seed stock does not have to be taken out of the shelf (12) for every operation, but that work may rather be done automatically on the seed stock.

10. The greenhouse according to any one of claims 1 to 9, further with a means for moving seed stock from the respective shelves (12) to different places in the greenhouse (2) in order for the seed stock to be provided with, inter alia, sufficient light, water, and/or fertilizer.

4. Vertically integrated greenhouse

Description

The present invention relates to structural systems for growing plants in urban settings. In particular, the invention is directed to a vertical greenhouse which is affixed to a façade of a multi-story urban building, or to the wall of a multi-story atrium or concourse.

Claims

1. A vertical growing system for cultivation of plants, the system comprising:

(a) a plurality of trays structurally configured for growing plants therein;

(b) a tray suspension system to which the trays are adjustably affixed one above another, wherein:

(i) the tray suspension system comprises a drive system, means for adjustment of the vertical position of the trays to the drive system, and a plant cable lift system which provides adjustable vertical raising and lowering of individual trays or sets of trays, and has a singular access point for user access and manipulation of the trays;

(ii) the spacing between the trays in the suspension system is adjustable to vary the amount of light passing through the tray suspension system to surfaces behind the tray suspension system; and

(ii) the tray suspension system is configured to allow natural lighting to pass to the plants growing in the trays; and
(c) a water distribution system comprising a reservoir, a pump, and a water supply tube, the water distribution system providing a flow of irrigation water to the plants growing in the trays, and drainage of excess water from the trays.
2. The growing system according to claim 1, wherein the trays are structurally configured for growing plants hydroponically, via a nutrient film technique, or in a solid growing medium.
3. The growing system according to claim 1, wherein the trays are spaced between about 10-30 inches apart in the suspension system during a growing cycle.
4. The growing system according to claim 1, wherein the trays have respective inlets and outlets, and the water distribution system provides water to an inlet of a upper tray and water exiting through an outlet of the upper the tray flows via gravity to an inlet of a lower tray.
5. The growing system according to claim 1, wherein the tray suspension system comprises means for tracking solar elevation for optimizing the amount of light provided to the trays.
6. The growing system according to claim 5, wherein the trays in the tray suspension system are arranged in a front row and a rear row; and the front and rear rows of trays are staggered and vertically adjustable relative to each other to optimize the amount of light passing to or through the trays.
7. The growing system according to claim 1, wherein the tray suspension system comprises motorized or manual means for adjusting the position of the trays.
8. The growing system according to claim 1, wherein the suspension system comprises automated means for adjusting the position of the trays.
9. A vertical growing system for cultivation of plants, the system comprising:
(a) a plurality of trays structurally configured for growing plants therein;
(b) a tray suspension system to which the trays are adjustably affixed one above another, wherein:
(i) the tray suspension system comprises a drive system, means for adjustment of the vertical position of the trays to the drive system, and has a singular access point for user access and manipulation of the trays;
(ii) the spacing between the trays in the suspension system is adjustable to vary the amount of light passing through the tray suspension system to surfaces behind the tray suspension system; and
(ii) the tray suspension system is configured to allow natural lighting to pass to the plants growing in the trays; and
(c) a water distribution system comprising a reservoir, a pump, and a water supply tube, the water distribution system providing a flow of irrigation water to the plants growing in the trays, and drainage of excess water from the trays; and
wherein the trays have respective inlets and outlets and are interconnected by one or more water distribution tube(s), and wherein the water distribution system provides water to an inlet of an upper tray, and water exiting through an outlet of the upper tray flows via gravity to an inlet of a lower tray.
10. The growing system according to claim 9, wherein the trays have a grade in the range of about 0.5-2 inches over 5 feet, or in the range of from 0.05° to 0.1°.
11. The growing system according to claim 9, wherein the water distribution system further provides plant nutrients to the trays.

12. The growing system according to claim 9, wherein the water distribution system is configured for recirculation of the irrigation water within the growing system.
13. A vertical growing system for cultivation of plants, the system comprising:
(a) a plurality of trays structurally configured for growing plants therein;
(b) a tray suspension system to which the trays are adjustably affixed one above another, wherein:
(i) the tray suspension system comprises a drive system, means for adjustment of the vertical position of the trays to the drive system, and has a singular access point for user access and manipulation of the trays;
(ii) the spacing between the trays in the suspension system is adjustable to vary the amount of light passing through the tray suspension system to surfaces behind the tray suspension system; and
(ii) the tray suspension system is configured to allow natural lighting to pass to the plants growing in the trays; and
(c) a water distribution system comprising a reservoir, a pump, and a water supply tube, the water distribution system providing a flow of irrigation water to the plants growing in the trays, and drainage of excess water from the trays; and
wherein the suspension system comprises a pulley assembly, a set of suspension wires for spatial alignment of the trays, and a set of lifting wires for vertical positioning of the trays.
14. The growing system according to claim 13, wherein the tray suspension system comprises a conveyor system which vertically conveys each tray through the growing system while maintaining a substantially static spacing between trays.
15. The growing system according to claim 14, wherein the water distribution system is mechanically independent of the conveyor system.
16. The growing system according to claim 13, wherein the trays are affixed to the suspension system via a releasable L-shaped bracket.
17. The growing system according to claim 13, wherein the water distribution system irrigates the trays simultaneously, sequentially, or a combination of both.
18. The growing system according to claim 13, wherein the growing system is structurally configured for mounting in an atrium.
19. The growing system according to claim 13, wherein the growing system is structurally configured for mounting to a façade of a building.
20. The growing system of claim 13, wherein the plant cable lift system enables collapsing of the trays on top of one another.

5. Natural ventilation augmented cooling greenhouse

Summary of the Invention

In accordance with an aspect of the present invention, there is provided a greenhouse comprising: one or more upstanding side walls providing a structural frame forming a periphery of the greenhouse and providing structural support for the greenhouse, the side walls defining an enclosed growing area within the greenhouse, each side wall comprising a top edge; a roof extending upward from the structural frame and covering the growing area, the roof having two or more roof sections each extending inwardly from the structural frame and terminating over a portion of the growing area, the roof sections comprising: a first roof section extending from a lower inward edge spaced laterally inwardly from the structural frame and terminating in a first remote edge disposed over the growing area; at least a second roof section terminating in a second remote edge disposed over the growing area; the second remote edge overlapping the first remote edge such as to define a roof overlap between the first and the second roof sections, the first and second roof sections being spaced apart to define a vertical gap between the first and second roof sections at said roof overlap, the vertical gap forming a first air flow opening permitting air circulation therethrough, a second air flow opening defined between the lower inward edge of the first roof section and at least one of the second roof section and the structural frame, a continuous air flow channel being formed between the first and second roof sections and extending between the first and second air flow openings to permit air circulation therebetween; and a cooling system mounted to at least one of the first and second roof sections and including nozzles operable to spray water vapour into the air circulating within the air flow channel defined between the first and second roof sections.

In accordance with another aspect of the present invention, there is provided a greenhouse as defined in the paragraph above, wherein the greenhouse comprises three roof sections, wherein: the first roof section extends from the inward edge spaced inwardly from a first side wall and terminates in the first remote edge disposed over the growing area; a middle roof section extends inwardly from the top edge of a second side wall opposed to the first side wall, and terminates in the second remote edge spaced inwardly from the second side wall, the first and second remote edges overlapping one another such as to define a first roof overlap between the first and the middle roof sections, a first vertical gap being defined between the first and middle roof sections at the first roof overlap to define a lower air flow opening permitting air circulation therethrough; and a third roof section extends inwardly from the top edge of the first side wall and terminates in a third remote edge spaced inwardly from the first side wall, the third and second remote edges overlapping one another such as to define a second roof overlap between the third and the middle roof sections, a second vertical gap being defined between the third and middle roof sections at the second roof overlap to define an upper air flow opening permitting air circulation therethrough, a side air flow opening defined between the inward edge of the first roof section and the third roof section, the continuous air flow channel being formed between the first and third roof sections permitting air circulation between the upper air flow opening and the side air flow opening.

There is further provided, in accordance with another aspect of the present invention, a method for cooling a greenhouse comprising a roof having two or more roof sections, each roof section extending inwardly from a structural frame defined by upstanding side walls to at least partially cover a growing area of the greenhouse, at least one roof section vertically overlapping another roof section such as to define a roof overlap between said roof sections, a continuous air flow channel being defined between said roof sections along said roof overlap, the air flow channel having an upper air flow opening permitting air circulation into and out of the greenhouse and a side air flow opening permitting air circulation into and out of the growing area, the method comprising the steps of: allowing air to circulate into the greenhouse via the upper air flow opening; adding water vapour to the air circulating within the air flow channel between at said roof sections, thereby cooling the air; allowing rising warm air to circulate from the growing area and out of the greenhouse through the upper air flow opening; and allowing the cooled air to circulate downward toward the growing area through the side air flow opening, thereby cooling the greenhouse.

Appendix K - Copy of CDR Slides

The CDR presentation can be seen at the end of the thesis (after the safety report).

Appendix L: Material Properties

Material properties are as shown below for the PVC. This applies to the fittings and PVC tubes.

Property	Value	Units
Elastic Modulus	870.226426	psi
Poisson's Ratio	0.47	N/A
Shear Modulus	290.0754753	psi
Mass Density	0.0466041935	lb/in^3
Tensile Strength	1885.49059	psi
Compressive Strength		psi
Yield Strength		psi

Figure K-1: Material Properties for PVC

The rebar in this design was assumed to be 1023 carbon steel, which has material properties as shown below. The rebar chosen is made from grade 40 steel, which has a yield strength of 40,000 psi and is assumed to be similar to the chosen material.

Property	Value	Units
Elastic Modulus	29732735.99	psi
Poisson's Ratio	0.29	N/A
Tensile Strength	61641.03897	psi
Yield Strength	40999.99998	psi
Tangent Modulus		psi
Thermal Expansion Coefficient	6.666666667e-06	/°F
Mass Density	0.2838881816	lb/in^3

Figure K-2: Material Properties for rebar

Appendix M: CAD Design Iterations

Version 1: The preliminary design is based on work done in previous quarters.

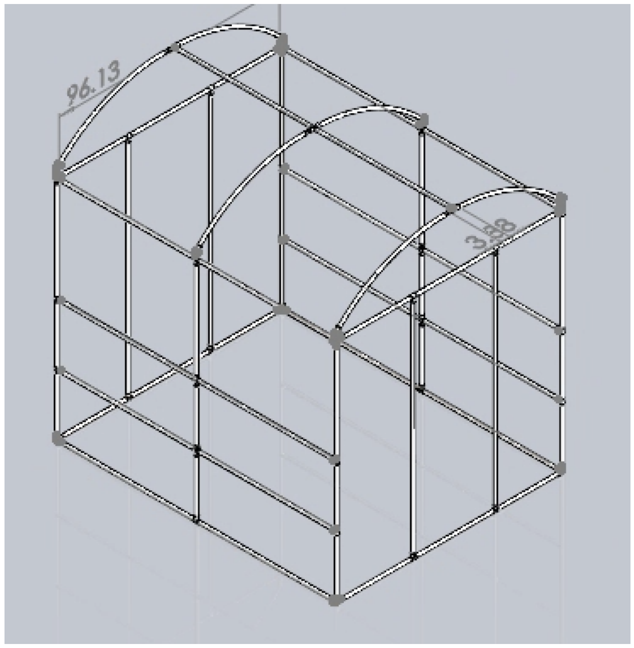


Figure L-1: Structural Version 2

Version 2: After doing preliminary FEA on the structure (not including a live load or wind load) it was determined that the doorframe did not have adequate support on the side of the door that the hinges were attached to. To try and fix this, a support bar was added.

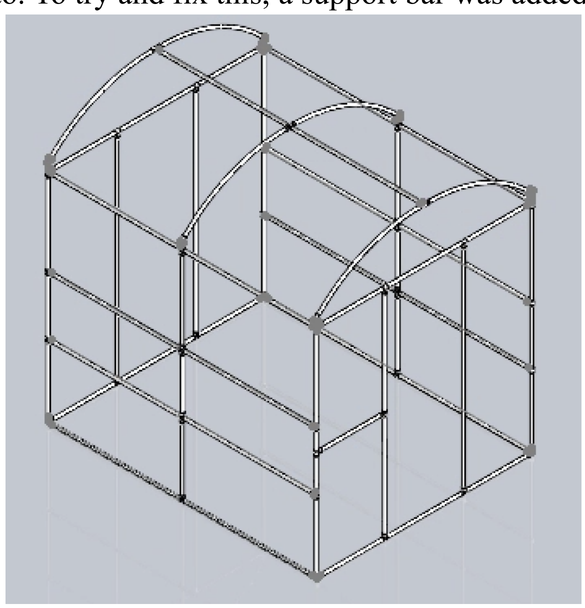


Figure L-2: Structural version 2

Version 2.5: It was determined that one support beam still led to excessive deflection, so another support beam was added. With this design, the structure had a max deflection of 1.259 inches under its weight.

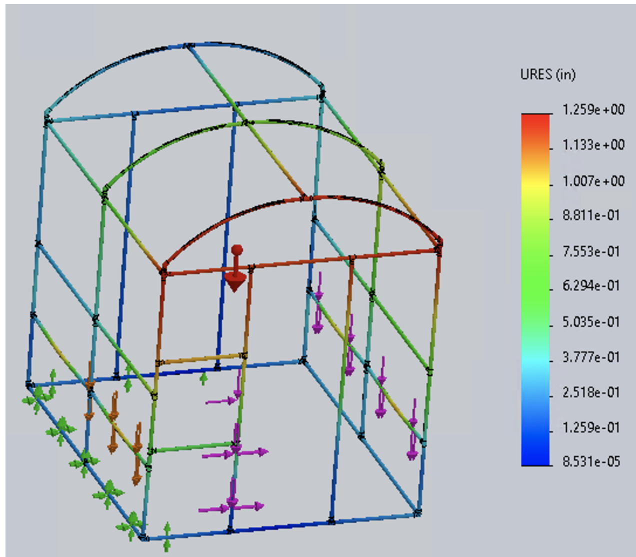


Figure L-3: Structural Version 2.5 FEA

Version 3: In the third version, a live load was added to the structure to test its vertical strength. When this load was added, it became apparent that the center of the roof beam was the most critical point on the structure and had unacceptable deflection. To try to fix this deflection, another beam was attached to the top beam to raise the moment of inertia and limit deflection

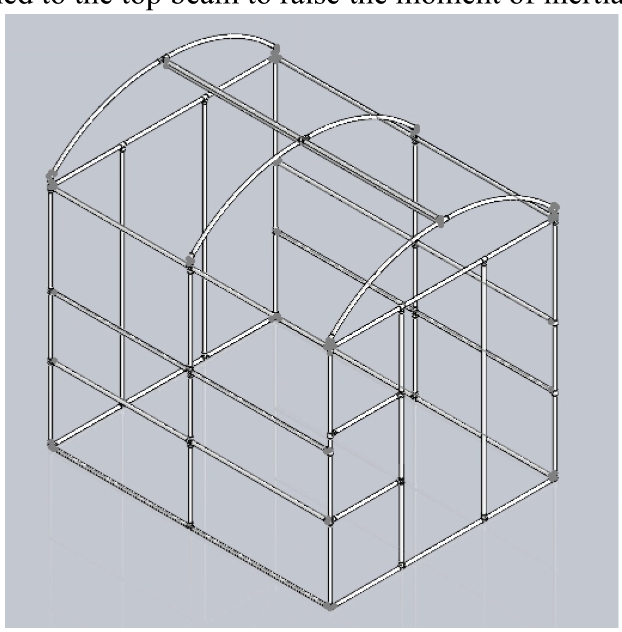


Figure L-4: Structural version 3

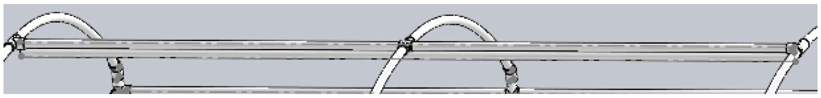


Figure L-5: Side view of version 3

Version 4: Unfortunately, simply adding another beam alone did not make the deflection in the roof acceptable. To further mitigate this problem, 45 degree angle supports were added to the structure.

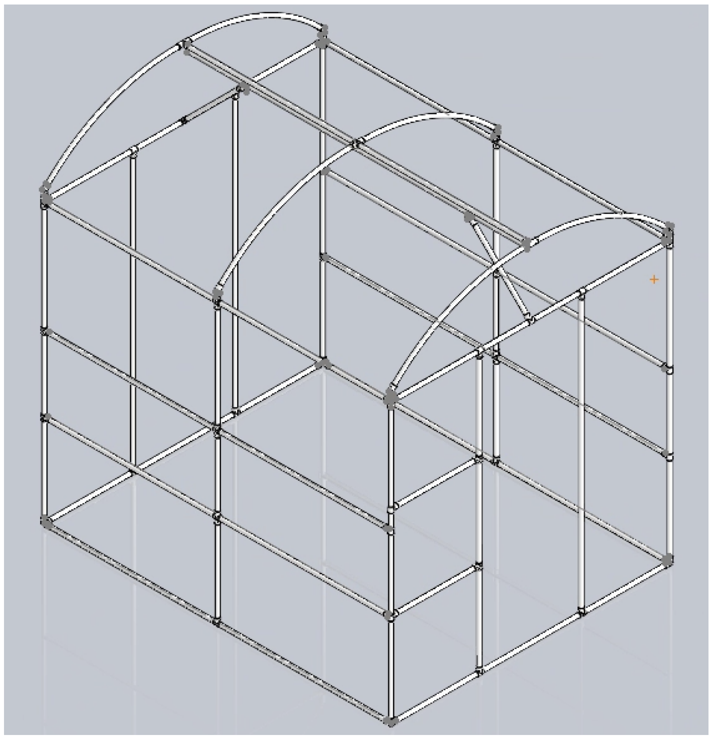


Figure L-6: Structural version 4

Version 5: While these 45 degree angle supports were helpful, they did not fix the problem of unacceptable deflection. To address this problem, a steel beam was attached to the top of the greenhouse and the second beam was eliminated.

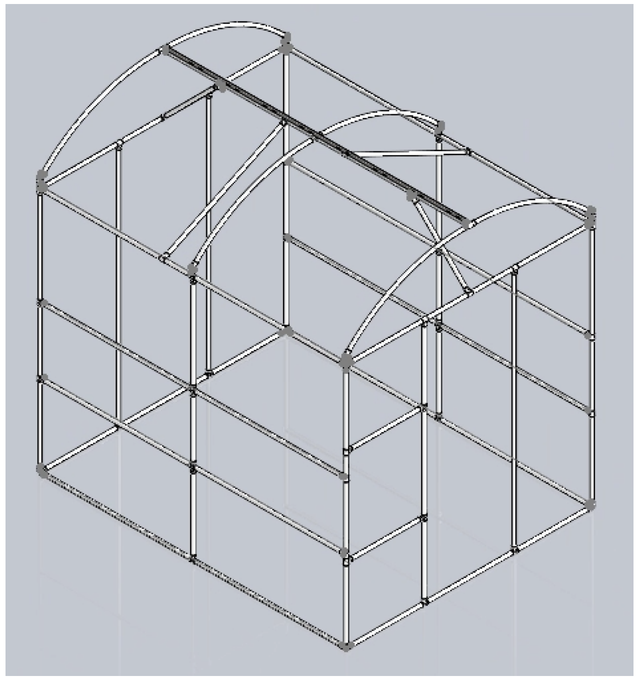


Figure L-7: Structural version 5

Version 6: This version changes the top steel beam. Although that beam was very effective in preventing deflection, it was outside of the cost range for the greenhouse. To use a cheaper alternative, it was decided to put rebar in the top beam of the greenhouse itself. It was assumed that the rebar was fixed to the inside face of the beam. Realistically, this could be achieved by driving a nail or screw through the PVC to ensure the rebar cannot move. This was a cheap, unintrusive, and effective way to improve the moment of inertia of the top beam.

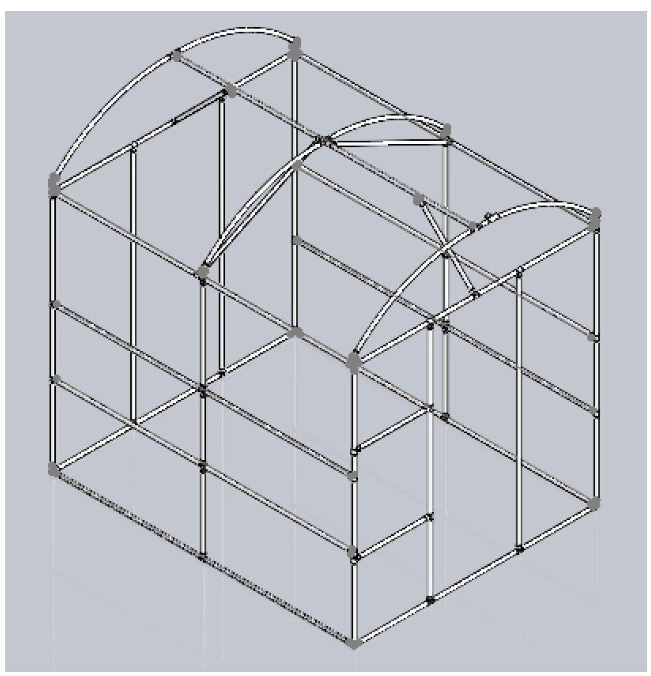


Figure L-8: Structural version 6

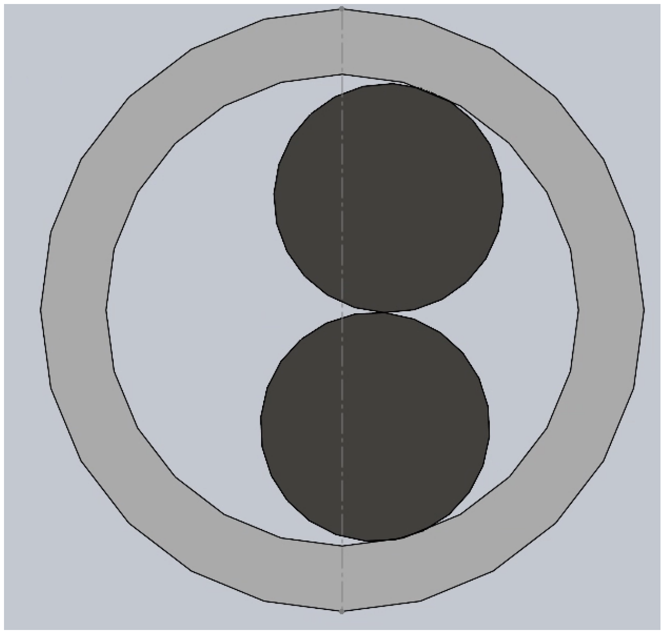


Figure L-9: Rebar in PVC configuration

Final Version: Finally, after the issues with the live load were fixed, the greenhouse was then subjected to a wind load. Although it withstood this loading fairly well, extra side supports were added to improve the resistance to a horizontal force.

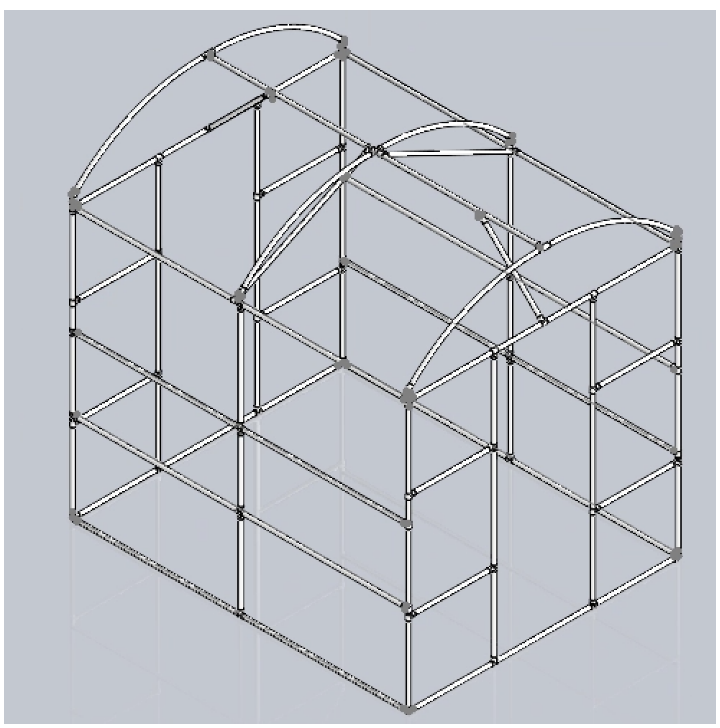


Figure L-10: Structural final version

Appendix N: Auxiliary Views of Final CAD Design

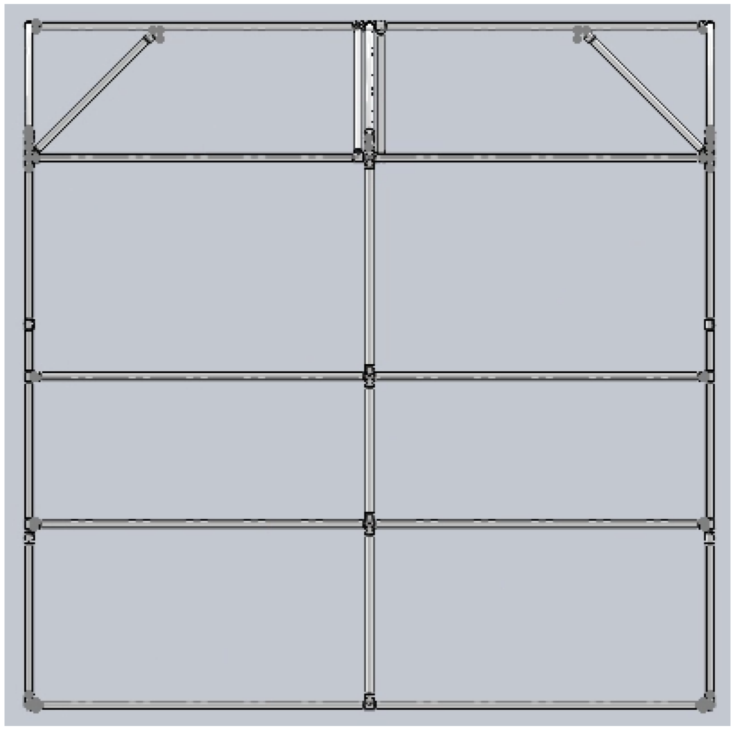


Figure M-1: Side view of final design

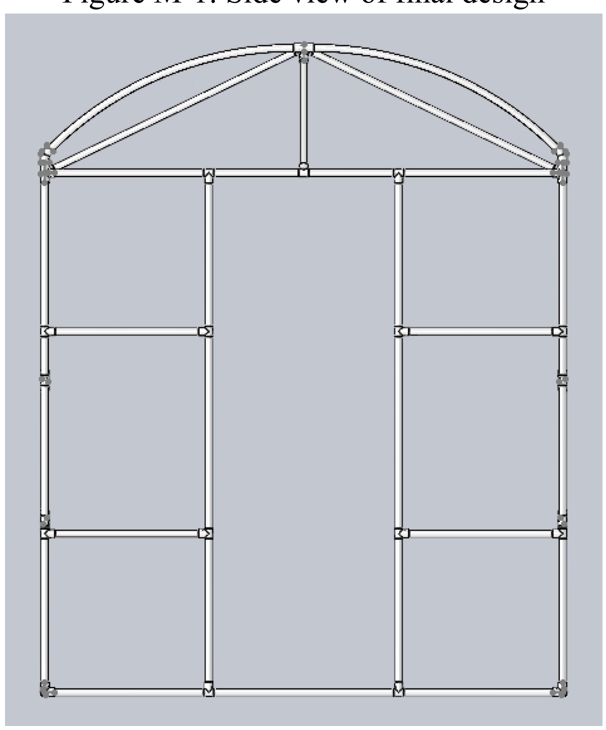


Figure M-2: Front view of the final design

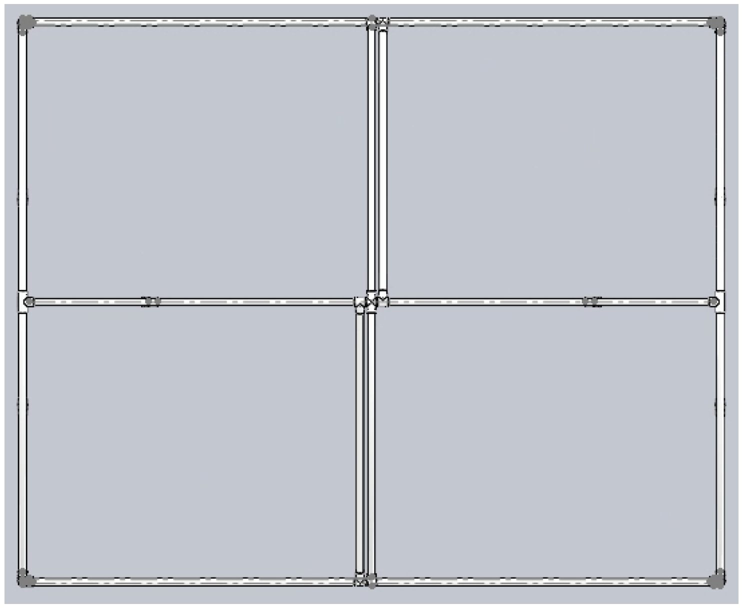


Figure M-3: Top view of the final design

Appendix O: Wind Load Calculations

Wind force was calculated in psf using the following equation[2]:

$$Q = .00256 * K_H * K_{ZT} * K_D * V^2 * I$$

Where:

Q = Wind force (psf)
K_H = Topographic factor evaluated at a height H
K_{ZT} = Topographic Factor
K_D = Directionality Factor
V = Wind speed (mph)
I = Importance factor

Given the dimensions and loading conditions of the greenhouse, K_{ZT} = 1 because the height of the greenhouse is less than 15 feet, K_D = .85 based on the geometry of the structure (rectangular and perpendicular to the wind), and I = .87 based on the distinction as an agricultural facility in a non-hurricane prone area. K_H can be calculated with the following equation when the structure is under 15 feet:

$$K_H = 2.01 * \frac{15}{Z_g}^{(2/a)}$$

Where Z_g and a are determined by the exposure conditions of the greenhouse. If it is assumed that the greenhouse is in an urban area, K_H = .43.

With all of these conditions, with a wind speed of 20 mph Q = .32 and with a wind speed of 50 mph Q = 2.01. If one multiplies Q by the wall area of the greenhouse (which is 80 square feet) the wind force is 25.6 lbf and 160.8 lbf respectively.

[2] https://www.buildingsguide.com/calculators/structural/ASCE705W/

Appendix P: CAD Drawings

These were used for clear communication between team members about the part and design dimensions. This allowed the Team to complete hand calculations more easily through online communication, whereas transferring SolidWorks models is more difficult.

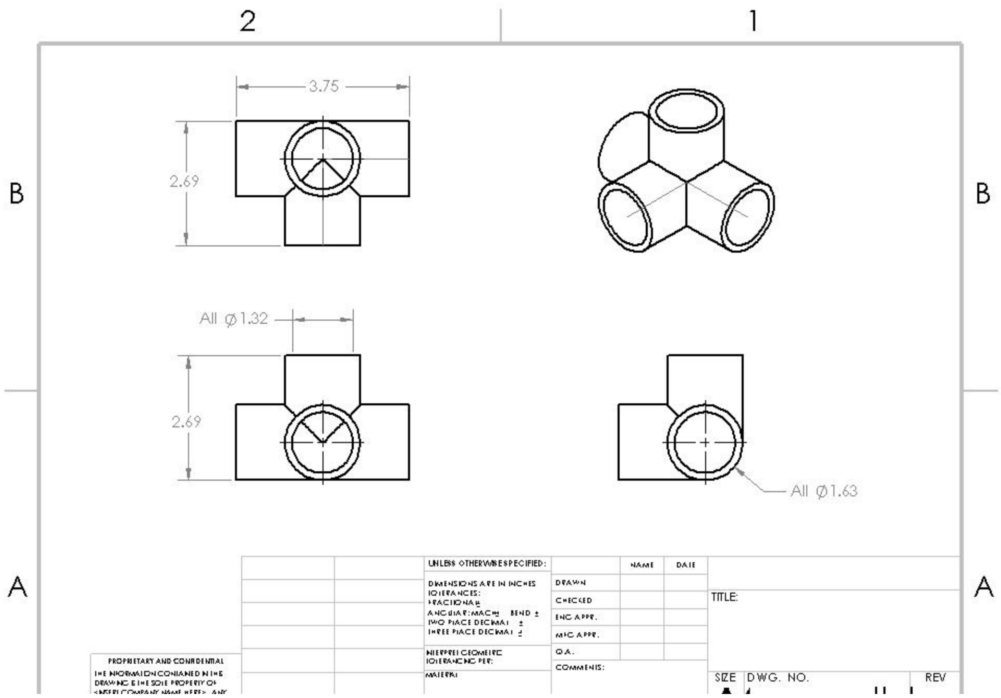


Figure O-1: 4-Way PVC Connector Drawing

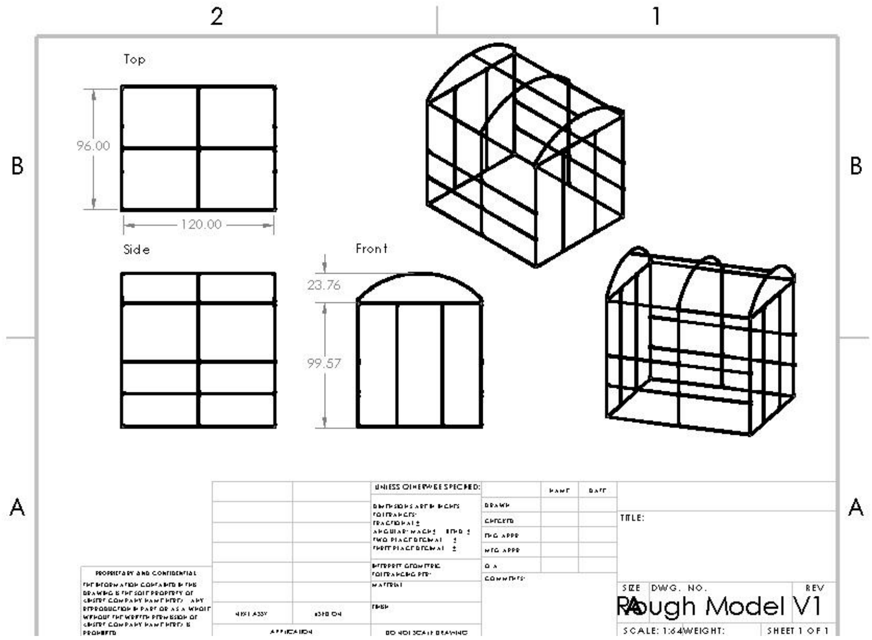


Figure O-2: Greenhouse Early Iteration

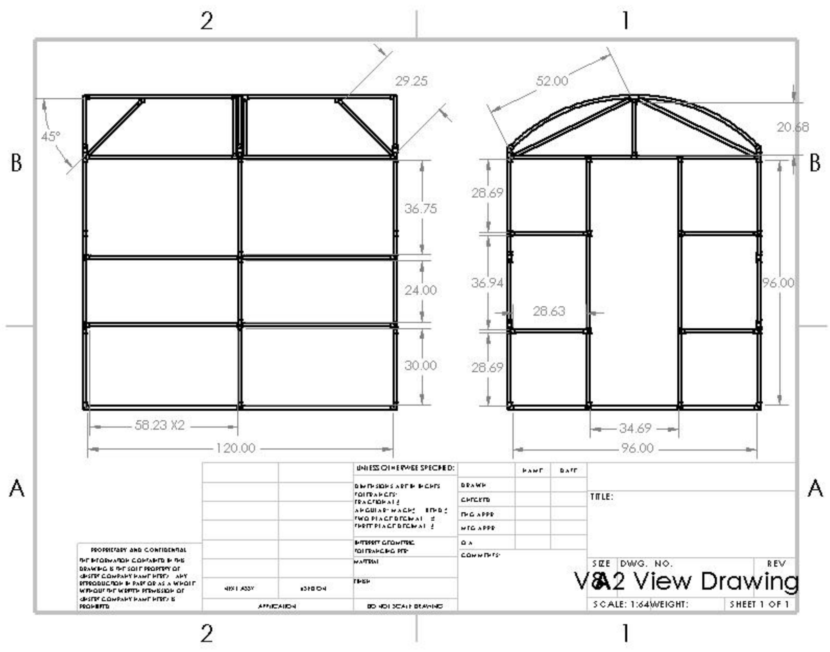


Figure O-3: Greenhouse Version 7 Front and Side View

Appendix Q: CAD Verification Calculations

The general approach for these calculations was to find key values, like area, the moment of inertia (individual and composite), support forces, and then assess deflection or failure based on critical loading and also the loading conditions described earlier. Appendix G provides more visuals that may supplement the raw calculations here.

$Area_{pipe} = \pi(1.315)^2/4 - \pi/4 = 0.5727\, in^2$

$I_{pipe} = \pi(1.315 - 1)/64 = 0.0976\, in^4$

Key equations for later reference

$For\ bending{:}\ \sigma = My/I$

$For\ buckling{:}\ P_{critical} = \pi^2 EI/L^2$

For the generalized, vertical column (any of the 4 corner support columns):

$P_{critical} = \pi^2 870 * 0.09769/96^2 = 0.0910\, pounds$

This answer makes intuitive sense: PVC is very sensitive and flexible, so any small force easily bends it. Luckily, it is not calculated to yield except under very large forces.

$P_{yield} = \sigma_{yield} A_{PVC} = 8000 * 0.5727 = 4581.9\, pounds$

The necessary answer is to find the maximum deflection under the sample load of 1000 pounds or 250 pounds per column.

For a simple pin-pin column, the deflection equation is as follows.

$M = EI * d^2v/dx^2$

$M =- pv$

$d^2v/dx^2 + Mv = 0$

$where\ the\ general\ solution\ is\ v = C_1 sin(\sqrt{Px/EI}) + C_2 cos(\sqrt{Px/EI})$

$and\ boundary\ conditions\ are\ v = 0\ at\ x = 0\ and\ x = L,\ thus\ C_2 = 0$

$v = C_1 sin(\sqrt{Px/EI}),\ and\ C_1 \neq 0$

$sin(\sqrt{PL/EI}) = 0 \rightarrow sin(\sqrt{PL/EI}) = n\pi$

Thus $v = C_1 sin(\pi nx/L)$.Unfortunately, the constant C_1 is mathematically undefined.

The vertical column supports are braced in many areas, and will not deflect as dramatically as the simple case. FEA analysis also supports this statement and does not show significant deflection on any of the four corners. Later hand calculations are validated (by a similar order of magnitude) by FEA, so it is reasonable to assume that the analysis is accurate in its deflection prediction for these members.

For the horizontal, roof pipe:

This member is of significant concern, as early FEA and hand calculations indicated that it might be a failure point. The member in its current design is supported by two arches on each end, two 45 degree posts, and one center arch with extra bracing. There are 5 supports total.

The 1000 pound load is assumed to be distributed evenly over the horizontal member for a load of 8.33 pounds per inch. Tributary areas were calculated concerning length, to find the support force from the 5 supports. See the Appendix G for a visual.
The 45-degree members were calculated to touch the member at 20.68 inches from each end ($29.25 sin(45) = 20.68, \ where \ 29.25 \ inches \ is \ the \ member \ length$).

$F_{arch+diagonal} = 39.32 * 8.33 = 327.64 \ pounds$

$F_{arch} = 0.5 * 20.68 * 8.33 = 86.17 \ pounds$

$F_{45} = 0.5 * (20.68 + 39.32) * 8.33 = 249.99 \ pounds$

With these support force values, shear and moment diagrams were created. See Appendix G.
Deflection for this member was modeled as a superposition of the beam with the distributed load and three supports along the span.

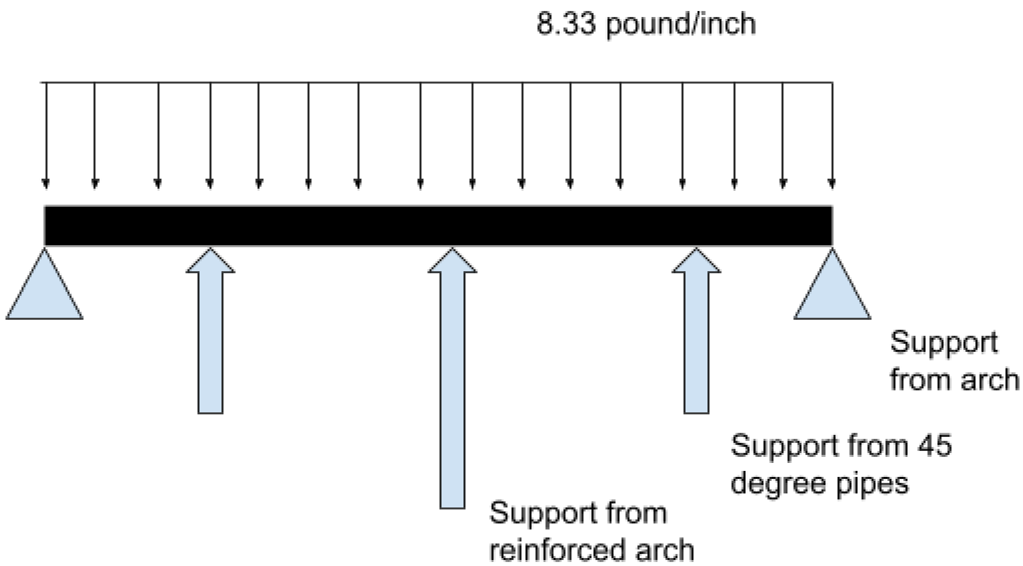


Figure P-1: Visualization of the load and its supports (supports along span were modeled as upward forces).

Deflection for the three cases is as follows:

$\delta_{distributed \ load} =- wx/24EI * (L^3 - 2Lx^2 + x^3)$where w is 8.33 pounds per inch

$\delta_{twin \ support} = Fx/6EI * (3aL - 3a^2 - x^2)$where F=249.99 pounds and a=20.68 inches for the range 0<x<a

$\delta_{twin \ support} = Fa/6EI * (3Lx - 3x^2 - a^2)$for the range a<x<L-a

$\delta_{center \ support} = Fx/48EI * (3L^2 - 4x^2)$for the range 0<x<L/2

For a sample calculation, just using the deflection caused by load and not considering upward deflection from supports, one can see that the PVC alone is weak. x=40.34 inches was chosen based on the moment diagram in Appendix G.

$- 8.333 * (40.34)/(481000 *.09769) * (120^3 - 2 * 120 * 40.34^2 + 40.34^3) =- 418 \ inches$

A larger value of E was used, in accordance with online material properties. The SolidWorks value for E gave a ridiculously large deflection, although this value is used along with the next step to find a composite E.

The deflection with rebar support was calculated and was plotted with Matlab.
As an aside, a new moment of inertia (using parallel axis theorem) and new modulus of elasticity (based on the ratio of areas) were used:
$E_{rebar} = 29732735.99\, psi,\ E_{PVC} = 870\, psi$
The area ratio of rebar and PVC gives a new modulus of elasticity, 1.2095E7 psi.
The moment of inertia was calculated to be 0.12836 quartic inches.

It is known that FEA gives a maximum deflection of 6-7 inches for the horizontal member. Hand calculations validate this order of magnitude.

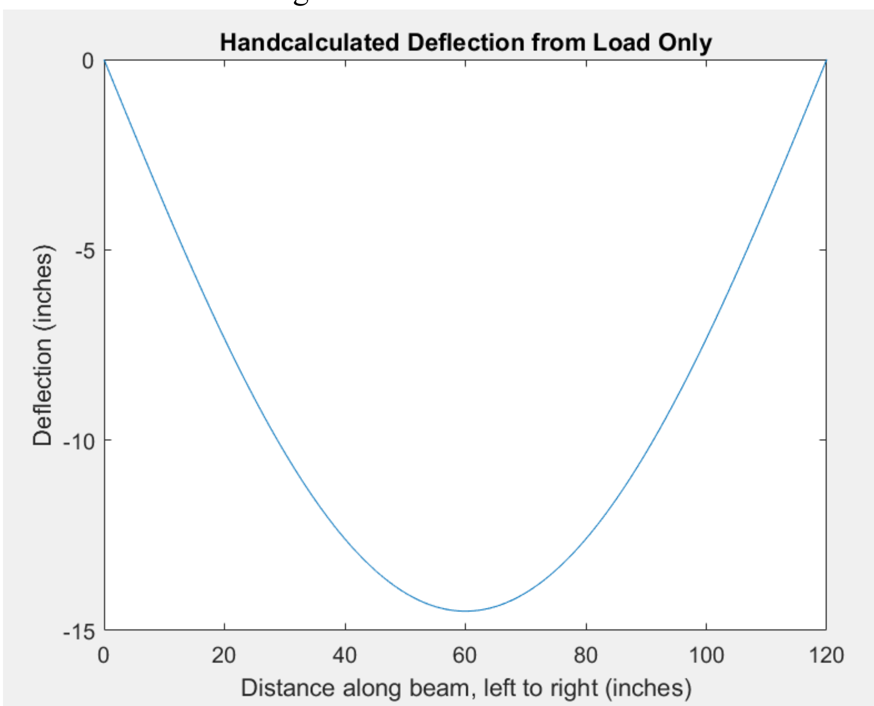


Figure P-2: Simply supported deflection.

In this Figure, the three extra supports in the middle are neglected to determine what the maximum deflection might be. 15 inches is of similar magnitude to the FEA 6-7 inches. Adding the supports via superposition improves the value of deflection, and creates a flattened parabola shape.

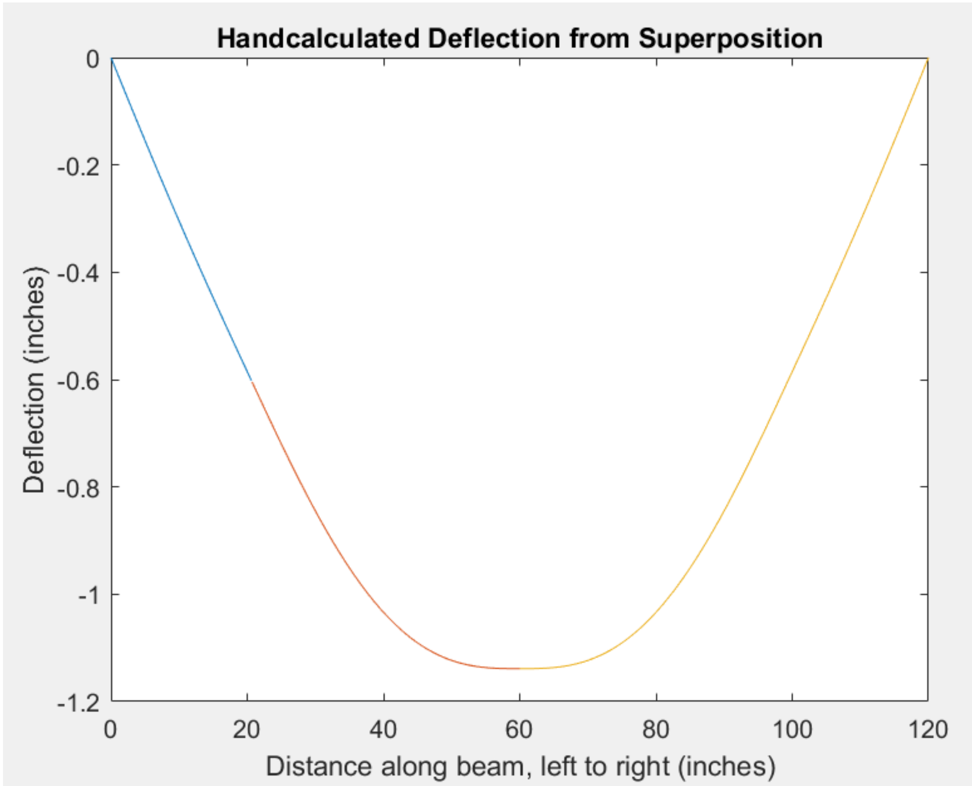


Figure P-3: Fully supported member.

In this Figure, one can see a more appropriate estimate of deflection. FEA still indicates a larger deflection than 1.2 inches, but this range is reasonable considering the unsupported maximum value is 15 inches (from the previous Figure).

Appendix R: Greenhouse Construction Progress Photos

Figure Q-1: First Wall with Vents

Figure Q-2: Two Vent Walls, Support Posts and Fittings Attached

Figure Q-3: Vent Walls Connected and Upright

Figure Q-4: Vertical and Horizontal Supports on Other Two Walls Added

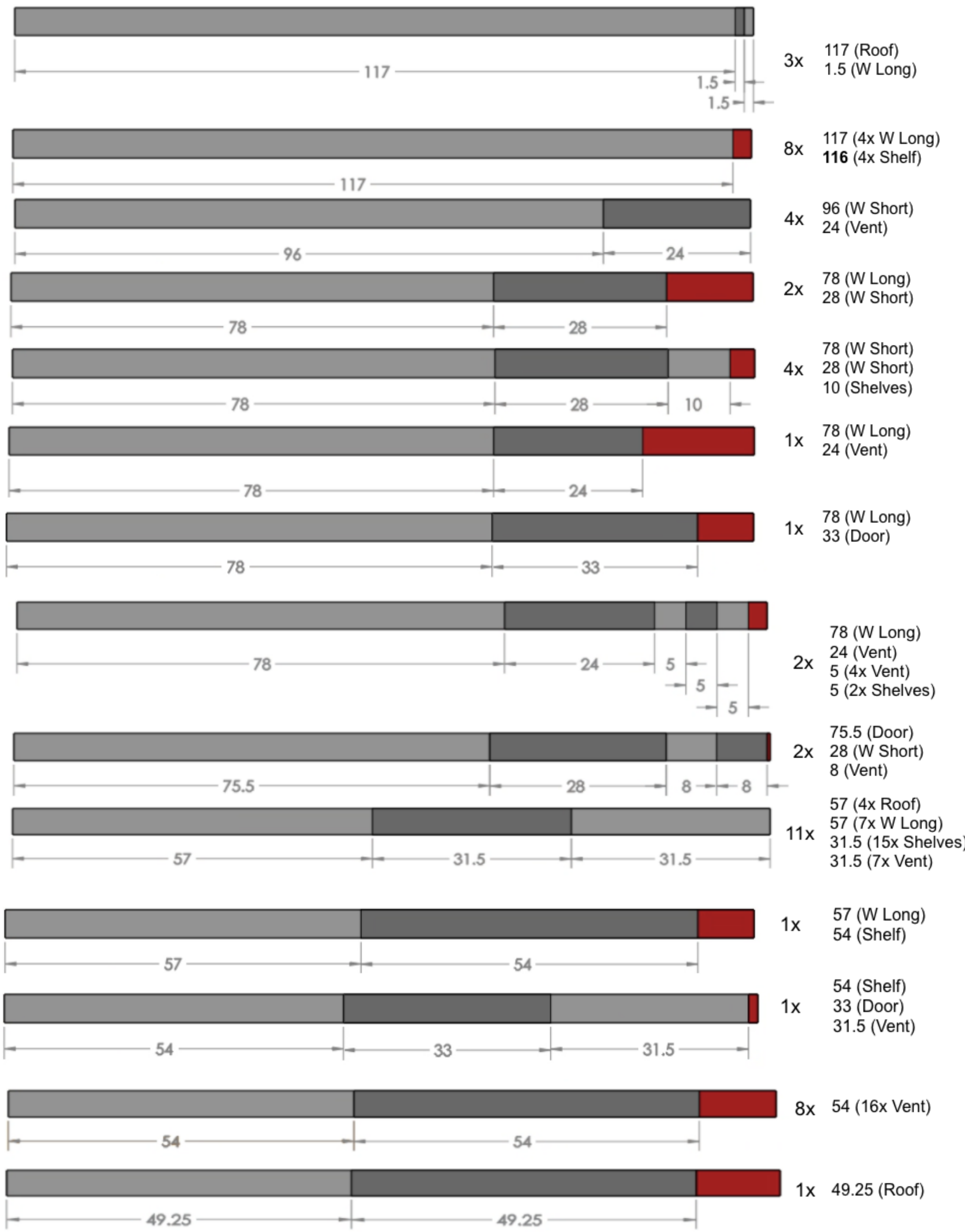
Figure Q-5: Greenhouse Turned Sideways, Domed Roof Beam Added (10’ length shown here)

Appendix S: PVC Cut List

*All measurements in inches

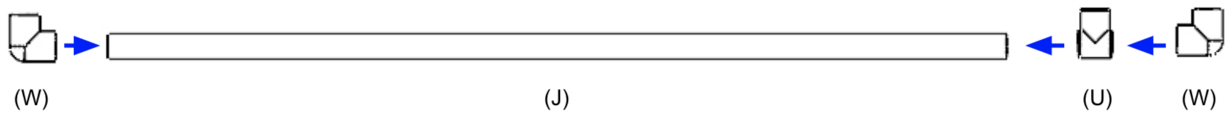
= Used

= Unused



Appendix T: Vent Construction Guide

1



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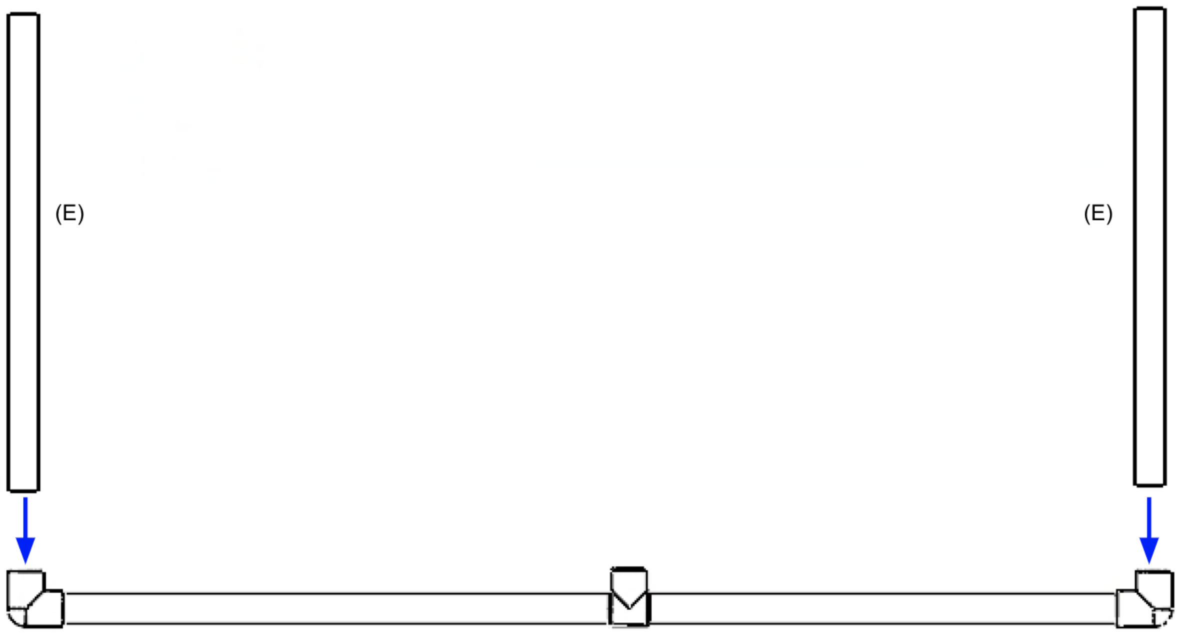

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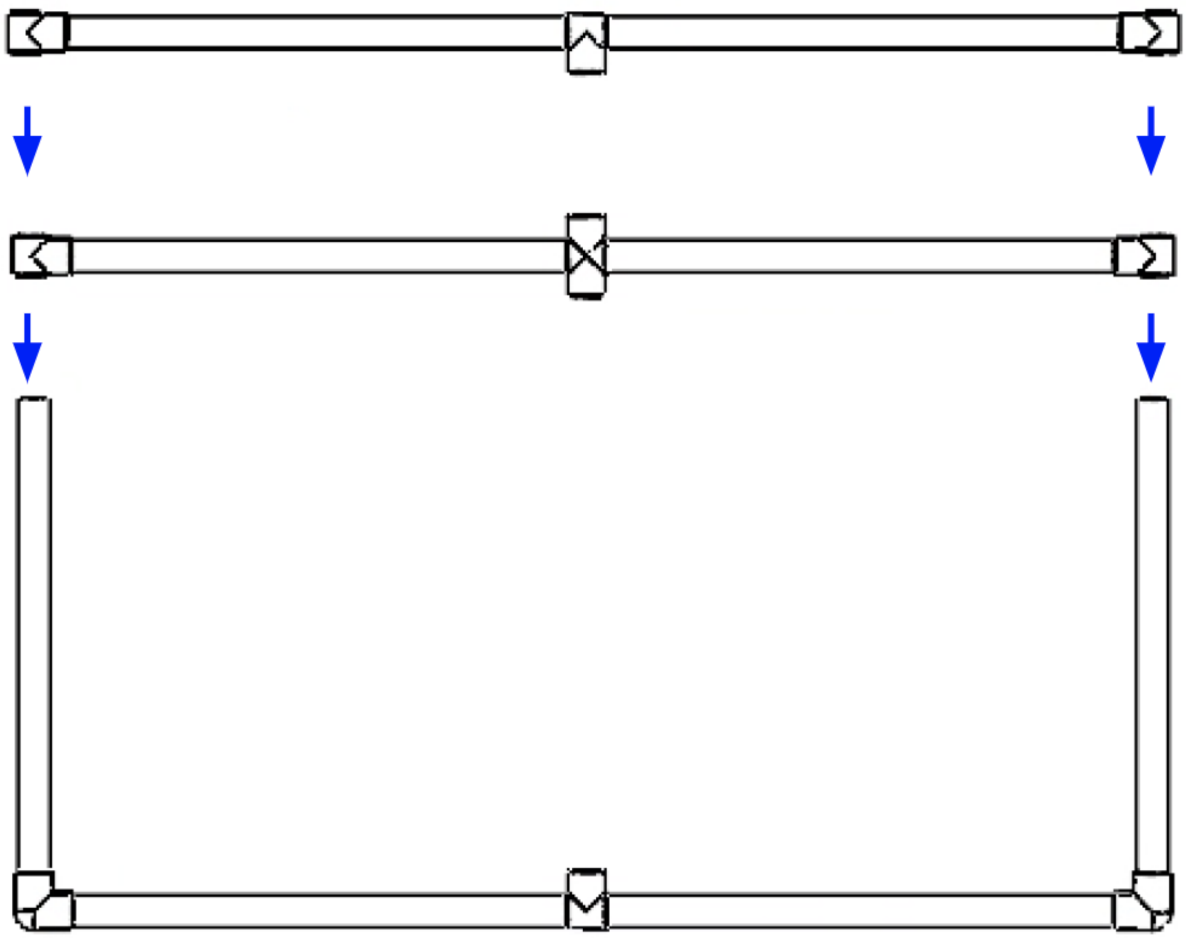

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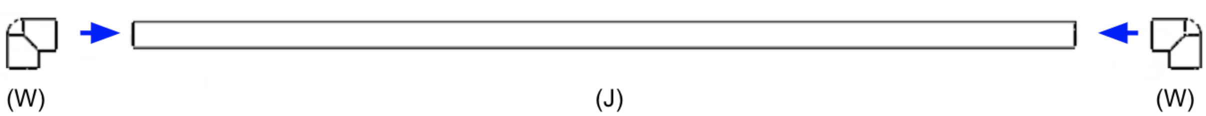

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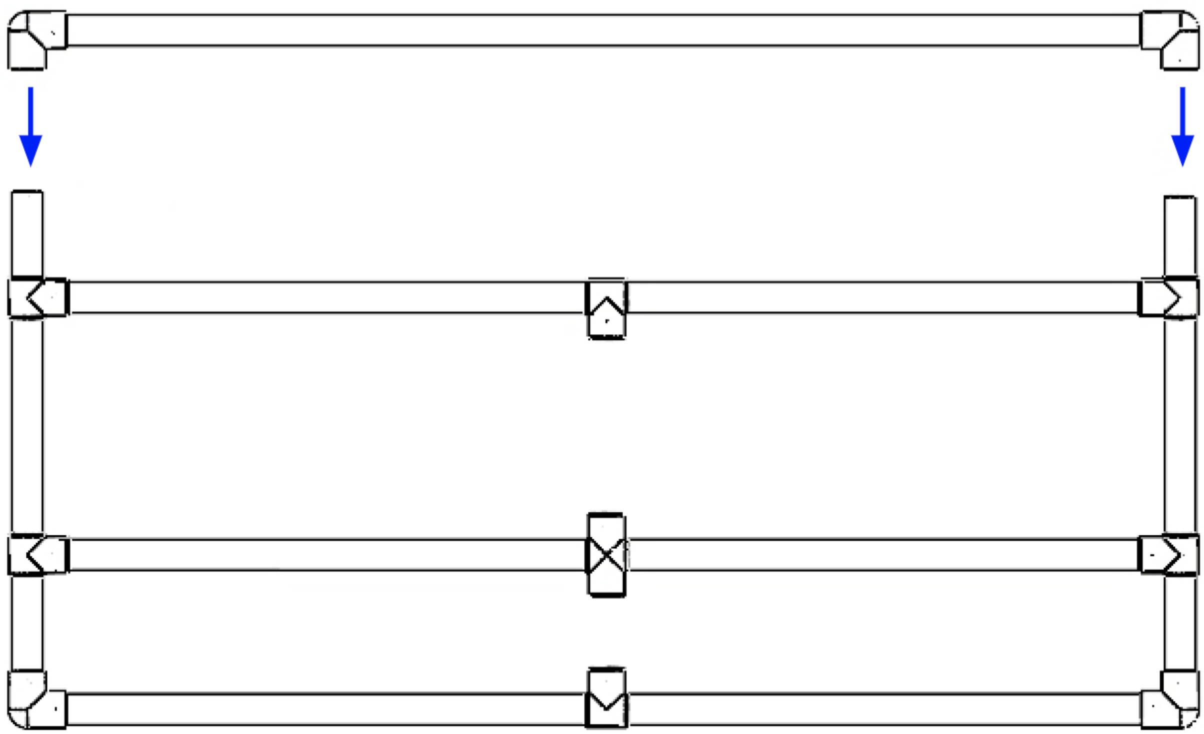

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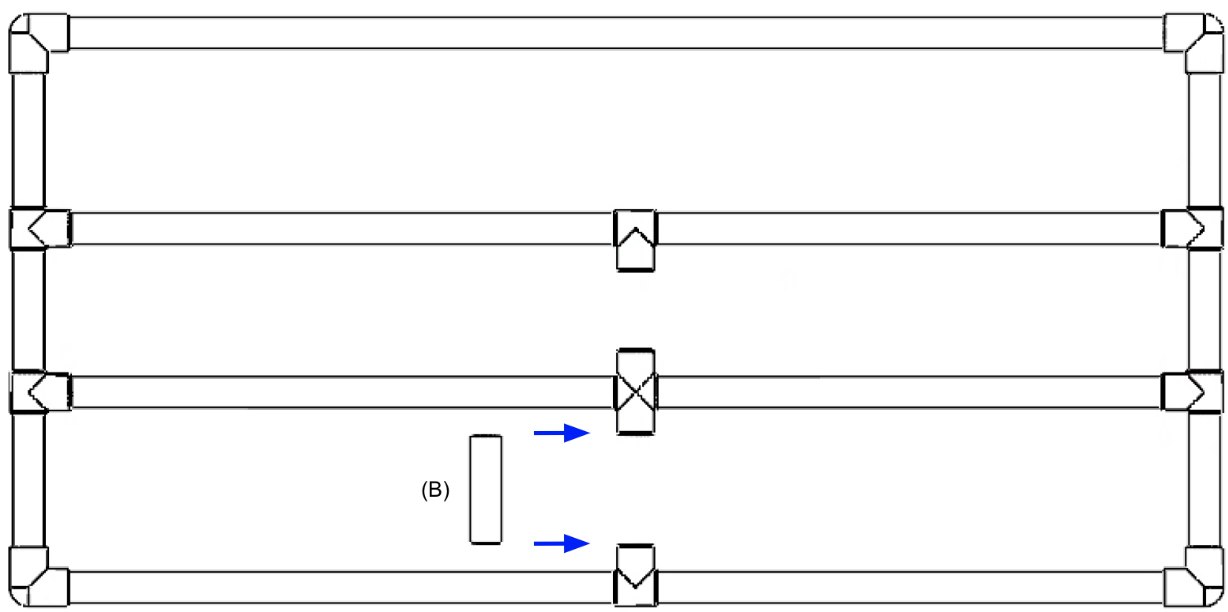

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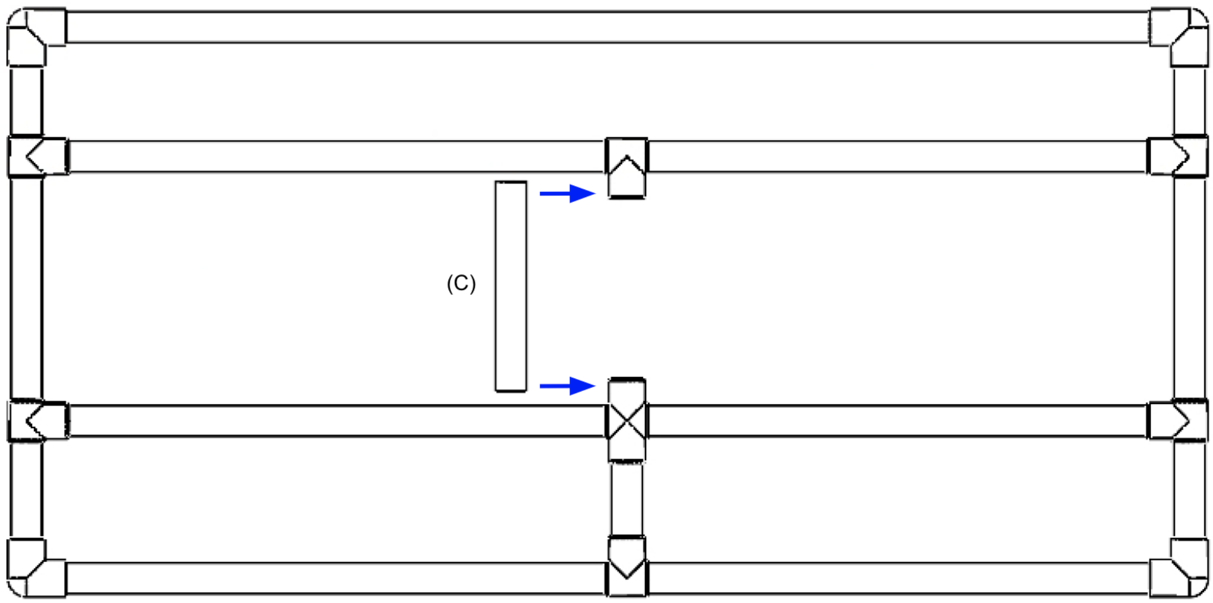

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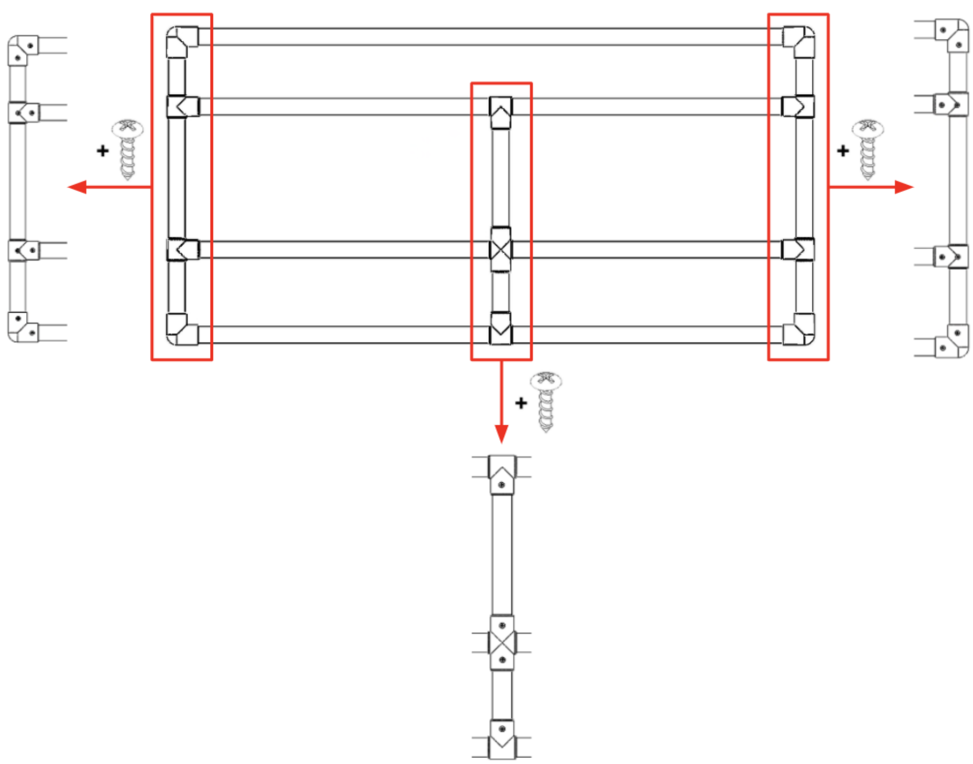

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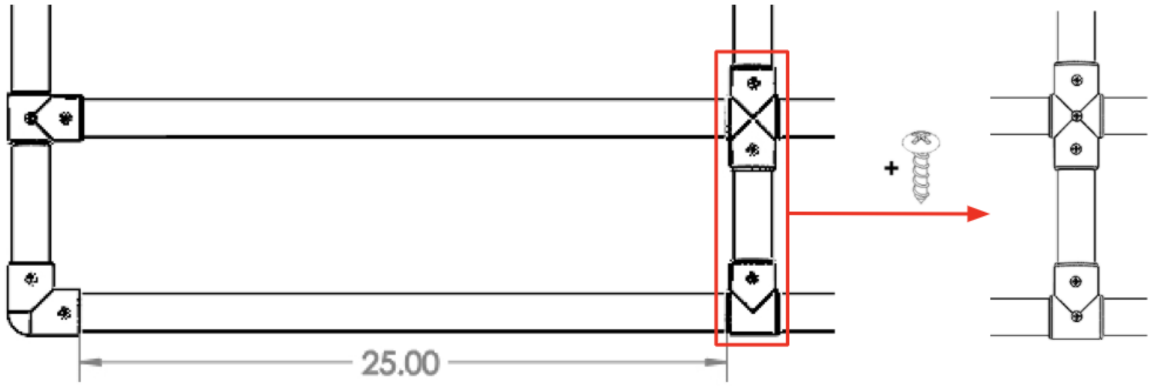

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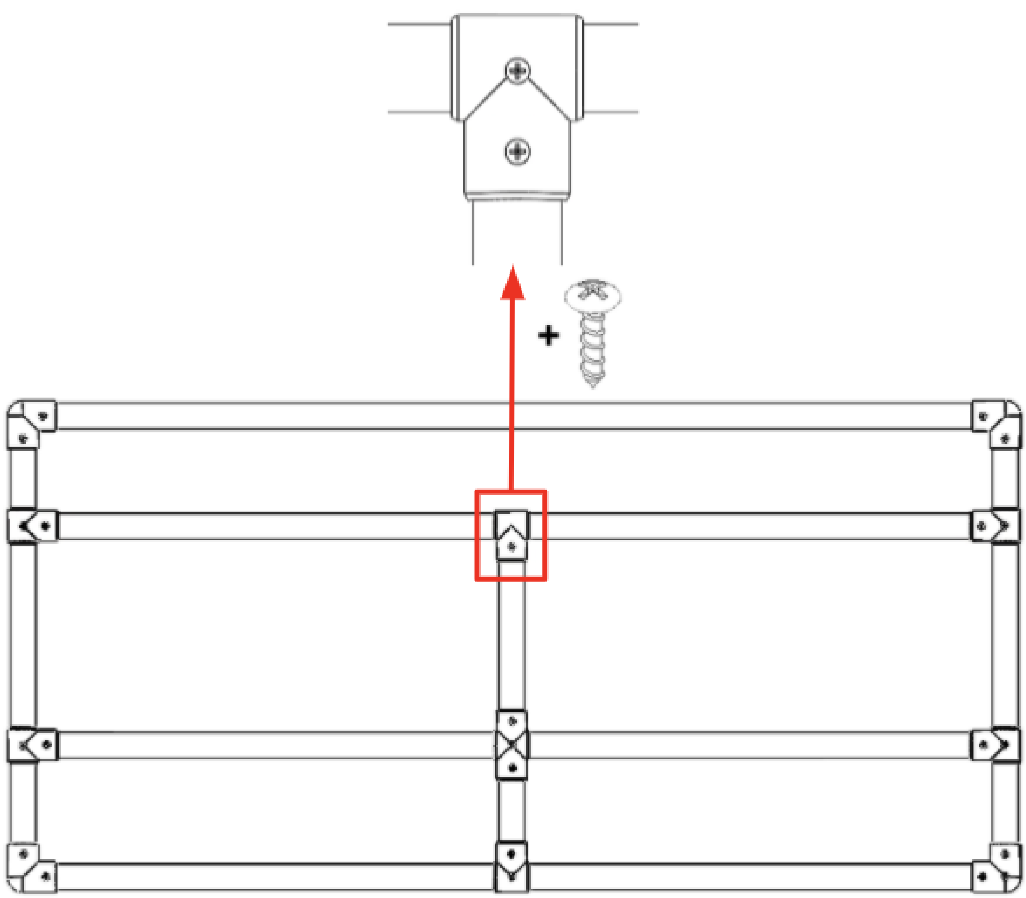

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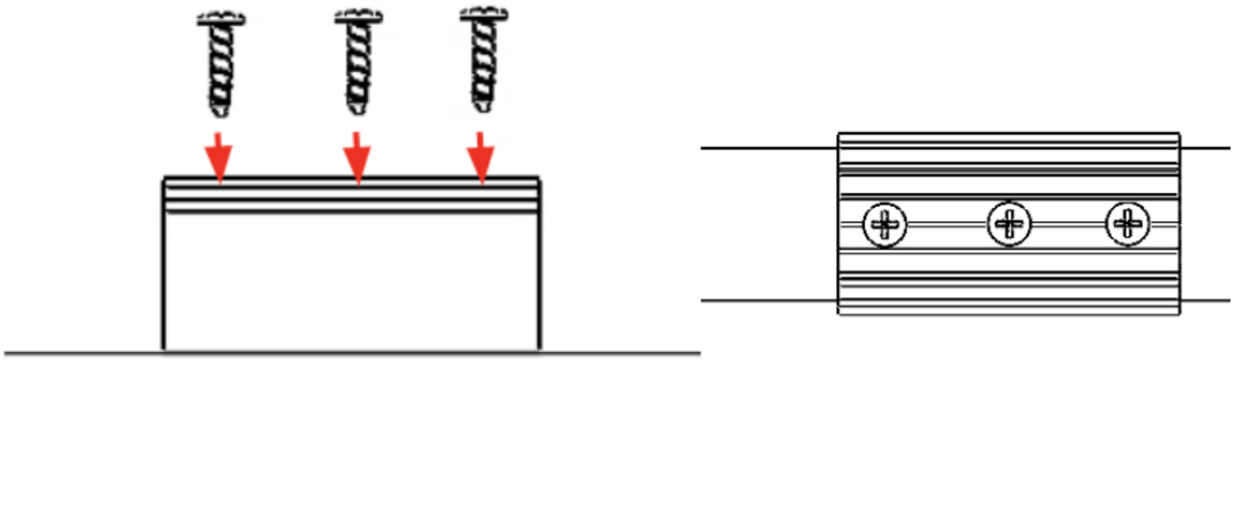

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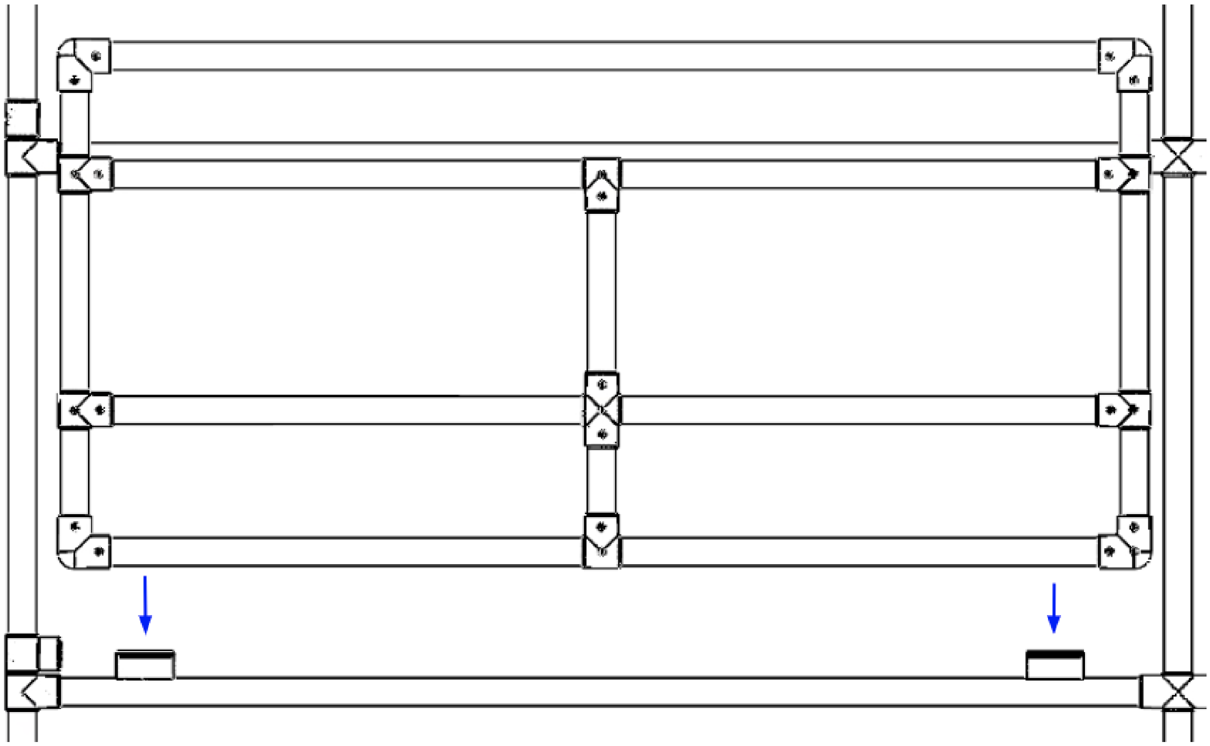

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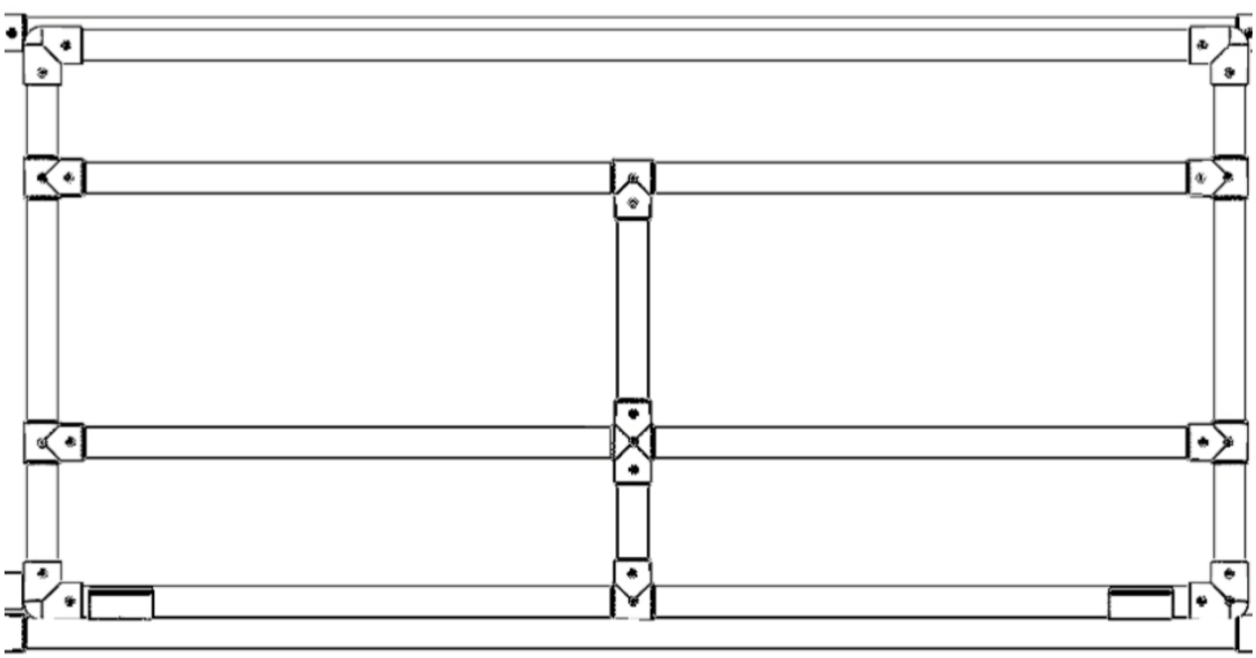


Student Project Hazard Assessment

A Hazard Assessment is designed to help students and project advisors recognize hazards associated with student projects at the early planning stages to find ways to minimize the chance of injury, loss, or harm while you are working on the project. This form is intended to be used for projects where the primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological focused projects require a separate project assessment form.

Each student project must complete a Hazard Assessment and must obtain the required approvals before proceeding with the project. It is important that all team members participate in the process, with close supervision of your advisor. To help ensure that hazards and risks associated with your project are not overlooked or underestimated, you are encouraged to contact any university staff (Lab Directors/Managers, EHS, etc.) with relevant knowledge or experience for guidance. However, your advisor and the department chair must approve this form prior to obtaining *formal* approvals from other relevant university staff.

The Hazard Assessment process usually involves these five steps below, with an example:

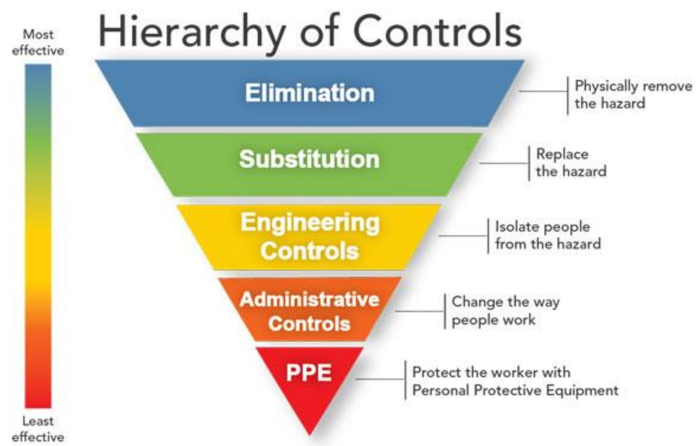
Step:	Example:
1. **Identify the specific tasks** that must be completed to reach your project goals	One of your project tasks involves testing a live electrical circuit
2. **Determine if there are hazards** associated with completing the tasks	On the form, you select the "Electrical parts and assemblies > 50V or high current", under the Hazardous Conditions/Processes/Activities, Electrical Hazard section
3. **Identify the risks** connected with the hazards of each task. Ask yourself, what could go wrong? If you are not already familiar with the risks, do a quick internet search	After some research, you learn that there is potential of electrical shock from accidental contact with exposed live components
4. **Develop a list of controls** (things you can do) to eliminate the hazard or reduce the risks. Refer to *Hierarchy of Controls* on the next page	To minimize the risk identified above, you could: ○ De-energize and isolate the system or ○ Guard live components to prevent accidental contact
5. **Create a safe working procedure**. Describe how you will safely complete each task	You write a detailed procedure for testing a live electrical wire, that includes all the information from your hazard/ risk assessment and which controls you will use to reduce the risks

Definitions:
A **Hazard** is something that has the potential to cause harm (injuries, accidents or other undesirable effects). Hazards can be eliminated but not reduced. A hazard can be in the form of an Agent, Condition, Process or Activity.
Risk is the likelihood (probability) of a hazard causing harm to people, property or the environment. Risks associated with a hazard can be reduced. Put another way, *Risk = Hazard x Exposure*
A **Hazard Assessment** is the process of identifying anything that can cause harm (hazardous agents, conditions, processes or activities).
A **Risk Assessment** is the process of determining how great the chance is of harm occurring from a given hazard.

Hierarchy of Controls

Unless the hazardous agent, condition or activity is removed, hazards cannot be eliminated. However, risks from the hazard can be minimized by employing the proper control measures and safe work practices that will have been identified from completing a hazard assessment.

Some controls are more effective than others at eliminating hazards or reducing risk. Use the hierarchy of controls chart below to evaluate the controls measures you plan to use. Priority should be given to the most effective controls at the top of the hierarchy (elimination and substitution) and moving down, rather than start with the easiest one. While personal protective equipment (PPE) should always be used, it should be considered the last line of defense from potential hazards.



Hierarchy of Controls		Description and Examples
Most Effective	Eliminate the Hazard	Use alternative work procedures
	Substitution	Use less hazardous material or process
	Engineering Controls	Isolate people from hazard using ventilation, barriers, lock-out, safer equipment and tools, etc.
	Administrative Controls	Change the way people work: rules, warning signs, training, alarms, safe working procedures, etc.
Least Effective	Personal Protective Equipment (PPE)	Appropriate clothing and footwear, safety glasses/goggles, lab coat, welding mask, face shield, ear plugs, etc. Best if used in combination with engineering controls

Student Project Hazard Assessment Form

This form is to be used for student projects where the primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological focused projects require a separate form. Complete this form and obtain all the required approvals (Faculty Advisor, Department Chair, Laboratory Manager, EH&S, etc.) before proceeding with the project. Please refer to the hazard assessment guide for assistance in filling this form.

Project Title: Frugal Urban Greenhouse

Project Team Members:
Alexandra Rivera, Emma Rosicky,
Connor Pearson

Project Advisor

Name:	Department:	Phone:	Email:
Godfrey Mungal	Mechanical Engineering		Mgmungal@scu.edu

Proposed Project Location(s) (Department, building, room#):
Mechanical Engineering – The Garage

Anticipated Dates of Project Duration:
12/1 – 6/1

Summary of Project Objectives:

The engineering senior design team ("the CAEL team") has partnered with the Frugal Innovation Hub (FIH) and local nonprofit 501(c)(3) Valley Verde (VV) to create a frugal urban greenhouse design. The vision with this project is to benefit an existing humanitarian cause, which supports the local community while also continuing to build upon the CAEL team's engineering skills. We are guided by the core values of active learning, engagement with others, and awareness of local needs. With respect to the project vision and core values, the goal is to provide a comprehensive design, guide to usage, and working prototype of an urban greenhouse that is cheaper, lighter, and more fruitful than the existing design. Our Team and advisor are all mechanical engineers by discipline, and plan to create a unique and appropriate solution to the problem using knowledge learned over the course of undergraduate study (i.e. from Heat Transfer, Machine Design, and Fluid Dynamics).

Hazard Checklist (check all that apply)
Identify all the tasks that must be completed for your project. Carefully evaluate each task to determine if there are any associated hazards. After identifying the hazards of your project, you will be asked to assess the risk connected to each hazard and to identify control measures that will either eliminate the hazard or reduce the risk to an acceptable level. Safe work procedures for each step involving a known hazard will need to be developed.

HAZARDOUS CONDITIONS/PROCESSES/ACTIVITIES		
Electrical Hazards ☐Electrical parts and assemblies > 50V or high current ☒Batteries ☒Control Panels	**Mechanical Hazards** ☒Power tools and equipment ☐ Machine guarding/power transmission – gears, rotors, wheels, shafts, belt/chain drives, rotating parts, pinch points ☐Robotics ☒Sharp Objects ☒ Stored Energy (springs, gravity, pneumatic, hydraulic, pressure)	**Physical Hazards** ☐ Extreme temps (high temp fluids: water > 160 °F, steam, hot surfaces > 140 °F, cryogenic fluids ☐ Material handling of heavy objects ☒ Elevated heights (scaffolding, ladders, roofs, lifts, etc.) ☒ Overhead falling objects (cranes, hoists, drones, projectiles, etc.) ☐ Confined Spaces ☐Airborne Dusts ☐Bonding / Grounding ☐Electrostatic Discharge
Reaction Hazards ☐Explosive ☐Exothermic, with potential for fire, excessive heat, or runaway reaction ☐Endothermic, with potential for freezing solvents decreased solubility or heterogeneous mixtures ☐Gases Produced ☐Hazardous reaction intermediates/products ☐Hazardous side reactions	**Hazardous Processes** ☐Generation of air contaminants (gases, aerosols, or particulates) ☐Heating Chemicals ☐Large mass or volume ☐Pressure > Atmospheric ☐Pressure < Atmospheric ☐Scale-up of Reaction ☒Metal Fabrication (welding, cutting, drilling, etc.), Soldering, ☒Construction/Assembly, etc.	**Other Hazards** ☐Noise > 80 dBA ☐Vehicle traffic ☐Hazardous waste generation ☐Other (list):

Hazard Checklist (continued)

HAZARDOUS AGENTS			
Physical Hazards Of Chemicals	**Health Hazards of Chemicals**	**Non-Ionizing Radiation**	**Biohazards**
☐Compressed Gases ☐Cryogens ☐Explosives ☐Flammables ☐Oxidizers ☐Peroxides or Peroxides Formers ☐Pyrophorics ☐Water Reactives	☐Acute Toxicity ☐Carcinogens ☐Nanomaterials ☐Reproductive Toxins ☒Respiratory or Skin Sensitization ☐Simple Asphyxiant ☒Skin Corrosion/ Irritation ☐Hazards Not Otherwise Classified	☐Lasers ☐Magnetic Fields (e.g. NMR) ☐RF/Microwaves ☐UV Lamps	☐Bsl-2 Biological Agents ☐rDNA ☐Human Cells, Blood, BBP ☐Animal Work ☐Other (List):

Description of Potential Hazards

Provide a summary of the procedure and describe the risks associated with each hazard that you have identified above or on the previous page. Use one box below per hazard. You may add supplemental pages if needed. Define the hazard control measures that will be employed to minimize the risks based on the hierarchy of controls (elimination, substitution, engineering controls, administrative controls, PPE), and then describe specific control measures you will use (e.g. Work on system de-energized, receive hazard specific training, shield hot surfaces, guard pinch points, relieve stored energy, wear protective equipment, use less hazardous chemical, etc.). Refer to "Hierarchy of Controls" in the instructions sheet for more information to decide which hazard controls measures are most appropriate

Hazardous Activity, Process, Condition, or Agent (identified from previous page):
Summary of Procedure or Tasks: Cutting PVC pipe to length and assembling it
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Misuse of power tools could lead to injury May need to use ladders/scaffolding for assembly
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Go through shop training Wear proper PPE (Appropriate clothing, safety glasses) Avoid distractions while working (headphones, conversation, etc.) Create a fabrication plan before cutting the material

Hazardous Activity, Process, Condition, or Agent (identified from previous page):
Summary of Procedure or Tasks: Creation of a control system to moderate and automate watering in greenhouse
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Batteries and control panels could lead to things like shocks/fire
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Use low voltages in control system applications (5V or less) Use proper casings and procedures to protect electronics Only handle electronics in a dry environment

Hazardous Activity, Process, Condition, or Agent (identified from previous page):
Summary of Procedure or Tasks: Using adhesives to glue things together
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Fumes may be flammable or dangerous to breathe
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Read labels to be aware of potential hazards related with fumes Use appropriate PPE based on risks (gloves, goggles, appropriate clothing)

Hazardous Activity, Process, Condition, or Agent (identified from previous page):
Summary of Procedure or Tasks: Cutting or machining metals
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Cutting metals may throw chips or create sharp objects Machinery can cut or crush if not used properly
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Go through shop training Follow lab safety procedures Wear appropriate PPE (safety glasses, appropriate clothing)
Hazardous Activity, Process, Condition, or Agent (identified from previous page):
Summary of Procedure or Tasks: Water storage at an elevated level for greenhouse moisture regulation
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Creates a potential falling hazard with heavy materials

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
Perform calculations ahead of time to ensure supports are theoretically effective
Test apparatus with dry weight and slowly add weight to ensure structure maintains efficacy
Keep appropriate distance (10 ft) while testing loading apparatus

SAFETY EQUIPMENT and PPE
Select the appropriate PPE and safety supplies you will need for the project (Check all that apply)
☒ Appropriate street clothing (long pants, closed-toed shoes)
☒ Gloves; indicate type: Nitrile Rubber Gloves (Pending adhesive used)
☒ Safety glasses/ goggles
☐ Face shield and goggles
☐ Lab coat
☐ Hearing protection
☐ Fire extinguisher
☐ Eyewash/safety shower
☐ Spill kit
☐ Other (list):

TRAINING REQUIREMENTS
Identify the appropriate training (check all that apply) ☐ Biology & Bioengineering Lab Safety Camino Course – contact Lab Manager or EHS to enroll ☐ Chemistry & Biochemistry Lab Safety Camino Course – contact Lab Manager or EHS to enroll ☐ Electrical Safety for Engineering Camino Course – contact EHS to enroll ☐ LiPo Battery Safety Training – contact MAKER Lab to enroll ☐ Review of SDS for chemicals involved in project – access SDS library at: rms.unlv.edu/msds/ ☒ Laboratory Specific Training – contact Lab/Shop Owner ☒ Project Specific Training – contact Project Advisor ☐ Other (describe below):

ACKNOWLEDGEMENT

By signing, I verify that:

1) I am aware of the hazards and risks of all the tasks associated with the project
2) I have received, or will receive all the necessary safety training and/or have read the safety manual and safety data sheets (SDSs) relevant to the project before performing any hazardous tasks
3) I will follow all required safety precautions while working on this project, including but not limited to use of engineering controls, following safe work practices, and wearing appropriate personal protective equipment

Name of Project Team Member	Signature	Date
Connor Pearson	Emma Pearson	11/17/2020
Emma Rosicky	EmmaRosicky	11/17/2020
Alexandra Rivera	Alexandra Rivera	11/17/2020

APPROVALS		
This document must be reviewed and approved by the people below before any project work can begin. A copy of the approved document must be kept where the work is being conducted		
Faculty Advisor		
Name: Godfrey Mungal		
Department: Mechanical Engineering	Signature G. Mungal	Date 16-Nov-2020
Department Chair		
Name Drazen Fabris	Signature	Date
Laboratory Director/Manager		
Name Rod Broome	Signature	Date
EH&S		
Name	Signature	Date
Other		
Name	Signature	Date

Frugal Urban Greenhouse Conceptual Design Review

The "CAEL" Team

C. Pearson, A. Rivera, E. Rosicky, L. Swanson

Mission Statement & Partners

The project:

- Benefits existing humanitarian causes
- Supports our local community
- Builds upon our engineering skills

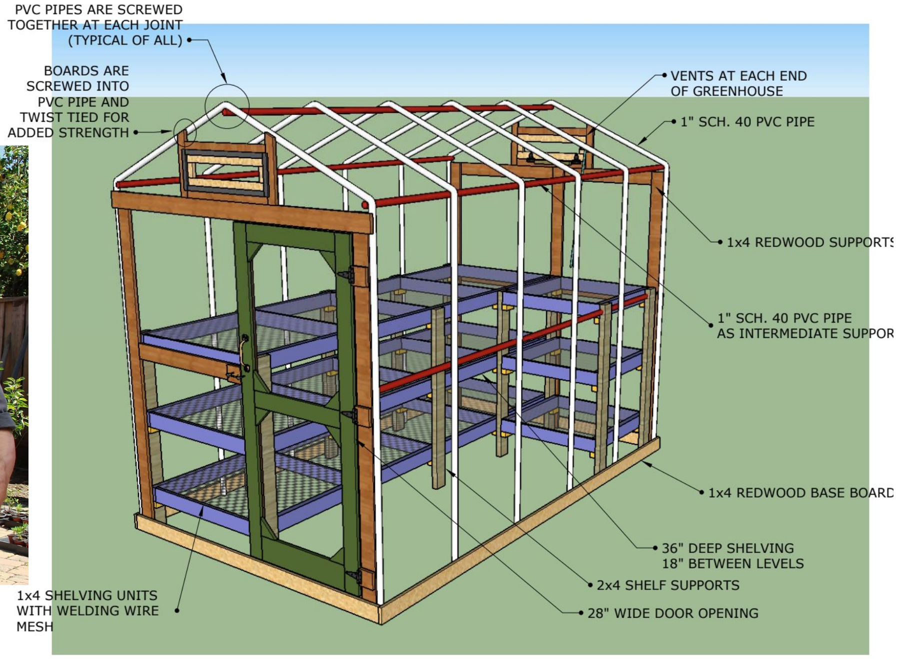
Core values:

- Active learning
- Engagement with others
- Awareness of local need

Frugal Innovation Hub, Santa Clara University School of Engineering

Valley Verde: Plant · Eat · Share

Background



Literature Review

Our sources fall into three categories:

- Previous similar senior engineering design projects
- Greenhouse specific research
- Integrated control systems

Market Research

Harbor Freight	Aluminum frame, UV-coated polycarbonate wall panels, Sliding door, Roof vents, Anodized finish	8 ft. 5 in.	6 ft. 3 in.	6 ft. 5 in.	74 lbs.	$399.99	
Gardeners Supply Company	Galvanized steel base, Aluminum frame, Magnetic swinging door, Gutters for rainwater collection, Optional shelving/plant hangers, Roof vent, UV-protected clear polycarbonate wall panels	4 ft.	6 ft. 3/4 in.	6 ft. 10-1/4 in.		$549	
Wayfair	Rollup zippered door, Plastic frame, Not weather resistant, Staked installation, Clear plastic cover, Adjustable shelves, Adjustable window vent	2 ft. 5 in.	4 ft. 8 in.	6 ft. 5 in.	15 lbs.	$64.99	
Eartheasy	Aluminum frame, Modular, Rigid plastic UV-protected paneling, Roof vent, Automatic vent operator available, Galvanized potting benches available, Gutters for rainwater collection	8 to 20 ft.	8 ft.	Apex: 8 ft. 6.5 in., Sidewall: 5 ft. 3 in.	146 lbs	$1,500	

Interviews / Customer Needs

Customer needs reports were conducted with greenhouse users like:

- Local businesses
- SCU students
- The Forge Garden

More inquiry is pending with VV greenhouse users and local farms.

1. Performance	2. Ease of Use/Ergonomics	3. Frugality	4. Monitoring/ Miscellaneous
1.1 Produces 500 seedlings per growing season	2.1 Lightweight and easy to assemble	3.1 Is low cost to build	4.1 Has effective ventilation
1.2 Has high crop yield rates	2.2 Eliminates redundant lifting/movement	3.2 Is low cost to maintain	4.2 Is able to heat or cool plants
1.3 Can be used year-round	2.3 Is low-tech and easy to operate	3.3 Keeps water and energy prices low (efficient)	4.3 Plants can be watered remotely
1.4 Can withstand wind/rain/snow etc.	2.4 Areas are at an appropriate height	3.4 Able to be repaired with local materials	4.4 Monitors temperature/humidity
1.5 Keeps out pests	2.5 Shelves are appropriate sizes for planters	3.5 Works easily with things available in peoples backyards	4.5 Is aesthetically pleasing
1.7 Made from inorganic materials	2.6 Door sizes make carrying plants/tools easier	3.6 Rainwater harvesting	
1.7 Made from inorganic materials	2.7 Reduces effort for hardening off* plants		
	2.8 Has a storage area		

Important Specifications

The following Product Design Specification (PDS) table:

- Gives qualitative & quantitative information
- Creates testable criteria
- Sets up targets

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PDS Chart

Elements		Requirements	
	Units	**Datum**	**Target Range**
Structure	US Customary Length (L x W x H)	10’-1 ½” x 6’-3 ¼” x 8’-¾”	8’ x 6’ x 8’
Weight (Dry)	Pounds	TBD. Qualitatively “heavy.”	75-100
Cost	Dollars	500	350-450
Seedling Yield	Units	400	500+
Shelf Strength	Pounds (to support)	150	200
Shadecloth	Percentage	80, 60, & 40	80, 60, & 40
Water	Liters/day	10	8
Life Span	Years	3	4-5
Indoor Temperature	Degrees Fahrenheit	75	75 ± 10
Outside Temperature Range	Degrees Fahrenheit	45 - 80	45-80
Rainfall	Avg. # Inches/year	16	16

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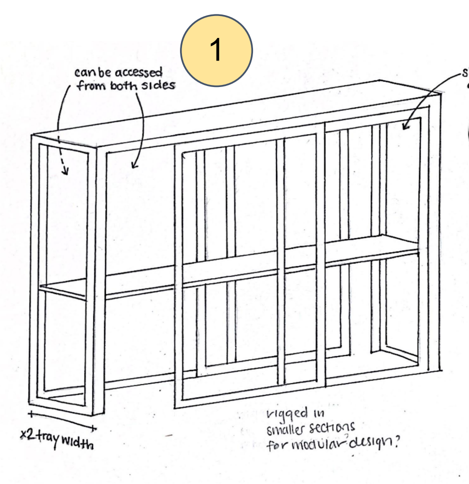
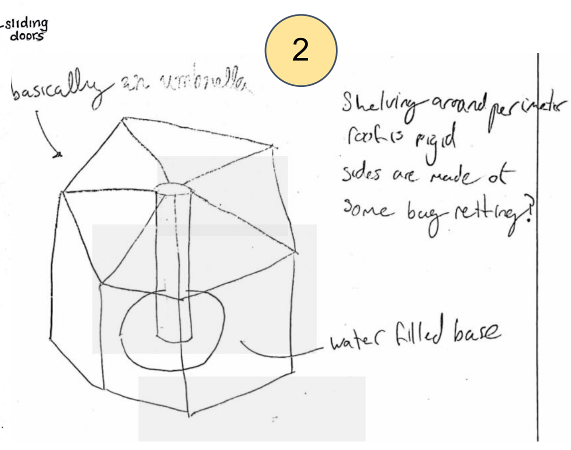
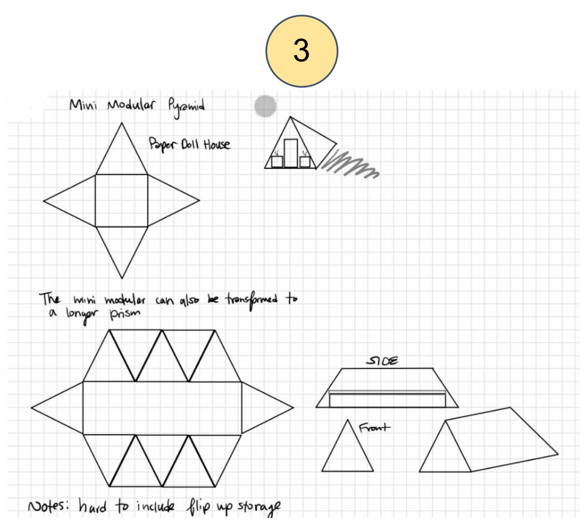
Brainstorming (1/5): Structural Shape







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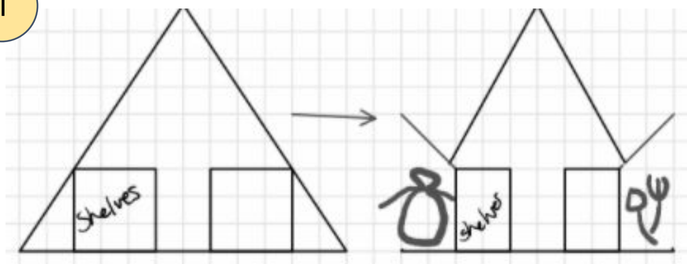
Brainstorming (2/5): Structure Elements

1



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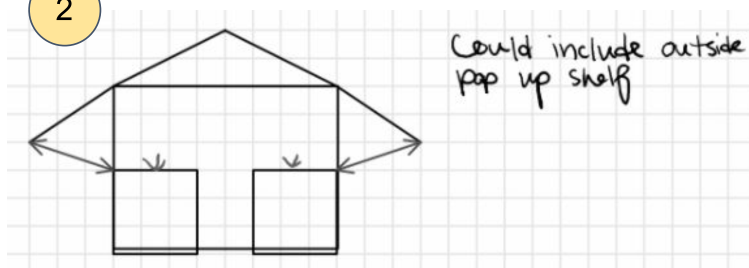

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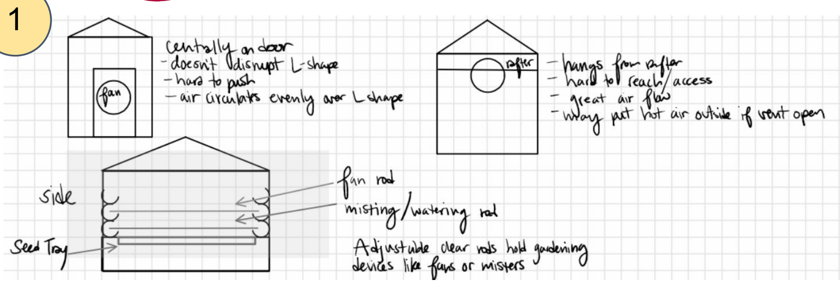
Brainstorming (3/5): Ventilation

1



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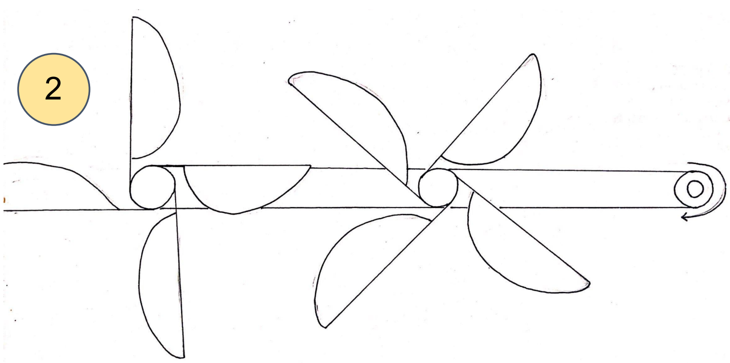

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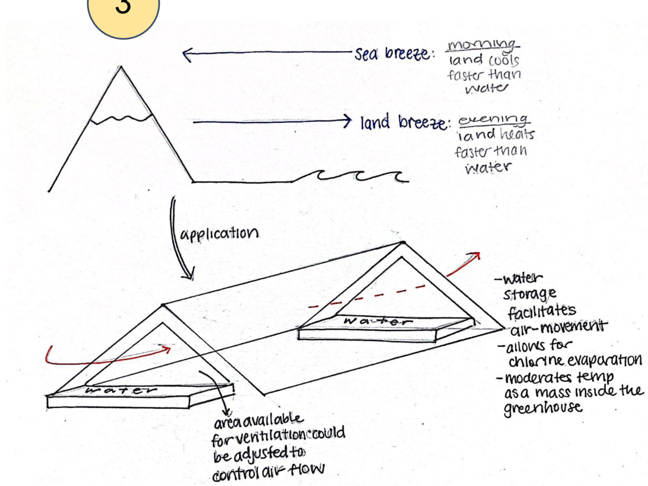

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Brainstorming (4/5): Water

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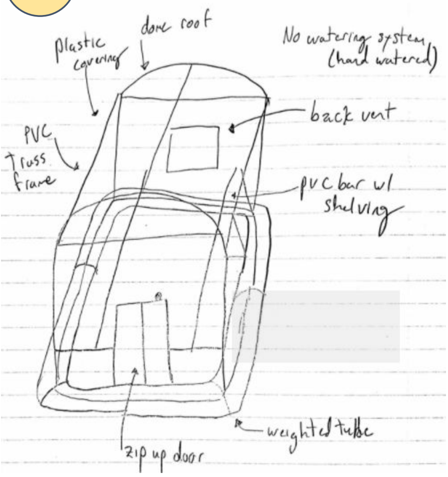

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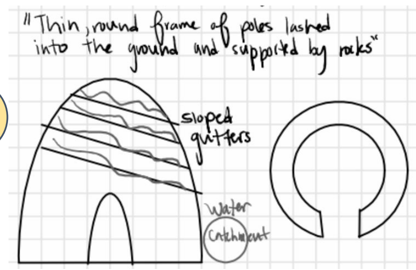

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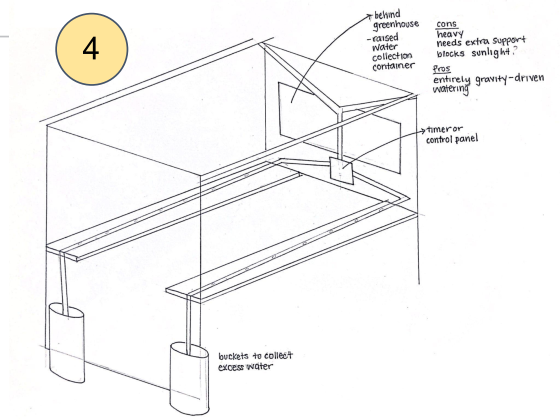

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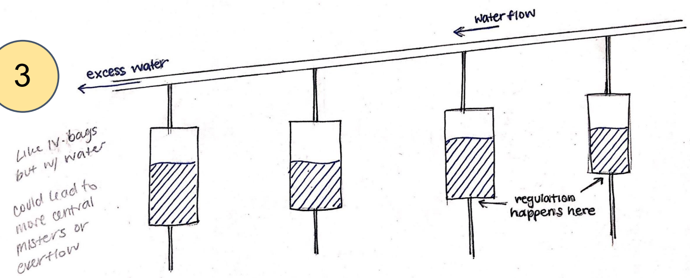

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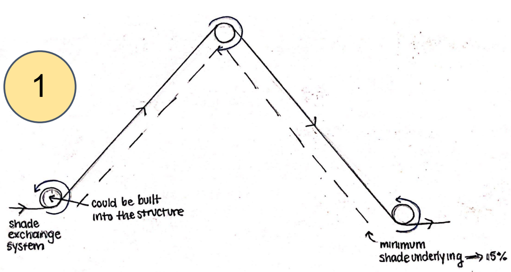
Brainstorming (5/5): Shade Cloth

1



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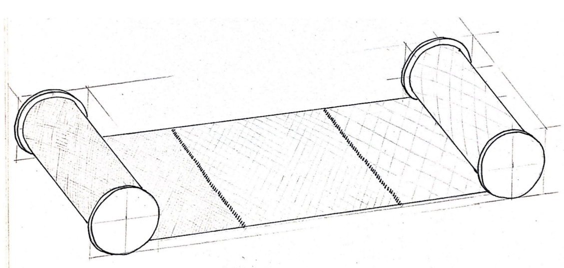

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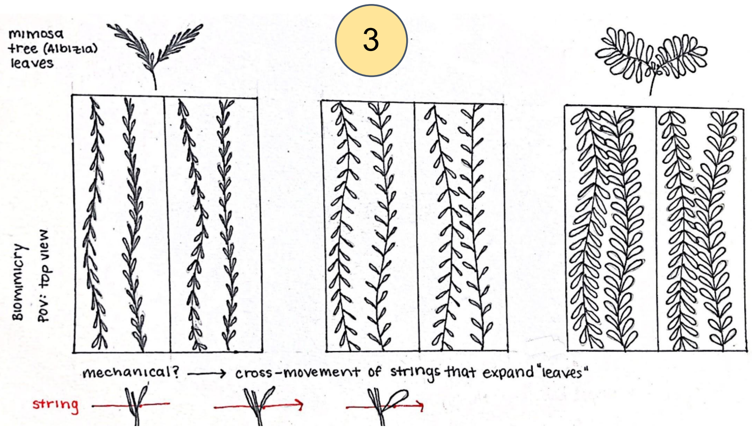


Weighted Criteria

Each criterion was weighed against the others, with emphasis on the factors:

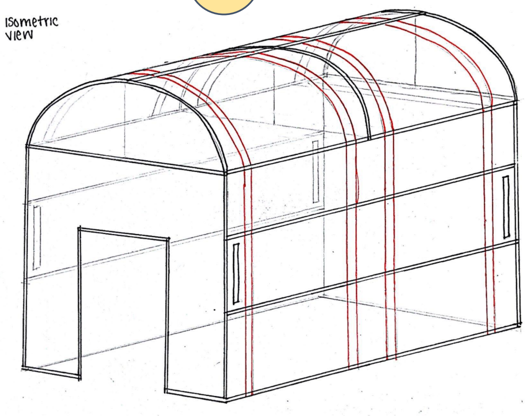
- **Temperature Regulation**
- **Moisture Regulation**
- **Air Circulation**

Sunlight was considered in the "Shading" criterion.

Criteria	Weight	Cost	Manufac	Temp R	Automa	Water E	Energy	Modular	Planting	Durabilit
Weight		0	0	0	1	0.5	1	1	0	0
Cost	1		0	0	1	1	1	1	0	0
Manufacturability	1	1		0	1	1	1	1	0	0
Temp Regulation	1	1	1		1	1	1	1	0.5	0.5
Automation	0	0	0	0		1	1	1	0	0
Water Efficient	0.5	0	0	0	0		1	1	0	0
Energy Efficient	0	0	0	0	0	0		0	0	0
Modularity	0	0	0	0	0	0	1		0	0
Planting Capacity	1	1	1	0.5	1	1	1	1		1
Durability	1	1	1	0.5	1	1	1	1	0	
Repairability	1	1	1	0	1	1	1	1	0.5	0
Moisture Regulation	1	1	1	0.5	0.5	1	1	1	0.5	0.5
Hardening Off	0	0	0	0	0	0	1	1	0	0
Storage space	0	0	0	0	0	0	1	0.5	0	0
Work space (Outside	0	0	0	0	0	0	1	0	0	0
Safety	1	1	1	1	1	1	1	1	1	1
Air Circulation	1	1	1	0.5	1	1	1	1	0.5	0.5

Final Design

1



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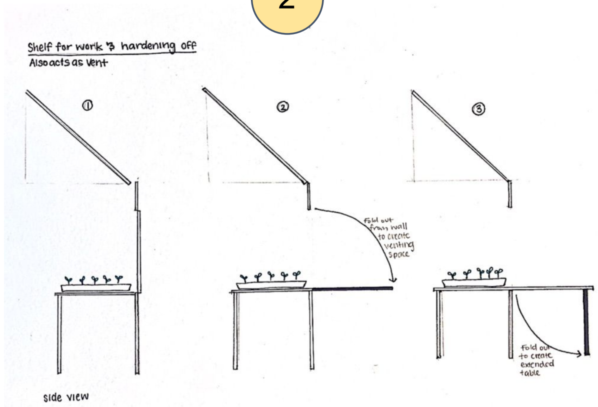

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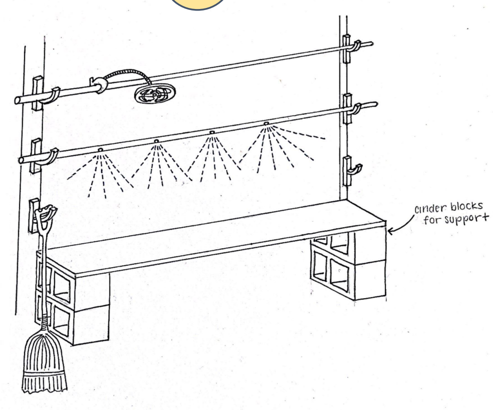

Shape and Shade Cloth | **Ventilation** | **Watering**

Future Plans

- **SolidWorks & FEA**
- **Material selection & structure design**
- **Moisture & watering testing**
- **Communication with Valley Verde**

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Conclusion

- Constant reiteration
- Maintain core values
- Stay creative
- Be open to advice

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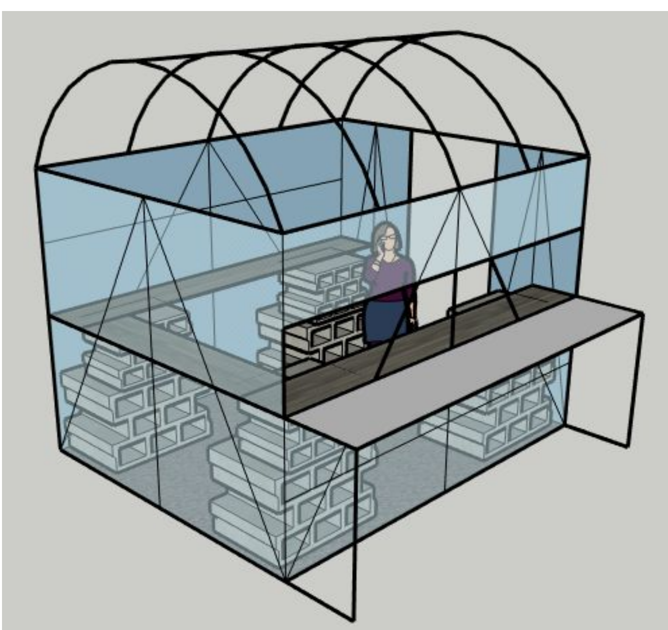
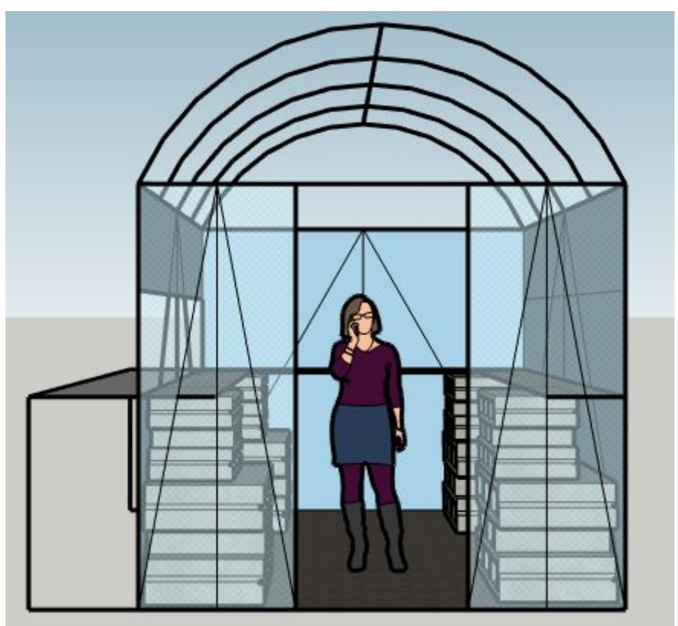
Appendix

Market Research (cont.)

Wayfair	Wood frame, Polycarbonate panels and roofing, Beautiful aesthetic, Safety glass windows, Plywood floring, Door with window and screen, Shelving included, UV-ray resistant	8 ft.	8 ft.	10 ft. 4 in.	1800 lbs.	$5,799.99	
Wish	Roman or Gothic arch styles available, Steel frame, Rollup door, Rollup windows, Spray-treated surface for rust/corrosion	11 ft. 9.6 in to 14 ft 9.6 in.	6 ft 10.8 in.	6.9 ft.	42.77 lbs. to 47.18 lbs.	$103	
Wayfair	Lean-to design, Sliding door, Aluminum frame, Frosted polycarbonate panels, Roof and door venting, 100% recycled content	6 ft.	4 ft.	7 ft. 3 in.	33.1 lbs.	$370	
Northern	Peak roof style, 4-tiered shelving, Steel mesh shelves, PVC covers, 15 minute snap assembly, Blocks UV rays, 5/16 in. steel frame, Rollup zippered door	5 ft. (dubious)	1 ft. 11 in.	4 ft. 8.37 in.	11 lbs.	$30	

3D Conceptual Modelling





Budget

Component	Justification	Cost ($)
Arduino Environmental Monitor Bundle	Create a baseline for the temperature, humidity, pressure, light, and UV levels.	50
Arduino Starter Kit	Necessary to integrate the Environmental Monitor Bundle into a full system.	92
¾ ” Diameter PVC Pipe	12 column support pipes at 6 feet high.	21
	12 roof support pipes at 4 feet length.	14
Shelf support braces	18 braces to make connections between pipe.	10
Slotted framing struts	4 struts at 10 feet length.	80
	4 struts at 6 feet height.	48
Flexible cover material	Comes in roll quantity, useful for multiple greenhouses.	191
Flat, corrugated metal sheets	Can be used for shelving and treated for rust. Multiple needed to hold minimum 22 seed trays.	220
Screen material	Necessary for door and any vents, to prevent insect entry.	21
Fans	Small, clippable fans for easy reconfiguration. Minimum 1 per seed tray, 22 total	308
⅝” Diameter flexible tubing	May be used in the misting system for cooling.	40
Miscellaneous fasteners	Estimated quantity to account for different needs.	100
Seed Trays	A few prototyping sample trays.	50
Soil	1 bag of soil for testing heat/humidity	15
Heating Mats	For regulating plant temperatures	230
Gravel/drainage rock	To stop plants from growing inside the greenhouse and make it easier to walk within (2 ft^3)	120
Subtotal		1663
+ *California Sales Tax*	Currently 7.25%.	135
Total		**1798**