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GraftThis: Modernizing Organic Farming

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ENTITLED

GraftThis: Modernizing Organic Farming

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

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GraftThis: Modernizing Organic Farming

By

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THESIS

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Abstract

Traditional plant characteristic improvement techniques are accompanied by certain disadvantages. Most notably, it takes several seasons in order to breed for favorable characteristics such as crop yield and disease resistance via deliberate selection. In order to expedite this improvement process, grafting - a method in which two separate plants with individual, desirable qualities are physically combined, may be used.

This report explores the development of a regulated environment as a solution to many of the problems associated with the grafting of plants during their recovery stage. The grafting chamber model necessitates: (1) an ability to maintain the specific temperature, humidity and ambient light necessary to produce healthy grafts, (2) ease of use including setup and operation, (3) system portability and an extended lifetime.

A review of scientific literature discussing the current state of typical grafting processes yields multiple requirements. The first of these requirements is a regulated environment that maintains a temperature between 72ºF and 85 ºF and a humidity between 85% and 95%. Also, the environment must be very dark and gradually increase to ambient conditions. The light, temperature, and humidity need to slowly taper to ambient conditions over the ten-day healing period in order to match the external environment. Due to the specificity of these conditions, grafting has historically been a labor-intensive process. Small-scale agricultural operations, those with less than 10,000 USD in annual sales, are impacted most severely by these constraints. The agricultural industry is often space-sensitive so collapsibility and portability are significant concerns.

Here, the proof of concept of a grafting chamber capable of satisfying the market need defined by the above, is developed and presented. Stages of the product design process are evaluated individually within the scope of the project

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1. Introduction

GraftThis, a project aimed to develop and produce a rapidly deployable grafting chamber, hopes to increase accessibility to the technology of grafting for small scale farms. Grafting allows farmers to combine a disease or drought resistant root-stock to a plant with a desired fruit. For example, heirloom tomatoes are not very resistant to common soil-borne diseases, therefore by grafting the top of the plant, also known as the scion, to a disease resistant root-stock the yield will be more robust.

After speaking with a local farmer from Santa Clara University's Forge Garden, the need for our project was uncovered. The farmer, Katharine Ronthaler, told us about a previous attempt to graft tomatoes. She attempted to graft 50 plants and only 4 of these attempts "took," or healed properly. Due to the labor intensive nature of grafting many farmers have this experience. The healing process can last for 10 days and currently requires immense attention and care. The humidity and temperature must stay within a specific range and taper to match environmental conditions over the 10 days. In Katharine's case, this meant checking on the plants daily to ensure the proper conditions [1].

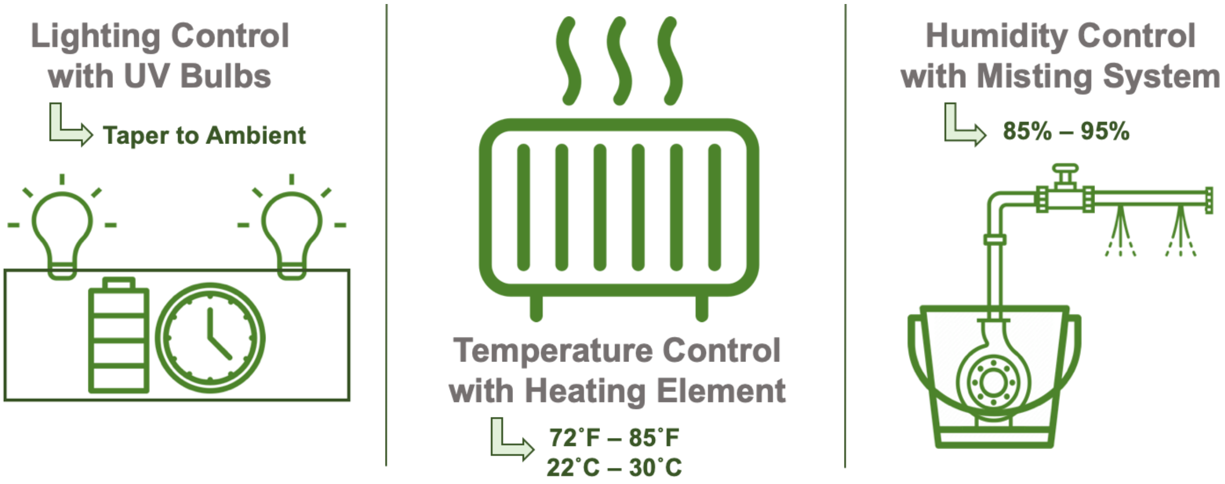


Figure 1. *General overview of grafting chamber expectations based on required environmental conditions.*

Project Objectives

Our goal is to demonstrate proof of concept for a self-regulating, rapidly deployable grafting chamber to be used in small-scale agricultural operations. Due to the worldwide pandemic, the hardware for our project consists of the working prototype that we developed over the first two quarters. We were able to make a lot of progress during those quarters and believe that the data collected is sufficient to show that our system works. One objective is to clearly show how our results provide proof of concept and how we would have continued with our project. Another objective is to prove that modern engineering methods are more effective than traditional agricultural methods. Traditional grafting methods rely on passive systems that are grounded in “guess and check” work, while modern engineering incorporates a predictive model that will control a heater, misting system, and light bulbs. A final objective is to thoroughly document all of the subsystems and processes within our project. This will allow a future user of the product to easily understand how to operate the grafting chamber and also allows the continuation of the project in the future.

Mission Statement

Our goal is to demonstrate proof of concept for a grafting chamber that is self-regulating and rapidly deployable that will help benefit our campus community. In doing so, we created the following mission for our team.

Mission Statement Breakdown	
Product Description	● A collapsible, self-regulating, reusable plant grafting chamber
Benefit Proposition	● Increased plant success rate ● Requires less manual attention than traditional methods ● Portable
Key Business Goals	● Product conceptualized in Fall 2019 ● Product prototyped and tested in Winter 2020 ● Product refinement and technical documentation in Spring 2020 ● Minimize individual unit cost and limit development cost to 2,000 USD
Primary Market	● Small scale agricultural operations (less than 10,000 USD in annual sales) ● Organic gardeners and farmers
Secondary Market	● Individual consumers and novice gardeners ● Nurseries ● Medium scale agricultural operations (less than 100,000 USD in annual sales)
Assumptions	● Self-regulating ● Humidity and temperature controlled ● Small footprint (less than 10 square feet)
Stakeholders	● User ● Plant purchaser (if grafts are sold by system owner)

The Grafting Process and Agricultural Explanation

Grafting is an ancient agricultural process that is used to combine favorable characteristics of two different plants. As seen in Figure 2, the two elements of a graft are the scion—the plant that has the fruit or flowers intended to be produced, and the rootstock—the plant with the root system that has characteristics to improve the scion. For example, during the Spring of 2019 the Forge Garden struggled with keeping their heirloom tomatoes alive because of a disease that was being spread throughout the garden. To combat this, the garden grafted an heirloom tomato scion with a disease resistant rootstock. Unfortunately, only a small fraction of the plants grafted actually bonded to one another. This shows just how difficult and sensitive conditions are in order to successfully graft two plants together.

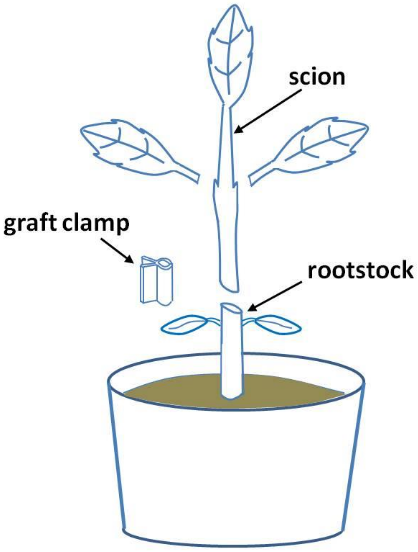


Figure 2. *Scion and rootstock diagram (reproduced without permission) [2].*

The process of grafting starts by having both the scion and rootstock seedlings reach a stem diameter of approximately 1.5-2mm [3]. It is important that both plants' stems are the same size for the chances of them taking to each other to be the greatest. Once they are at this stage, both plants are then cut at a 45 degree angle with a sterile cutting tool. Cutting at an angle as opposed to a straight cut is more effective in this process because it allows a greater surface area of both plants to be exposed to one another. Once both plants are cut, they need to be joined using a grafting clip and immediately moved to an enclosure with specific conditions in order for the plants to heal.

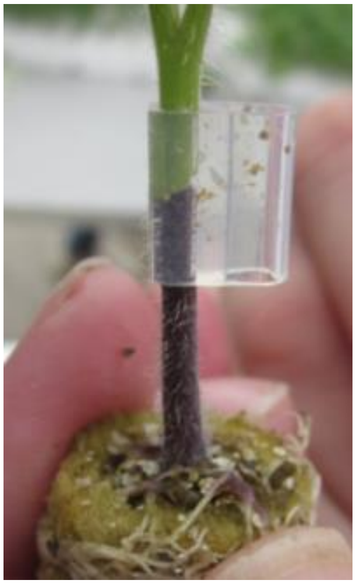


Figure 3. *Image of plant ready to be placed in grafting chamber (reproduced without permission) [4].*

If grafting a single plant, a plastic bag is commonly used to create a humid environment for the plant, but if multiple plants are being grafted then a larger enclosure needs to be constructed. The material needs to be opaque to block out sunlight as well as have the ability to retain moisture. Depending on what's being grafted, the plants can stay in the grafting chamber anywhere from 6-10 days. The beginning part of this healing period requires 85%-95% humidity and no sunlight [3]. This moist environment promotes bonding between the scion and rootstock. As time goes on, the humidity should be slowly decreased and exposure to sunlight should be increased. Once the healing period is complete, the successfully grafted plants should be immediately moved to where they will permanently reside.

Grafting plants is a very involved process for the grower. It requires frequent attention in order to adjust the environment's conditions based upon the progress of the graft. If the grower is not present for the entire week long healing period, then it is very difficult to produce successful grafts. This was part of the struggle for the Forge Garden. The person overseeing the grafting process was out of town for a couple of days and in that time, many of the grafts failed.

The goal for our project is to design a fully automated, portable grafting chamber. Equipped with a microcontroller, heating system, misting system and humidity and temperature sensors the chamber will automatically taper the chamber conditions to the ambient conditions as time goes on. The structure and all components will also be easily assembled and collapsed in order for it to be portable and storable. The final product will make the grafting process more feasible to the beginner gardeners as well as the gardener who doesn't have the time to constantly be checking the plants.

Existing Products

There is no current product on the market that is exactly like what we are designing, but there are a few products that are similar enough to compare. Most grafting chambers are designed and built by the gardeners and farmers who will be using them. Consequently, there is huge variation in size, shape, material, and technique used to maintain chamber conditions. One example that we chose to examine is a popular and standard method of a DIY grafting chamber that was created by the University of Florida. The second product on the market that we will compare our design against is the EcoQube, a small enclosure that creates constant environmental conditions for plants. These two products will be explained in greater detail in the following section in order to better understand why they are good market comparisons.

Neither of these products have the ability to fully automate the healing period of the grafting process. After some research, we did find a prototype of a fully automated grafting machine from Japan [5].

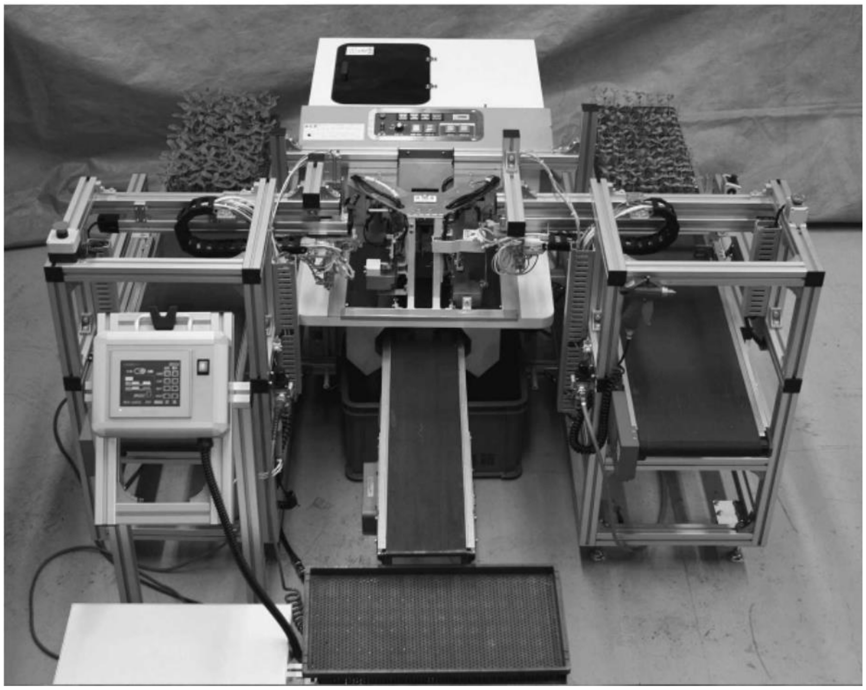


Figure 4. *Automated grafting robot (reproduced without permission) [5].*

However, this machine automates the preparation of the grafts instead of the healing period. It has the capability of creating 750 grafts per hour [5]. Existing grafting processes have a few different subsystems, which will be discussed below.

After delving into the grafting process, we found a useful scholarly article titled *Effect of Healing Chamber Design on the Survival of Grafted Eggplant, Tomato, and Watermelon* written by Sacha J. Johnson and Carol A. Miles. The article compares three different types of healing chambers. The first used shade cloth, plastic, and humidifier, the second used shade cloth and plastic, and the third only used shade cloth [6]. This study came to the conclusion that a humidifier was not necessary for the success of the plants throughout the healing period [6]. This helped us decide to not use a humidifier and instead go forward with a misting system.

Structure

A common problem associated with existing grafting chambers and "micro greenhouses" is their lack of portability. Portability is a desired trait given that grafting and other specialty processes are executed at select times of the year. As such, a collapsible chamber is favorable as it can be conveniently stored when not in use. This is particularly beneficial for gardeners who prefer to graft in larger greenhouses as valuable greenhouse space can be preserved by a collapsible structure. As many of these structures are built from repurposed materials in "do-it-yourself" fashion, they are often cumbersome. Figure 5 and Figure 6 illustrate two such home-made grafting chambers which are fixed in place [7].

Figure 5. *A grafting chamber built from a repurposed raised garden bed.*

Figure 6. *A home-made wooden* grafting *chamber.*

On the opposite end of the spectrum, “micro greenhouses” have recently emerged as popular consumer products. Often placed in homes, these small enclosures typically contain one or two plants which need specific conditions to survive. Figure 7 contains an example of a “micro greenhouse.”

Figure 7. *A table top “micro greenhouse” designed to house a single plant (reproduced without permission) [8].*

In this respect, “micro greenhouses” act as long-term microclimates for plants which would struggle to otherwise exist, whereas the larger grafting chambers shown in Figure 5 and Figure 6 temporarily nurture plants during a vulnerable stage.

While established grafting chambers such as those in Figure 5 and Figure 6 are capable of housing multiple plants they lack the portability associated with systems such as that of Figure 7. Conversely, “micro greenhouses,” which are more adept at mimicking specific environmental conditions are unable to house a sufficient number of plants to rationalize their cost outside of hobby use [9]. As such, there is a market opportunity for a rapidly-deployable and easily stored product which meets both of these criteria.

Given that physical structure dictates the ultimate dimensions and constitutes the majority of the volume occupied by grafting chambers, constructing a portable grafting chamber necessitates constructing a portable housing. As such, the frame and enclosure must be easily assembled, collapsible, water resistant, and durable. A potential solution lies in a structure based on separable parts, similar to a tent frame. Figure 8 and Figure 9 illustrate the various components of tent poles as well as assembled configurations.

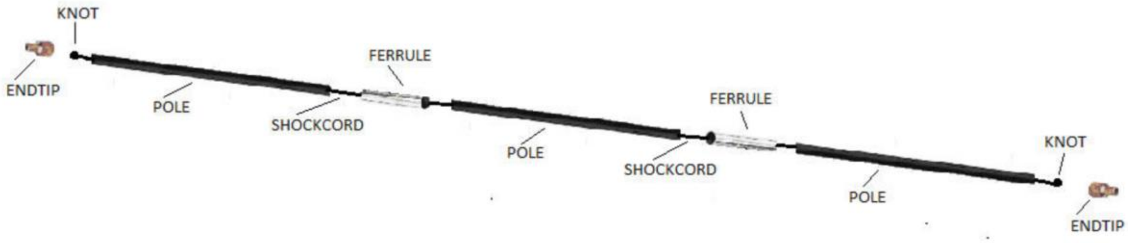


Figure 8. *Anatomy of a tent pole: using various components and orientations structures of almost any shape and size can be created (reproduced without permission) [10].*

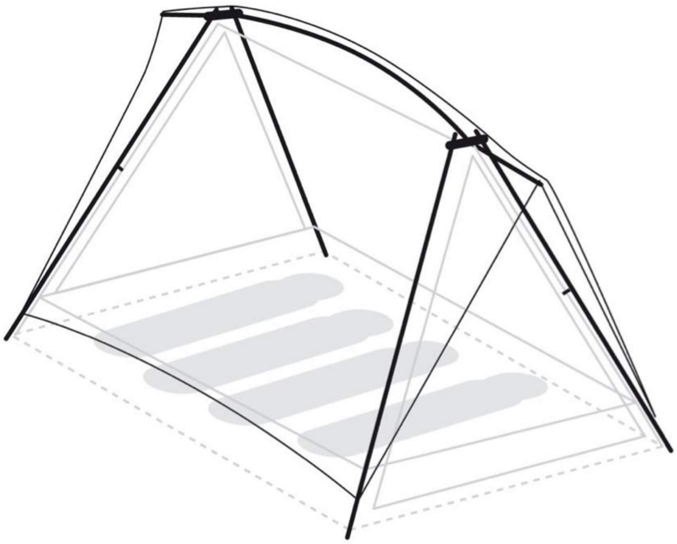


Figure 9. *Tent-frame structure constructed from individual tent poles.*

Tent poles are available as consumer products in predesigned kits, and also as individual components conducive to customization [11]. Consequently, such a structural system can be designed according to the available space and target number of plants to be housed. As a product built for repeated outdoor use, assembly, and disassembly, tent poles are rugged, durable, and waterproof [11]. Refer to Appendix B for further details on subsystems. Another potential solution is to construct the enclosure using PVC pipes because they are easy to assemble and take apart. PVC pipes are also very sturdy and can easily be stored when not in use.

Humidity, Temperature and Light Exposure

As mentioned before, one of the most important parts of the grafting process is creating the proper environment for the grafts to survive. This requires very high humidity, minimal light exposure, and proper temperature at the beginning of the process and then the grafts are slowly exposed to more sunlight and less humidity as the process goes on. Creating the right environment for the graft can be very hard because it requires lots of maintenance. This is sometimes the reason that some growers do not graft their own plants. We hope to ease the process by automating the humidity and temperature control and potentially light exposure using a microcontroller, humidifier, and humidity and temperature sensors. This will hopefully give growers what they need to successfully graft plants which will allow them to choose their own scion and rootstock for the process and oversee the whole growing of their plants rather than having someone else do the grafting process [12].

One of the current methods of creating a high humidity environment within the grafting chamber is by filling the bottom layer of the chamber with a layer of water which will increase the humidity when the chamber is closed. Other chambers use humidifiers like the one in Figure 10 [13].

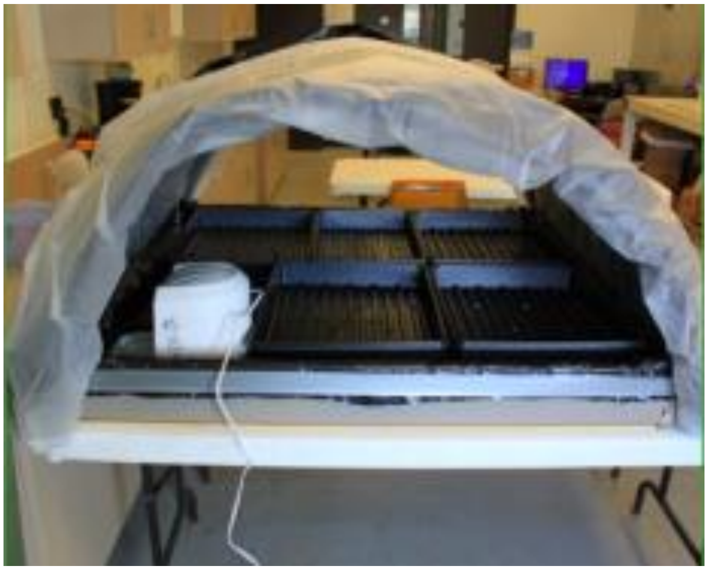


Figure 10. *Grafting chamber that uses a 1.3 gallon tabletop humidifier to keep the conditions for the healing process optimal.*

While these are both viable options, we decided to control the humidity in the chamber with a misting system. Having a misting system will be an easy way to quickly provide moisture to the grafts. We were able to control our misting system using a microcontroller and an electronic valve.

The next step to automating the environment of the grafting chamber was to monitor the humidity inside of the chamber. Soil moisture sensors already exist and we explored the possibility of using them to monitor the humidity conditions inside the chamber or if a DHT humidity and temperature sensor would work better. In the end, we decided that the soil moisture is not as important because the part of the graft that will be healing is exposed to the chamber conditions, not the soil conditions. To measure the chamber conditions, we used DHT sensors that also have an operating range that is easy to work with. To control the temperature of the chamber we planned to compare a heating pad and a space heater. By performing a thermal analysis, we came to the conclusion that a space heater would better suit our needs.

To control light exposure, current grafting chambers make use of opaque fabric that blocks out the sun and over time they reduce the number of layers that they put on top of the chamber. To automate the tapering of sunlight exposure, we decided to use UV light bulbs and an AC light dimmer to gradually expose the grafts to light.

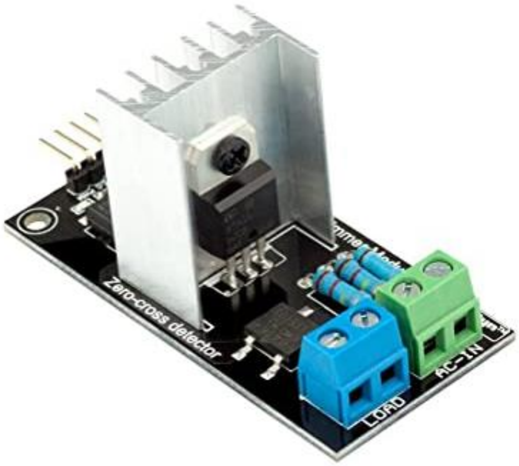


Figure 11. *AC Light Dimmer used to gradually expose plants to light using UV light bulbs (reproduced without permission) [14].*

2. Grafting Chamber - System Level Explanation

The following section will give a brief overview of our design process. We will address the customer needs and product specifications of our project. We will also outline other aspects of our design process, including a system level sketch, user scenario, functional decomposition, concept selection, and design evaluations.

Customer Needs

As the pilot location for the grafting chamber, the Forge Garden at Santa Clara University is an example of the product's primary market. The Forge Garden is a "half-acre edible, organic garden" which has a 400 square foot greenhouse and approximately 15,000 square feet of garden beds [15]. We sat down with Katharine Rondthaler, who has been the Forge Garden Manager since 2015, to better understand the scope and particulars of grafting at the Forge Garden.

Katharine began by explaining that the Forge Garden attempted grafting in the spring of 2019 using a hand-made chamber composed of three Rubbermaid bins and a personal humidifier; however, the process was largely unsuccessful with less than 10% return [1]. She attributed these results to the specific environmental conditions required to facilitate the healing of the grafted seedling. In order to ensure future success, she laid out multiple guidelines for the grafting process. These included requirements for misting, temperature, humidity, and light level. The specific needs she mentioned will be discussed further in the Product Specification section.

In addition to the functional aspects of the system, Katharine also included that "about 32" plants are desired per grafting cycle and that the seedlings are typically contained in 4 inch by 4 inch plastic pots [1]. Furthermore, the element of space merited additional consideration as Katharine mentioned that "I don't want something so big that it is taking up space [in the greenhouse]" [1].

The interview concluded with further acknowledgement of the difficulty associated with grafting as Katharine included that grafted plants are a valuable commodity. As the process is often involved, “people pay a lot of money for grafted tomatoes and cucumbers” and “[grafted plants] are really good money generators” [1].

Another potential customer that we interviewed is also a hobbyist farmer, her name is Michelle Sims from Monterey, CA. Michelle’s knowledge of farming comes mostly from the internet and from trial and error. She is very interested in creating a grafting chamber because she loves the idea of not using pesticides, but the reason why she does not go through with it is because it requires a lot of maintenance. She also does not want to go through the hassle of buying all the materials and putting in the time to build the chamber itself. When asked if she could benefit from having a fully automated grafting chamber for her plants, she said, “That would be awesome and I think it would be something cool to show my kids [16].” She also loved the idea of having a grafting chamber that could be assembled quickly and moved around. Michelle says that with her kids playing sports, their yard is always accumulating more things and having a compact and portable grafting chamber would really suit her needs [16].

We contacted a novice gardener named Karen Misfelt from Corvallis, Oregon [17]. She told me that she has never attempted to graft her plants, but admits that there were a few seasons when many of her tomato plants died from disease and pests. She said she would like a way to prevent these diseases and pests from killing all her plants, but she does not have time to graft. I then pitched our grafting chamber design to Karen and she was very interested in the idea of it. She liked how it was fully automated and did not require a lot of maintenance or care once assembled. Because she is a novice, Karen said it would be nice if there were instructions to guide her through the process.

This interview with Karen was very helpful because it illustrated the potential interest from novice gardeners that don't have the time to invest in a traditional grafting process. The grafting chamber that we are designing would alleviate a lot of the stress and concerns with doing the process manually. This interview also brought to the group's attention that an instruction manual or guide would be very helpful to those not so well versed in grafting.

The final interview that we conducted was with Jacob Shrogen, a farmer at OnePointOne. OnePointOne is an aeroponic vertical farming startup that is working on a fully automated system to produce food more efficiently, using less water and zero pesticides. While OnePointOne does not graft any plants because they focus on leafy greens, we thought that they would have some useful information about automating agricultural processes. On top of that, Jacob also had knowledge about grafting from previous experiences. The important points that we took away from our interview with Jacob was that it is important to break the agricultural processes into smaller subsystems and really focus on having subsystems that can perform their tasks consistently. Jacob also said that one of the hardest parts about grafting is having a system that can produce consistent results [18]. We hope to use this information to better our design and product.

Preliminary Organization of Needs

Based on the above and supplemental research, the following hierarchy of needs was generated. Here, items listed in bold represent primary needs while the plain text below each primary need corresponds to a secondary need. The secondary needs are presented in order of importance beneath their corresponding primary need. The primary needs appear in no particular order. Note that the abbreviation 'GC' represents 'grafting chamber.'

Based on the above and supplemental research, the following hierarchy of needs was generated. The primary needs of the chamber include:

1. Ability to produce healthy grafts
2. Sufficient power for the entire recovery period
3. Automated environmental control
4. Portability
5. A capacity of 50 grafts.

The criteria to measure the ability to produce healthy grafts includes the stability of the grafts once the grafting clips are removed. By fulfilling this criteria, the grafted plants will be successful in producing plants with more desirable traits. To satisfy the second primary need of sufficient power, the grafting chamber will need to have the ability to be powered by a solar array as well as powered by the grid. The chamber will need to be able to supply constant power to all necessary sensors, actuators, and controls. The third primary need requires that temperature, humidity, and light exposure are all automated. The fourth need will require an easily assembled and disassembled structure. It is also ideal for the chamber to have a small footprint during storage periods. The final need of the chamber is to hold 50 grafts. Assuming a success rate of 80% of grafts, this will ideally produce 40 grafts. Additional grafts can be sold for a profit.

Hierarchy of Needs

In compiling the specifications and customer requirements for the grafting chamber, it was important to rank each need by relative importance. The most crucial need will earn an importance ranking of 5, and the least important will receive a 1.

Table 1. *Grafting chamber customer needs with corresponding relative importance with 5 being the most important and 1 being the least important.*

Need #	Need		Imp.
1	The chamber	will maintain humidity between 85% and 95%	5
2	The chamber	will maintain a temperature between 72°F and 85°F	5
3	The chamber	can be reused for multiple grafting cycles	5
4	The chamber	will be lightweight	4
5	The chamber	is completely automated	4
6	The chamber	is not high maintenance	4
7	The chamber	is versatile	4
8	The chamber	produces healthy grafts	4
9	The chamber	doesn't take up too much space	3
10	The chamber	is easily assembled	3
11	The chamber	is quickly assembled	3
12	The chamber	is easily collapsible	3
13	The chamber	is compact	3
14	The chamber	can hold a reasonable amount of grafts	3
15	The chamber	will provide sufficient amount of light for the plants	3
16	The chamber	can support multiple levels of grafts	2
17	The chamber	will complete grafting process in a reasonable amount of time	2
18	The chamber	will be affordable	2
19	The chamber	can house plants of different weights	1

Once the exact specifications have been outlined, it is important to compare specifications of existing products. By matching the specifications to the given metrics of existing products, our team was more equipped to shape the needs and specifications of our design. Before moving forward with the design process, it is crucial to lay out in great detail the specifications required of the design. To the best of our ability, we have attempted to design a chamber with the ideal values for the specifications outlined in Table 3. However, there is a chance that these exact values may not be able to be attained: for this reason we have provided a marginal value that will be considered successful. From the table, it is apparent that the two most important needs are the temperature and humidity of the chamber. In order to have a high success rate of grafts, we want to ensure the conditions are precise for the duration of the 10 days. Another need that has high importance is the lifetime of the chamber. We want the chamber to be reusable for a minimum period of 5 years. Ideally, the chamber will be used for 2 to 3 grafting cycles per year, totaling about 30 days in use per year.

We want the grafting chamber to be adaptable to both inside and outdoor applications, but the outdoor option will have more extreme conditions, so we placed more emphasis on this option. While the grafting chamber could be used in a greenhouse, the temperature within the greenhouse will be somewhat stable. Outdoors, the grafting chamber will be susceptible to the temperature swings that come along with day and night fluctuations, UV radiation and degradation, wind, and rain.

System Level Sketch and User Scenario

The purpose of this project is to design a rapidly deployable and self-regulating grafting chamber to satisfy the needs of our customers. In Figure 12, a full system sketch including all subsystems is presented. Ideally, our completed project will require a minimal amount of labor for the customer. Most of the work will go towards preparing the grafts to be placed into the chamber, which is not the purpose of this project. Our goal is to create a user-friendly product that will assist farmers with the healing of grafts. While our system will require inputs from the user, we plan to minimize the required work needed to monitor the grafting chamber.

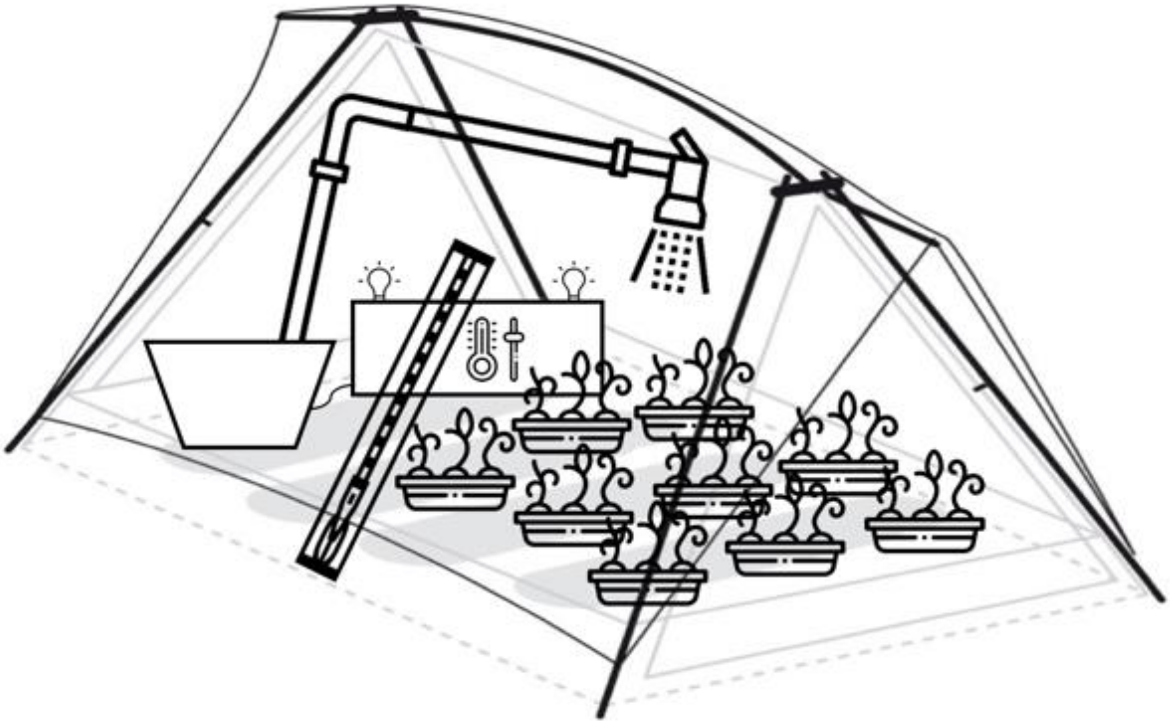


Figure 12. *Full system sketch including all subsystems.*

Functional Decomposition

To decompose the grafting chamber and its functions, it helps to look at some of the different subsystems that make up our project. The biggest subsystem of the project is the structural component. The structure of the grafting chamber has a couple of different functions. The first and most obvious is to support the chamber and the grafts inside by preventing external forces (such as wind) from collapsing the chamber. The second function is to minimize light exposure to the grafts, which is vital to the healing process. Third is to prevent moisture from leaving the chamber so that the humidity can be maintained at the desired value. Lastly, our project uses many electronic devices and requires a structure that will keep water from damaging the hardware.

Another component of the project is the sensors and actuators in our system. Digital temperature and humidity (DHT) sensors will be used to record the temperature and humidity inside of the grafting chamber, which will then be used to operate the misting system and space heater. UV light bulbs and a AC light bulb dimmer module will be used to control the light exposure over time. All of these components will be controlled using a microcontroller. The microcontroller will also be able to send live data to the user so that they can easily check on the conditions of the grafting chamber.

Inputs, Outputs, and Physical Constraints

While the healing process of grafting is very complicated and requires a lot of attention, our project intended to have minimal input from the user and still be able to produce successful grafts. The following diagram shows the different inputs and outputs of our system.

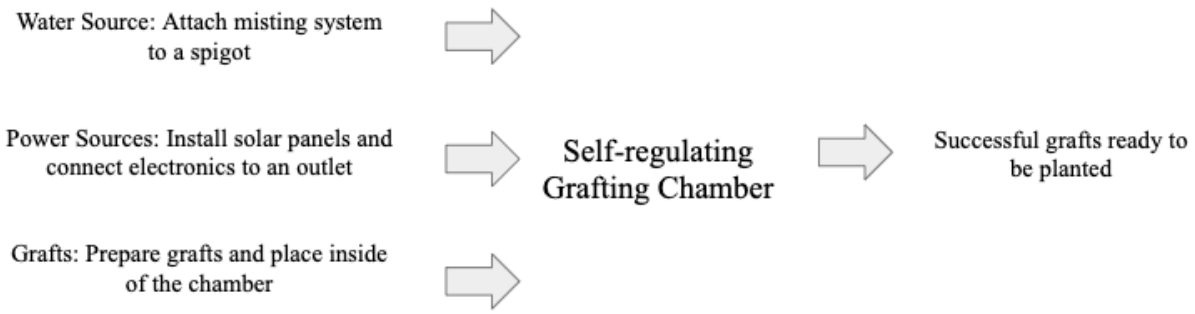


Figure 13. *Diagram that shows the different inputs and outputs of the system.*

Due to our main customer, the organic garden at Santa Clara University, there were a couple of physical constraints on our project. The biggest constraint was that our grafting chamber needed to fit under one of the workbenches inside of the greenhouse to save space. This limited the size of our chamber to a five foot length, two foot width, and two foot height. Having this size constraint would also limit the number of grafts that would fit in the chamber and would also affect the size of heater and misting system required to maintain desirable conditions. On top of the size constraint, our system needed to be near a water source to supply the misting system and a power source to power the space heater.

Product Specifications

During the initial design stages, our team used the market research and knowledge of existing systems to begin defining specifications. We came up with a detailed table of requirements of any graft healing system. From Table 1, it is clear that maintaining humidity and temperature, as well as longevity of the system, were the most important.

Competitive Benchmarking

While there is no product that targets the same audience and scope as our desired Grafting Chamber, we found similar products in order to compare our preliminary design to two similar products. The EcoQube Air is a “desktop greenhouse,” that serves as just that; a closed environment that can be controlled from a phone app [19]. The second comparison product we used was just a do-it-yourself grafting chamber, that any farmer or individual could build. Many people use Rubbermaid tubs with small heaters and spray bottles.

***Table 2**. Competitive benchmarking chart for two similar products based on metrics with corresponding relative importance and units of measurements.*

Metric #	Need(s) #	Metric	Imp	Units	EcoQube Air	DIY Grafting Chamber
1	1	Maximum humidity deviation	5	%	±5	±15
2	2	Maximum temperature deviation	5	°F	±2	10
3	4,19	Maximum weight allowance	4	lbs	15	100
4	5,6,15	Hours of attention post-set up and initialization	4	hrs	0	12
5	8	Percent of successful grafts	4	%	85	10
6	10,11,12	Time to assemble grafting chamber and initialize process	3	mins	10	120
7	9,13	Area occupied by assembled system	3	ft^2	2	25
8	9,13	Volume occupied by collapsed grafting chamber	3	liters	45	2000
9	18	Price	2	USD	199.95	100
10	3	Lifetime	5	years	1	2-3
11	7	Indoor and Outdoor Capability	4	binary	No	No
12	17	Time to complete grafting process	2	days	10	10
13	6,10,11	Number of people required to assemble	3	people	1	1-2
14	14	Number of grafts in chamber	3	grafts	1	50
15	16	Number of levels in chamber	2	levels	1	1-3

Target Grafting Chamber Specifications

After closely analyzing the different values of our competitors, we compiled a list of specifications for our grafting chamber. Similar to Table 1, the precision of the temperature and humidity, as well as the lifetime of the chamber, were the most important to us. We based design decisions off of these specifications and the relative importance of each mark.

Table 3. *Grafting chamber target specifications with units, importance, marginal value, and ideal value for each metric.*

Metric #	**Metric**	**Units**	**Imp**	**Marginal Value**	**Ideal Value**
1	Maximum humidity deviation	%	5	±5	±2
2	Maximum temperature deviation	°F	5	±4	±2
3	System weight when collapsed and stored	lbs	4	35	25
4	Hours of attention post-set up and initialization	hrs	4	2	0
5	Percent of successful grafts	%	4	50	80
6	Time to assemble grafting chamber and initialize process	mins	3	35	25
7	Area occupied by assembled system	ft^2	3	15	10
8	Volume occupied by collapsed grafting chamber	liters	3	65	50
9	Price	USD	2	500	300
10	Lifetime	years	5	5	10
11	Indoor and Outdoor Capability	binary	4	No	Yes
12	Time to complete grafting process	days	2	14	10
13	Number of people required to assemble	people	3	2	1
14	Number of grafts in chamber	grafts	3	30	50
15	Number of levels in chamber	levels	2	3	2

Concept Selection and Design Evaluations

This section contains preliminary design evaluations based on the criteria presented in the previous section. Consideration of complete system functionality as well as individual subsystems is included. A section on team management is also presented here, alongside important details related to project execution.

System Level Design

As part of the design process, each team member conceptualized grafting chamber solutions. These included system level sketches, subsystem and component formalization, and workflow development. Example results of this ideation process are shown in Appendix C. Additionally, two system-level designs were generated and are shown below and in Figure 12. Figure 12 shows the horizontal orientation.

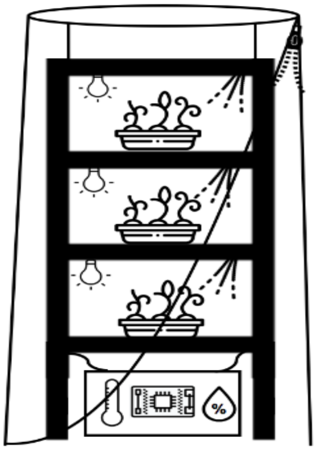


Figure 14. *System-level grafting chamber concepts: horizontal orientation (see* ***Figure 12****) and vertical orientation (shown above). Designed by Jack Margolis.*

Using tabulated customer needs, a scoring matrix was generated in order to quantitatively evaluate the two high-level grafting chamber designs. Each team member independently ranked each design on a scale of 1 - 5, with a score of 5 representing the highest possible score. Then, the individual member scores were averaged and multiplied by the corresponding category weight. The weights of the categories in the scoring matrix were determined by the importance of the needs. The horizontal grafting chamber received the most total points and the team has pursued this design. The complete scoring matrix is shown below in Table 4.

Table 4. *Design evaluation of proposed vertically and horizontally oriented grafting chambers held against an existing DIY system. Score columns represent the average of each of the four team member's individual scores on a (1-5) scale. Total scores are calculated as the sum of the scores multiplied by their corresponding weights.*

Need	Weight	Vertical Chamber Score	Horizontal Chamber Score	Existing DIY System
The chamber will maintain humidity between 85% and 95%	5	2.5	5	3
The chamber will maintain a temperature between 72°F and 85°F	5	2.5	4.5	3.25
The chamber can be reused for multiple grafting cycles	5	4.5	4.75	4
The chamber will be lightweight	4	2.75	3	4
The chamber is completely automated	4	4.5	4.5	1
The chamber is not high maintenance	4	3.25	3.75	1
The chamber is versatile	4	3.5	4	3.25
The chamber produces healthy grafts	4	3.5	4	2
The chamber doesn't take up too much space	3	3.25	3.75	3.5
The chamber is easily assembled	3	2.25	3.75	3.5
The chamber is quickly assembled	3	2.25	3.5	3.25
The chamber is easily collapsible	3	3.5	4.75	1
The chamber is compact	3	3	3.5	2.25
The chamber can hold a reasonable amount of grafts	3	3.75	4	3.5
The chamber will provide sufficient amount of light for the plants	3	3.5	3.75	2.25
The chamber can support multiple levels of grafts	2	5	1.5	1
The chamber will complete grafting process in a reasonable amount of time	2	5	5	4.75
The chamber will be affordable	2	2.25	2.75	5
The chamber can house plants of different weights	1	3.25	5	5
Total		206.6	252.8	180.5

Main Subsystems

The grafting chamber can be broken into 4 main subsystems: (1) the chamber structure, (2) the microcontroller and sensor array, (3) the power system, and (4) the control system. Each of these subsystems is discussed in detail in the "Subsystem Design" section of the report.

Team and Project Management

A section on team management is presented here, alongside important details related to project execution such as budget, timeline, and design philosophy.

Project Challenges and Constraints

Water Exposure

To capture the environmental conditions inside the chamber, an array of three DHT-22 sensors monitor both temperature and humidity. As electrical components, the space heater, sensors, microcontroller, relay and other components are sensitive to water exposure. To avoid the problem of contamination, a system of "weather stations" was devised allowing the maximum amount of electrical components to be contained outside the chamber, and those inside to be waterproofed. Under this system, only the space heater and sensors must remain in the chamber.

To protect the space heater, an acrylic enclosure was designed and fabricated so as to not impede the heater's ability to heat the chamber while preventing exposure to droplets. This is shown in Figure 15.

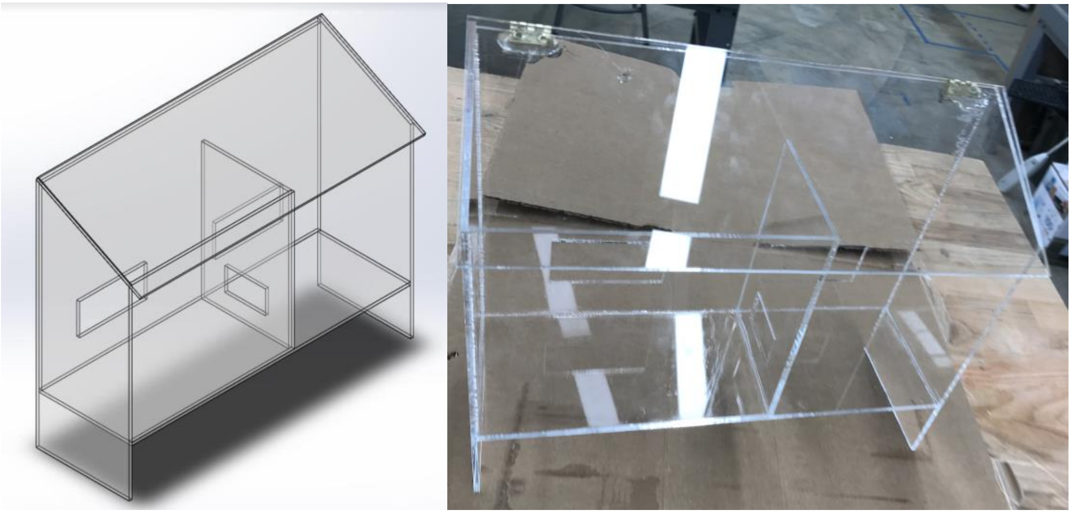


Figure 15. *CAD model and fabricated acrylic space heater enclosure.*

Each data collection “weather station” consists of a temperature and humidity sensor housed in a small screw-top plastic enclosure which is connected via ½” flexible plastic tubing to the main electronics housing outside the chamber. Individual waterproofing components are connected with pneumatic push-to-connect fittings. In order to protect the sensor from water damage while still allowing accurate environmental monitoring, each weather station contains strategically sized holes. Figure 16 details a single weather station connecting to the central hub including a focused view of the sensor housing.

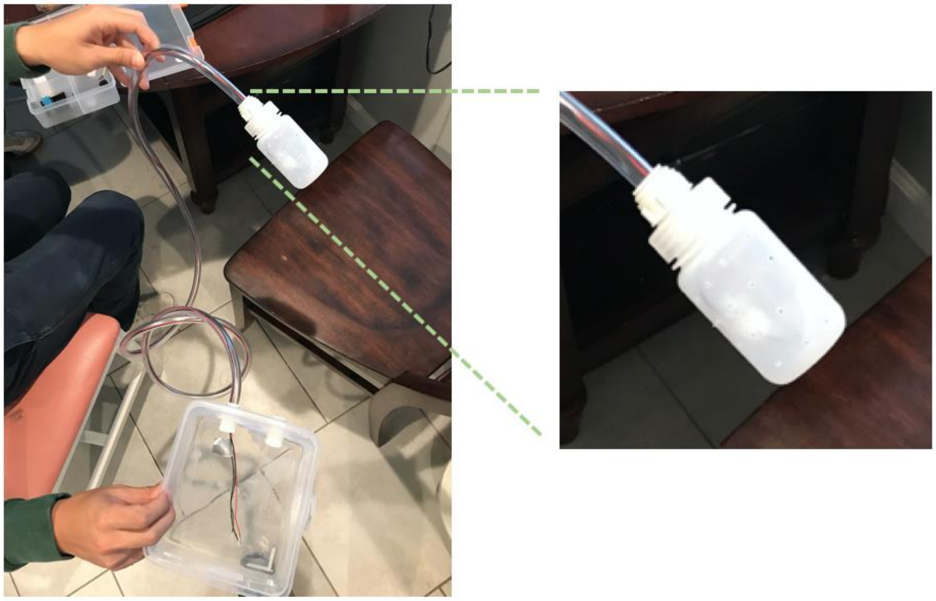


Figure 16. *A data collection "weather station" connected to the central electronics hub (left) and sensor housing (right).*

Budget

Our team was granted $2,000 through Santa Clara University's School of Engineering Undergraduate Programs. We divided the budget into the four different subsystems, and calculated the total expenditures for each section The structure subsystem included costs such as the PVC fittings for both prototypes, the garden hoops from prototype 1, the fabric enclosure for both prototypes, and anything else related to either prototype. The microcontroller and sensor array category includes the multiple DHT sensors we purchased, the Beagle Bone Black, and the remaining components that we used. The power system category included the 100 Watt solar panel kit, extension cords, etc. The humidity and temperature control subsystem included the space heater, the various passive test components we used, and the misting system. There is also a "miscellaneous" section which includes small pieces or parts that we needed along the way.

Table 5. *High order budget of actual expenditures.*

Subsystem	**Total Expenditures**
Structure	225.32
Microcontroller and Sensor Array	243.45
Power System	307.74
Control System	173.16
Misc.	82.61
Remaining Budget = $**967.72**	

Timeline

Our team made use of Gantt style charts to lay out individual and concurrent tasks for the duration of the project. These can be seen in Figures H1 - H3 in Appendix H.

Design Philosophy

Throughout the design process, our team was influenced by the specific need which motivated the project - making modernized graft healing techniques available to the smallholder farmer. This need defined the core evaluation metrics for all design decisions including: increased functionality, durability, manufacturability, ease of use, and reduced cost. In this respect, we often revisited the project's fundamental purpose in order to ensure that our decisions adhered to it.

While implementing potential solutions, our team placed heavy emphasis on experimental testing using physical results to troubleshoot the system. The justification for this is twofold. First, in accordance with the desire to increase manufacturability and reduce system cost, components were both inexpensive and readily available. This allowed for an abbreviated simulation phase, which included only those analyses deemed critical, transitioning efficiently to multiple experimental trials using various physical systems and components. Second, as we sought to demonstrate that actively controlled systems more aptly controlled the environment inside the grafting chamber when compared to passively controlled systems, experimental results helped to justify this claim.

Risk Assessment and Hazard Mitigation

While this project is definitely not considered high risk, there are activities that are worth noting to have potential hazards. The first was constructing the physical structure of the grafting chamber. This involved light fabrication with hand-held power tools. These tools included a drill driver, circular saw, and Dremel. Using hand-held power tools bore risk of injury to the operator and bystanders if the tools were used improperly or malfunctioned. There was the potential for injury of fingers and hands. In order to control the hazards associated with using power tools, team members worked in pairs in the MakerLab with supervision from both teammates and MakerLab supervisors. In the event that an injury did occur, which it did not, campus safety would have been alerted and first responders would have evaluated the scenario and determined the next steps.

The next aspect of the project that posed a risk was the power that was supplied to microcontrollers, temperature and humidity sensors, heater, and misting system. We connected wires that transferred the current in order to power all the electrical devices. If we had wired them incorrectly, there could have been exposed live wires that could've shocked the user. To control this hazard, we ensured that no power was applied to the circuit when devices were being installed. We also guarded live components when the system was in operation. If we had been electrocuted, campus safety would have been contacted and in the event that it was life threatening, the nearest AED would have been used.

The act of storing energy from the solar panel with a lead acid battery also posed a risk. A defective battery has the potential to leak corrosive materials into the ground and on anyone nearby. To prevent leakage, we made sure to unplug the battery when it was not in use. If the battery would have shown signs of corrosion, it would have been disconnected and properly disposed of immediately.

We used a misting system to control the humidity of the environment. If the electronics were poorly wired, exposed to water, or improperly grounded it would have greatly increased the potential for electric shock. To prevent this, we made sure that all the electrical components were in a waterproof housing outside of the enclosure. The temperature and humidity sensors were put in "weather stations" because they needed to be within the enclosure and able to sense the environmental conditions. These "weather stations" are described in greater detail earlier in the report. If we would have been shocked, campus safety would have been contacted and in the event that the shock was life threatening, the nearest AED would have been used.

Team Management

The design process is long and has many different steps. To be successful, good team management is a necessity and will make the process manageable. We have managed to break our project into subsystems and by doing so, appropriately delegated tasks to each member. But at the same time, we would meet as a whole group and discuss our progress as needed. This allowed us to be productive individually and still work as a team. Another important part of working as a team is reflecting on the progress we have made and trying to find room for improvement. The best teams realize where they need improvement and work towards becoming a better team. Overall, communication and honesty have been vital to our success. While we completed a lot of work individually, it was very important to clearly communicate what we had done and what still needed to be done. This ensured that every team member was on the same page and allowed us to work towards completing the design process.

3. Subsystem Design

This section delves into each of the four subsystems which together comprise the grafting chamber and identifies individual components that allow the system to function as a whole.

Grafting Chamber Structure

All of the environmental control components regulate the environment created by the chamber structure. This subsystem consists of the chamber frame and covering. Design of the chamber structure was centered around creating a durable and portable structure without sacrificing its ability to maintain the necessary environmental conditions inside to produce healthy grafts.

Frame

Keeping these criteria in mind, our team designed two frame prototypes. The first of these, shown In Figure 17, consists of a PVC base and 26” gardening row covers connected using pneumatic push-to-connect fittings. Advantages of this design include: a limited number of separate components and minimal time to assemble. Disadvantages include: connection strength, row cover hoop cost, and connection novelty.

Figure 17*. Grafting chamber structure, prototype #1: row covers and PVC.*

Recognizing the flaws in our first prototype, our team designed a second prototype designed to eliminate the disadvantages of Prototype #1 without sacrificing its advantages. This new prototype, shown in Figure 18 is entirely constructed of off-the-shelf PVC components and stock fittings. Advantages of this design include: increased durability, lower cost, and smaller storage footprint. Disadvantages include a slightly increased number of components and assembly time.

Figure 18. *Grafting chamber structure prototype #2, PVC.*

Ultimately, the increased functionality associated with a more robust design accompanied by the reduction in cost and ease of component replacement associated with our second prototype led the team to pursue the improved prototype.

Covering

In order to separate the grafts from ambient conditions, multiple fabrics were considered to enclose the structure. The criteria for the covering material included ease of sewing, water resistance, cost, and other factors all compared in

Table 6.

Table 6. *Decision matrix for structure covering.*

Material	**SilPoly**	**Canvas**	**Blue tarp**
Cost	$$	$	$
Water Resistance	High	Medium	Medium
Light Resistance	High	High	Medium
Ability to be sewn	Moderate	Difficult	Difficult

The water resistance paired with the ability to be sewn were the strongest factors that led to the final decision. As we were sewing the enclosure ourselves, we wanted to ensure that we could do so in a timely and neat manner. The final decision was to enclose the chamber by the dark, rip-stop nylon SilPoly covering.

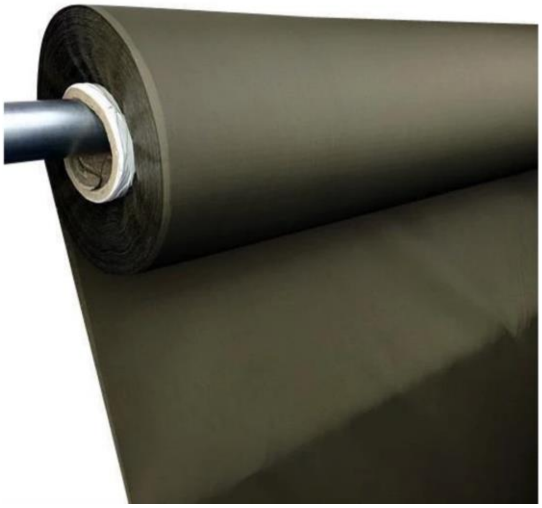


Figure 19*. "SilPoly" a rip-stop nylon derivative, will be used to enclose the structure (reproduced without permission) [20].*

This silicone coated polyester fabric is known for its water resistance and high strength. The material was chosen given these characteristics. This will be important in maintaining both the temperature and humidity within the chamber. Also, the dark color will ensure that limited light will infiltrate the chamber as relative darkness is important in the healing process of the grafts. Notable material properties of silicone coated polyester include [21]:

- Melting point: 220°C
- Sun Protection Factor: UV 30
- R-value (insulation): 6.8 Km^2/W

Microcontroller and Sensor Array

During the research phase of this project, the appropriate microcontroller needed to be chosen to be the brain of the electronics system. Initially we considered using an Arduino Uno. The pros of this device were that it is very cheap, simple to use, and every group member had experience using it. The cons were that it wasn't very powerful and did not have built-in Wi-Fi capabilities. This would mean that to connect our project to the internet, we would need to add a Wi-Fi module to the system. The second microcontroller that we considered was a BeagleBone Black. This device was very powerful and had the ability to store local data on a micro SD card. However the BeagleBone was much more expensive and similar to the Arduino, did not have Wi-Fi capabilities. Lastly, we considered a Particle Photon Board. This microcontroller was just as inexpensive as the Arduino Uno and had the built-in Wi-Fi capabilities that we were looking for. The downside was that no group member had experience using it. In the end we decided to go with the Particle Photon Board because it was inexpensive and could connect to the internet.

The Particle Photon (Figure 20) can be powered by the USB micro B connector on the board or directly to the VIN pin with 3.6VDC to 5.5VDC [22]. The 3V3 pin can output 3.3V and has a max load of 100mA [22]. When the device is initialized, it needs to be manually connected to the Wi-Fi and then after that it will automatically connect to the network whenever it is powered on. Code can be uploaded by directly connecting the device to a computer or completely wirelessly using the Cloud. Once a certain code is uploaded, it is stored on the device and will run when powered on until new code is uploaded.

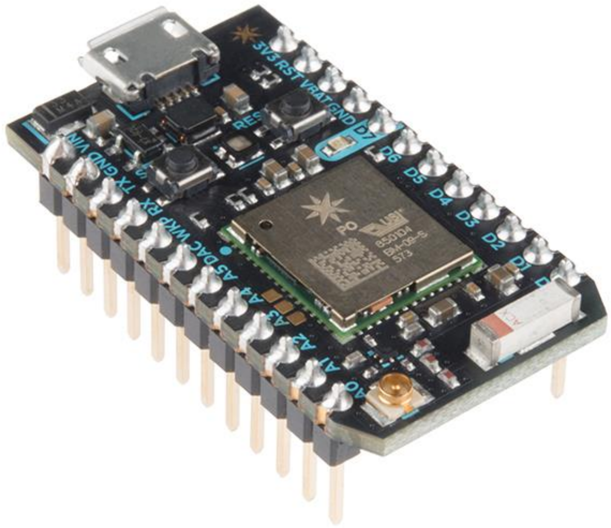


Figure 20. *Particle Photon Board (reproduced without permission) [23].*

DHT22 sensors (Figure 21) were used to read the temperature and humidity within the chamber. These sensors require a power supply of 3.5V to 5.5V and have an operating current of 0.3mA [24]. DHT22s can read temperatures from -40°C to 80°C and humidities from 0% to 100% with an accuracy of ±0.5°C and ±1% respectively [24]. These sensors are less expensive in comparison to other temperature and humidity sensors on the market.

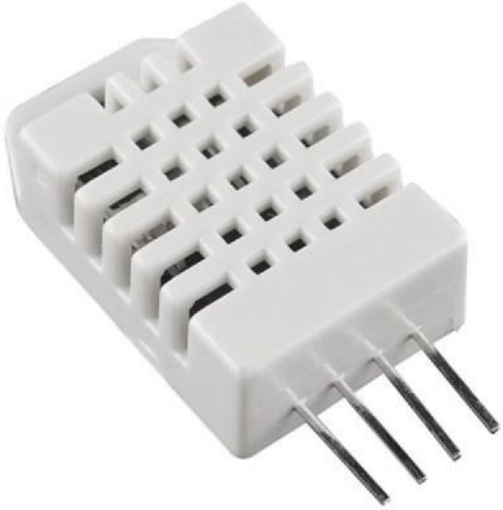


Figure 21. *DHT22 Temperature and Humidity Sensor (reproduced without permission) [25].*

It was decided that four DHT22s would be used in the system. Three would be placed in different positions within the chamber to get an accurate reading of the temperature and humidity throughout the whole chamber and one would be outside the chamber to read the ambient conditions. All would be powered by the Photon's 3V3 pin and would be read by different serial pins on the microcontroller. It is worth noting that the 3V3 pin outputs a slightly lower voltage than is recommended to power a DHT22, but this will be addressed in the System Integration, Testing, and Results section of this report.

Power System

In the initial phases of the project, the idea of solar power was explored. In order to promote a sustainable agricultural operation and be able to cater to small scale, potentially off-grid farms, solar power was an ideal component of the project. However, after defining the restraints and specifications of our project, we concluded that it would not be feasible to power the whole system with solar. The space heater, a 500 Watt device, would require a panel that was out of our initial budget of a product could be sold for under $500. However, we still wanted to prove that our chamber was compatible with solar power.

Figure 22. *100 Watt solar panel set-up, used to power lights in chamber.*

This led the team to purchase a 100 Watt solar kit that was used to power only the lighting array in the chamber.

Control System

As mentioned earlier, one of the most important functions of the grafting chamber is monitoring and controlling the environmental conditions. The three conditions that need to be controlled are temperature, humidity, and light exposure. In the first three days of the healing period, temperature needs to be kept between 72˚F (22˚C) and 85˚F (30˚C), humidity must be maintained between 85% and 95%, and there must be minimal light exposure. Over the remaining days of the healing period, the conditions must be gradually tapered to the conditions of the greenhouse where the grafts will be stored. This will ensure that the maximum number of grafts survive after being removed from the grafting chamber. Based on the temperature and humidity readings from the DHT sensors, we will operate a space heater to control temperature and a misting system to control humidity. Light exposure will be controlled using UV light bulbs and an AC light bulb dimmer module.

Light Exposure

Since light exposure is only a function of time and lumens, the control system is relatively simple. We planned to use our microcontroller to gradually send a smaller and smaller signal over time to the AC light bulb dimmer module. This would gradually increase light exposure as the light bulb would become brighter.

Temperature

In the preliminary stages of our project, we operated a space heater and misting system using simple "if" statements that would attempt to keep the conditions inside of a desired range. After performing a few tests and analyzing the data, we realized that the temperature would sometimes drop out of the desired range. If by chance the temperature was at around 22℃ at the same time as a dramatic outdoor (outside of the chamber) temperature decrease, our temperature control system would not be able to react fast enough to maintain the desired temperature. To better explain this we made this hypothetical scenario and plotted the temperatures. The figure below shows how temperature can drop below 22℃.

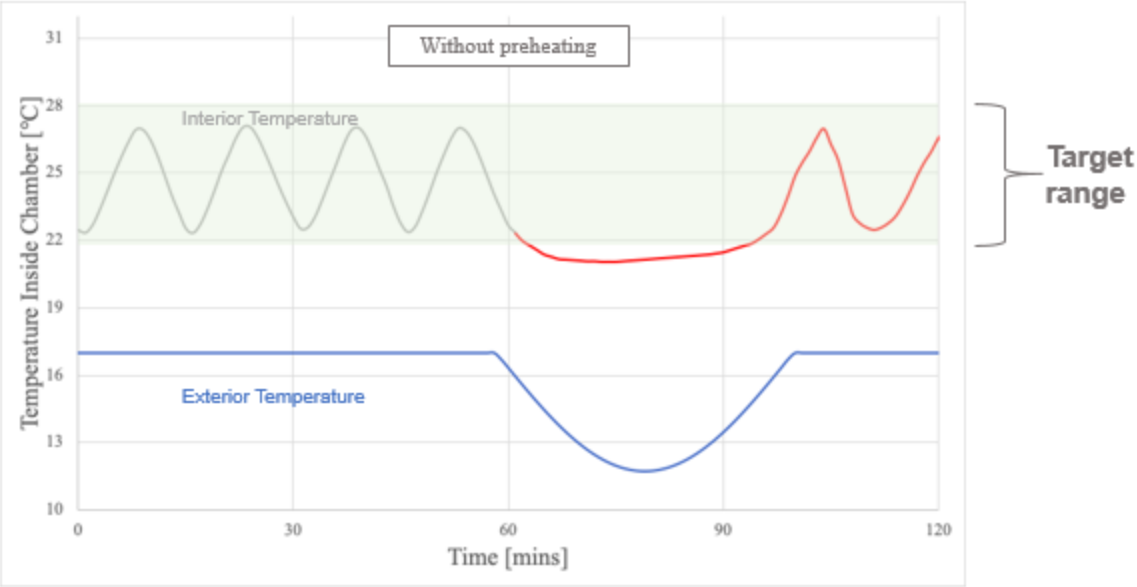


Figure 23. *Hypothetical temperature inside and outside of our chamber using our first temperature control method (simple "if" statements).*

After realizing this, we decided to add preheating to our temperature control method. In practice, we would heat the chamber to a narrower upper region (25°C to 28°C) of our desired range before the temperature drops. This would keep the chamber inside the target range even when there is a dramatic drop. Below is a hypothetical plot of the temperature when we implement preheating to our control method.

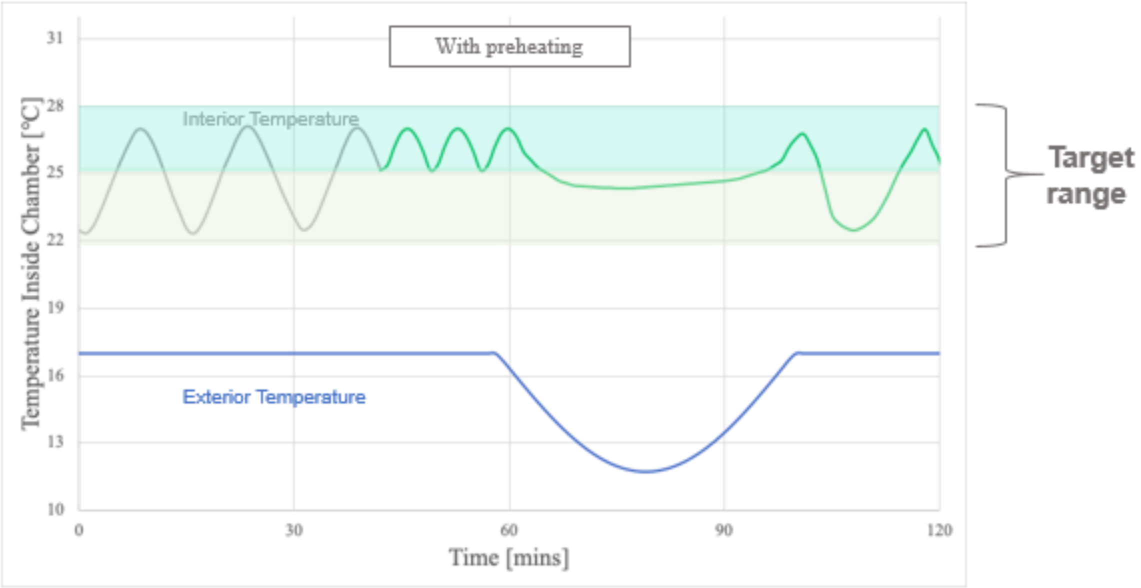


Figure 24. *Hypothetical temperature inside and outside of our chamber implementing preheating to our temperature control method.*

To be able to preheat the system, we had to figure out a way to predict these dramatic temperature changes. We were able to do this by using a machine learning algorithm to predict the temperature outside of the chamber which would allow us to control the conditions inside our chamber more effectively. To predict temperature we used an algorithm that used previous temperature values as inputs to predict future temperature values, the outputs. We put the inputs into a matrix, Y, and the outputs into another matrix, U.

Table 7. *Table that shows the temperature values used as inputs and outputs. The green values are the inputs (including the current time that is boxed in yellow) and the red values are the outputs.*

Description	3 Days Before	2 Days Before	1 Day Before	Today (0 days Before)
1:00pm	T(3,1)	T(2,1)	T(1,1)	T(0,1)
2:00pm	T(3,2)	T(2,2)	T(1,2)	T(0,2)
3:00pm	T(3,3)	T(2,3)	T(1,3)	T(0,3)
4:00pm	T(3,4)	T(2,4)	T(1,4)	T(0,4)
5:00pm	T(3,5)	T(2,5)	T(1,5)	T(0,5)
6:00pm	T(3,6)	T(2,6)	T(1,6)	T(0,6)

The goal is to find some relationship between Y and U so that we can take any Y values and predict the corresponding U values. This relationship comes in the form of another matrix, P. The equation below demonstrates how the P matrix can be used with a known Y matrix to determine the U matrix:

Equation 1

$$Y \times P = U$$

To figure out the values in the P matrix, we can look at past temperature data where we already know the U values and use a little bit of linear algebra.

Equation 2

$$P = (Y^T Y)^{-1} Y^T U$$

$$\underset{n \times 12}{\begin{pmatrix} Y(1,1) & Y(1,2) \ldots & Y(1,12) \\ \vdots & \vdots & \vdots \\ Y(n,1) & Y(n,2) \ldots & Y(n,12) \end{pmatrix}} \underset{12 \times 3}{\begin{pmatrix} P(1,1) & P(1,2) & P(1,3) \\ P(2,1) & P(2,2) & P(2,3) \\ \vdots & \vdots & \vdots \\ P(12,1) & P(12,2) & P(12,3) \end{pmatrix}} = \underset{n \times 3}{\begin{pmatrix} T(1,4) \ldots T(n,4) \\ T(0,5) \ldots T(n,5) \\ T(0,6) \ldots T(n,6) \end{pmatrix}}$$

Figure 25.*Correct dimensions for each matrix where n is the number of training values.*

This process is called training our algorithm. Typically, more training data will produce a better algorithm, but collecting data is time consuming so we needed to figure out how much training data would be sufficient for our project. Along with that we also had to figure out how many values should go in the Y matrix and how many values we could accurately predict.

To make all of these decisions and come up with the final temperature prediction model that we planned to use, we used past temperature data of the San Francisco area to test different models and see what worked best. To quantify our results we used both statistical analysis and graphical comparisons. The following table shows the average error using different input sizes and is an example of how we used statistical analysis to choose 3 days of inputs because using more only improved the model by a marginal amount. We decided that 3 would be sufficient and would satisfy the needs of our project. The plots give a visual representation of how predicting 5 values ahead is not very accurate. We ended up choosing to use three values rather than just one because we thought that three hours would be enough to preheat the system, and one hour would not be enough. In the end, we performed both of these analyses to decide the parameters, training data size, and how many values to predict (see Appendix I).

Table 8. *Standard Deviation and Mean Error between predicted temperature and actual temperature using past temperature data of the San Francisco area using different inputs. Three days were chosen for our project because using more did not improve the model by a substantial amount. Each trial has 100 test values, 216 training values and uses the reduced parameters from Table I1 in Appendix I.*

Days of Inputs	7 days	5 days	3 days
Mean Error [°C]	0.7466	0.7408	0.7516
Standard Deviation [°C]	0.7188	0.7357	0.7395

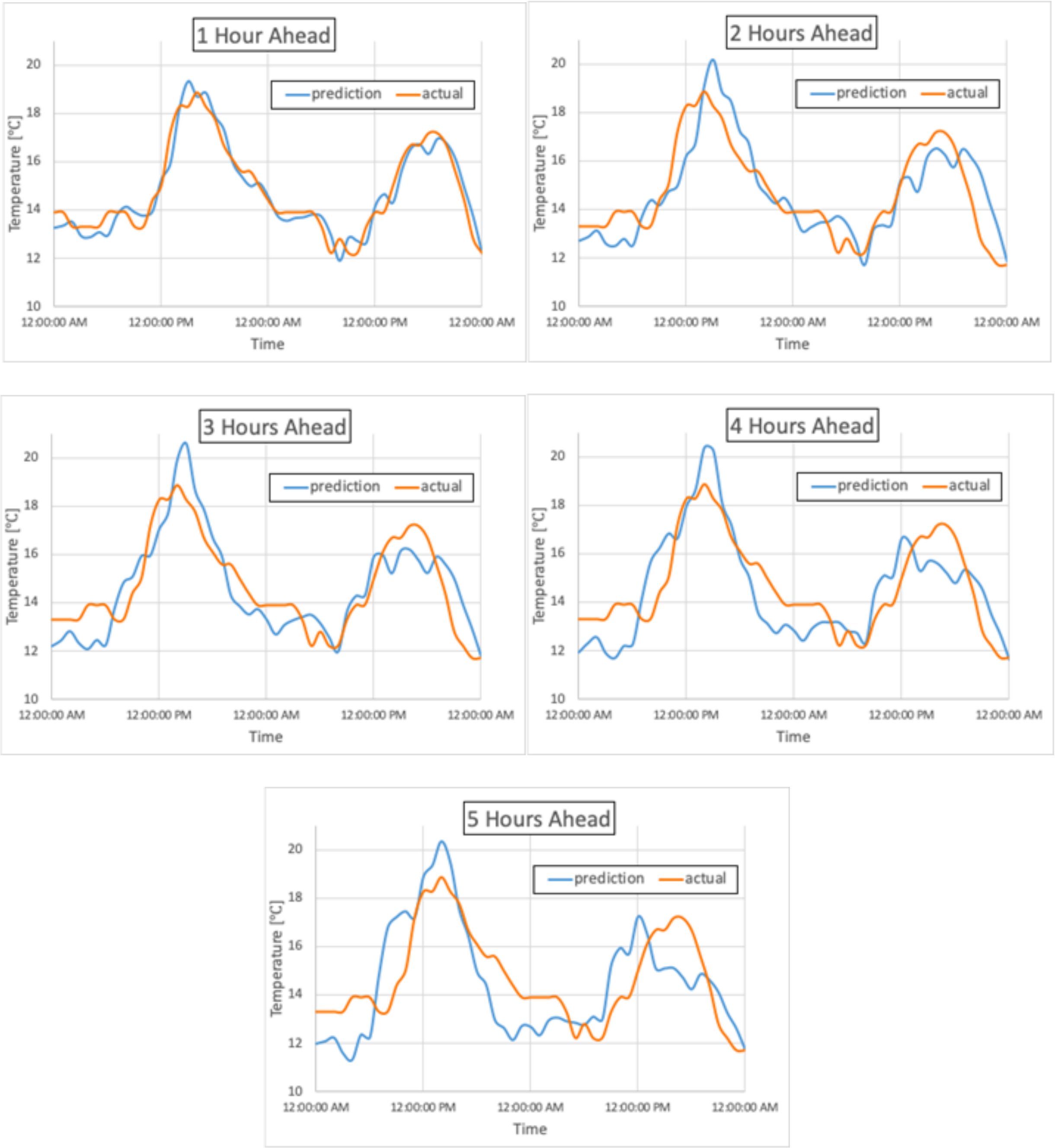


Figure 26. *Visual representation of how accurate future predictions are.*

The final temperature forecast model for our project would require two weeks' worth of training data. Due to the current situation we were unable to collect the data we wanted to but we planned on recording two weeks of data at the Forge garden, which is where we planned to pilot our system.

Humidity

Originally, we had also planned to control the humidity using a prediction model. This model would have been more complicated than the temperature prediction model because relative humidity is defined as the ratio of the actual vapor pressure to the saturated vapor pressure and the saturated vapor pressure is a function of temperature. So humidity is not only a function of time, but also a function of temperature. We looked at many different ways to predict humidity and even decided that the best model for our project would have been to use temperature *and* humidity as inputs to predict just humidity.

After doing all of this, while we were collecting data for our misting system with manual operation, we realized that a complicated prediction model was unnecessary. Even though humidity is a function of temperature, the temperature of our chamber is already being controlled and is relatively constant. So humidity in our system is practically only a function of time (there will be small fluctuations due to the temperature oscillations inside of the desired temperature range). We noticed that every time we misted our system manually for a constant amount of time, the humidity rose and fell at the same rate every time. This can be seen in our semi active (heater is automatically controlled while the misting system is manually controlled) test data shown in Figure 27.

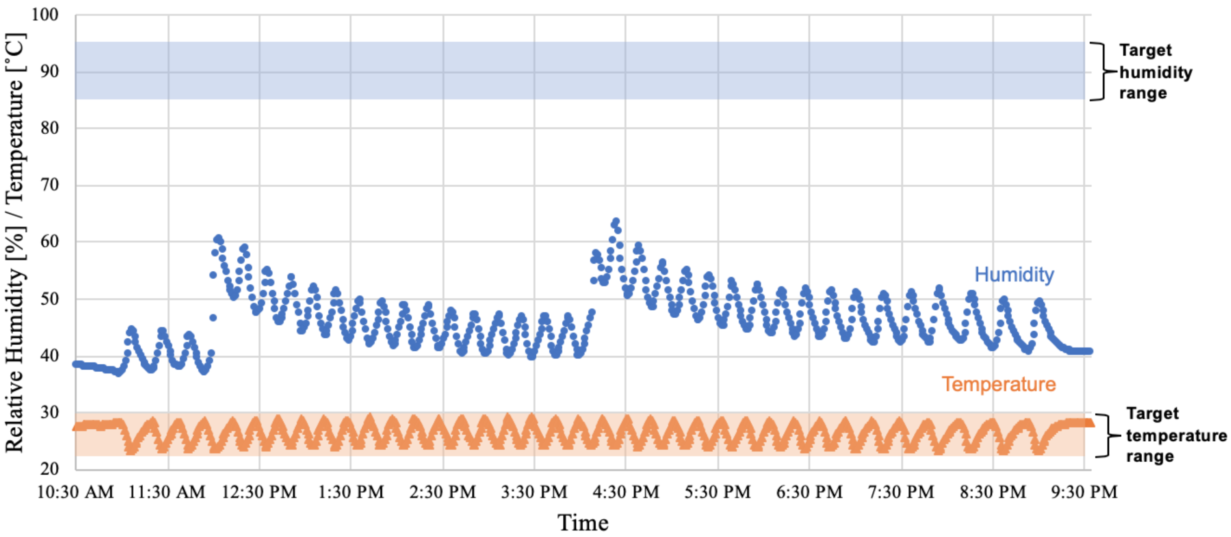


Figure 27*. Semi active data (automatic heater control, manual misting system control) that shows how the humidity rises and falls at a uniform rate. The fluctuations in humidity occur because the temperature oscillates within a range of temperatures.*

After making this realization, we decided to create an optimized schedule for our misting system that would maintain our desired humidity conditions. To do this we sought out to use a non-linear optimization algorithm to minimize the difference between our desired humidity value and the actual humidity value. To do this we first had to calculate the rate at which the humidity increases when the misting system is being operated and the rate at which humidity decreases when the misting system is not being operated. Due to the oscillating temperature, we converted humidity into actual vapor pressure. Doing this made our calculations simpler because vapor pressure does not depend on temperature. So now we had to find the rate of vapor pressure increase and decrease.

To find the rate at which the misting system increased vapor pressure we manually operated the misting system for 7 seconds multiple times and measured the humidity increase. We then converted the humidity into vapor pressure using the following equations and took an average of all of our trials. These measurements can be found in Table 9.

Equation 3

$$P_s = 6.11 * 10.0 * 7.5 * T_C/(237.7 + T_C)$$

Equation 4

$$P_{actual} = P_s * RH$$

Where P_s is the saturated vapor pressure in millibar at the current temperature in °C, T_C, P_{actual} is the actual vapor pressure in millibar, and RH is the relative humidity in %.

***Table 9**. Different trials that measured the increase in vapor pressure after misting the chamber for 7 seconds.*

Trial	Increase in Actual Vapor Pressure after 7s of Misting [millibar]
1	9.14
2	7.14
3	7.89
4	7.07
5	5.63
6	8.34
Average/Std. Dev.	7.54/1.107

With an average increase of vapor pressure of 7.54 millibar over 7 seconds we determined the rate of increase to be 1.08 millibar/second. We found the rate of decrease by similarly taking an average for each of the tests. This value came out to be 0.30 millibar/second.

Now we were ready to use a non-linear optimization algorithm. We used Excel's Solver tool to minimize the difference between our desired vapor pressure value and the actual vapor pressure value to create the optimal misting schedule. Since the desired humidity changes throughout the healing period, this schedule also changes. Below is a plot that compares manual control of the misting system and optimized control of the misting system. The manual control could have been improved as this was our first attempt, but this still shows that an optimized schedule is preferred.

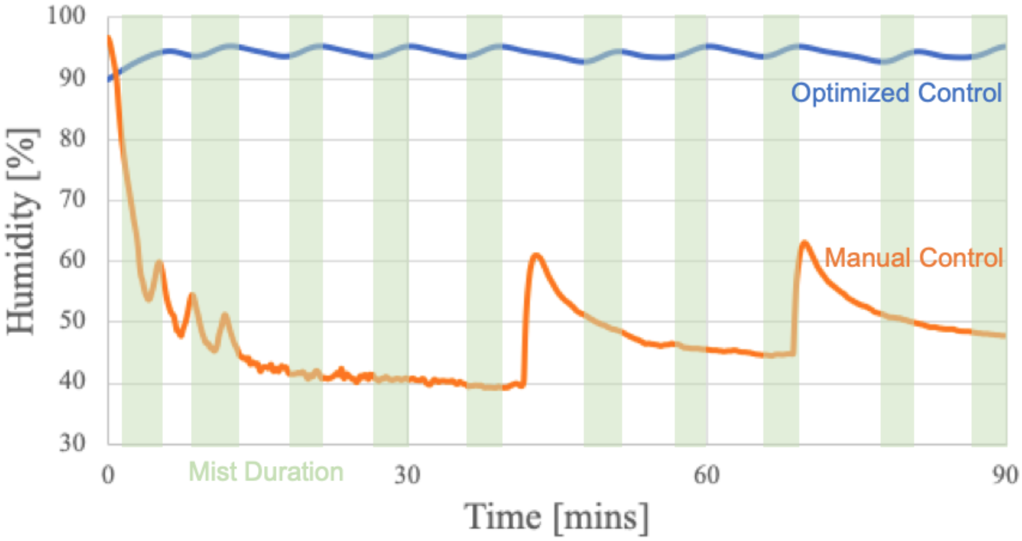


Figure 28. *Humidity of chamber with manual control of misting system vs optimized control of misting system.*

4. Critical Analyses

This section of the report details the simulations, models, and other engineering analyses which assisted decision making in various stages of the design process. Computer aided design and modeling supplemented and verified hand calculation and general engineering knowledge. Included analyses make use of CAD, FEA, and CFD models using a variety of platforms, design, and simulation tools.

Finite Element Thermal Analysis

Methods of Chamber Heating

In order to maintain a specific temperature, our team had to decide on whether to use a series of heating pads or a space heater. There are benefits as well as drawbacks to each option. The heating pad primarily propagates heat through conduction, whereas the space heater mainly transfers heat through convection.

The heating pad, which utilizes conductive heat transfer, has several benefits, however it also has many drawbacks. The heating pad would be easily implemented in the chamber. It occupies minimal space, and fits under the layers of plants. The addition of a space heater would infringe on the footprint, therefore allowing 3-4 less plants. However, because the heating pads will be under the plants, most of the heat will go to the soil in the potting cups instead of the ambient air. Our product specifications call for a specific ambient temperature, not soil temperature. The heating pad is designed to heat the soil and roots of the plants anywhere from 10°F to 20°F above the ambient temperature [20]. Therefore, the heating pad does not provide the desirable heat transfer mode.

The major benefit of the space heater is that it can control the temperature of an environment via convection. This allows for the temperature of all the components within a certain area to be affected by the produced heat. When paired with a fan, the heat can propagate throughout the enclosure, creating uniform environmental conditions.

The downside to using a space heater is the high voltage that is required to power it. Most standard space heaters require a voltage of around 115 V AC. This is the voltage provided from a standard wall outlet, however, we are trying to power the system using a solar panel and battery, so this will need to be addressed.

We expected the space heater to match our required specifications better than the heating pads. While the heating pads would be easier to use, we predict that the convection from the space heater will be more effective at raising the ambient air temperature than the conduction from the heating pad.

Thermal Analysis

In order to determine the energy needs required to maintain an ambient air temperature of ~75 - 85°F (~297 - 303 K), a thermal analysis was conducted using a SolidWorks simulation. The simulation was conducted using the SolidWorks model shown in Figure 29 first using heating pads, and subsequently with a space heater.

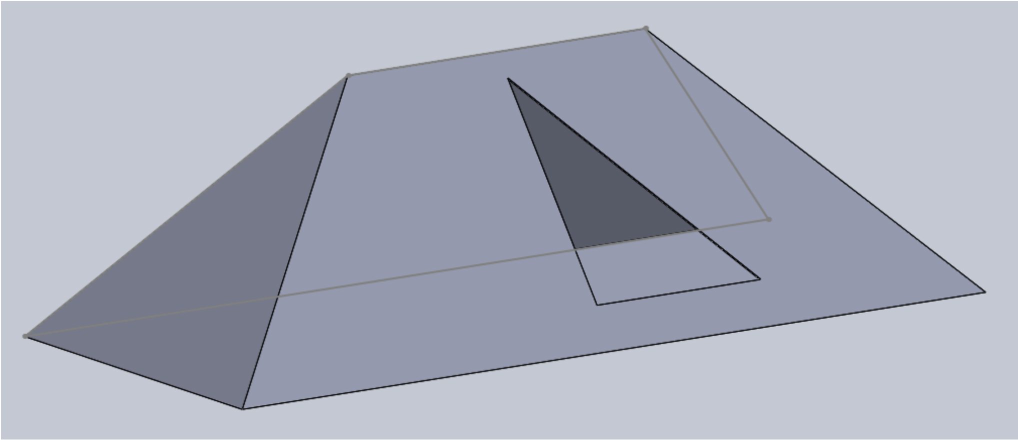


Figure 29. *Representation of grafting chamber, shown with flap open for clarity, used in thermal analysis.*

For the simulation with the heating pads, the three heating pads were modelled as rectangular prisms made out of silicon. The silicon has a thermal conductivity of 124 W/mK. The tent enclosure material was selected to be rubber to mimic the silicone coated polyester fabric that will be used. This has a thermal conductivity of 0.14 W/mK. Lastly, to determine the temperature gradient inside the tent, the volume inside was selected to be air with a thermal conductivity of 0.027 W/mK. The top faces of the heating pads were selected to be heat sources of 20W and the convection along the faces was modelled with a convection heat transfer coefficient of 10 W/m^2K with an ambient temperature of 293K.

For the simulation with a space heater, the material of the heater was chosen to be chromium copper with a thermal conductivity of 171W/mK and an emissivity of 0.75. For this simulation, radiation from the space heater provided heat with a view factor of 1 because the tent encloses the entire space heater. The temperature of the space heater was assumed to be 373K. Similarly, air and rubber were used to represent the space in the tent and the tent itself, respectively. A convection heat transfer coefficient of 10 W/m^2K with an ambient temperature of 293K was also used.

The results of the two analyses are shown below in Figure 30 and Figure 31. Additional images are provided in Appendix E.

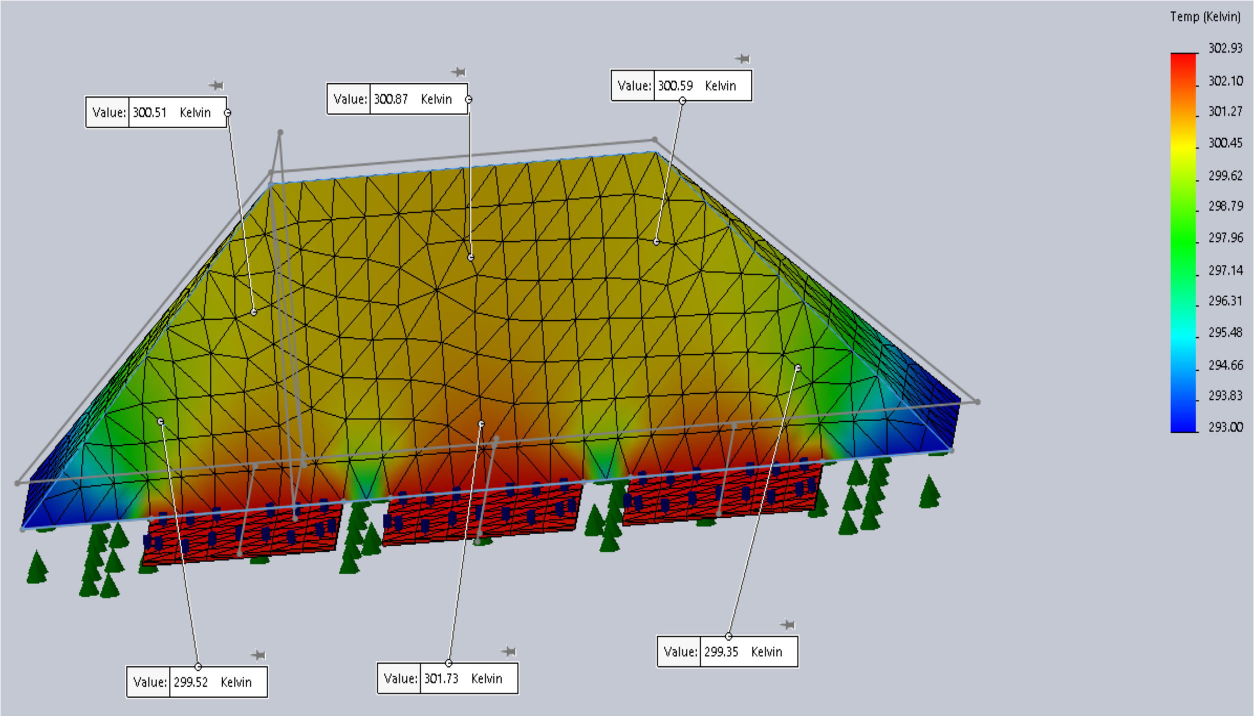


Figure 30. *Result of simulated thermal analysis: heating pads with probes at 6 locations throughout the chamber. The top row of probes from left to right reads: 300.51K, 300.87K, 300.59. The bottom row of probes from left to right reads: 299.52K, 301.73K, 299.35K.*

As shown in Figure 30, the bulk of the air inside the grafting chamber was heated to ~300K. This is within the specified range of ambient temperatures required to produce healthy grafts [1]. As expected, heat propagation throughout the grafting chamber is non-uniform, as the geometry of the heating pads is conducive to warming the air directly above them. As such, the coolest areas in the chamber are located in its lower corners. It is expected that this disparity will become more apparent when the misting system is installed in the chamber as introduction of room temperature water at the edges of the chamber will lead to a greater temperature differential within the chamber.

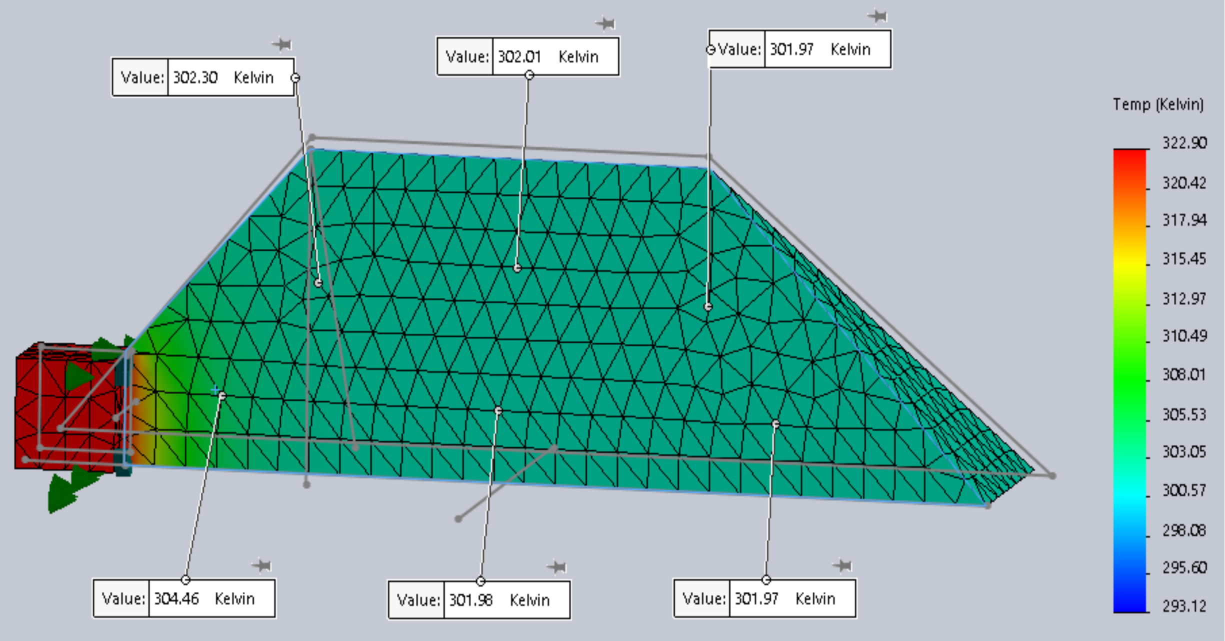


***Figure 31**. Result of simulated thermal analysis: space heater with probes at 6 locations throughout the chamber. The top row of probes from left to right reads: 302.30K, 302.01K, 301.97. The bottom row of probes from left to right reads: 304.46K, 301.90K, 301.97K.*

Figure 31 yields similar temperature data to that of Figure 30. Here, the bulk of the air inside the grafting chamber was again heated to a suitable temperature, slightly higher: ~302K. However, the simulation utilizing the space heater achieved a more even temperature distribution throughout the entirety of the grafting chamber. While the coolest location in the chamber was behind the space heater, airflow created by the space heaters integrated fan will likely alleviate a portion of this difference. This motion of air also encourages even temperature distribution throughout the chamber.

The thermal simulations were verified through a series of hand calculations. Hand calculations were conducted to find the temperature at the plant location, the total surface area of the chamber, and the heat transfer through the chamber wall. These calculations can be seen in Appendices E4 - E6, E7, and E8 respectively, and yielded an ambient chamber temperature of 302K.

Computational Fluid Dynamics Air Flow Analysis

As it had been determined to incorporate a space heater as the chamber's heating element, further simulation using the SolidWorks add-in FlowSim, modeled the air circulation within the chamber for a variety of fan configurations in order to determine if an additional air circulation component was necessary. Here, the three configurations include: (1) no additional fan, (2) an additional fan placed directly in front of the space heater, and (3) an additional fan placed separate from the space heater. The fan is modeled as a 4 inch square, 10 watt DC fan and all instances of the model also include our space heater model's integrated 15 watt fan. The results of this study are shown in Figure 32.

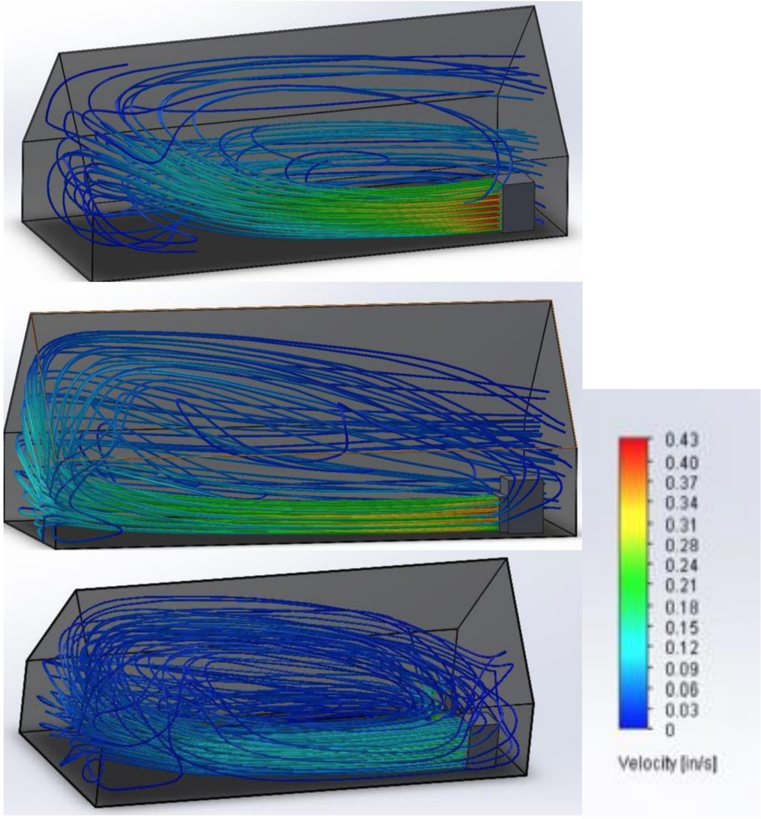


Figure 32. *Results of air flow analysis for three fan configurations: (top) no additional fan; (middle) additional 10 W fan in front of heater; (bottom) additional 10 W fan offset from heater.*

The results of the study are in accordance with expectation. Here, the addition of a fan directly in line with the space heater encourages air propagation along the axis perpendicular to the space heater's face of a magnitude greater than that in the heater's absence. Additionally, the third configuration shows a greater distribution of air flow in axes which are not directly in line with the space heater as the additional fan was offset from the heater in this configuration.

An important note must be made regarding the magnitude of the results of this study. In all configurations, the maximum airspeed does not exceed 1 mile per hour. At this scale, the addition of a 10 watt fan is largely insignificant. Here, in place of purchasing and incorporating additional components, in accordance with our design philosophy, we elected to perform a physical test using our space heater alone, and found it sufficient to maintain the necessary temperature conditions required to produce healthy grafts.

Heat Loss Modeling

Heat transfer modeling using the multi-physics platform COMSOL, indicated the expected heat loss through the grafting chamber walls as a result of the temperature difference between the interior and exterior of the chamber. Given that the desired interior temperature is a known value based on the healing specifications for the plants, the heat transfer rate can be found based on the thermal conductivity of the silicone-coated polyester enclosure material.

This analysis was based on the determined R-value (insulation) of 6.8 Km^2/W associated with the enclosure material, and its total exposed area ~4 square meters. The experiment was conducted assuming a 10˚C temperature differential between the target (inner) temperature, and the ambient (outer) temperature. The results of this analysis are shown below, in Figure 33.

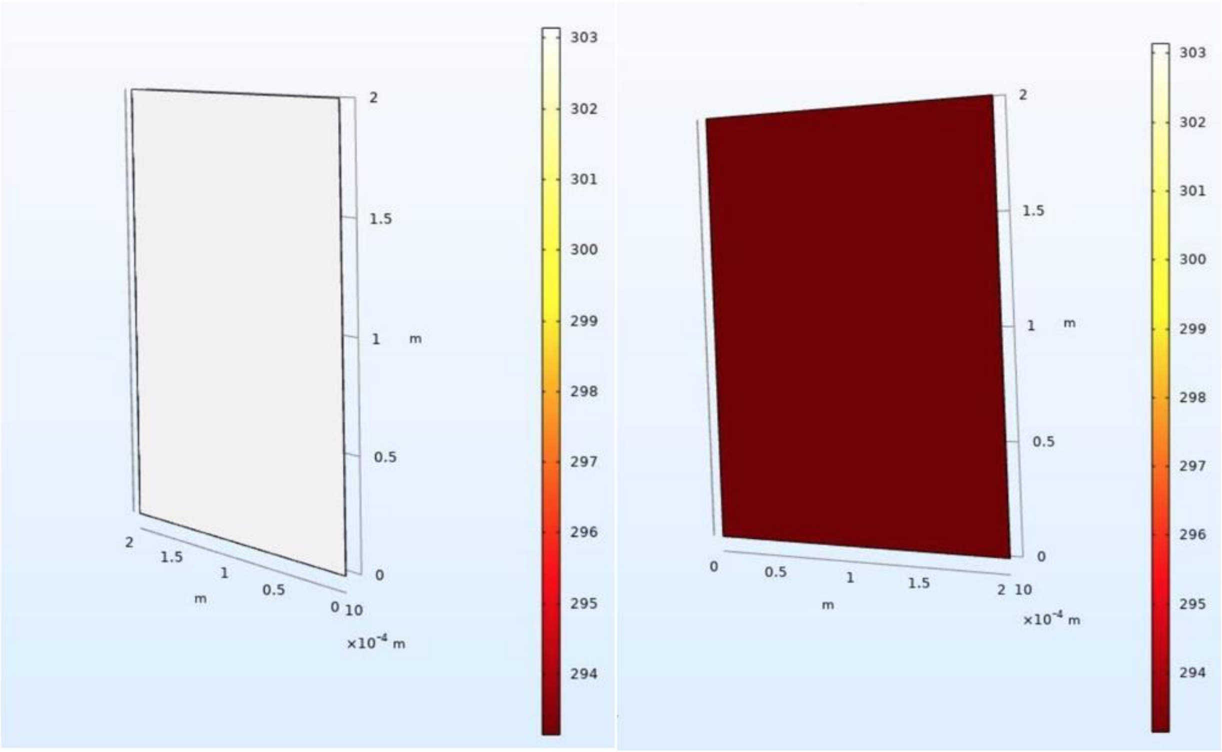


Figure 33. *Results of heat transfer analysis for the interior (left) and exterior (right) chamber walls with a 10ºC temperature differential, yielding q ≈ 5 W/s.*

The results of the analysis shown in Figure 33 are in accordance with hand calculations shown in Figure E8 of Appendix E, and assisted in determining the appropriate wattage for our space heater, such that it can adequately heat the enclosed space.

Junction Analysis

One of the main factors in deciding between prototype 1 and prototype 2 was the robustness of the structure. Prototype 1 used a knuckle, push to connect fitting that would allow the garden hoop to be set into the top. Figure 34 shows the connection.

Figure 34. *Prototype 1 structure fitting including push to connect fitting nested in a PVC pipe, with a garden hoop set on top.*

It was clear from trying to move the structure, and watching it experience small wind gusts, that these junctions were not sturdy. The green garden hoops would often pop out of the knuckles, causing the structure to collapse. These observations led us to reassess the structure and begin designing a new prototype.

Our second prototype was made entirely out of PVC components. By using uniform material, we were able to ensure proper fittings for the joint. One of the main downfalls of the first prototype was the loose nature of the garden hoop in the PVC frame.

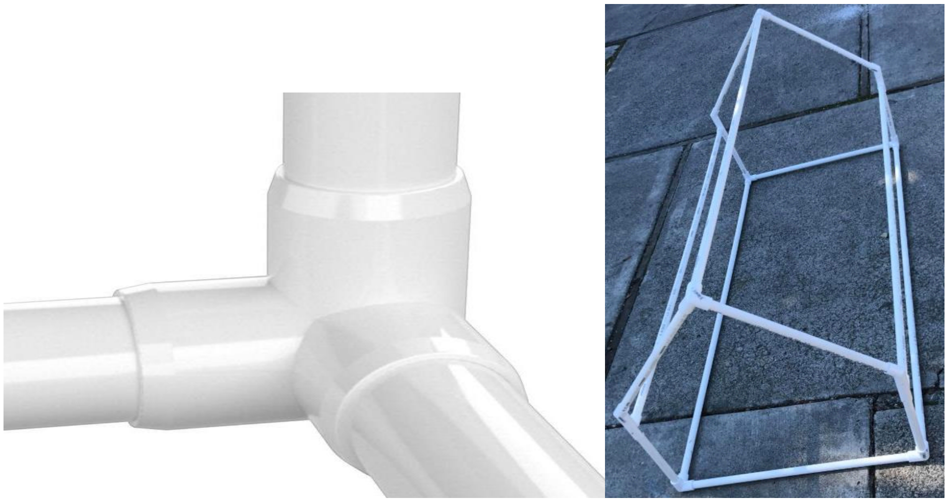
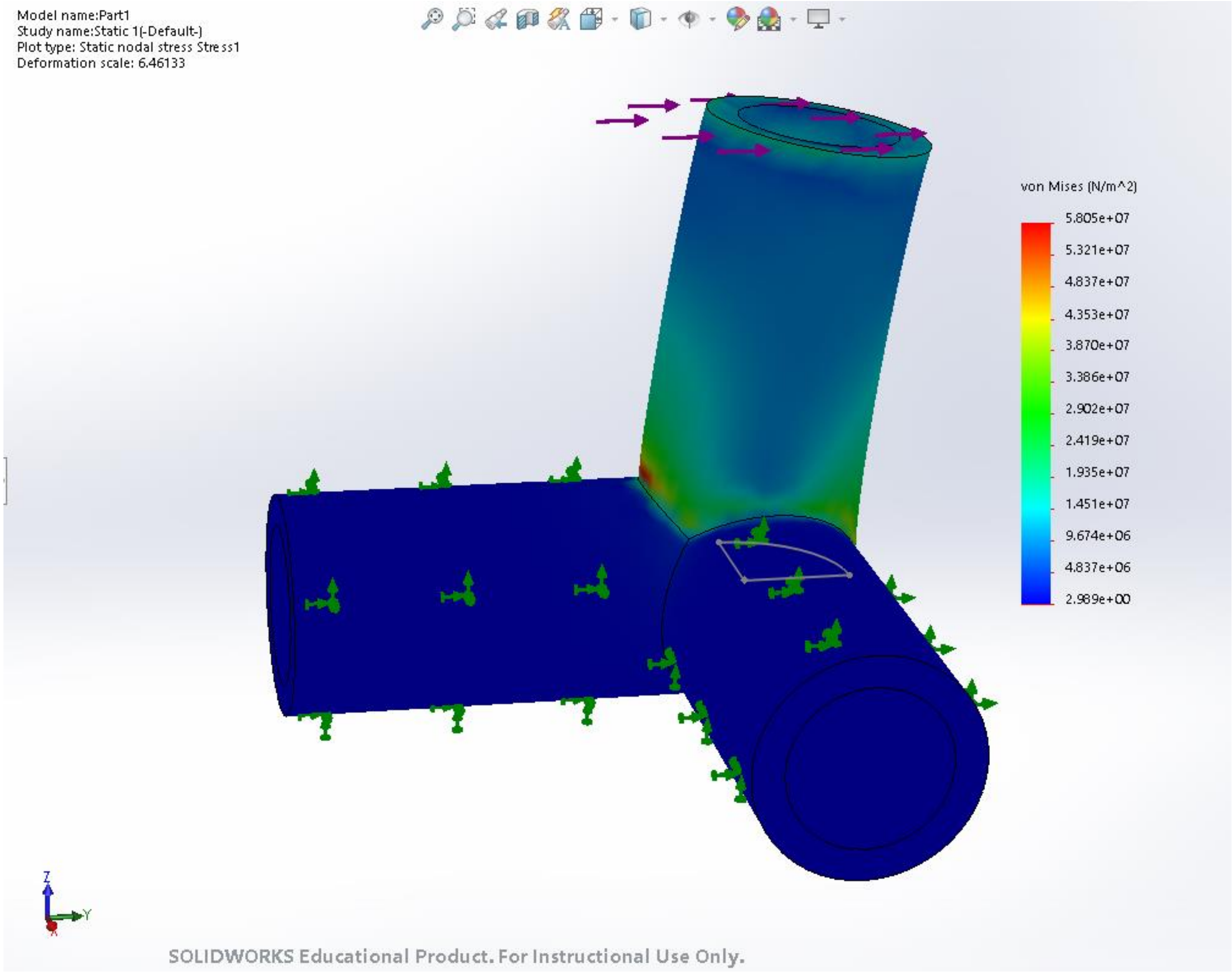


Figure 35. *PVC elbow and pipes makeup the second structure prototype.*

The ½” PVC material provided a sturdy structure that could withstand wind gusts and could be easily moved around without falling apart. We ran a basic force analysis on the junction shown in Figure 35 to prove that it could withstand any potential higher-than-expected forces. This simulation is seen in Figure 36.



Model name:Part1
Study name:Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 6.46133

Figure 36. *Static analysis on junction from prototype 2.*

While this is not necessarily relevant to our project, as the system is not intended to be load bearing, it helps show that the second prototype is more robust. It is also important to note that we could not use any glue for the junctions, as one of our criteria for design was to create an easily collapsible chamber. Another note that we considered when deciding to move forward with the second prototype was the fact that the garden hoops were starting to show signs of rust. In order to create a chamber exhibiting longevity, PVC was the better option.

5. System Integration, Testing, and Results

After building the second prototype, and before fully implementing the control systems, baseline data was collected in order to compare with the data from the fully active, integrated chamber. This section contains information regarding the methods and scope of prototype testing.

Experimental Protocol

To prove that our grafting chamber was more effective than the basic, traditional techniques, we decided to conduct multiple different tests. First, we wanted to take a baseline test to show what the temperature and humidity cycles were inside of the empty chamber. Then, we moved on to passive tests. We wanted to see how the humidity and temperature were affected by a single, passive factor that was placed into the chamber. This included placing a block of floral foam, humidipacks, and a tray filled with water inside the chamber. Lastly, we conducted active tests that used our system's heater and misting system to automatically control the environmental conditions. We did not get the chance to run a full 10-day active cycle, but from the data we were able to collect, we could prove that the ideal temperature and humidity values were better maintained by the active control.

With each test performed, we recorded at least two days' worth of data, with the frequency of readings at 1 per minute. This would allow us to analyze how the environmental conditions changed from early morning to late at night. This data helped us decide how big of a heater was needed, how often it would need to be turned on, and how often we needed to mist the system to ensure the ideal temperature and humidity range was maintained.

Anomaly Detection

When performing these tests, we soon realized that the DHT22 sensors would often record very inaccurate temperature and humidity values (i.e., negative relative humidity) at random times. We decided that this was either due to the fact that the sensors were being powered with a slightly lower voltage (3.3V) than recommended (3.5V) or that the sensors were cheaply made. Regardless of the reason, we decided as a group that in order to keep our project low cost, we would introduce anomaly detection code to the system instead of investing in a more expensive sensor with higher accuracy. To do this, we implemented a simple five step method that used the standard deviation of 10 previous measurements to decide whether or not a reading was an anomaly. The five steps are:

Step 1: Record initial 10 measurements.

Step 2: Calculate the standard deviation of the initial 10 measurements.

Step 3: If the next measurement is outside of 2 standard deviations from the last value, reject that value. If it is within 2 standard deviations, keep the value.

Step 4: Recalculate the standard deviation with the most recent 10 measurements

Step 5: Repeat steps 3 and 4 until data collection is complete.

We implemented this method for both temperature and humidity measurements for our data collection. Figure 37 shows a sample of temperature and humidity data without anomaly detection present while Figure 38 shows the same sample including anomaly detection.

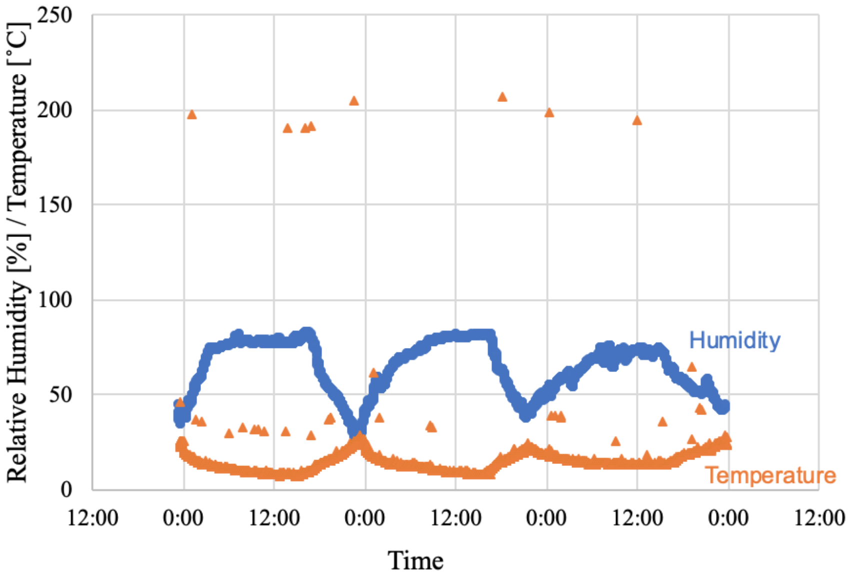


Figure 37. *Temperature and humidity versus time, without anomaly detection.*

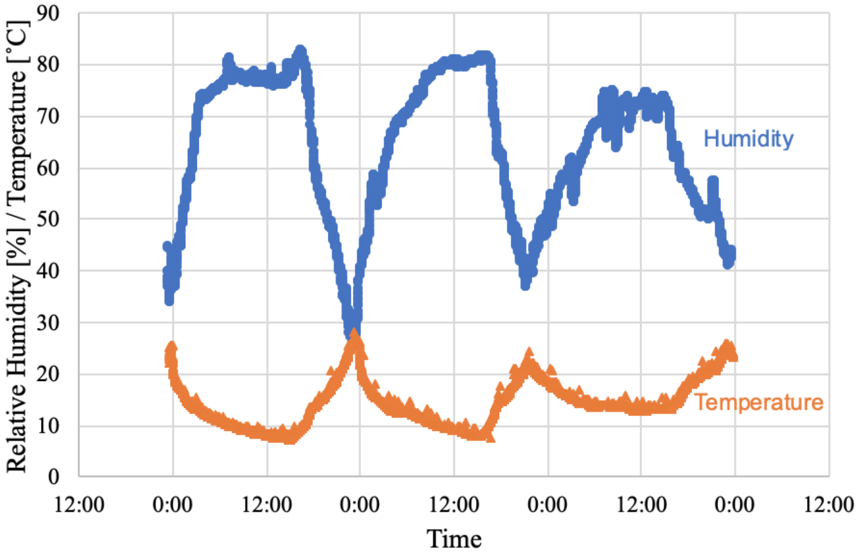


Figure 38. *Temperature and humidity versus time, with anomaly detection.*

Passive Control

In order to prove that our grafting chamber would be more effective than a traditional, DIY chamber with manual control, we ran a series of tests with various levels of control. First, we ran a baseline test to show the temperature and humidity cycles in an empty chamber over three days.

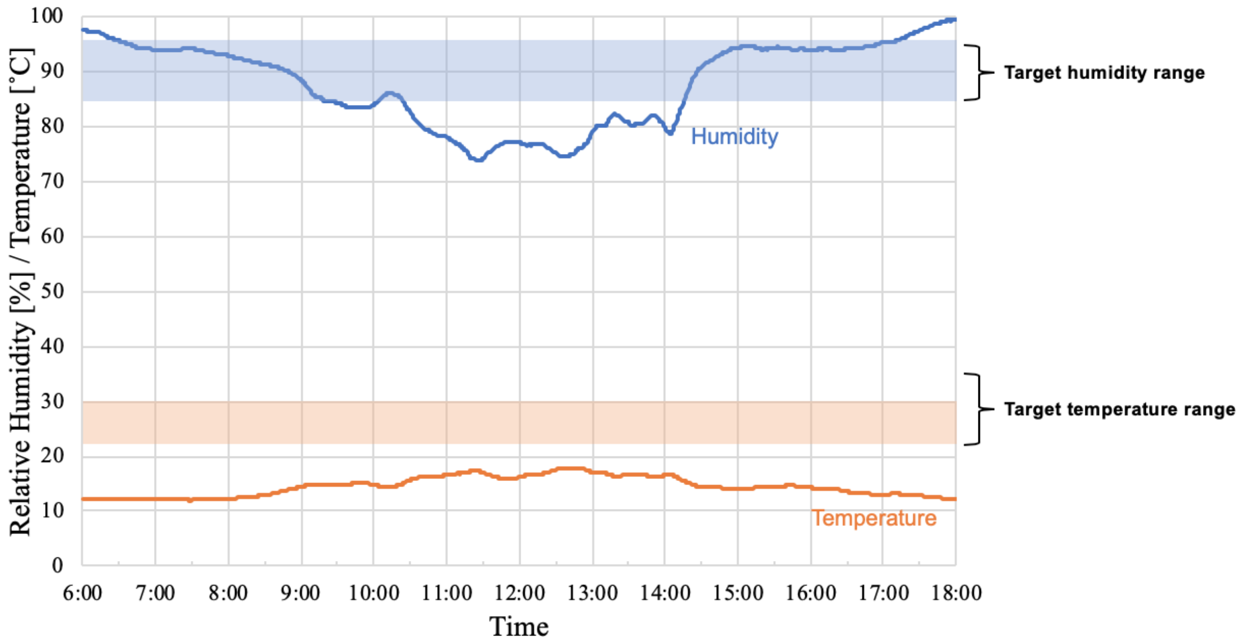


Figure 39. *Baseline test, with no control.*

Next, a series of passive tests were conducted. This was to show how a single, passive factor that was placed within the chamber would affect temperature and humidity. One of the first factors introduced was a tray of water sitting in the chamber. The thought behind this idea was that having a reservoir of water in the chamber would increase humidity.

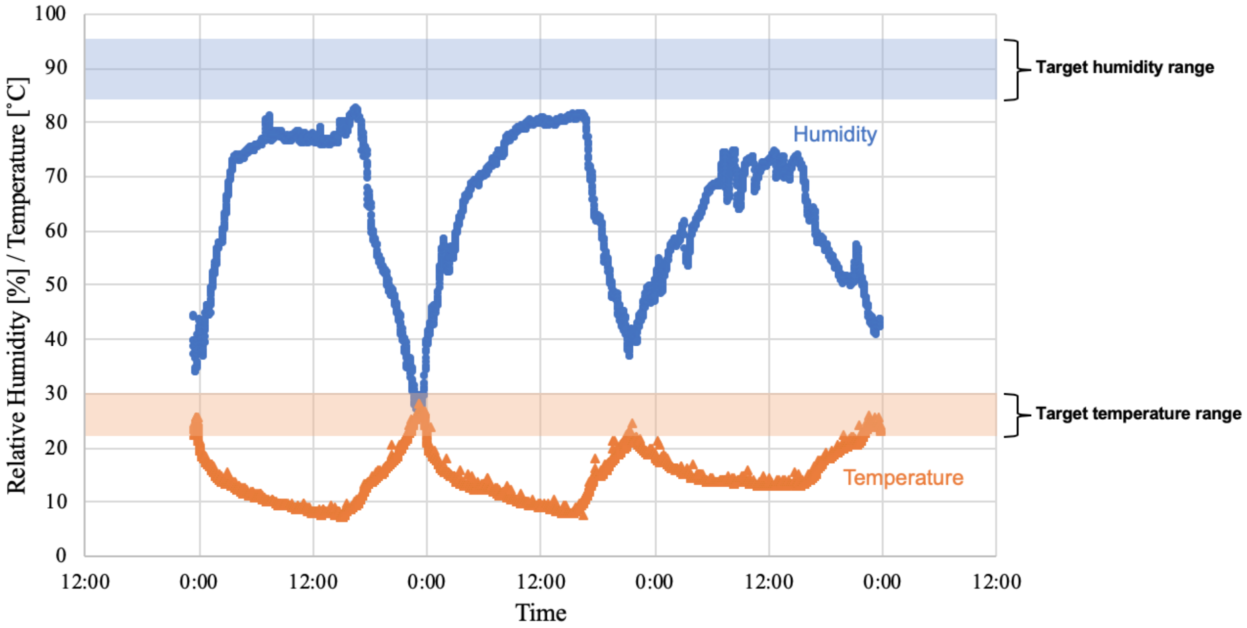


Figure 40. *Passive control with constant heat and water tray*

The next test included two chunks of floral foam that were soaked in water. The floral foam has small capillaries throughout the material that can hold water and release it gradually. There were complications in downloading and saving the data from the floral foam tests, so those are not included in this report. The final passive test that was supposed to be run was utilizing humidipacks. Humidipaks are often used to maintain humidity for cigars, but we wanted to use the same packets to see how they could maintain the humidity within the chamber.

Figure 41. *84% Humidipack that was to be used to run a passive test (reproduced without permission) [26].*

Due to the shelter in place restrictions, we were unable to complete the final test using humidipacks and therefore have do not have data on whether or not these packets are successful in maintaining humidity.

Active Control

The active control tests that we were able to do included a heater with fully automated control and a misting system that was manually operated. The code that the heater used to stay within the ideal range of temperatures is best illustrated by the flowchart below (Figure 42). This code proved to be effective as is shown in the plot below (Figure 43).

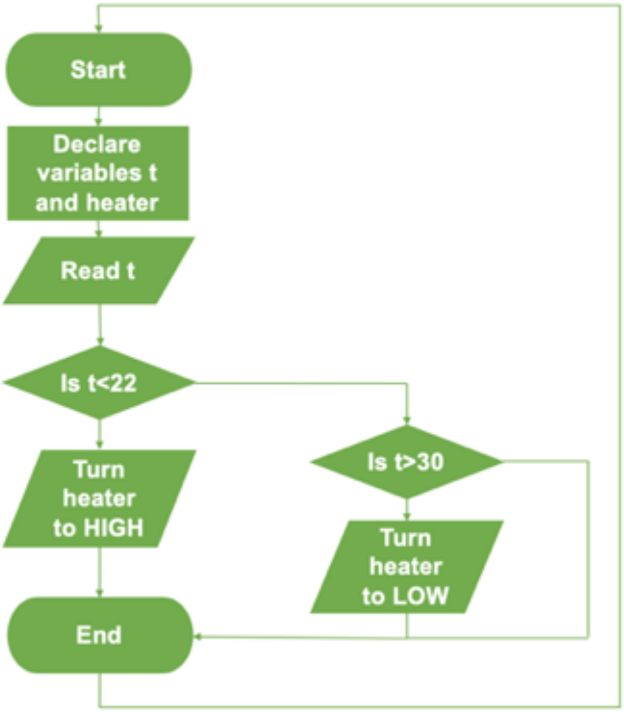


Figure 42. P*seudocode flowchart used for initial heater automation.*

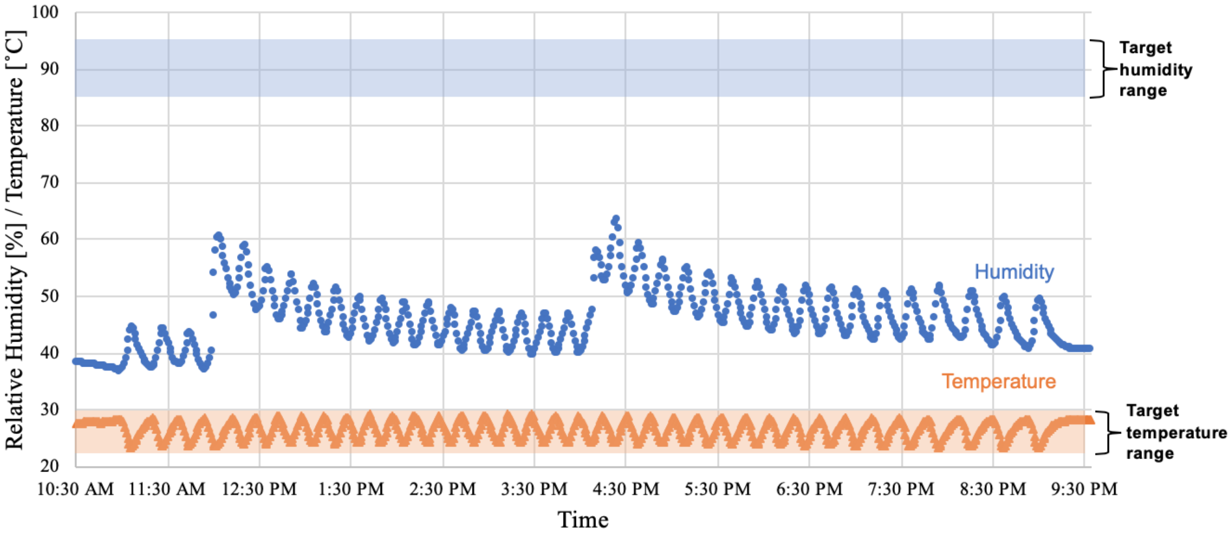


Figure 43. *Active heating and semi-active misting test.*

As shown the temperature stays within the desired range. This test had a duration of 36 hours, but this is just a 9 hour snapshot of what happened in the late morning to evening. The two major spikes in the humidity data is when the misting system was manually turned on. The next step of the project was to automate the misting system in order for it to be maintained within the ideal range. This would have required multiple tests to see how the duration and frequency of mists affected the humidity. With this data, a code similar to the heater's would have been implemented to turn the electronic valve on and off when necessary.

Comparison to Predictions

When we started this project our goals were to get both the temperature, humidity, and light exposure within the desired ranges. We were able to successfully do this with light exposure and temperature, but when the shelter-in-place order began we still were in the process of automating the misting system to control the humidity. However, we were able to find the ideal duration of mists as can be seen in Table 9 and mapped out an optimized schedule to keep the humidity within the range as can be seen in Figure 28. Because we were unable to perform any real healing periods with grafted plants, the only predictions we can compare to are ideal environmental conditions which were completely met in regards to temperature and mostly met for humidity.

6. Cost Analysis

This section of the report examines the expenses associated with the development of the grafting chamber. It includes a comprehensive bill of materials as well as an examination of the savings associated with prolonged use of a functional prototype.

Overall Prototype Cost and Budget

Here, project expenses are compared to allotted funding by the Santa Clara University (SCU) School of Engineering. This is shown in Table 10.

Table 10. *Funding v. total expenses.*

	Amount [USD]
SCU School of Engineering Funding	**2,000.00**
Total Project Expenses	**1,032.28**
Remaining Budget	**967.72**

The total project expenses are further broken down by subsystem, shown below in Table 11.

Table 11. *Total expenses by subsystem.*

Subsystem	**Cost of Subsystem Components [USD]**
Structural Elements	251.11
Sensor Array	112.88
Power System	267.74
Control System	400.55
TOTAL	**1,032.28**

A comprehensive bill of materials, separated by subsystem and including all purchases, is available in Appendix G.

Projected Savings

A grafting chamber of the type presented in this report can prove to be both a labor saving and cost reducing device. Here, a self-regulating environment dramatically reduces the amount of labor required to oversee the healing process. Also, due to the difficulty associated with producing healthy grafts as a result of the specific environmental requirements, grafted plants can be quite lucrative, typically costing ~5.00 USD [1]. As grafted seedlings typically cost <1.00 USD, there are significant cost savings associated with grafting at home [1].

To quantify the relationship between the value of the grafting chamber and the upfront cost associated with its development, a projected savings chart was generated and is shown in Figure 44. This comparison was performed beginning with the negative cash flow associated with the total cost of development: 1032.28 USD. Cumulative savings were calculated assuming (1) the saved labor from one employee being paid 15.00 USD/hr who would no longer be required to check on the plants for a duration of 1 hr each day over the course of the 10 day grafting cycle, and (2) the direct savings of 4.00 USD/plant associated with grafting at home.

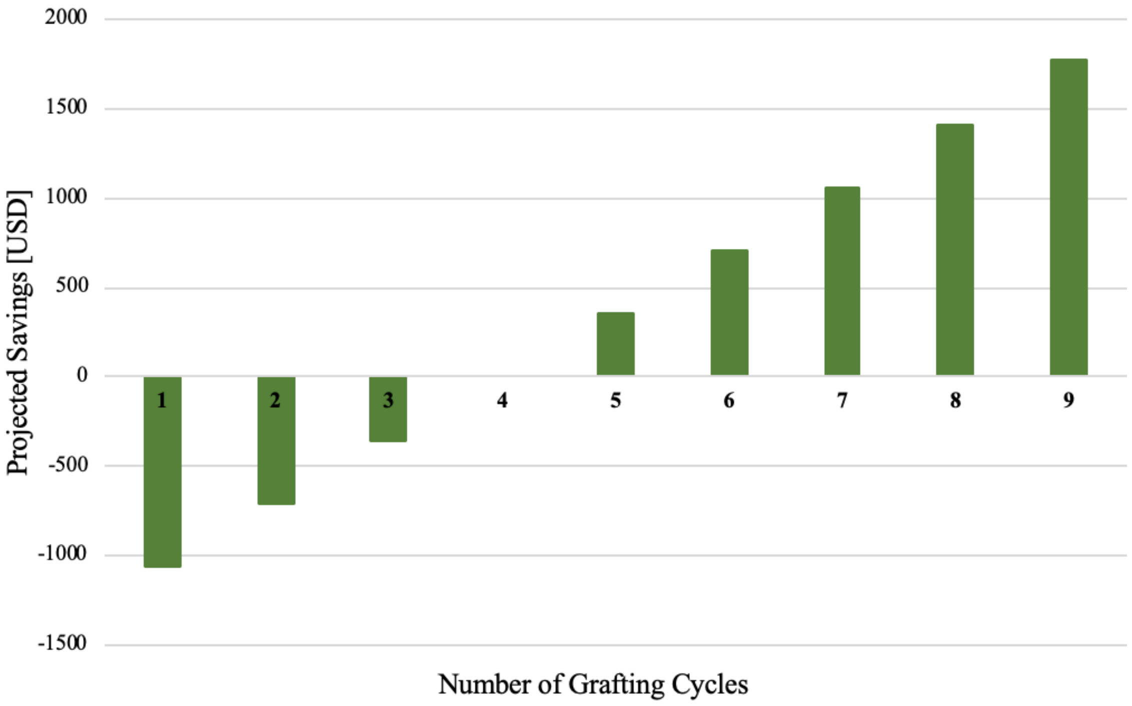


Figure 44. *Projected savings and payback period for grafting chamber development.*

Figure 44 shows that given the assumptions stated above, the development cost associated with creating a functional prototype can be recouped in four grafting cycles (~40 days).

7. Business Plan

Our company is built around a rapidly deployable, completely self-regulating grafting chamber. The target market is small-scale agricultural operations and the main competitor is simple DIY grafting techniques. In order to consistently have 100 chambers in stock being sold at $350 per chamber, the company would require an initial investment of $126,000 over three and a half years. However, It will only take a year for the business to produce positive period cash flow. The grafting chamber modernizes a fundamental agricultural technique that has previously only been readily available to large scale farming operations.

GraftThis, a project aimed to develop and produce a rapidly deployable grafting chamber, hopes to increase accessibility to the technology of grafting for small scale farms. Grafting allows farmers to combine a disease or drought resistant root-stock to a plant with a desired fruit. For example, heirloom tomatoes are not very resistant to common soil-borne diseases, therefore by grafting the top of the plant, also known as the scion, to a disease resistant root-stock, the yield will be more much hardier and abundant.

Due to the fact that large scale farmers have already adopted many modernized agricultural techniques, this project aims to assist small scale farmers. While the primary customer for this project is the Forge, the organic garden at Santa Clara University, a grafting chamber of this scale can be used by a large range of farmers. This grafting chamber can be used in a home garden, and it could also be used in small scale agricultural businesses. More specifically, the target audience for this project is agricultural operations with less than 100,000 USD annual sales, or approximately two hectares of land.

Healing grafted plants has been a historically challenging undertaking due to the strict temperature and humidity requirements associated with successful healing. As such, grafted seedlings are quite lucrative, typically costing ~$5 USD while ungrafted seedlings cost a fraction of that amount [1]. In order to avoid this recurring expense, many small-scale farmers have opted to generate their own grafted seedlings. However, the same stringent environmental conditions which drive the high cost of grafted seedlings also mean that grafting at home is a labor intensive process. Few automated solutions exist to assist in this process. Thus, the competition in this market is minimal and only exists as similar products (see competitors section). While there are many components that make up the grafting chamber, only a few employees will be needed to run the business. The most work will go into the development stage, but after that production will be efficient and require minimal labor.

Goals and Objectives

The biggest goal of the company is to produce a grafting chamber that allows small scale farming operations to effectively and sustainably graft plants on site. We hope this product incentivizes farmers to choose to graft disease resistant rootstock onto their existing crops instead of relying on common pesticide and herbicide techniques.

We also want to be able to sell the product at a low and affordable cost. Since we are looking at selling to a market of smaller scale farms, we understand that expensive technology is not a reasonable investment, which is why the structure is constructed entirely from off the shelf PVC components and we will be headquartered in a relatively cheap location in the United States. We also believe that a lot of the initial costs will quickly be offset by the lucrative nature of producing healthy grafted plants.

Product Description

As mentioned in the introduction, our product is a rapidly deployable, completely self-regulating grafting chamber. Grafting is an ancient agricultural technique that has never been automated in this sense. The grafting chamber allows people with minimal knowledge of the grafting process to produce healthy and sustainable grafts with ease.

Once the PVC and electronics system is assembled, all one needs to do is place the newly cut plants into the chamber, and turn on the system. Because the system is fully automated, the chamber takes care of the entire 10 day grafting period. The heating and misting system regulates the temperature and humidity to ensure it stays within the ideal range. Using the Blynk app, the user can view the live environmental conditions to ensure the chamber is working as intended. Once the cycle is complete the plants can be transferred to where they will permanently reside and the system can be turned off, collapsed, and stored until the next time it is needed.

Target Market

The primary market for the grafting chamber is in small-scale agricultural operations which the USDA defines as those with less that 100,000 USD in annual sales or occupying less than 2 hectares of land [27]. Farms of this size constitute between sixty and ninety percent of the total number of farms globally, with the numbers even higher among organic farms [28]. As such, the majority of farmers are without access to anything but a novelty grafting process.

Grafting is both desirable and ubiquitous. Jacob Shogren, a grower at the AgTech start-up OnePointOne notes that, “grafting is immensely important in agriculture in general” and “the hardest part about grafting is being precise and consistent” [18]. In order to try and achieve this replicability, adoption rates for technology in agriculture have been consistently increasing over the past few decades, with the field known as “precision agriculture” currently occupying a 5+ billion dollar market with projections as high as 10 billion by 2024 [29].

The earliest adopters of these technologies have been farms which occupy and operate on the greatest share of cropland acres, and as such, there is an opportunity to join the future of agriculture and address a market with minimal competition.

Competitors

As our grafting chamber targets a largely unaddressed market, there are few true competitors. Existing products tend to serve individual niche plant owners, or large scale agricultural operations. Here, automated terrariums such as the EcoQube, Biopod, and HPotter are designed to contain an individual, or small number of plants allowing hobbyists to grow plants outside of their preferred climates [30]. These devices typically retail between \$100 - \$300 USD. These “micro greenhouses” are limited by their size and high price point. On the opposite end of the spectrum, retrofitting kits for commercial greenhouses are available with varying degrees of automation. Companies such as koolfog™ offer fully automated solutions which are available at over \$10,000 USD, a capable system but far too expensive for many considering grafting [31].

Given the limited range of turnkey solutions, most small-scale farms opt for a D.I.Y. style grafting method, modifying raised beds or planting in containers to attempt to regulate the environment sufficiently so as to promote graft healing. As these grafting chambers are designed and built by the gardeners and farmers who will be using them, there is some degree of variation in size, shape, material, and technique used to maintain chamber conditions. Two such examples are shown in Figure 5 and Figure 6. These systems are typically constructed for ~\$100 USD and require routine attention to ensure proper functionality.

Sales and Marketing Strategies

As the primary consumers of this grafting chamber are those operating small scale agricultural operations, a review of purchasing patterns has yielded the following generalizations regarding this market base [12]:

- The typical consumer of this product could be described as:
    - Resourceful
    - Comes from a background other than engineering
    - Practical
    - Economical

These descriptions influenced the design of our grafting chamber, and should also be noted for their relevance to our sales and marketing strategy. As the majority of small scale farmers interested in grafting have constructed their own D.I.Y. system, offering a turnkey solution would prove viable insofar as it: (1) improved yield of successful grafts when compared to typical D.I.Y. systems, (2) fit the budget of the typical small-holder farmer, (3) is easy to operate and maintain. These elements include the way in which the chamber is to be described when marketed, primarily via paid promotions in the D.I.Y. community [13].

The two most common platforms for exchange of a system of this nature are the internet, and hardware stores. With a website offering a platform for remote orders, as well as shelved units at retailers such as Home Depot and Lowe’s, the majority of our market base could be reached without needing any dedicated storefront.

Manufacturing plans

The grafting chamber structure is built entirely from off the shelf PVC components. Also, many of the components can be bought in bulk from various retailers. The electronic assemblies contained within the chamber are relatively simple to wire together, therefore we would potentially contract this small part out to an external company. We will have a small number of employees who will then assemble the chamber kits, which includes the electronic assemblies, PVC pieces, a pre-sewn fabric casing, and more. In the early stages of the product release, we will only want to have about 200 chambers on hand. As we ramp up advertising and start reaching the smaller scale farms in rural areas, we will begin to increase production to meet the growing need.

Product Cost and Price

There is only a small overhead cost for the company, as there will be no formal store front. We will have to pay a small amount for an industrial garage for product assembly and preparation for shipping. In order to reduce cost, we will have this garage in a central, yet inexpensive region of the United States.

Table 12. *This table contains the cost of each component which was used to determine the sales price.*

Component	**Cost [USD]**
PVC Piping & Elbows	3.00
1.5 yards SilPoly	7.88
Zipper	0.50
Microcontroller	15.00
DHT Sensors	5.50
Lights	7.00
Heater	10.99
Misting system	3.99
Blynk app for user	20.99
Carrying case	10.00
Total cost of production	**84.85**
Sale Price	**350.00**

On top of the hardware costs, we will need to pay our employees an hourly wage, which depends on the minimum wage in the region. We decided to lease space in Denver, Colorado. We decided this as it is a central location within the United States, making shipping and service easier. Also, it has a relatively moderate cost of living.

Table 13. *This table shows the other expenditures for our business plan.*

Other Expenditures	Price
Rent	$66.67/month
Employee pay	$2,933/month
Total	$3,000/month

The inventory will start at around 20 chambers, and slowly as business begins to pick up, we will establish an inventory of 100 chambers.

Relative to other products, our price of $350 is very on target. While there is not an exact product comparison, the one similar product that we can compare to is an EcoQube. This product is about $150, but does not have even half the capacity that our product will provide. Therefore, our higher price is justified because we can heal many more grafts. In comparison to large industrial greenhouses that are maintained at the necessary conditions, our product is inexpensive. Equipping greenhouses with necessary sensors, heaters, and misting systems can cost thousands of dollars.

Service and Warranty

Our product will have a 1 year warranty guarantee. The chamber will ideally last much longer than one year, as it is only used a couple months out of the year, before peak growing season. Within the first year, all of the service will be paid for by the company. Due to the novelty of many of the components within the chamber, most repairs will be very inexpensive.

Any repairs to the structure or enclosure could be fixed with a new PVC pipe, or a small patch to the exterior. The most expensive repair would involve the microcontroller, but our service-people (the same people who assemble the kits) will be able to rule that out pretty easily. If and when there are problems with someone's product, we will have employees available for phone screening to determine what the problem is, and then that specific part can be shipped back to repair at the manufacturing site, or extra parts can be mailed to the customer.

Financial Plan

Selling price for the grafting chamber is estimated to be about \$350, and per-chamber profits would be around \$265. The cost of production per chamber is about \$85. This does not include the cost of any solar setup. Estimates for startup costs include \$3,000 for development over the first three months, \$1,000 for prototypes, and \$3,000 for manufacturing equipment. Manufacturing equipment includes a sewing machine, computers to develop the control algorithm, and equipment needed to build the structure. Each month there will be a fixed cost of \$3,000 dollars for advertising, promotion, inventory, and other costs. After three months of development, production and sales are expected to grow by five chambers and three chambers, respectively. We plan to start with an inventory of 20 grafting chambers after the first three months of development and have an initial monthly sales of 10 grafting chambers. Our maximum sales will be 30 grafting chambers per month and we plan to produce chambers until we have an inventory of 100 chambers. Once we have reached maximum inventory, we plan to produce chambers at the same rate that we sell them. Taking all of this into account, our business would require an investment of \$126,000 over three and a half years. The initial investment would be \$16,000 for the first three months, then it would be \$3000 per month after that. To obtain this money, we plan to look for investors to invest in our company and also to take out loans to start the business.

Using all of this information, we were able to make a cash flow diagram that shows the timeline for income and outflow. It will take about a year for the business to start to produce positive period cash flow, but from that point on, the cash flow will increase.

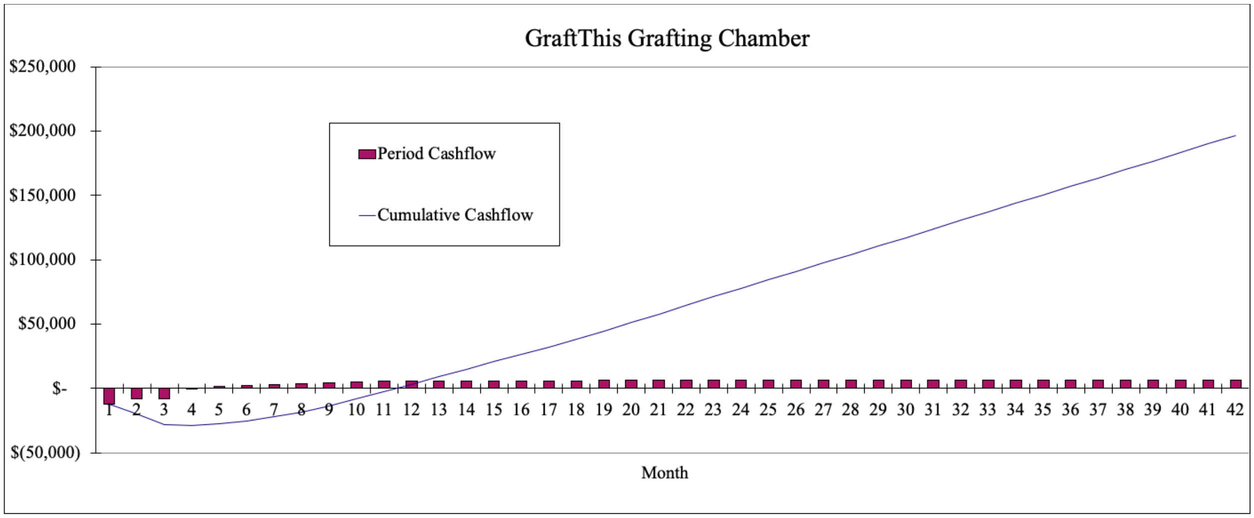


Figure 45. Cash flow diagram over 42 months for our grafting chamber.

After 42 months, our business will have made a significant net profit. With a $126,000 investment, the net present value of our business would be $147,000 and we would also have an inventory of 100 grafting chambers.

We plan to have 100 grafting chambers in inventory because if there is a halt in production, our inventory should be able to last more than three months. These three months should be enough time for our business to continue production. We chose to have three months of inventory because three months was the amount of time we allotted for development. In the worst case scenario, like a natural disaster, our business will be able to go through the development process again.

In the end, we believe our business is worth investing in because in only a few years, we will be able to make a substantial profit. Our product is also one that helps small scale agricultural businesses modernize their farming techniques. Grafting is also a sustainable technique that promotes organic farming. Not only will our customers be able to graft plants for themselves, they will also be able to sell any unused grafts to make a profit of their own. To conclude, our business will be able to improve the environment, help small businesses, and earn a profit.

8. Engineering Standards and Realistic Constraints

The grafting chamber fills a hole in the agricultural industry. While it is feasible for larger scale farmers to maintain the required conditions for graft healing, this is not possible for small scale, organic farmers. There are any economic and sustainable, as well as societal factors that our product will address.

Economic Factors

While developing our final design and business plan, the economic factors were large considerations. To ensure that the grafting chamber would be a solid investment, we created a low cost solution that had the capacity to produce 48 grafts per healing cycle. As mentioned in a previous section, the chamber can be used approximately three times per year at the beginning of the peak growing season. If we have a 100% success rate of graft healing, this would produce 144 grafts per year. Sold at $5 a piece, the total sale price for all of the grafts would be $720. We produced a cost effective solution for the market gap that is accessible to small scale farmers.

Agricultural and Sustainable Factors

Due to the fact that large scale farmers have already adopted many modernized agricultural techniques, this project aims to assist small scale farmers. While the primary customer for this project is the Forge, the organic garden at Santa Clara University, a grafting chamber of this scale can be used by a large range of farmers. This grafting chamber can be used in a home garden, and it could also be used in small scale agricultural businesses. More specifically, the target audience for this project is agricultural operations with less than 100,000 USD annual sales, or approximately two hectares of land. A grafting chamber will allow these customers to reduce the use of chemical soil additives, save space by collapsing the chamber when it is not in use, and reduce the required labor to graft plants by self-regulating the conditions inside the chamber.

Societal Impact

Over the past two decades, the field known as "precision agriculture" has seen a consistent increase as farmers across the United States and beyond incorporate increasingly modern technology into their agricultural processes with the hope of improving crop yield and sustainability while reducing cost. This trend can be seen in the adoption rates of several modern agricultural techniques as reported by the 2018 study whose results are shown in Figure 46.

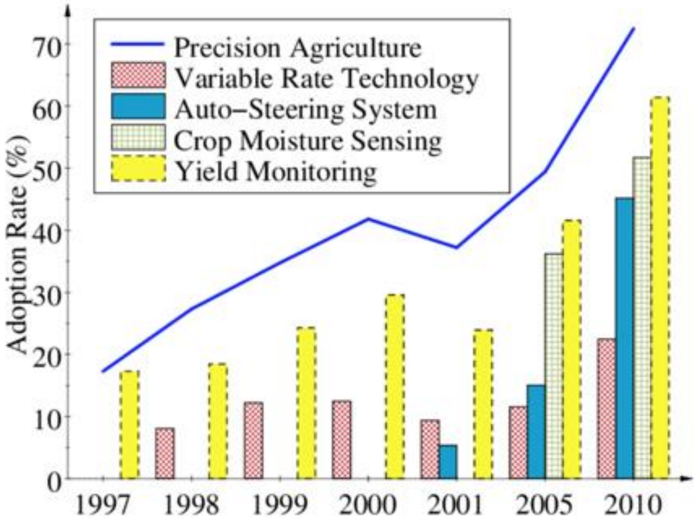


Figure 46. *Smart Farming Technologies Adoption Rates Over Time (reproduced without permission) [32].*

While this trend toward the modernization of agricultural techniques is broad, it is not evenly distributed. The earliest adopters of agricultural technology are large farms which utilize the majority of the available cropland acres. This disparity is shown in Figure 47.

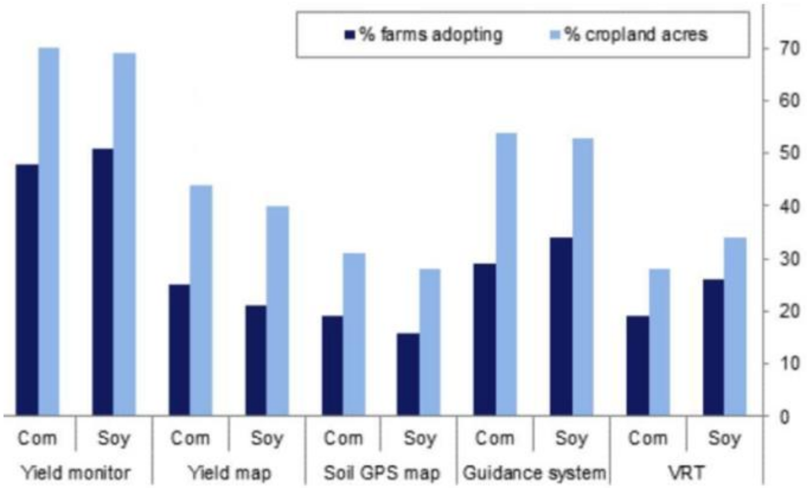


Figure 47. *Smart farming technologies adoption rates by sector (2016) (reproduced without permission) [33].*

Figure 46 and Figure 47 illustrate that despite its increasing adoption, precision agricultural techniques such as a self-regulating graft healing process are largely unavailable to the smallholder farmer.

Societal Repercussions

The benefits of grafted plant recovery can be tremendous. A study performed in Indonesia and published in the Asian Journal of Agricultural Research found survival rates between sixty and seventy percent for one month old whip grafts [34]. When the Santa Clara University Forge Garden sought to replicate these results using the same style of graft and age of seedling, a mere 4/50 grafts survived. The difference: the grafts from the Indonesian study healed in a nursery with remarkably consistent environmental conditions, whereas the grafts in the Forge Garden were healed in a small-scale DIY system. Figure 48 depicts the potential disparity in results.

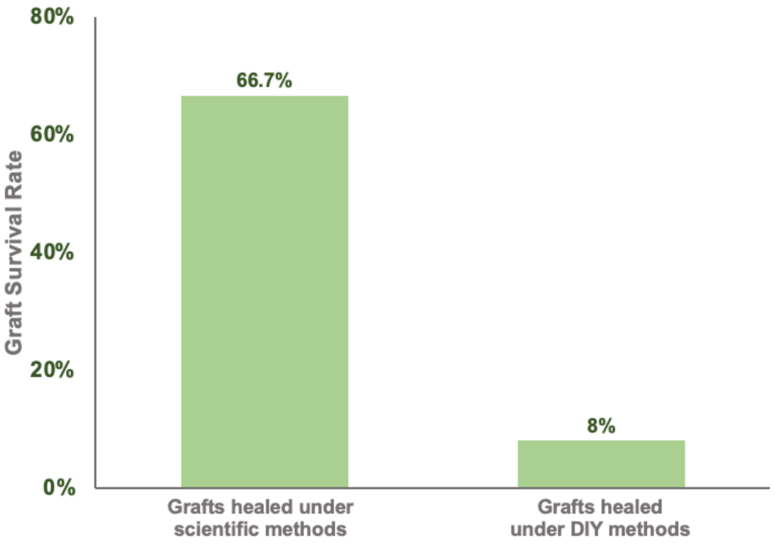


Figure 48. *Percentage of one-month old 'whip' grafts healed successfully using two methods (reproduced without permission) [34].*

Where scientific or commercial grade nurseries and greenhouses are unavailable, so too is consistent, replicable graft healing. Given that small farms constitute between sixty and ninety percent of the total number of farms globally, with the numbers even higher among organic farms, the majority of farmers are without access to anything but a novelty grafting process [35]. In this respect, this project has the potential to empower smallholder farmers with advanced grafting technology that has traditionally been limited to large-scale operations.

Environmental Impact

One of the most attractive outcomes of grafting is the ability to grow almost any plant without pesticides or herbicides. Grafting, which combines two types of plants with favorable characteristics, dramatically reduces the need for chemicals in gardening. While using pesticides might be the easier solution to address pests or disease in an agricultural setting, there is an overwhelming amount of hazards that can result from using synthetic chemicals [36].

Despite the tremendous benefits that pesticides might appear to provide, the chemicals used can have direct impacts on humans and the surrounding environment. Not only do pesticides kill weeds and unwanted insects, but they can be toxic to other organisms. This can include birds, fish, and insects that help the biodiversity of an environment. The chemicals can also seep into the water table and contaminate surrounding areas. It is near impossible to have synthetic chemicals only affect the target pest or disease without harming some other, non-targeted organism [36]. According to a comprehensive set of studies performed by the U.S. Geological Survey on dominant river basins across the United States, "more than 90 percent of water and fish samples from all streams contained one, or more often, several pesticides" [36].

Grafting allows farmers to cultivate crops with desirable traits and resistances without using any of these harmful chemicals. The positive impacts of avoiding synthetic chemical usage are plentiful. Whether that means cleaner groundwater, more fertile soil, or all around a healthier ecosystem.

After analyzing the effects that a grafting chamber will have on society, it is clear that its creation will be beneficial for many agricultural operations. It will open up many opportunities for smaller scale agricultural services by providing new technology that was not previously available. It also has a positive environmental impact by giving an alternative to herbicide and pesticide use. Overall, an easily deployable, self-regulating grafting chamber will have a positive impact on society and the environment.

User Experience

The grafting chamber will come in a kit with detailed instructions on how to assemble the PVC structure. The misting tubing will also be pre-setup so that it will only need to be placed along the top of the chamber and connected to a standard hose. The electronics will all be on a printed circuit board, so all that will need to be done is connecting the system to a power source when the grafting cycle is ready to be started.

To use the grafting chamber, you first need to cut both the scion and rootstock and clip them together using a grafting clip. This should be done 48 times because the chamber's capacity is 48 grafted plants. Once that is complete, all the plants are placed within the chamber and the electronics can be turned on, starting the healing period.

During the healing period, there is no work that needs to be done by the user. The user can connect the system with the Blynk app in order to have the live temperature and humidity data pushed to the phone. This allows the user to understand the environmental conditions within the chamber to ensure that the grafts are healing correctly. Once the cycle is complete, the temperature and humidity within the chamber will match ambient conditions, and then grafts can be transferred to soil in a garden.

Health and Safety

The grafting chamber allows small scale farming operations to use a healthier alternative to pesticides. By grafting disease resistant rootstock onto the plants that need protection from harmful diseases and bacteria, completely prevents the need for use of harmful chemicals. This promotes a healthier, more sustainable lifestyle.

The grafting chamber is a very safe system. If the user follows the instructions and correctly uses the waterproof housing to enclose the electronics system, then there is no risk to anyone's safety. Once the healing period is complete, the system automatically shuts off and can be unplugged to ensure maximum safety.

9. Summary and Conclusions

Our initial goal was to develop a rapidly deployable self-regulating grafting chamber to increase accessibility to the technology of grafting to small scale farms. While we were limited in our efforts to achieve this goal, we were able to show that an actively controlled grafting chamber would be able to maintain specific conditions more effectively than a non-active control system. We were fortunate to have had two prototypes built and the control system near completion. If we were able to have continued work, we would have fully implemented and tested the chamber with actual grafted plants in the Forge Garden.

Overall Design Evaluations

In this section we will evaluate the different components of our system and design. One component of our system is the structure. Our goal was to build a structure that could easily be deployed and is also collapsible. This would allow the user to store the chamber when it was not in use, so that they can still utilize the space. With these motivations, we were able to come up with our final structure that was made out of PVC piping parts. By using PVC, we were able to keep our costs low but also satisfy our needs of a easily deployable and collapsible structure. Our design was built for a specific customer, the organic garden at Santa Clara University, and we were successful in being able to build a structure that would fit in a designated space in the garden's greenhouse.

Another component of our system is the combination of the microcontroller, sensor array, and actuators. Grafting requires very specific conditions throughout the healing process. To maintain the conditions, our system implemented a sensor array and microcontroller that would be able to measure temperature and humidity. Using that information, we operated actuators to maintain the desired conditions. The three actuators that we implemented were a space heater, misting system, and light bulbs. By collecting data using our system to control the conditions inside our chamber, we were able to show that our design was capable of maintaining the desired conditions.

The last component of our system is the control system. We were able to devise a method that implemented a machine learning algorithm to predict the outdoor temperature so that we could operate our system more efficiently by using preheating. We also developed an optimal schedule for misting that would maintain the humidity within the desired range. Lastly, we used an AC light dimmer module that would gradually increase light exposure over time. To collect data for analysis and also to control our system we implemented an anomaly detection method that was very effective and removed unrealistic measurements. While each component of our system was successful, we believe there is room for improvement.

Suggestions for Improvement and Further Work

After evaluating the overall design of our project, although successful, we would like to mention some suggestions to improve our design and offer some potential ideas to further our work. The first possible area of improvement is the temperature control model. While we believe we have come up with a satisfactory method of predicting temperature to implement preheating, there are many opportunities to improve our forecast model. The current forecast model uses a regression method to predict temperature but there are many different methods that could be explored (i.e. K-NN, K-Means, Random Forest, ANN, etc.). Each method has its advantages and disadvantages and it would be helpful to compare them to see which would be best for our project. Another opportunity to improve our model would be to implement an algorithm that identifies the optimal inputs for our algorithm. We performed a "trial and error" process to decide the inputs but more complicated and effective methods exist (i.e. Genetical Swarm

Optimization, firefly optimization, particle swarm optimization, etc). A third opportunity that we did not get the chance to address is to get a deeper understanding of preheating. We were unable to optimize the preheating method and determine the best time to start preheating our system based on the temperature forecast and to what degree our system should be preheated to.

While our project focused on the grafting of heirloom tomatoes, there are many other types of plants that can be grafted, and each requires its own specific environmental conditions throughout the healing process. Another opportunity for further work is to develop a set of files that have preset temperature, humidity, and light exposure values that correspond to commonly grafted plants. The user could then select the file for their plant and upload it to the microcontroller. Furthermore, a final area for improvement and additional work is to make the grafting chamber more user-friendly. While our project can maintain the conditions required for grafting, a non-engineer may have trouble assembling and running the system on their own. To solve this issue, a user manual with clear assembly instructions would be helpful. Another possible opportunity to make the system more user-friendly would be to explore the capabilities of Blynk. While we were able to use Blynk to broadcast live data, there are many more functions that the app has to offer. One idea is to use Blynk as a remote manual operation vehicle. If the user would like to operate the misting system, there could be a button on the Blynk app that could allow them to do that using their mobile device.

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Appendix A: Customer needs

Transcript A1: Email interview with Jacob Shrogen from One Point One.

What does your company do?

OnePointOne is an aeroponic vertical farming startup that is working on a fully automated system to produce food more efficiently, using less water and zero pesticides.

How have you been able to automate any agricultural processes? What problems do you usually encounter and how do you solve them?

Our primary focus has been the automation of multiple steps in the production process, particularly seeding and moving plants around the facility. Due to the proprietary nature of this technology, I can't go into detail about the design/engineering of it.

Does your company graft plants? Why is grafting useful in agriculture? If your company does not graft plants, why not?

We are not currently doing any grafting, because we are focusing on growing leafy greens, which are not able to be grafted. In general, grafting is useful because it allows you to grow a crop (scion) with desirable traits (ie high quality fruits, high yield) on root tissue (rootstock) that confers resistance to disease and/or environmental stresses.

How much of a role does grafting play in your business or in the agriculture community in general?

As I said above, grafting does not currently play a role at my company, however, grafting is immensely important in agriculture in general. Virtually all fruit/nut trees as well as wine grapes in California are grafted.

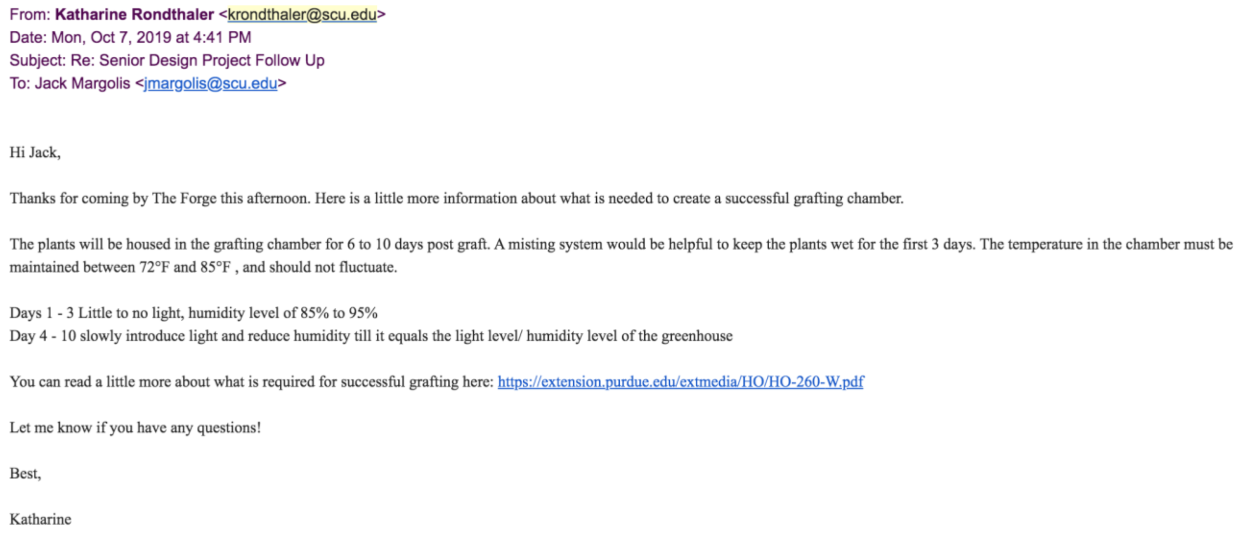
What are the benefits of grafting?

The benefits of grafting are that a rootstock can convey certain advantages to a scion, such as: disease resistance, increased tolerance to environmental stress as well as increased vigor. A good example of this is wine grape production. The different varieties of wine grapes (Vitis vinifera) are often grafted onto the rootstock of the native California grape (Vitis californica) or other species of grape native to North America. These native grape species are resistant to naturally occurring root mealybugs that can completely kill wine grapes when they are planted on their own roots.

What is the hardest part about grafting?

The hardest part about grafting is being precise enough and consistent enough that there is a high success rate over hundreds or thousands of plants. Grafting is a technique that requires a lot of practice to do well.

Transcript A2: Email conversation with Katharine Rondthaler, SCU Forge Garden Manager, regarding chamber specifications.



From: **Katharine Rondthaler** <krondthaler@scu.edu>
Date: Mon, Oct 7, 2019 at 4:41 PM
Subject: Re: Senior Design Project Follow Up
To: Jack Margolis <jmargolis@scu.edu>

Hi Jack,

Thanks for coming by The Forge this afternoon. Here is a little more information about what is needed to create a successful grafting chamber.

The plants will be housed in the grafting chamber for 6 to 10 days post graft. A misting system would be helpful to keep the plants wet for the first 3 days. The temperature in the chamber must be maintained between 72°F and 85°F , and should not fluctuate.

Days 1 - 3 Little to no light, humidity level of 85% to 95%
Day 4 - 10 slowly introduce light and reduce humidity till it equals the light level/ humidity level of the greenhouse

You can read a little more about what is required for successful grafting here: https://extension.purdue.edu/extmedia/HO/HO-260-W.pdf

Let me know if you have any questions!

Best,

Katharine

Appendix B: Key system level decision matrices

Table B1: *Design evaluation of proposed vertically and horizontally oriented grafting chambers held against an existing DIY system. Score columns represent the average of each of the four team member's individual scores on a (1-5) scale. Total scores are calculated as the sum of the scores multiplied by their corresponding weights.*

Need	Weight	Vertical Chamber Score	Horizontal Chamber Score	Existing DIY System
The chamber will maintain humidity between 85% and 95%	5	2.5	5	3
The chamber will maintain a temperature between 72°F and 85°F	5	2.5	4.5	3.25
The chamber can be reused for multiple grafting cycles	5	4.5	4.75	4
The chamber will be lightweight	4	2.75	3	4
The chamber is completely automated	4	4.5	4.5	1
The chamber is not high maintenance	4	3.25	3.75	1
The chamber is versatile	4	3.5	4	3.25
The chamber produces healthy grafts	4	3.5	4	2
The chamber doesn't take up too much space	3	3.25	3.75	3.5
The chamber is easily assembled	3	2.25	3.75	3.5
The chamber is quickly assembled	3	2.25	3.5	3.25
The chamber is easily collapsible	3	3.5	4.75	1
The chamber is compact	3	3	3.5	2.25
The chamber can hold a reasonable amount of grafts	3	3.75	4	3.5
The chamber will provide sufficient amount of light for the plants	3	3.5	3.75	2.25
The chamber can support multiple levels of grafts	2	5	1.5	1
The chamber will complete grafting process in a reasonable amount of time	2	5	5	4.75
The chamber will be affordable	2	2.25	2.75	5
The chamber can house plants of different weights	1	3.25	5	5

Total	206.6	252.8	180.5

Table B2: *Design evaluation of proposed grafting chambers frame shapes. Score columns represent the average of each of the four team member's individual scores on a (1-5) scale. Total scores are calculated as the sum of the scores multiplied by their corresponding weights.*

Need/Criteria	**Weight**	**PVC Rectangular prism Score**	**Row Cover Semi-Circle Score**	**PVC Pentagonal Prism Score**
The frame doesn't take up too much space	4	4	4	4
The frame is easily assembled	5	5	4	5
The frame is quickly assembled	4	5	5	4
The frame is readily collapsible	3	4	4	5
The assembled frame allows easy access to plants	5	3	2	5
The frame affords all plants adequate headroom	3	2	4	5
The chamber can hold sufficient grafts	4	5	5	5
The frame will be affordable	4	5	2	4
The frame will be durable	5	4	2	4
The chamber is versatile	3	4	3	4
The frame can be constructed with stock components	4	5	3	5
Components are easily replaceable	4	5	3	4
Chamber geometry prevents drips/water buildup	5	2	4	5
Number of people required to assemble	2	5	5	5
Total		226	191	251

Table B3: *Design evaluation of proposed microcontrollers. Score columns represent the average of each of the four team member's individual scores on a (1-5) scale. Total scores are calculated as the sum of the scores multiplied by their corresponding weights.*

Need/Criteria	**Weight**	**Photon Score**	**B.B.B.* Score**	**Arduino Score**
The microcontroller has suitable Inputs/Outputs	5	5	5	5
The microcontroller has built-in Wi-Fi capability	5	5	3	1
The microcontroller is affordable	4	4	3	4
The microcontroller is user-friendly	4	4	4	5
The microcontroller is compatible with remote monitoring	5	5	3	3
The microcontroller has sufficient local storage for machine learning data	5	5	4	4
The microcontroller is dependable	4	3	4	5
The team has experience with the microcontroller	2	3	5	4
The microcontroller has an established community for troubleshooting	3	5	5	5
The microcontroller has a user-friendly IDE	3	4	4	5
Microcontroller size (smaller is better)	4	5	3	3
IDE can be accessed from any device	4	5	3	3
Total		217	180	183

*Here, the abbreviation 'B.B.B.' stands for BeagleBone Black.

Appendix C: Preliminary sketches of subsystems and components

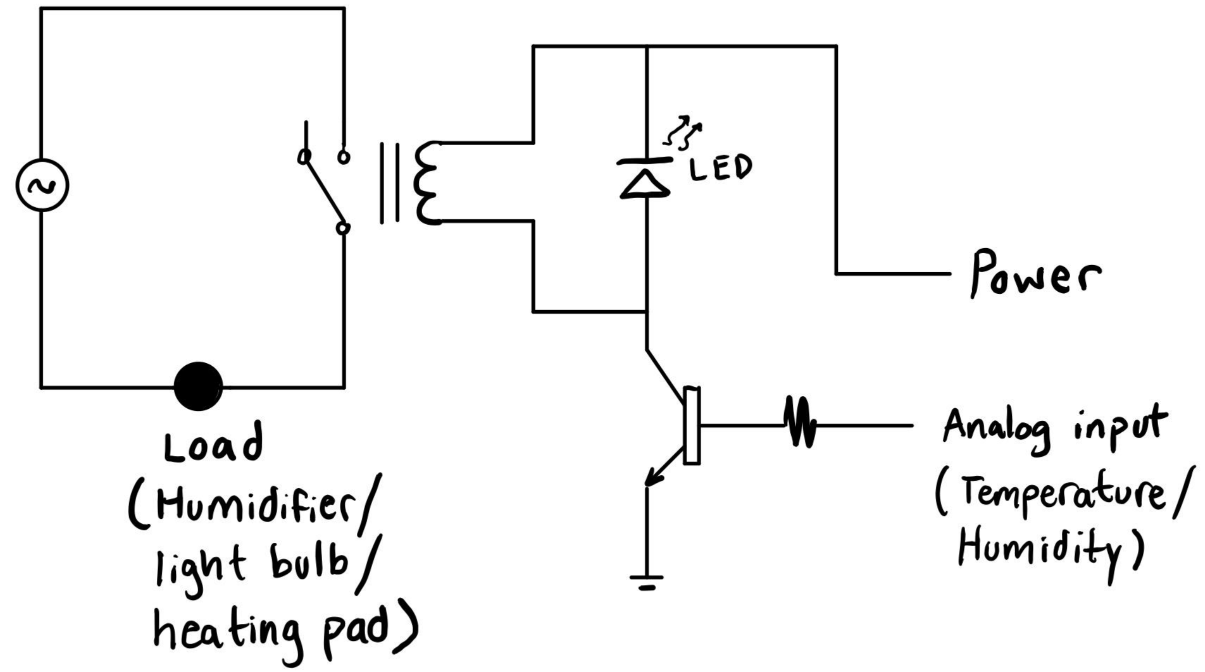


Figure C1: *Potential Circuit Diagram for operating the humidifier, light bulb, and heating pad using a relay and the microcontroller. Design by Kaleb Pattawi.*

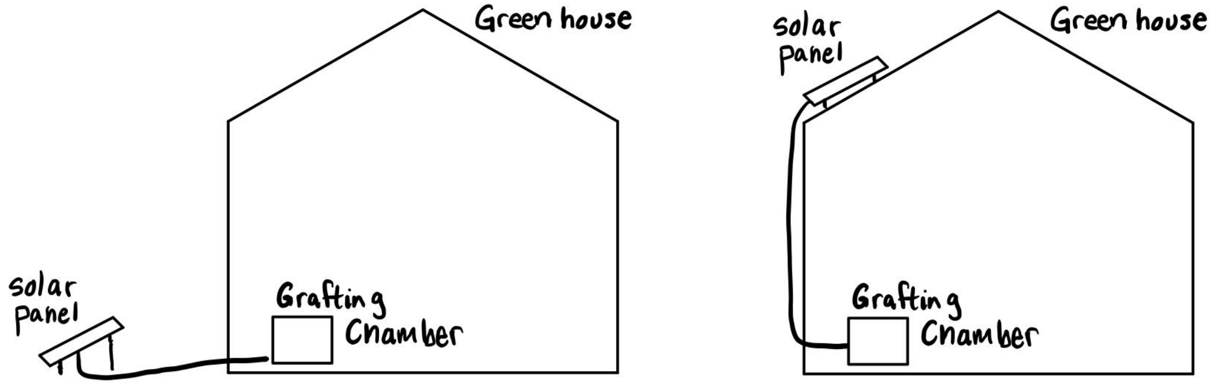


Figure C2: *Drawings of potential locations to install the solar panel for maximum solar irradiation. Design by Kaleb Pattawi.*

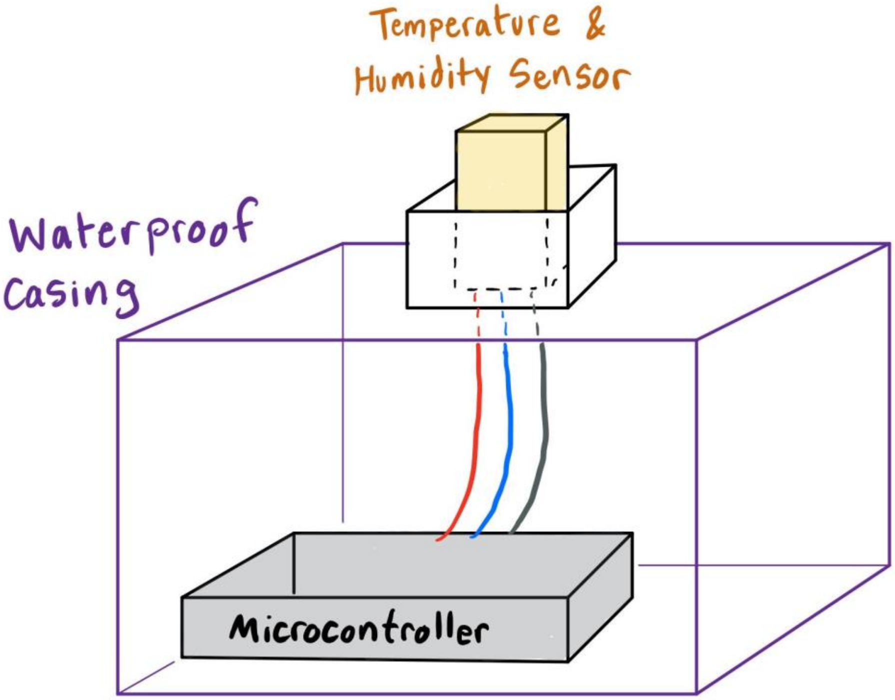


Figure C3: *Drawing of a potential waterproof casing for the microcontroller that can still allow the Temperature and Humidity sensor to collect data. Design by Kaleb Pattawi.*

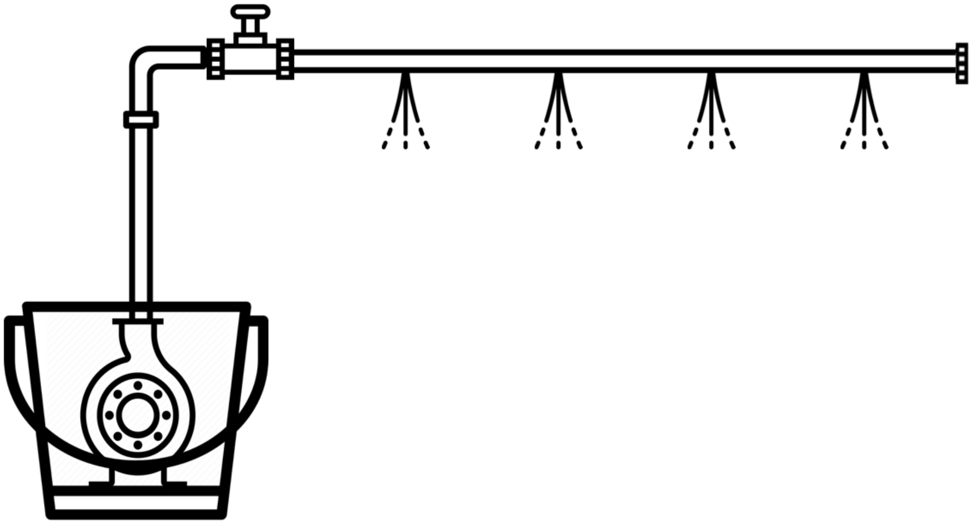


Figure C4: *Misting system concept including: water reservoir, pump, rigid tubing, valve, and misting orifices. Design by Jack Margolis.*

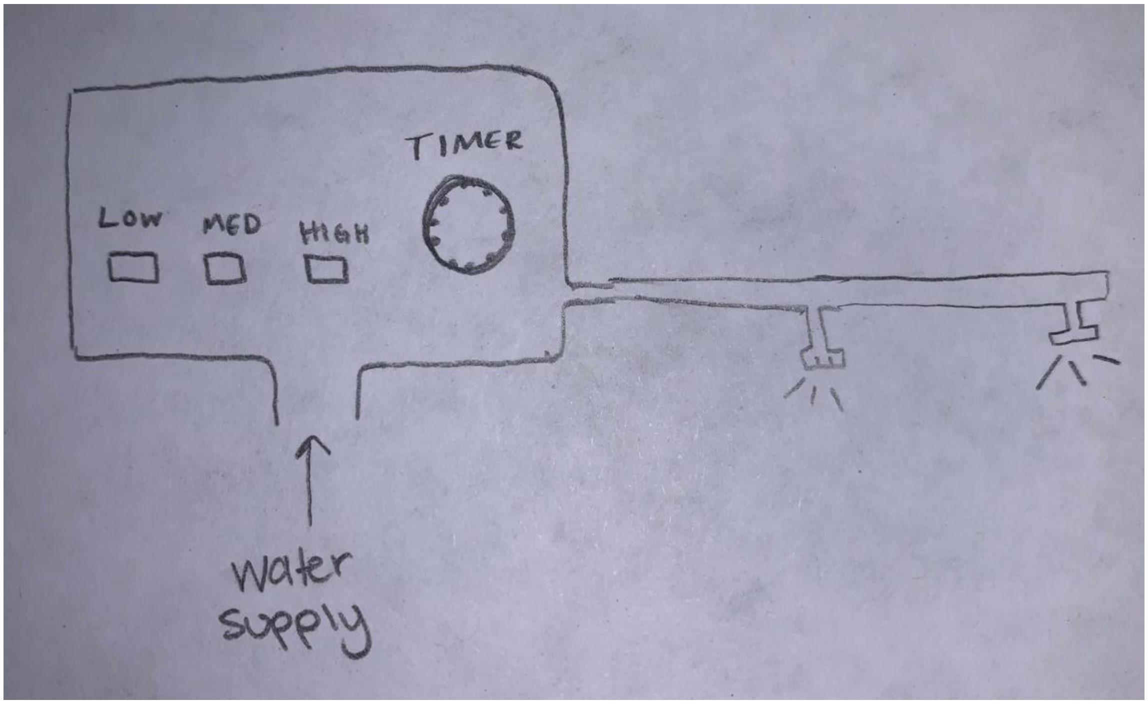


Figure C5: *Mister control panel which allows for different settings as well as a timed shut off. Design by Molly Jansky.*

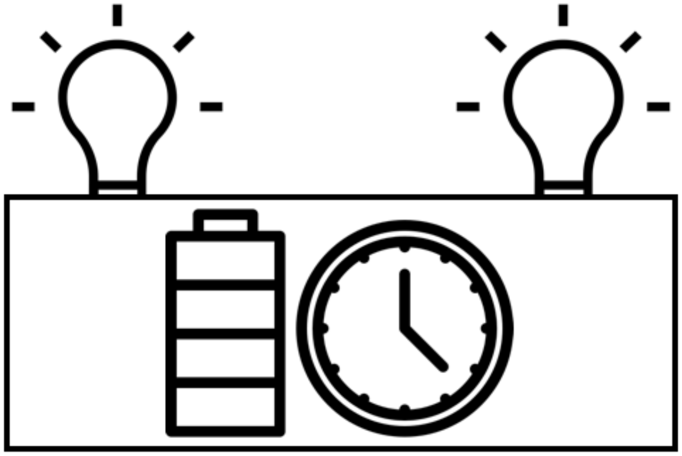


Figure C6: *Lighting system concept including: waterproof electronic housing, power source, time delayed actuator, and UV light bulbs. Design by Jack Margolis.*

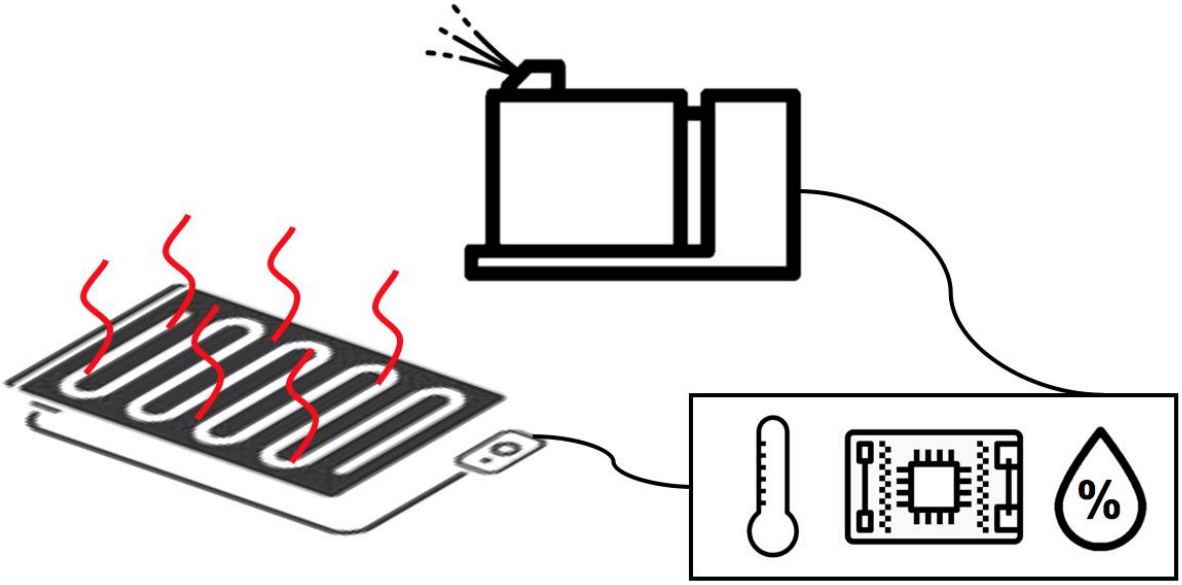
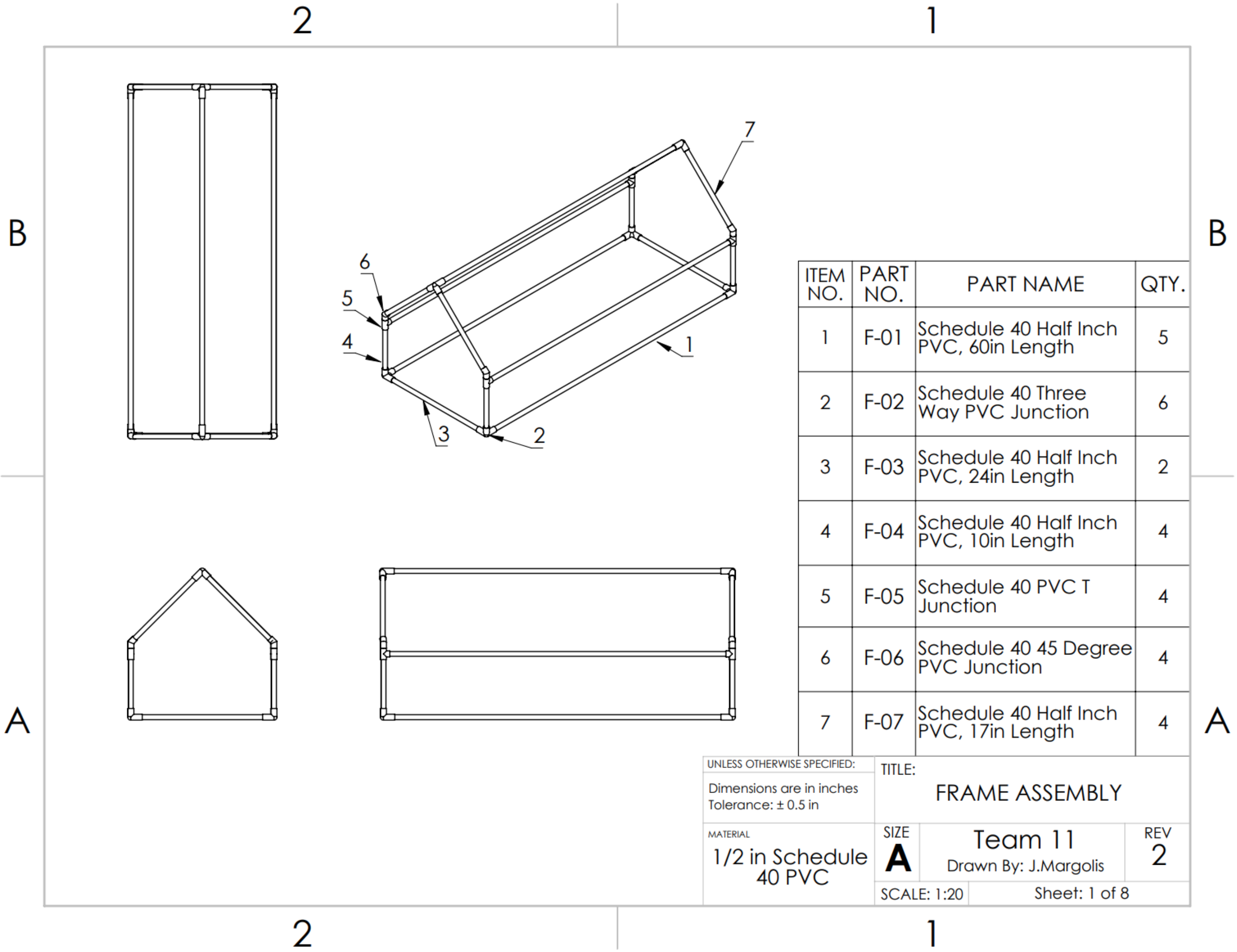


Figure C7: *Dual temperature and humidity control system concept including: waterproof electronic housing, temperature sensor, humidity sensor, microcontroller, portable humidifier, and heating pad. Design by Jack Margolis.*

Appendix D: Detail and assembly drawings



ITEM NO.	PART NO.	PART NAME	QTY.
1	F-01	Schedule 40 Half Inch PVC, 60in Length	5
2	F-02	Schedule 40 Three Way PVC Junction	6
3	F-03	Schedule 40 Half Inch PVC, 24in Length	2
4	F-04	Schedule 40 Half Inch PVC, 10in Length	4
5	F-05	Schedule 40 PVC T Junction	4
6	F-06	Schedule 40 45 Degree PVC Junction	4
7	F-07	Schedule 40 Half Inch PVC, 17in Length	4

UNLESS OTHERWISE SPECIFIED:
Dimensions are in inches
Tolerance: ± 0.5 in

TITLE:
FRAME ASSEMBLY

MATERIAL
1/2 in Schedule 40 PVC

SIZE
A

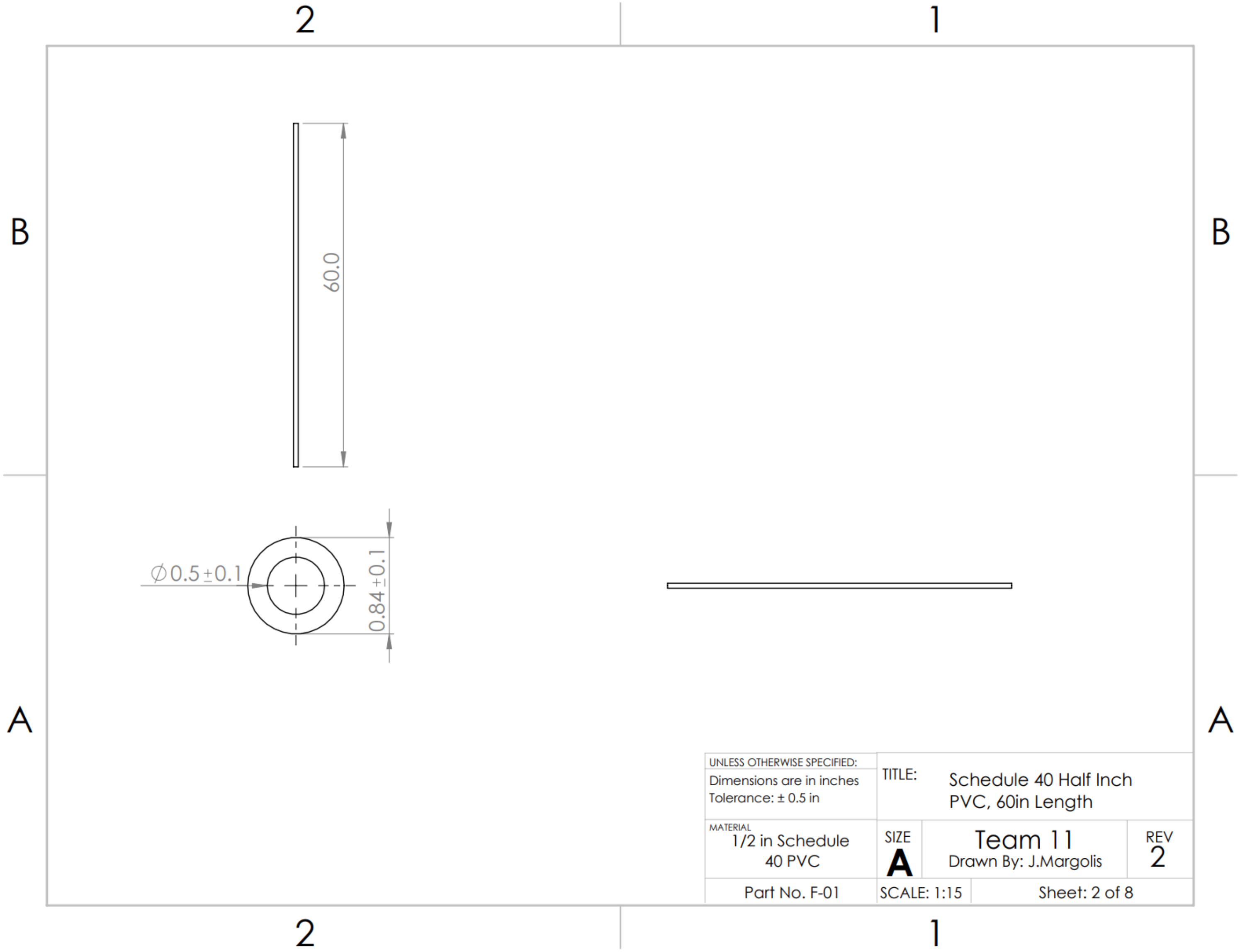
Team 11
Drawn By: J.Margolis

REV
2

SCALE: 1:20

Sheet: 1 of 8

Figure D1: *Structure design, prototype 2.*



UNLESS OTHERWISE SPECIFIED:
Dimensions are in inches
Tolerance: ± 0.5 in

TITLE: Schedule 40 Half Inch
PVC, 60in Length

MATERIAL
1/2 in Schedule
40 PVC

SIZE
A

Team 11
Drawn By: J.Margolis

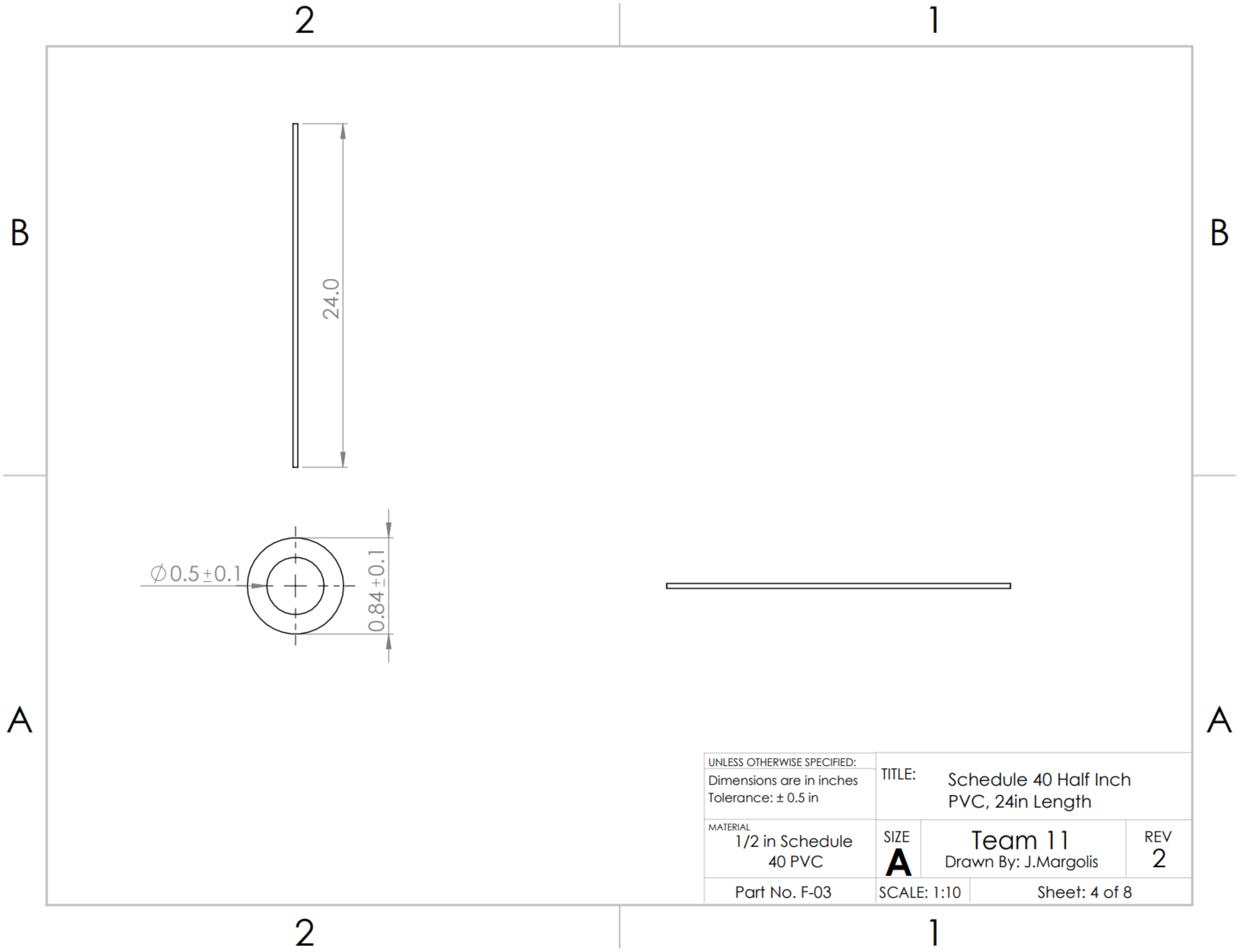
REV
2

Part No. F-01

SCALE: 1:15

Sheet: 2 of 8

Figure D2: *Structure drawing, PVC pipe.*



UNLESS OTHERWISE SPECIFIED:
Dimensions are in inches
Tolerance: ± 0.5 in

TITLE: Schedule 40 Half Inch PVC, 24in Length

MATERIAL
1/2 in Schedule 40 PVC

SIZE **A**

Team 11
Drawn By: J.Margolis

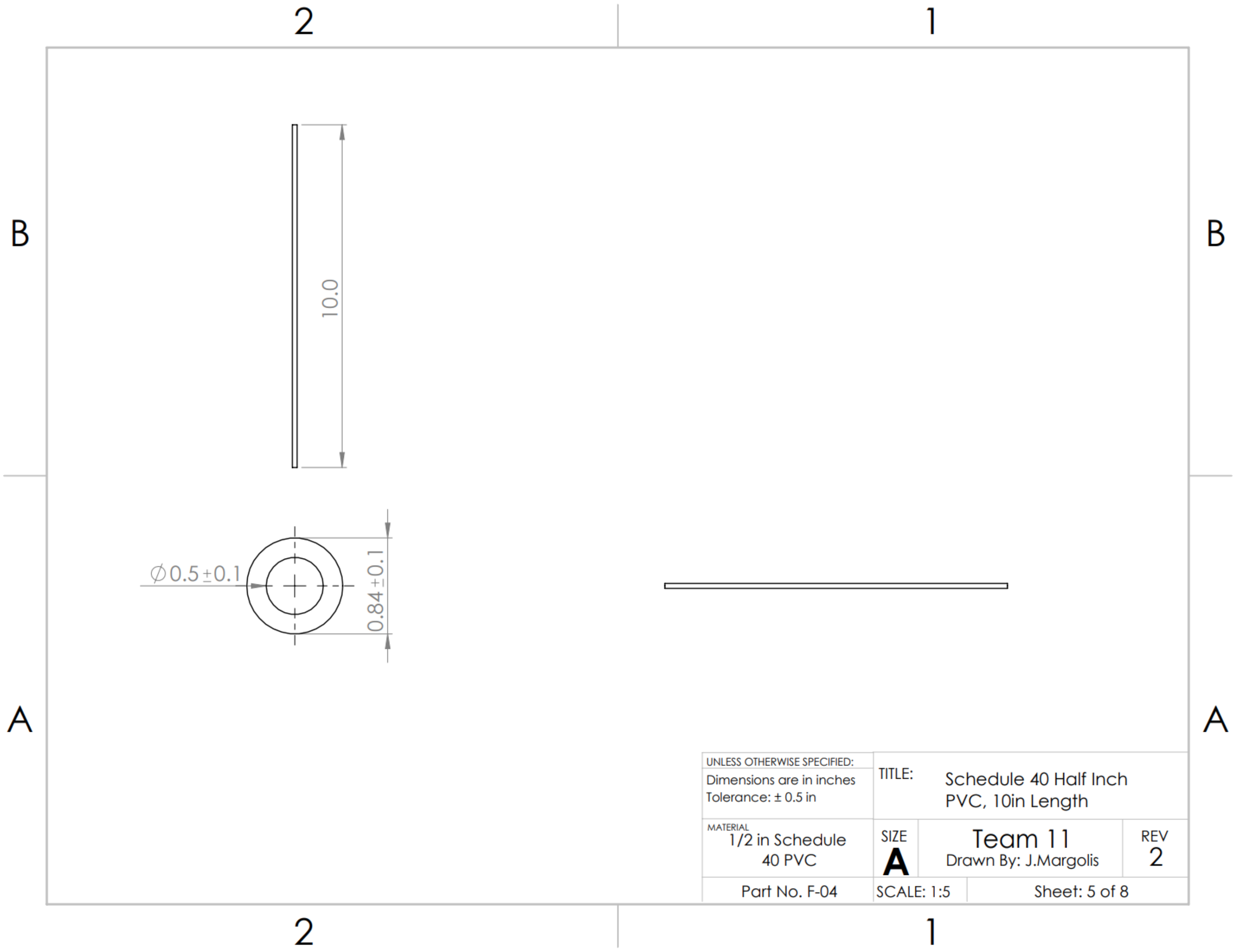
REV 2

Part No. F-03

SCALE: 1:10

Sheet: 4 of 8

Figure D3: *Structure drawing, PVC pipe.*



UNLESS OTHERWISE SPECIFIED:
Dimensions are in inches
Tolerance: ± 0.5 in

TITLE: Schedule 40 Half Inch PVC, 10in Length

MATERIAL: 1/2 in Schedule 40 PVC

SIZE: A

Team 11
Drawn By: J.Margolis

REV: 2

Part No. F-04

SCALE: 1:5

Sheet: 5 of 8

Figure D4: *Structure drawing, PVC pipe.*

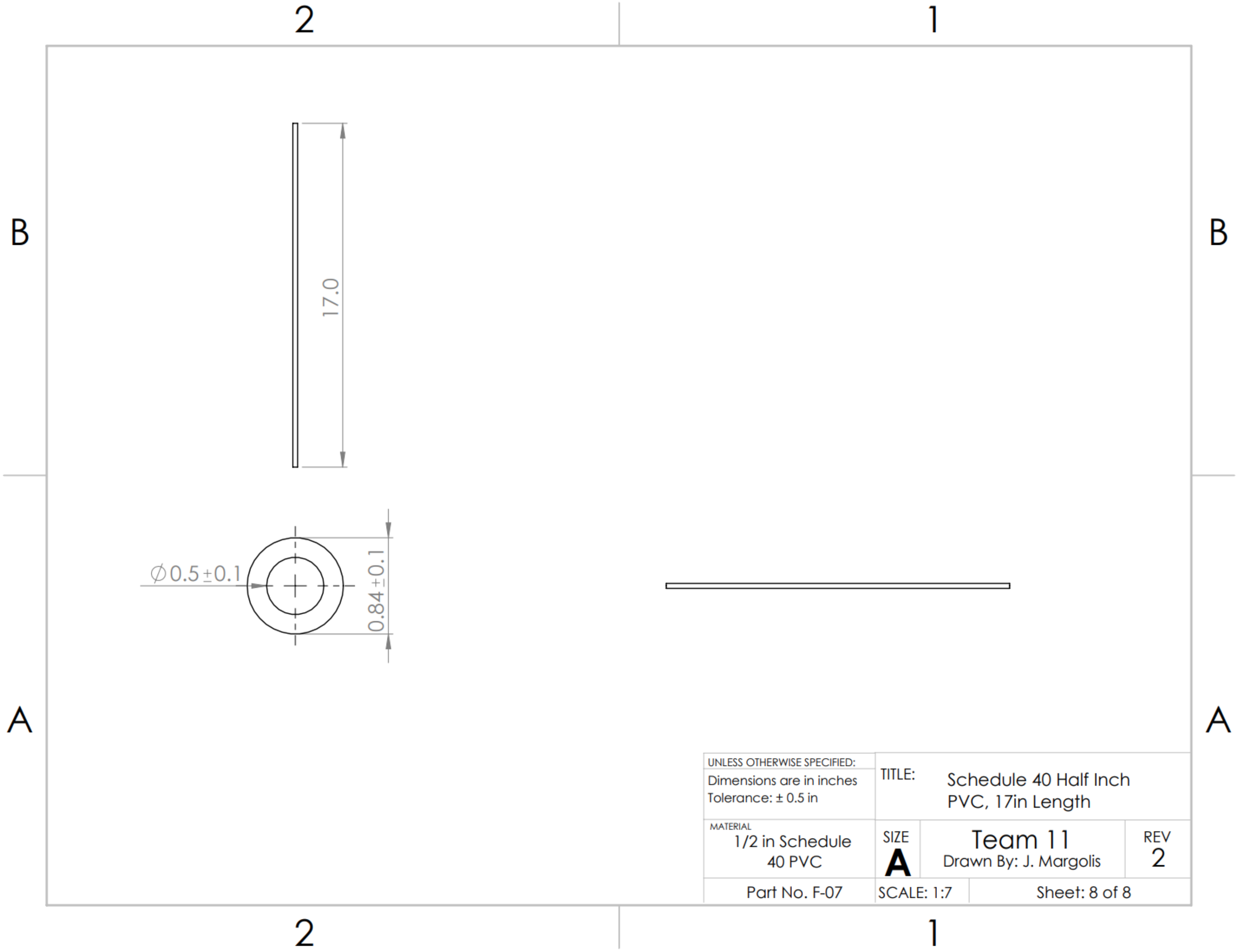


Figure D5: *Structure drawing, PVC pipe.*

Appendix E: Critical analyses - further information

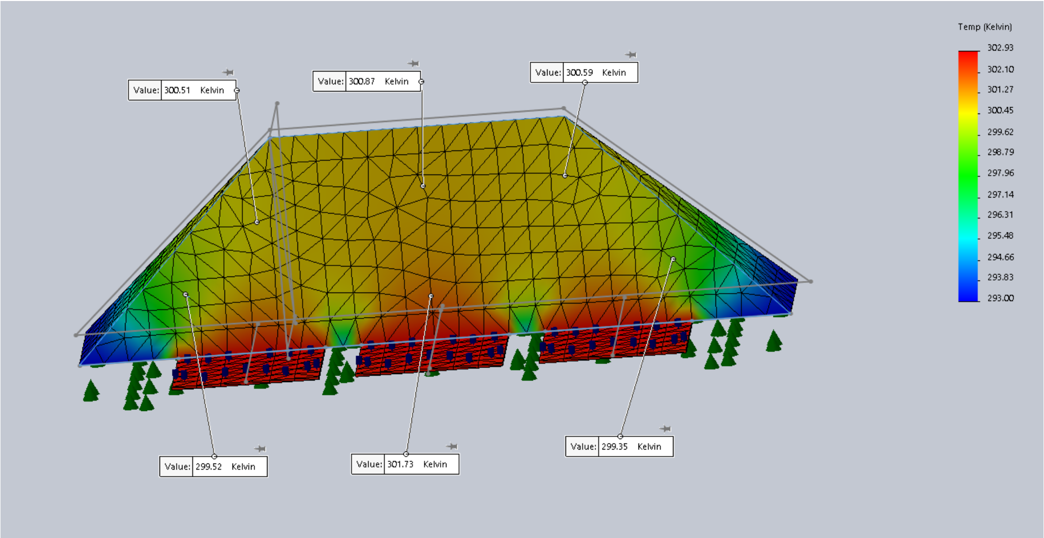


Figure E1: *Heating pad thermal analysis, exploded view.*

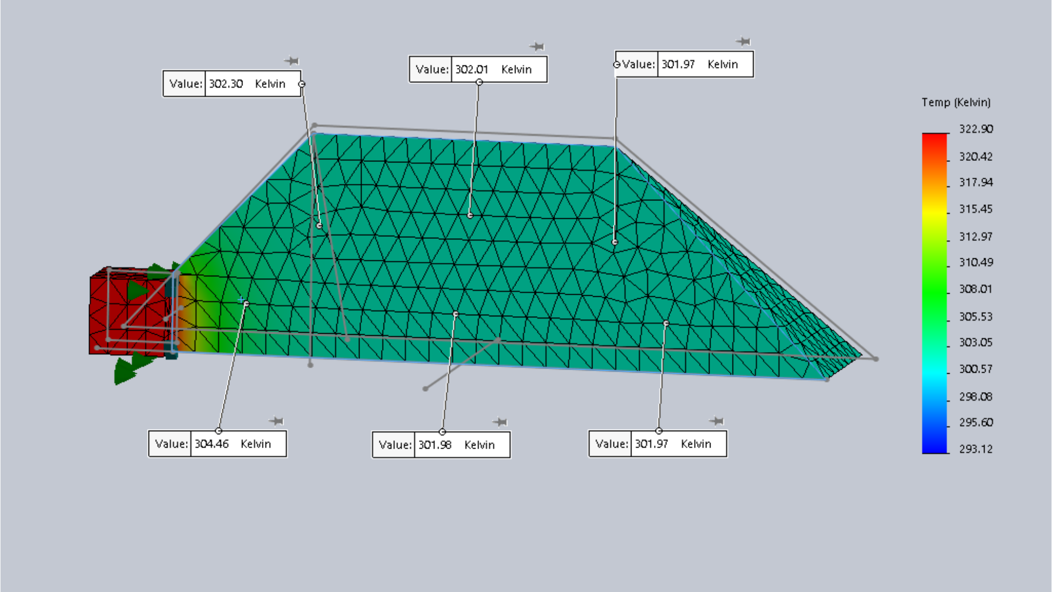


Figure E2: *Space heater thermal analysis, fine mesh.*

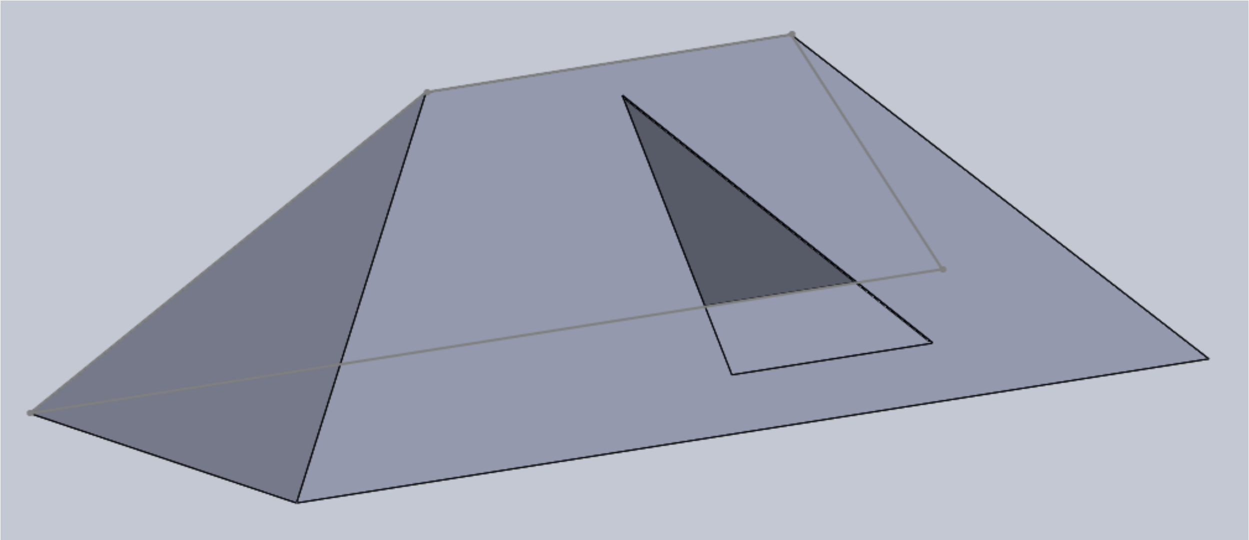
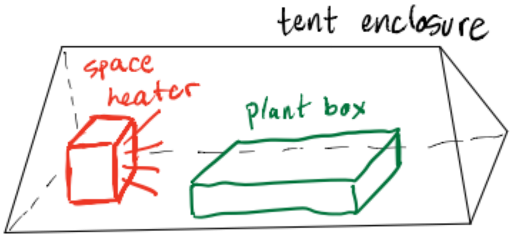
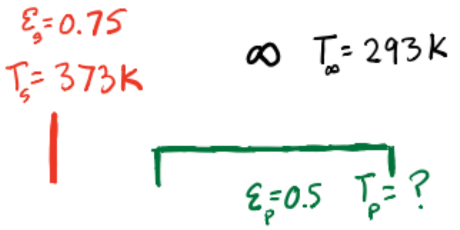


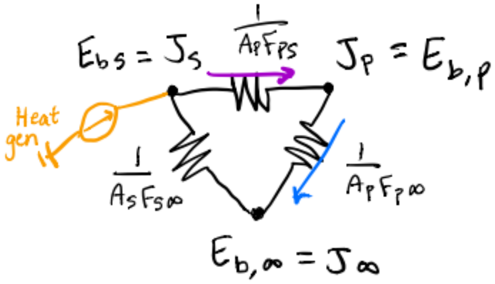
Figure E3: *Representation of grafting chamber, shown with flap open for clarity, used in thermal analysis.*



Eventhough it might not be the best assumption, assume 2D so that we can use our knowledge of heat transfer to predict the temp of the plant box.

Also neglect convection & conduction heat transfer, and assume the tent enclosure to be very large compared to the space heater and plant box. Assume space heater is a black body and the plant box to be a black body.





$$\longrightarrow \; = \; \swarrow$$

$$\frac{J_p - J_s}{\frac{1}{A_p F_{ps}}} = \frac{J_\infty - J_p}{\frac{1}{A_p F_{p\infty}}}$$

Figure E4: *Temperature at location of plants, hand calculation, part 1.*

$$(J_p - \sigma T_s^4)F_{ps} = (\sigma T_\infty^4 - J_p)F_{p\infty}$$

$$\underbrace{(F_{ps} + F_{p\infty})}_{=1} J_p = \sigma T_s^4 F_{ps} + \sigma T_\infty^4 F_{p\infty}$$

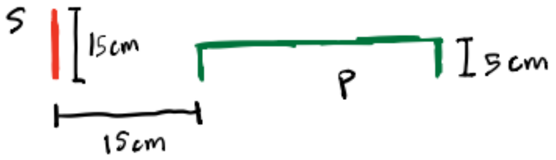
$$J_p = \sigma T_p^4 = \sigma T_s^4 F_{ps} + \sigma T_\infty^4 F_{p\infty}$$

$$T_p^4 = F_{ps}(373)^4 + F_{p\infty}(293)^4$$

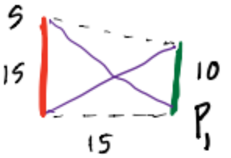
$$T_p^4 = 1.94\times10^{10} F_{ps} + 7.37\times10^9(1 - F_{ps})$$

$$\underline{0.107}$$

Find view factor: $F_{ps}\ldots = \frac{A_s}{A_p} F_{sp}$



first look at...



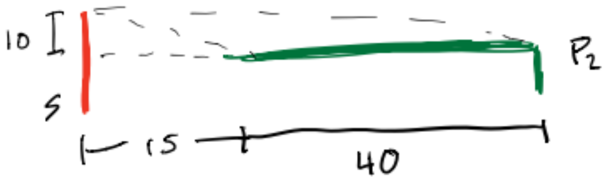
use Hottel's rule

$$F_{sp_1} = \frac{15\sqrt{2} + \sqrt{325} - \sqrt{250} - 15}{30}$$

$$= 0.281$$

Figure E5: *Temperature at location of plants, hand calculation, part 2.*

now . .



$$F_{sp_2} = \frac{10+55-55.9}{20} - \frac{10+15-18}{20}$$

$$= 0.455 - 0.35 = 0.12$$

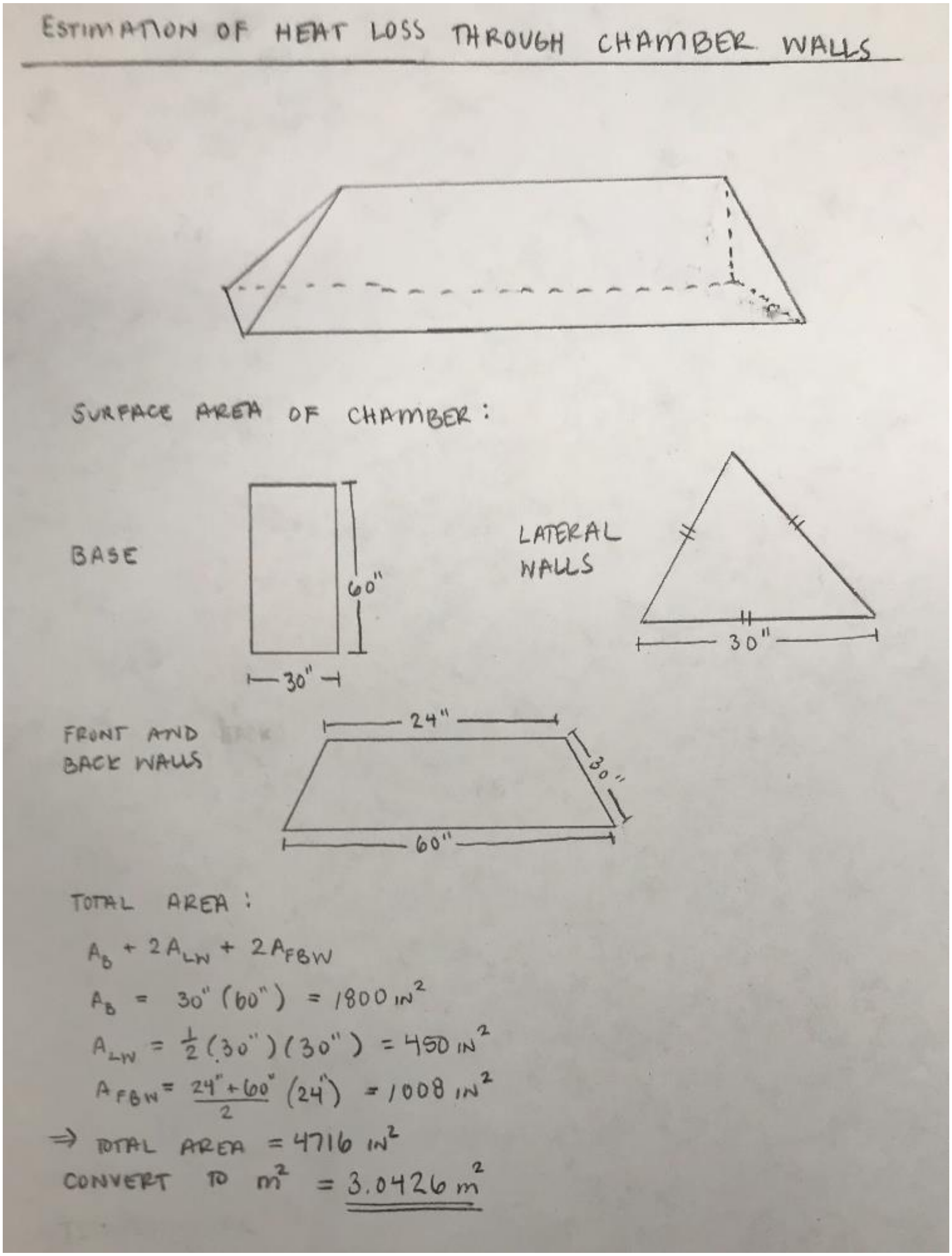
$$F_{sp} = 0.400$$

$$\therefore \quad F_{ps} = \frac{10}{50}(0.400) = 0.080$$

Finally... $T_p^4 = 1.94\times10^{10} F_{ps} + 7.37\times10^{9}(1-F_{ps})$

$$\boxed{T_p = 302 \text{ K}}$$

Figure E6: *Temperature at location of plants, hand calculation, part 3.*



ESTIMATION OF HEAT LOSS THROUGH CHAMBER WALLS

SURFACE AREA OF CHAMBER:

BASE

LATERAL WALLS

FRONT AND BACK WALLS

TOTAL AREA:

$A_B + 2A_{LW} + 2A_{FBW}$

$A_B = 30''(60'') = 1800 \text{ IN}^2$

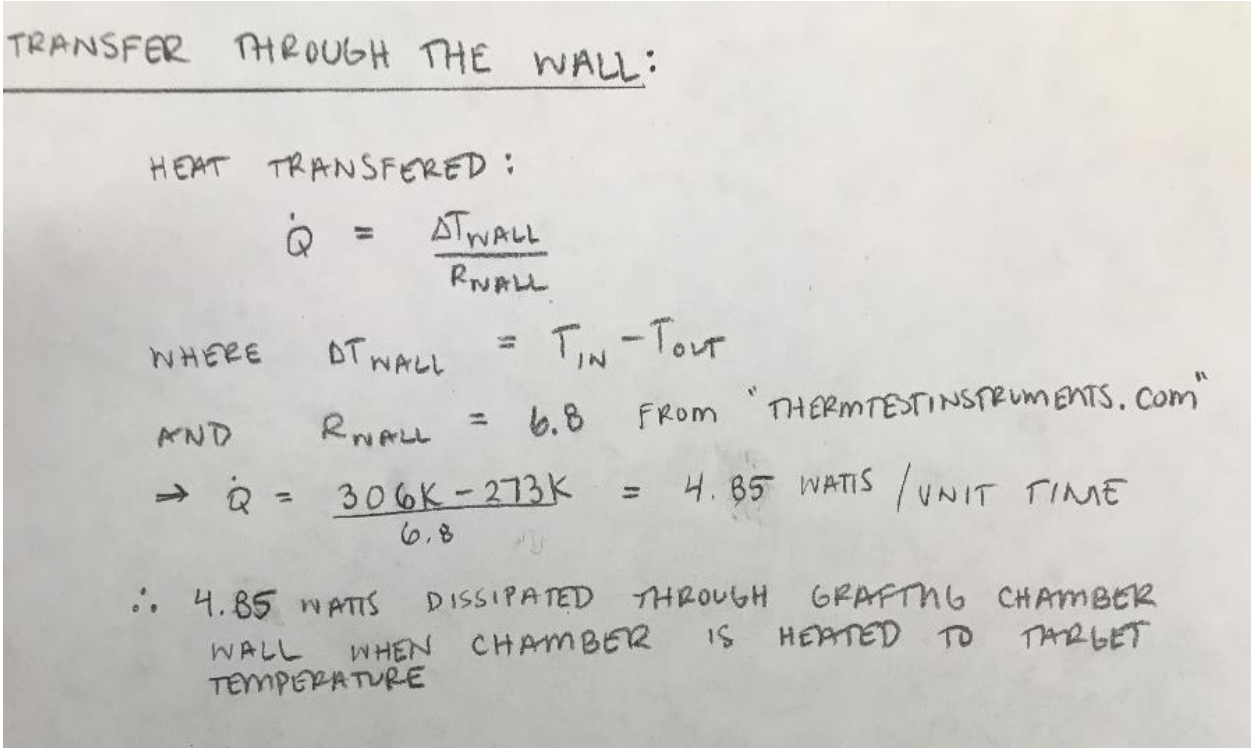
$A_{LW} = \frac{1}{2}(30'')(30'') = 450 \text{ IN}^2$

$A_{FBW} = \frac{24''+60''}{2}(24'') = 1008 \text{ IN}^2$

$\Rightarrow$ TOTAL AREA $= 4716 \text{ IN}^2$

CONVERT TO m^2 $= \underline{\underline{3.0426 \text{ m}^2}}$

Figure E7: *Hand calculation to determine total surface area through which heat can be lost.*



TRANSFER THROUGH THE WALL:

HEAT TRANSFERED:

$$\dot{Q} = \frac{\Delta T_{WALL}}{R_{WALL}}$$

WHERE $\Delta T_{WALL} = T_{IN} - T_{OUT}$

AND $R_{WALL} = 6.8$ FROM "THERMTESTINSTRUMENTS.COM"

$$\rightarrow \dot{Q} = \frac{306K - 273K}{6.8} = 4.85 \text{ WATTS / UNIT TIME}$$

∴ 4.85 WATTS DISSIPATED THROUGH GRAFTING CHAMBER WALL WHEN CHAMBER IS HEATED TO TARGET TEMPERATURE

Figure E8: *Hand calculation for overall heat loss through chamber walls.*

Appendix G: Bill of materials, by subsystem

Table G1: *Bill of materials, structural elements*

Greenhouse Hoops	25.98
1.1 oz SilPoly	102.68
3/8” push-to-connect pneumatic fittings	34.56
PVC fittings 3 – way connections	20.34
½” schedule 40 PVC tubing	19.61
PVC fittings – 45˚ elbows	4.74
Acrylic housing material	25.79
Sewing supplies	17.41
Total	**251.11**

Table G2: *Bill of materials, control system*

Sprinkler System	26.15
Solenoid valve	32.98
½” Plastic water valves	20.85
3-Pack LED lights	17.99
Misting System End Cap	4.48
Beagle Bone Black Microcontroller	76.29
Blynk App	21.99
LED strip	20.46
AC light dimmer module	23.96
Waterproof Cable protection	42.55
Humidipaks	17.85
Particle Photon Microcontrollers	95.00
Total	**400.55**

Table G3: *Bill of materials, sensor array*

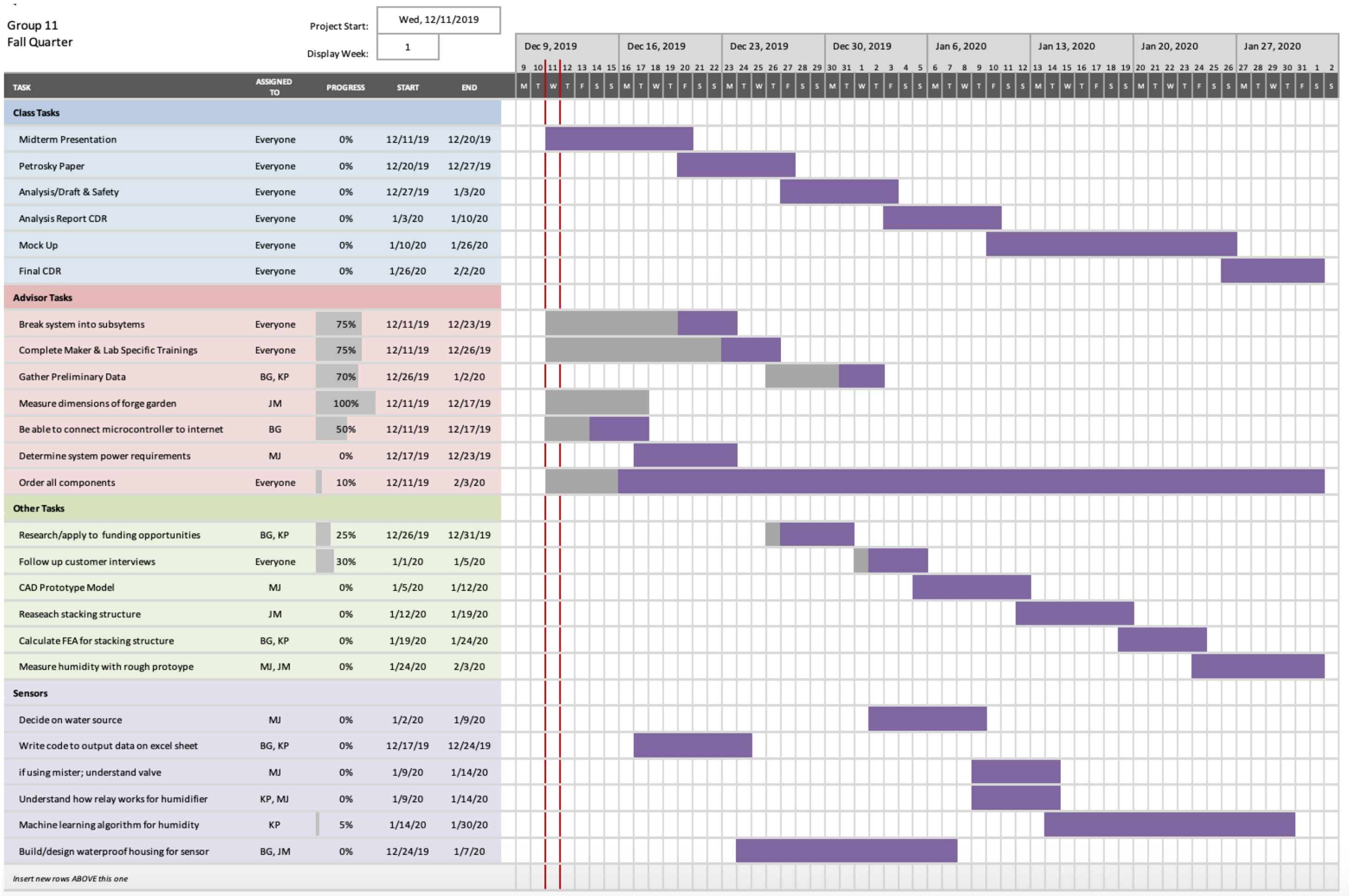
DHT Sensor Housings	7.28
Acrylic from SCU Maker Lab	16.00
DHT Sensors	89.60
Total	**112.88**

Table G4: *Bill of materials, power system*

Male-to-male converter	7.25
Relays	23.40
Solar Connector	6.76
USB barrel adapter	5.38
25’ extension cord	14.44
1’ extension chords	12.98
4-pack lightbulb outlet converter	8.56
Solar panels and controller	163.49
18” connecting cables	8.99
Power strip	16.49
Total	**267.74**

Appendix H: Project timeline - Gantt charts

Table H1: Detailed quarterly plan - Fall.

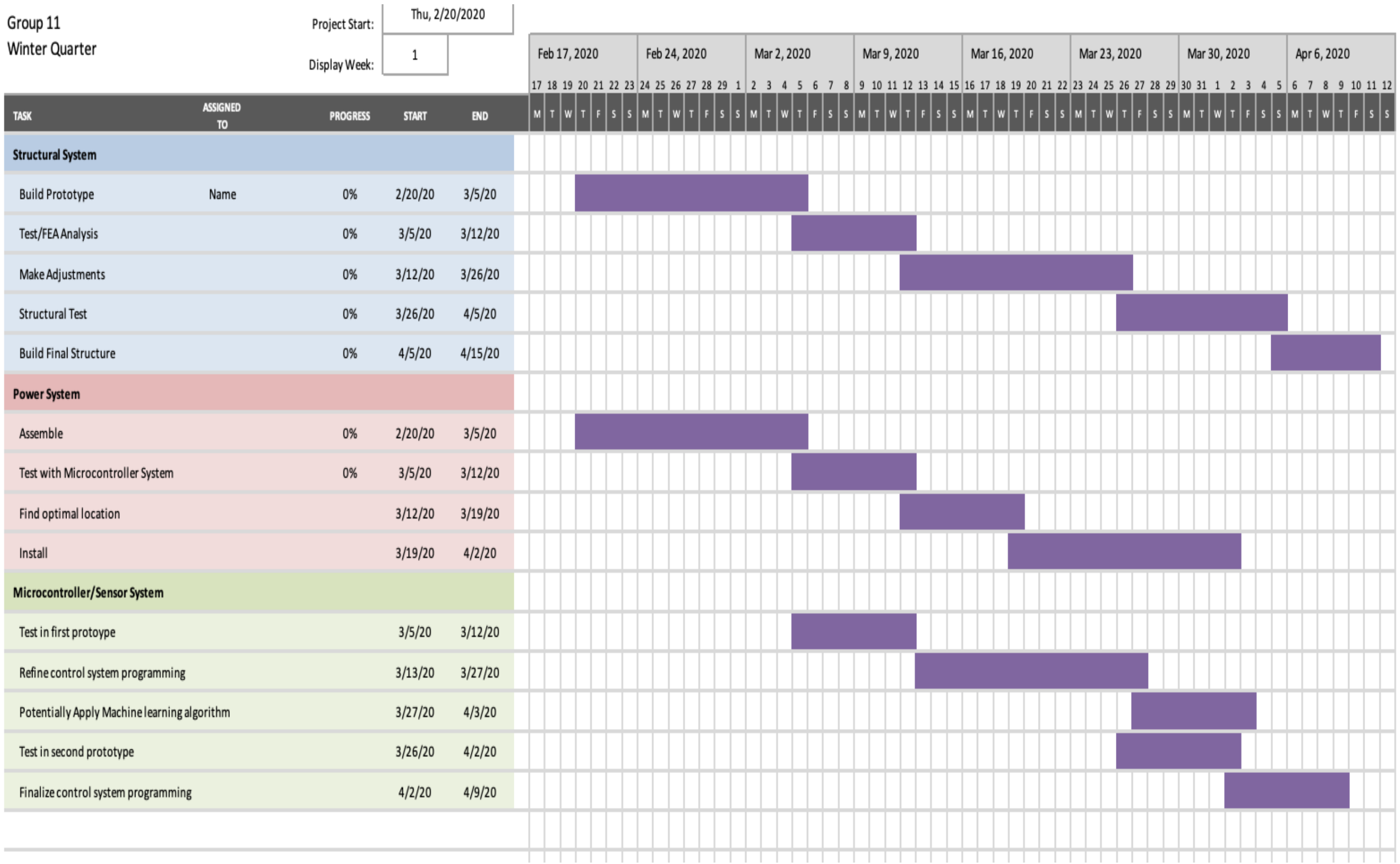


Group 11
Fall Quarter

Project Start: Wed, 12/11/2019
Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Class Tasks				
Midterm Presentation	Everyone	0%	12/11/19	12/20/19
Petrosky Paper	Everyone	0%	12/20/19	12/27/19
Analysis/Draft & Safety	Everyone	0%	12/27/19	1/3/20
Analysis Report CDR	Everyone	0%	1/3/20	1/10/20
Mock Up	Everyone	0%	1/10/20	1/26/20
Final CDR	Everyone	0%	1/26/20	2/2/20
Advisor Tasks				
Break system into subsytems	Everyone	75%	12/11/19	12/23/19
Complete Maker & Lab Specific Trainings	Everyone	75%	12/11/19	12/26/19
Gather Preliminary Data	BG, KP	70%	12/26/19	1/2/20
Measure dimensions of forge garden	JM	100%	12/11/19	12/17/19
Be able to connect microcontroller to internet	BG	50%	12/11/19	12/17/19
Determine system power requirements	MJ	0%	12/17/19	12/23/19
Order all components	Everyone	10%	12/11/19	2/3/20
Other Tasks				
Research/apply to funding opportunities	BG, KP	25%	12/26/19	12/31/19
Follow up customer interviews	Everyone	30%	1/1/20	1/5/20
CAD Prototype Model	MJ	0%	1/5/20	1/12/20
Reaseach stacking structure	JM	0%	1/12/20	1/19/20
Calculate FEA for stacking structure	BG, KP	0%	1/19/20	1/24/20
Measure humidity with rough protoype	MJ, JM	0%	1/24/20	2/3/20
Sensors				
Decide on water source	MJ	0%	1/2/20	1/9/20
Write code to output data on excel sheet	BG, KP	0%	12/17/19	12/24/19
if using mister; understand valve	MJ	0%	1/9/20	1/14/20
Understand how relay works for humidifier	KP, MJ	0%	1/9/20	1/14/20
Machine learning algorithm for humidity	KP	5%	1/14/20	1/30/20
Build/design waterproof housing for sensor	BG, JM	0%	12/24/19	1/7/20

Insert new rows ABOVE this one

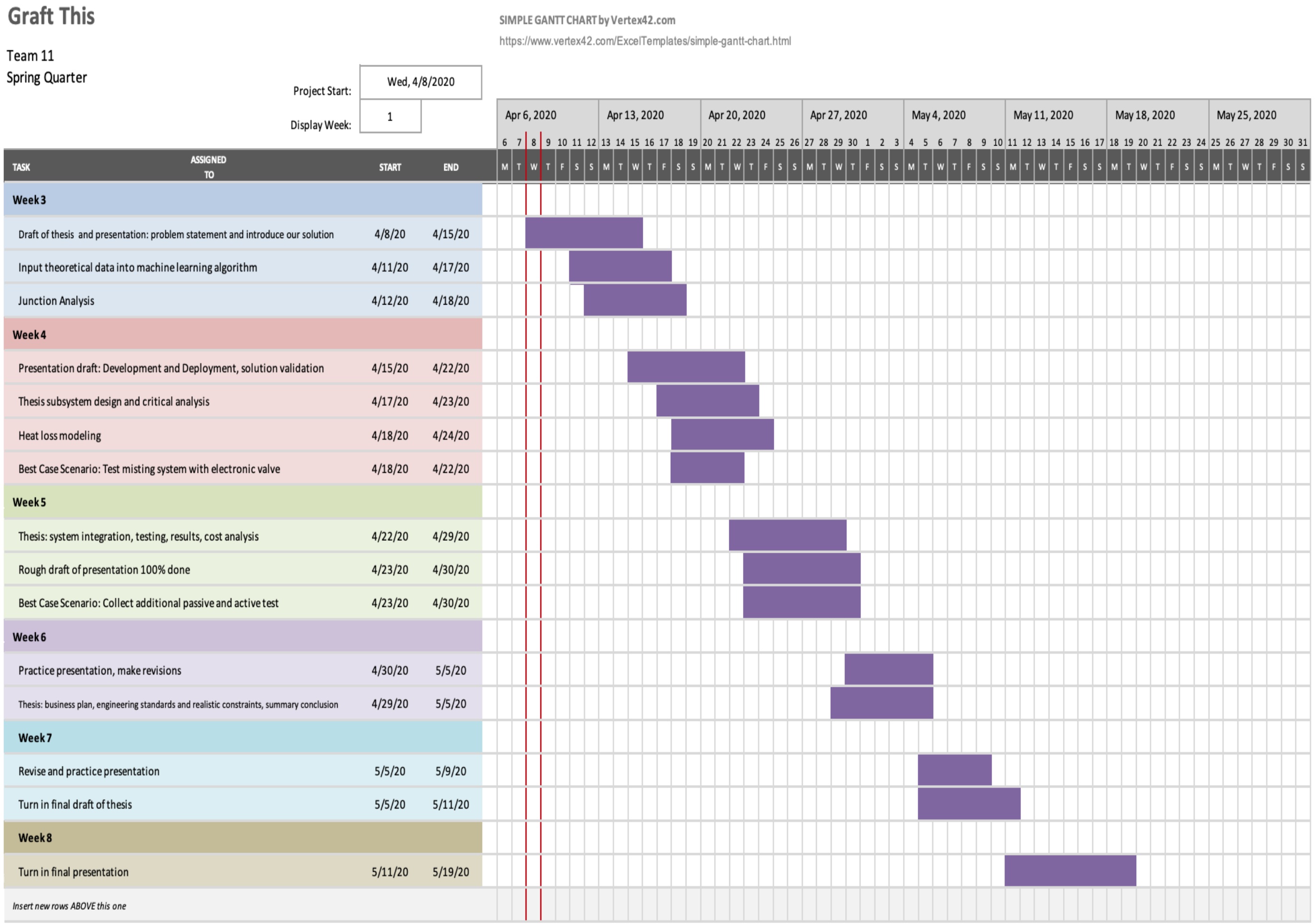


Group 11
Winter Quarter

Project Start: Thu, 2/20/2020
Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Structural System				
Build Prototype	Name	0%	2/20/20	3/5/20
Test/FEA Analysis		0%	3/5/20	3/12/20
Make Adjustments		0%	3/12/20	3/26/20
Structural Test		0%	3/26/20	4/5/20
Build Final Structure		0%	4/5/20	4/15/20
Power System				
Assemble		0%	2/20/20	3/5/20
Test with Microcontroller System		0%	3/5/20	3/12/20
Find optimal location			3/12/20	3/19/20
Install			3/19/20	4/2/20
Microcontroller/Sensor System				
Test in first protoype			3/5/20	3/12/20
Refine control system programming			3/13/20	3/27/20
Potentially Apply Machine learning algorithm			3/27/20	4/3/20
Test in second prototype			3/26/20	4/2/20
Finalize control system programming			4/2/20	4/9/20

Table H1: Detailed quarterly plan - Winter.



Graft This

Team 11
Spring Quarter

Project Start: Wed, 4/8/2020
Display Week: 1

TASK	ASSIGNED TO	START	END
Week 3			
Draft of thesis and presentation: problem statement and introduce our solution		4/8/20	4/15/20
Input theoretical data into machine learning algorithm		4/11/20	4/17/20
Junction Analysis		4/12/20	4/18/20
Week 4			
Presentation draft: Development and Deployment, solution validation		4/15/20	4/22/20
Thesis subsystem design and critical analysis		4/17/20	4/23/20
Heat loss modeling		4/18/20	4/24/20
Best Case Scenario: Test misting system with electronic valve		4/18/20	4/22/20
Week 5			
Thesis: system integration, testing, results, cost analysis		4/22/20	4/29/20
Rough draft of presentation 100% done		4/23/20	4/30/20
Best Case Scenario: Collect additional passive and active test		4/23/20	4/30/20
Week 6			
Practice presentation, make revisions		4/30/20	5/5/20
Thesis: business plan, engineering standards and realistic constraints, summary conclusion		4/29/20	5/5/20
Week 7			
Revise and practice presentation		5/5/20	5/9/20
Turn in final draft of thesis		5/5/20	5/11/20
Week 8			
Turn in final presentation		5/11/20	5/19/20
Insert new rows ABOVE this one			

***Table H3:** Detailed quarterly plan - Spring.*

Appendix I: Machine Learning Algorithm

Table I1: *Standard Deviation and Mean Error between predicted temperature and actual temperature using past temperature data of the San Francisco area using different parameters. The reduced parameters were chosen for our project because using more did not improve the model by a substantial amount. More Parameters uses 24 parameters (4 days before and 4 hours before) while Reduced Parameters uses 8. Each trial has 100 test values and uses 216 training values.*

Description	**More Parameters**				**Reduced Parameters**			
Trial	1	2	3	Average	1	2	3	Average
Mean Error [°C]	0.7147	0.9606	0.6820	0.7858	0.6104	0.9978	0.6141	0.7408
Standard Deviation [°C]	0.4821	1.0173	0.6271	0.7089	0.4846	1.1049	0.6177	0.7357

Table I2: *Standard Deviation and Mean Error between predicted temperature and actual temperature using past temperature data of the San Francisco area using different sized training sets. Two weeks were chosen for our project because using more did not improve the model by a substantial amount, in fact it worsened the results. Each trial has 100 test values and uses the reduced parameters from Table I1.*

Description	**One Week of Training Data**				**Two Weeks of Training Data**				**Three Weeks of Training Data**			
Trial	1	2	3	Average	1	2	3	Average	1	2	3	Average
Mean Error [°C]	1.0403	1.1867	0.8695	1.0322	0.6104	0.9978	0.6141	0.7408	0.6291	1.0371	0.6168	0.7610
Standard Deviation [°C]	0.7139	1.1201	0.6027	0.8122	0.4846	1.1049	0.6177	0.7357	0.4993	1.1434	0.6496	0.7641

Table I3: *Standard Deviation and Mean Error between predicted temperature and actual temperature using past temperature data of the San Francisco area using different output sizes. Three hours ahead was chosen for our project because using more could not accurately predict temperature and using less would not be enough time to preheat our chamber. Each trial has 100 test values, 216 training values and uses the reduced parameters from Table I1.*

Description	**1 hour ahead**				**2 hours ahead**				**3 hours ahead**			
Trial	1	2	3	Average	1	2	3	Average	1	2	3	Average
Mean Error [°C]	0.5897	0.9688	0.5751	0.7112	0.9452	1.2362	0.9226	1.0347	1.0249	1.3631	1.0817	1.1566
Variance [°C^2]	0.2097	0.9965	0.3128	0.5063	0.3982	1.2858	0.5922	0.7587	0.5531	1.4242	0.6719	0.8831
Standard Deviation [°C]	0.4579	0.9982	0.5593	0.6718	0.6310	1.1339	0.7695	0.8448	0.7437	1.1934	0.8197	0.9189

Description	**4 hours ahead**				**5 hours ahead**			
Trial	1	2	3	Average	1	2	3	Average
Mean Error [°C]	1.1704	1.5469	1.2071	1.3081	1.2827	1.6654	1.3374	1.4285
Variance [°C^2]	0.7777	1.5922	0.8325	1.0675	0.9244	2.0272	1.0758	1.3425
Standard Deviation [°C]	0.8819	1.2618	0.9124	1.0187	0.9615	1.4238	1.0372	1.1408

Code I1: *Final Matlab code for our temperature prediction model.*

```
%--------------------------------------------------------------%
temp = SFtempdata{1:60:end,2};  % importing our data
train = 216;
parameters = 12;

% train to get P matrix
start = 1900;   % specific to the data set that we used
u1 = ones(train,3);
y1 = ones(train,parameters);
counter = 0;
for ii = 1:train-1
% making the y1 matrix
% temperature:
   % same day going 3 hrs before (temp)
   y1(ii,1) = temp(start+ii-1);
   y1(ii,2) = temp(start+ii-2);
```

```
    y1(ii,3) = temp(start+ii-3);
    % same hour going 3 days back (temp)
    y1(ii,4) = temp(start+ii-24);
    y1(ii,5) = temp(start+ii-48);
    y1(ii,6) = temp(start+ii-72);
    % 1 hour ahead going 3 days back (temp)
    y1(ii,7) = temp(start+ii-24+1);
    y1(ii,8) = temp(start+ii-48+1);
    y1(ii,9) = temp(start+ii-72+1);
    % 2 hours ahead going 3 days back (temp)
    y1(ii,10) = temp(start+ii-24+2);
    y1(ii,11) = temp(start+ii-48+2);
    y1(ii,12) = temp(start+ii-72+2);

% making u1 matrix
    % temperature:
    u1(ii,1) = temp(start+ii);
    u1(ii,2) = temp(start+ii+1);
    u1(ii,3) = temp(start+ii+2);
end
p = (y1'*y1)^-1*y1'*u1;

start = start+train;
test = 100;
y2 = ones(test,parameters);
actualVals = ones(test,3);
for ii = 1:test
% making the y2 matrix
% temperature:
    % same day going 3 hrs before (temp)
    y2(ii,1) = temp(start+ii-1);
    y2(ii,2) = temp(start+ii-2);
    y2(ii,3) = temp(start+ii-3);
    % same hour going 3 days back (temp)
    y2(ii,4) = temp(start+ii-24);
    y2(ii,5) = temp(start+ii-48);
    y2(ii,6) = temp(start+ii-72);
    % 1 hour ahead going 3 days back (temp)
    y2(ii,7) = temp(start+ii-24+1);
    y2(ii,8) = temp(start+ii-48+1);
    y2(ii,9) = temp(start+ii-72+1);
    % 2 hours ahead going 3 days back (temp)
    y2(ii,10) = temp(start+ii-24+2);
    y2(ii,11) = temp(start+ii-48+2);
    y2(ii,12) = temp(start+ii-72+2);
    % making a matrix with the actual values to compare
    actualVals(ii,1) = temp(start+ii);
    actualVals(ii,2) = temp(start+ii+1);
    actualVals(ii,3) = temp(start+ii+2);
end
% making u2 matrix
u2 = y2*p;

error = abs(actualVals(:,1)-u2(:,1));   % CHANGE THIS LINE TO LOOK AT DIFFERENT VALUES
```

```
aveError = sum(error)/length(error)
mu = aveError*ones(test,1);
var = sum((error-mu).^2)/length(error);
std = sqrt(var);

timeVar = [0:(3000-1)]';    % used to plot results

figure(1)
plot(timeVar,u2(:,1),timeVar,actualVals(:,1))
title('predicting 0 values ahead')
xlabel('time [hrs]')
ylabel('humidity [%]')
legend('Hum Prediction', 'Hum Actual')
% too much data so I am adding an axis to take a snip of the data
axis([0, 48, 10, 25])

figure(2)
plot(timeVar,u2(:,2),timeVar,actualVals(:,2))
title('predicting 1 values ahead')
xlabel('time [hrs]')
ylabel('humidity [%]')
legend('Hum Prediction', 'Hum Actual')
% too much data so I am adding an axis to take a snip of the data
axis([0, 48, 10, 25])

figure(3)
plot(timeVar,u2(:,3),timeVar,actualVals(:,3))
title('predicting 2 values ahead')
xlabel('time [hrs]')
ylabel('humidity [%]')
legend('Hum Prediction', 'Hum Actual')
% too much data so I am adding an axis to take a snip of the data
axis([0, 48, 10, 25])
%-------------------------------------------------------------------%
```

Appendix J: Santa Clara University School of Engineering Senior Design Conference Presentation Slides

GraftThis:
Modernizing Organic Farming

Santa Clara University
School of Engineering

Design Conference Presentation
Brendan Gescher, Molly Jansky,
Jack Margolis, Kaleb Pattawi

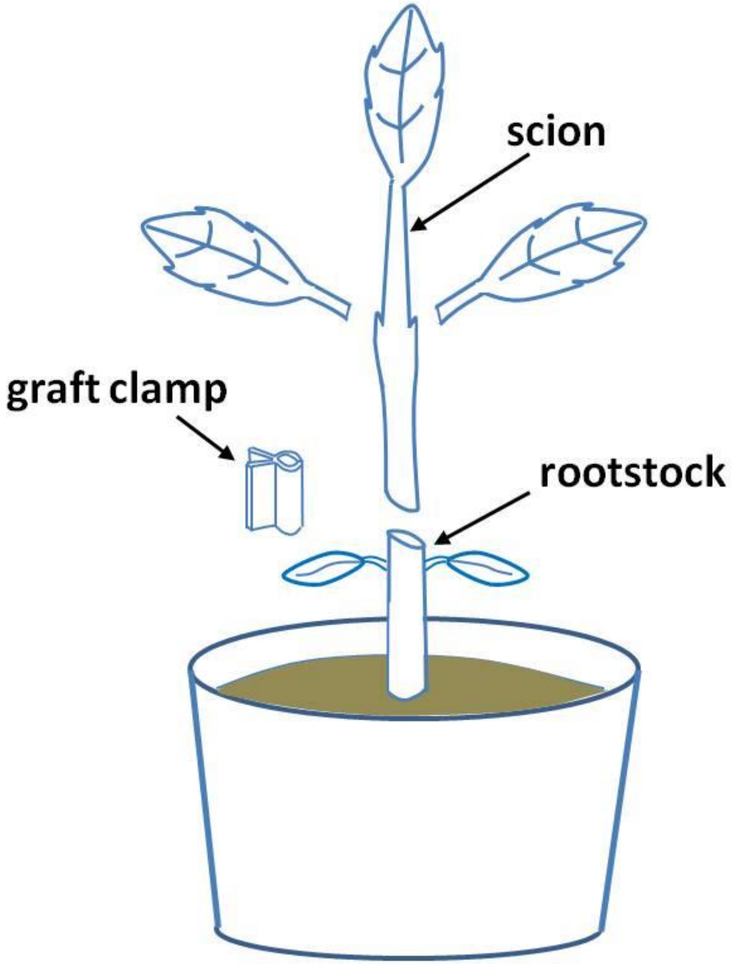
THE FORGE GARDEN

Advisor: Hohyun Lee, Ph.D. *Associate Professor, Mechanical Engineering*

Our team began with the question:

"How can organic farmers avoid the adverse effects of pests and disease without resorting to synthetic chemicals?"

Solution: Grafting. This farming technique involves combining two different plants in order to produce one plant which possesses the favorable characteristics of each parent plant.

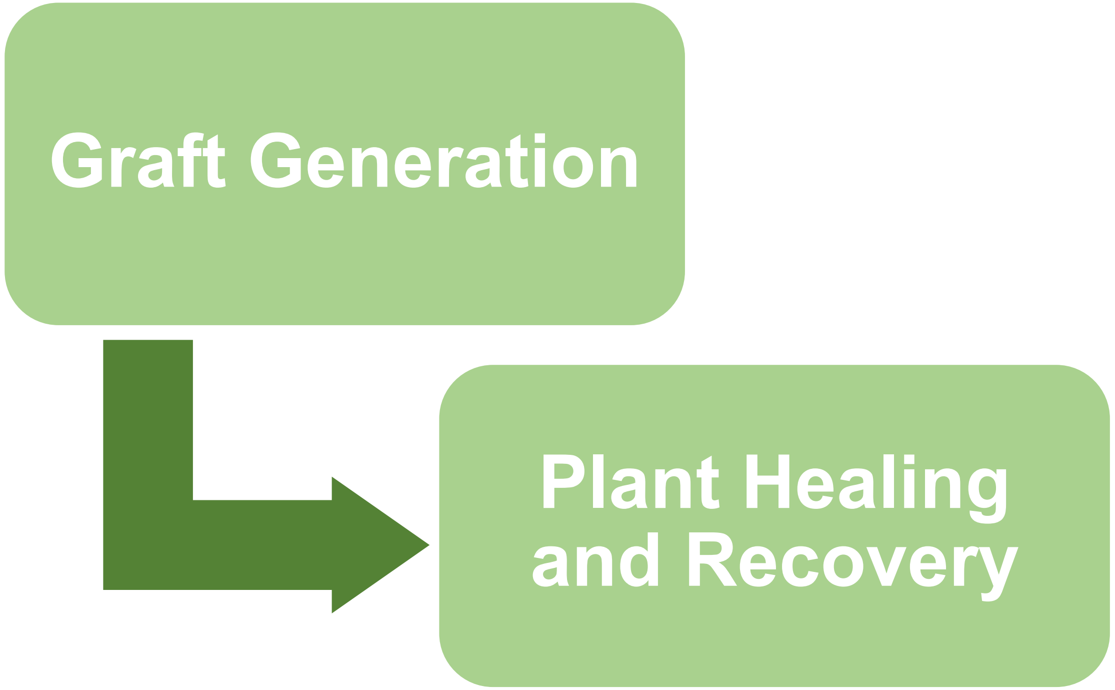


"Grafting is immensely important in agriculture in general. Virtually all fruit/nut trees as well as wine grapes in California are grafted."

- Jacob Shogren, Grower at OnePointOne, Inc.

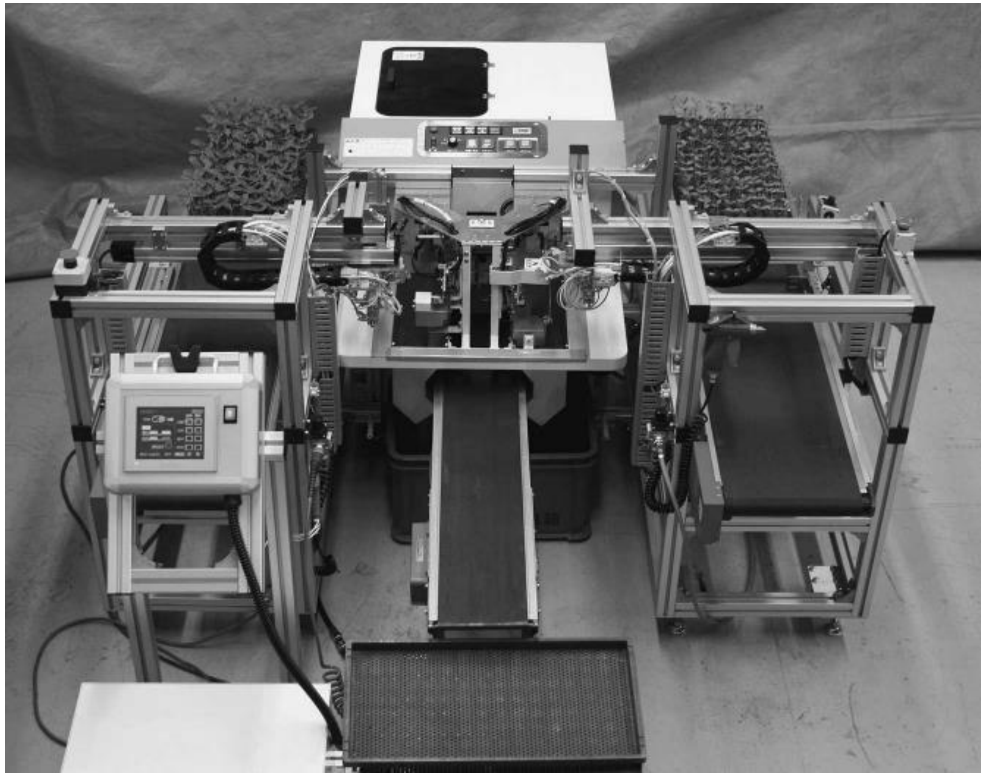
The Processes: While the first stage has been modernized, no automated solution has been presented to address the plant healing and recovery phase of the grafting process.

Two-part Process



Graft Generation

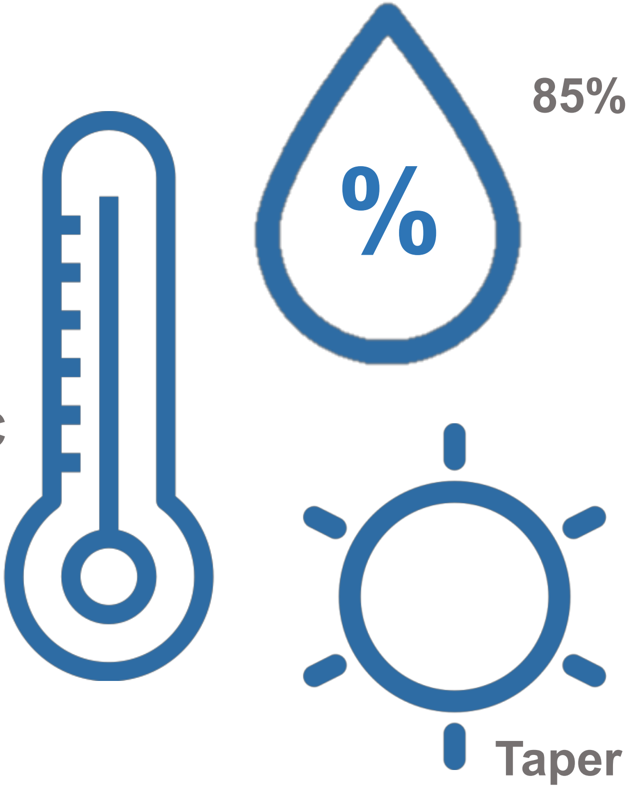
Plant Healing and Recovery



https://www.researchgate.net/figure/A-prototype-of-a-fully-automated-grafting-robot-for-cucurbits-with-a-capability-of-750_fig2_43273277

Traditional Challenges: During the recovery phase, maintaining the specific environmental conditions associated with healing is difficult and labor intensive.

Technically Challenging



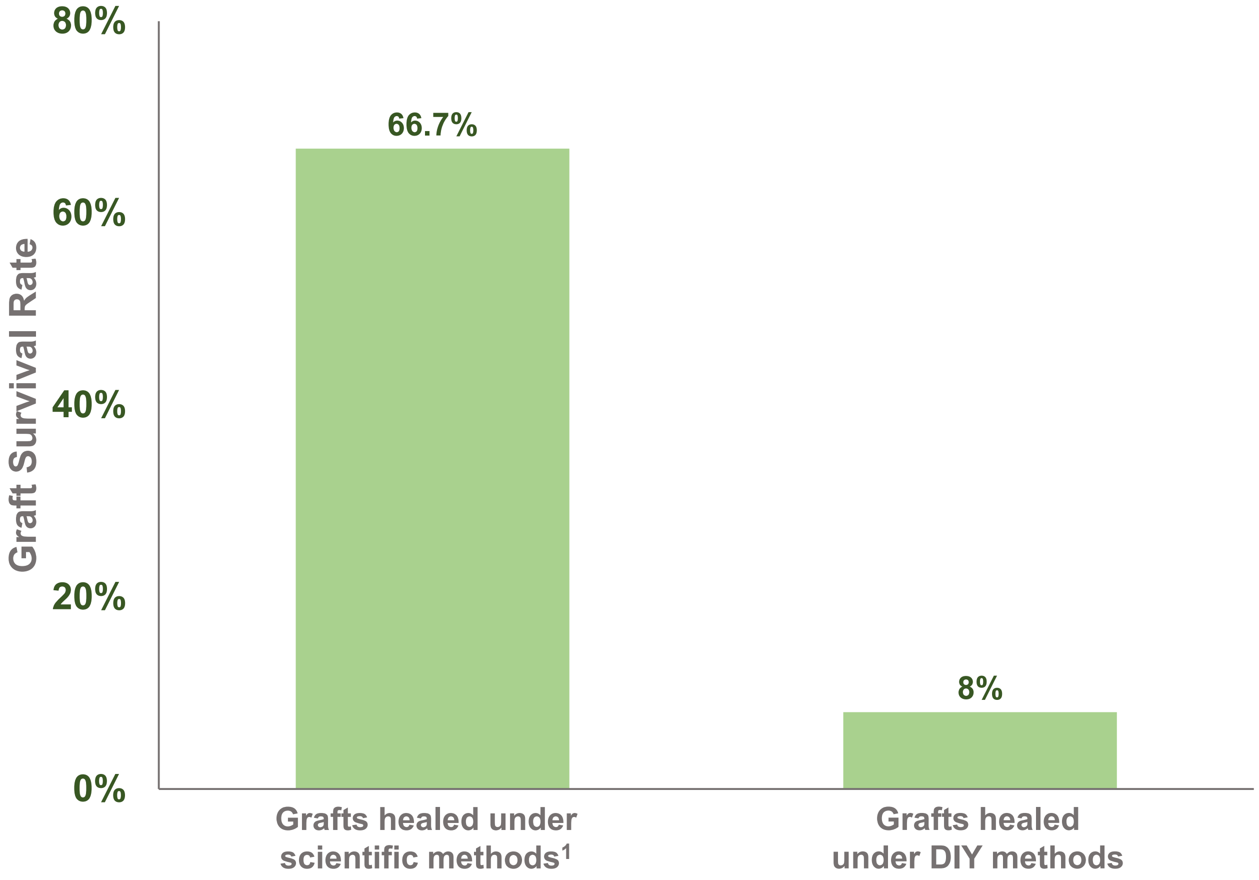
85% – 95%

72˚F – 85˚F
22˚C – 30˚C

Taper to Ambient

Routine checks required

Modernizing the Process: Existing research confirms that engineering-based methods are more efficient and effective than unassisted agricultural techniques.

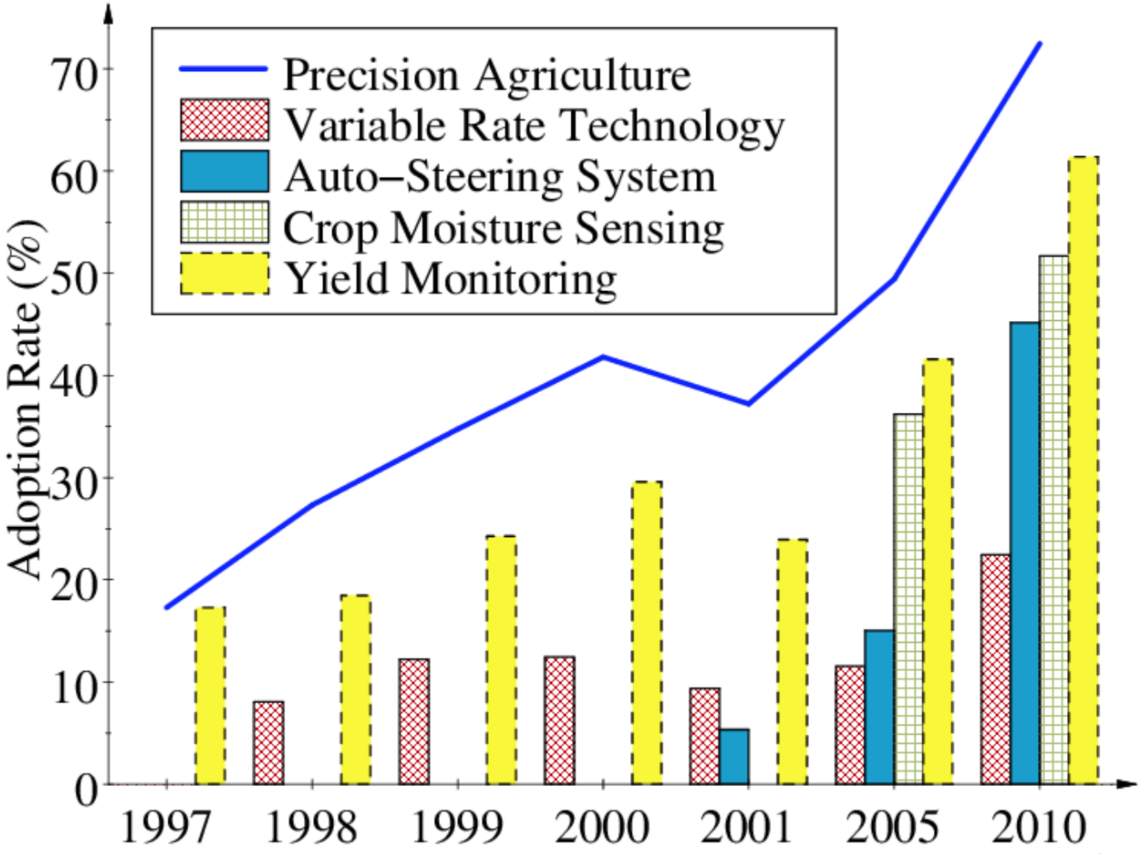


Percentage Of One-month Old Whip grafts Healed Successfully Using Two Healing Methods.

"We grafted three trays of seedlings and only four grafts took."
- Katharine Rondthaler, SCU Forge Garden Manager

[1] Mohammad Cholid, Hariyadi , Slamet Susanto, Djumali and Bambang Sapta Purwoko, 2014. Effects of Grafting Time and Grafting Methods Used on Scion and Rootstock Compatibility of Physic Nut (*Jatropha curcas* L.). *Asian Journal of Agricultural Research, 8: 150-163.*

Current Landscape: As the agricultural industry has modernized, smallholder farming has been less empowered by technological advancement.



Smart Farming Technologies Adoption Rates Over Time[1]

“Larger farms are more likely to adopt these [precision agriculture] technologies, with some of the highest adoption rates being on farms with more than 3,800 acres.”[2]

---

[1] Vuran, Mehmet & Salam, Abdul & Wong, Rigoberto & Irmak, Suat. (2018). Internet of Underground Things: Sensing and Communications on the Field for Precision Agriculture.

[2] Say, Sait & Keskin, Muharrem & Sehri, Mustafa & Sekerli, Yunus. (2017). Adoption of Precision Agriculture Technologies in Developed and Developing Countries.

Overarching Goal: Our goal was to prove the scalability of a precise graft recovery environment to suit the needs of the smallholder farmer.

https://www.pflanzenkrankheiten.ch/component/content/article?id=295:auswinterung-frostschaeden

http://waywardspark.com/how-to-graft-tomatoes-gathering-together-farm-method/

Market Research: In the case of grafting, existing solutions serve niche plant owners and large-scale operations.

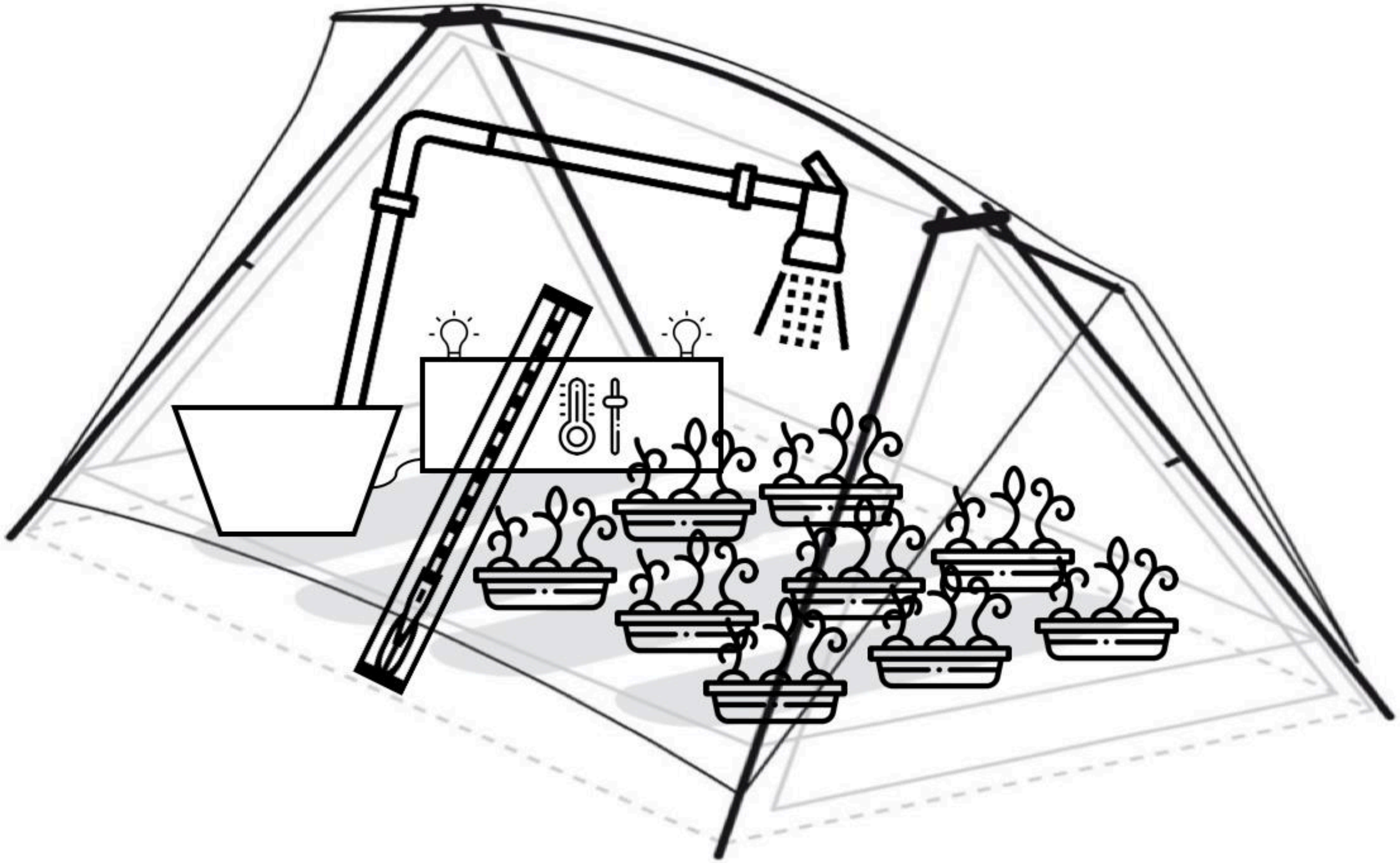
EcoQube™. $169.99

D.I.Y. systems. $100.00 avg.

koolfog™ industrial greenhouse. $16,283.00

Robbins, J. (2014). Starting a Greenhouse Business (Part 1) Some Basic Questions. University of Arkansas Division of Agriculture, (FSA6051).

Project Purpose: The purpose of this project is to design a rapidly deployable and self-regulating grafting chamber that targets this gap in the market.



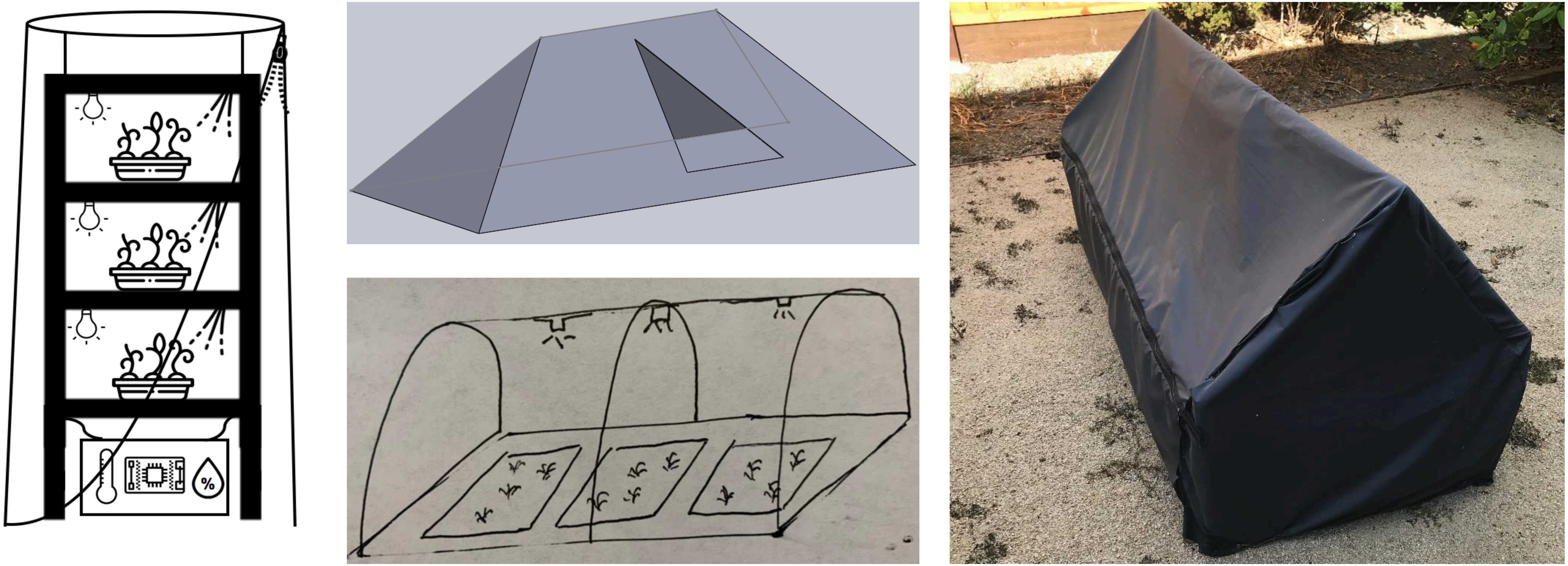
Target Audience: The primary market for the grafting chamber is small scale agricultural operations (less than 100,000 USD annual sales or 2 hectares), with particular appeal among organic gardeners and farmers.

- Disease resistant rootstocks reduce the need for chemical soil additives.
- A collapsible structure reduces the off-season footprint in locations with spatial restrictions.
- Self-regulating environmental conditions minimize labor requirements.

Santa Clara University Forge Garden

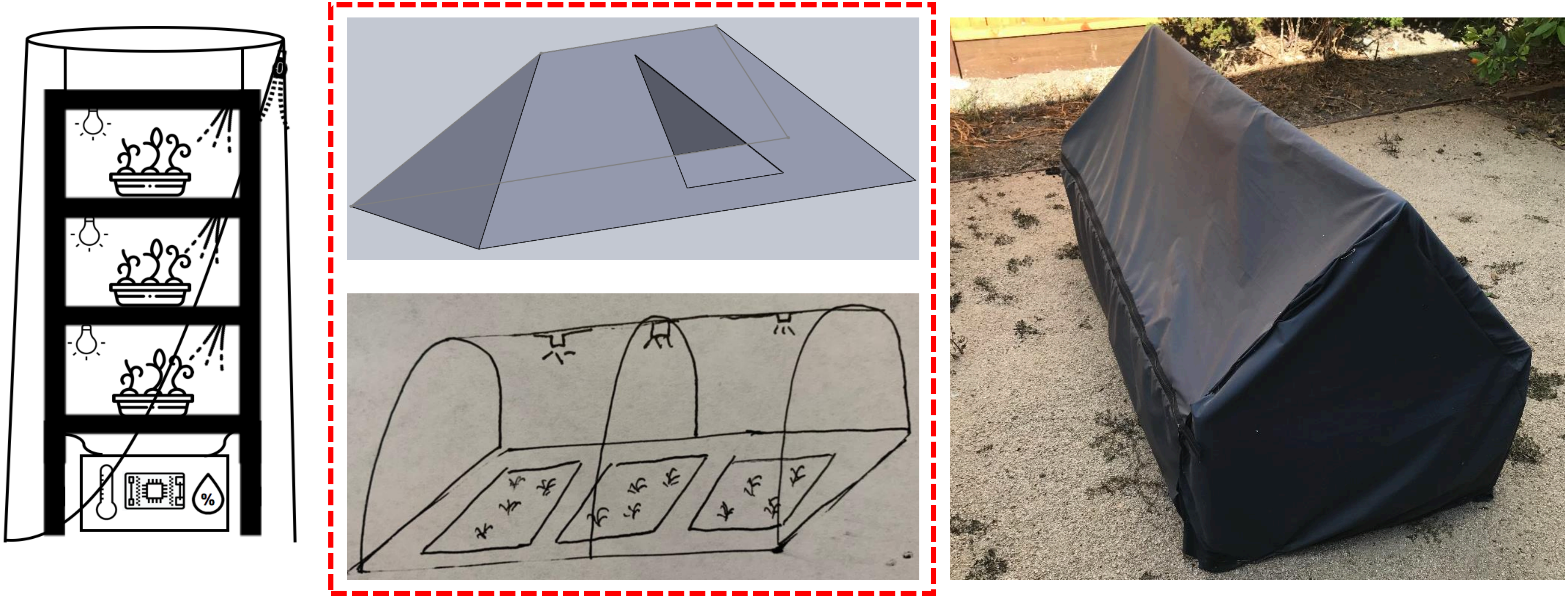
https://tensepresent.wordpress.com/2017/04/25/forging-a-sustainable-future/

Design Approach: Market research, competitive benchmarking, and discussion with advisors and members of industry refined the specifics of the project.



Preliminary grafting chamber conceptualizations (left and center) and current prototype (right).

Design Approach: Market research, competitive benchmarking, and discussion with advisors and members of industry refined the specifics of the project.

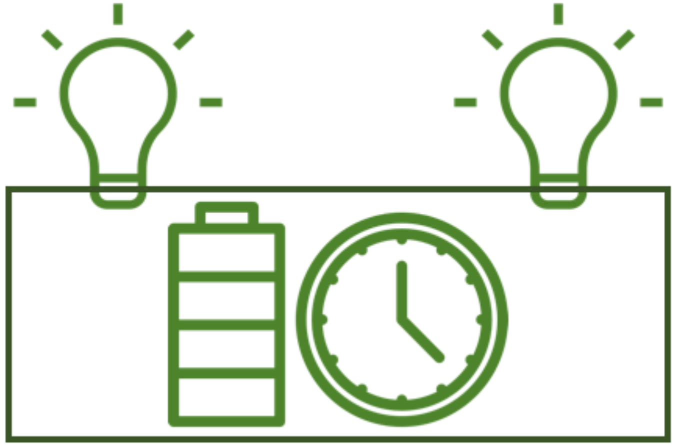


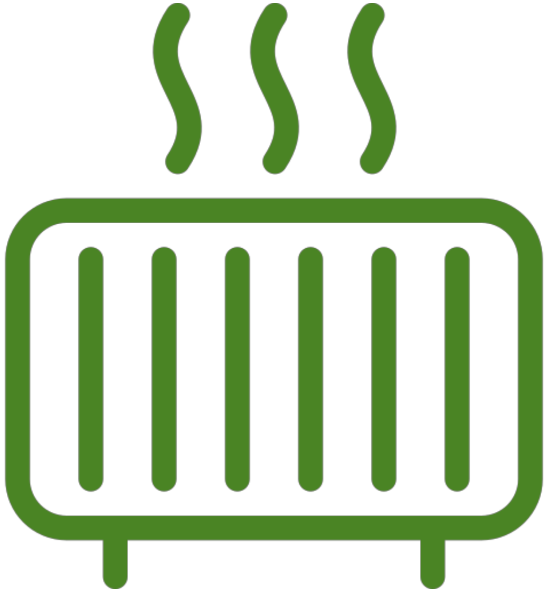
Preliminary grafting chamber conceptualizations (left and center) and current prototype (right).

System Overview: A series of sensors and actuators monitor and control humidity, temperature, and ambient light to maintain the specific environmental conditions required to produce successful grafts.

Lighting Control with UV Bulbs

Taper to Ambient



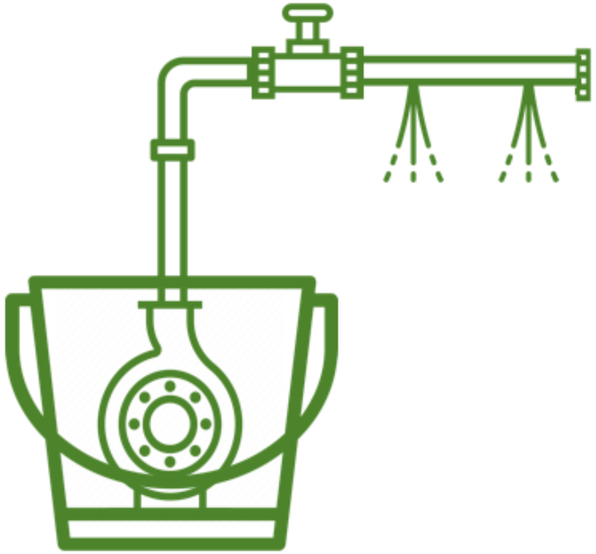


Temperature Control with Heating Element

72˚F – 85˚F
22˚C – 30˚C

Humidity Control with Misting System

85% – 95%



Subsystem One – Structure: The essential function of the grafting chamber structure is to facilitate the maintenance of the necessary healing environment within.

Key Attributes:
- Water/light resistant
- Durable
- Portable

Prototype v.1

Prototype v.2

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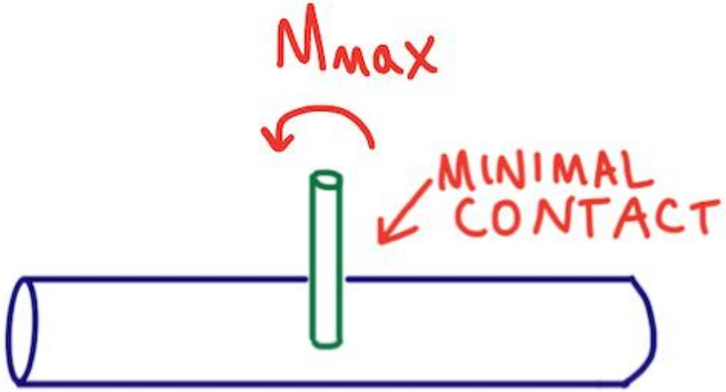
SCHOOL OF ENGINEERING

Junction Analysis: Consideration of static forces and material properties also influenced structural decision making.

Prototype v.1



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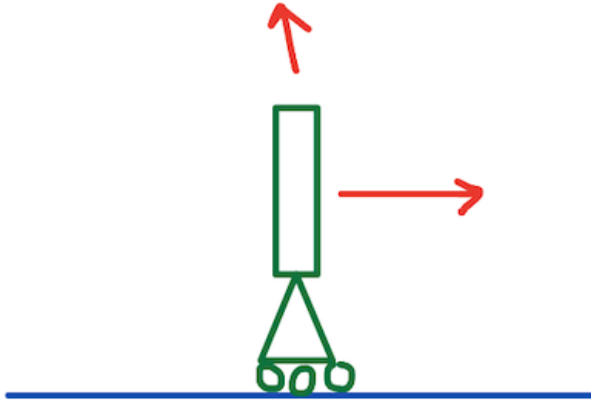
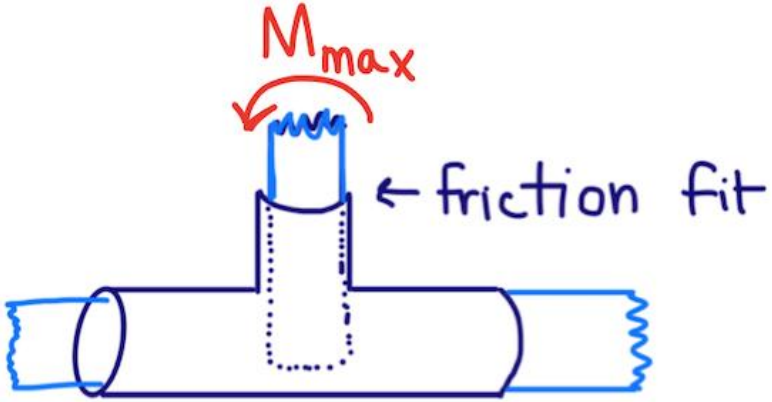


Prototype v.2



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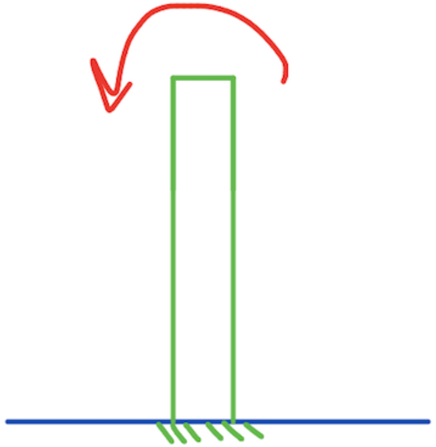

Enclosure Fabric Comparison: Material Selection was primarily based on efficacy of environmental regulation, and supplemented by considerations of cost and durability.

Comparison of enclosure materials for grafting chamber project.

Evaluation Criteria	SilPoly	Canvas	Blue Tarp
Water resistance	High	Medium	High
Light resistance	High	High	Medium
Cost	$$	$	$
Ability to be sewn	Moderate	Difficult	Difficult

Enclosure Fabric Comparison: Material Selection was primarily based on efficacy of environmental regulation, and supplemented by considerations of cost and durability.

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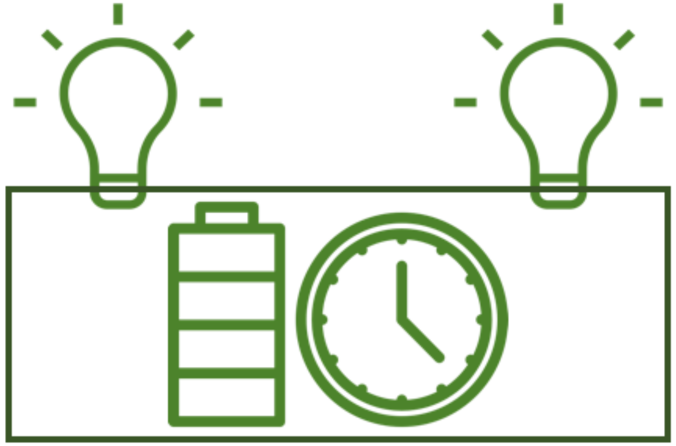
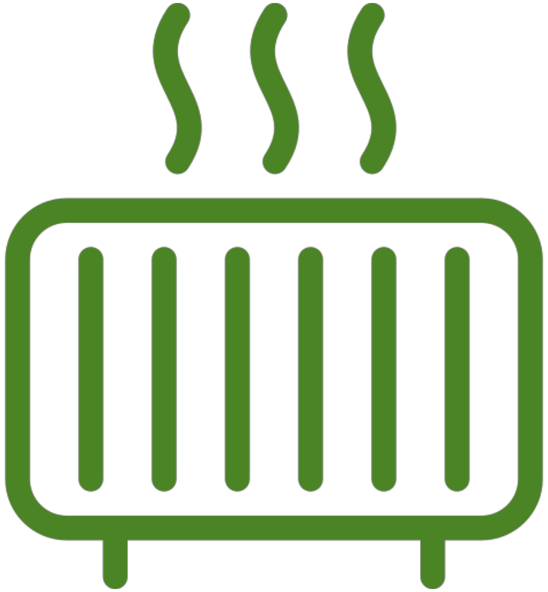
Light resistance	High	High	Medium
Cost	$$	$	$
Ability to be sewn	Moderate	Difficult	Difficult

Control Subsystem: Lighting.



Lighting Control with UV Bulbs

Taper to Ambient

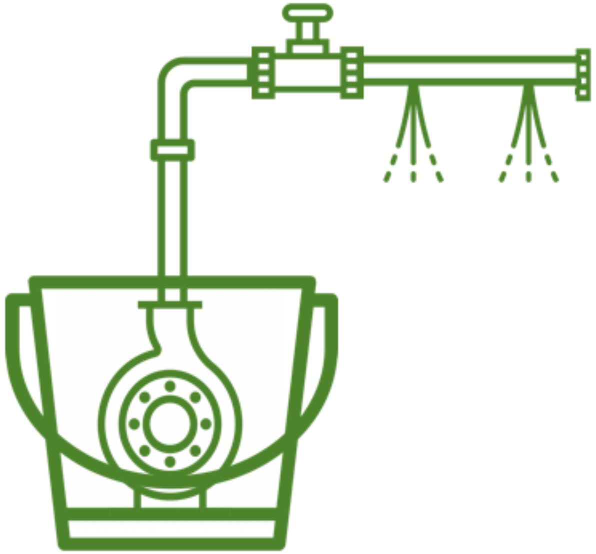


Temperature Control with Heating Element

72˚F – 85˚F
22˚C – 30˚C

Humidity Control with Misting System

85% – 95%

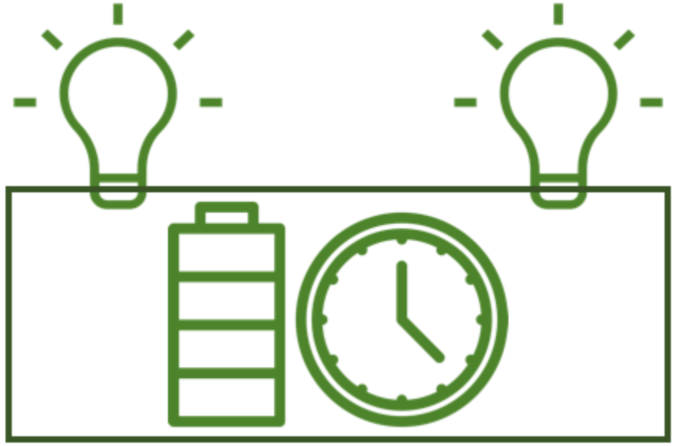


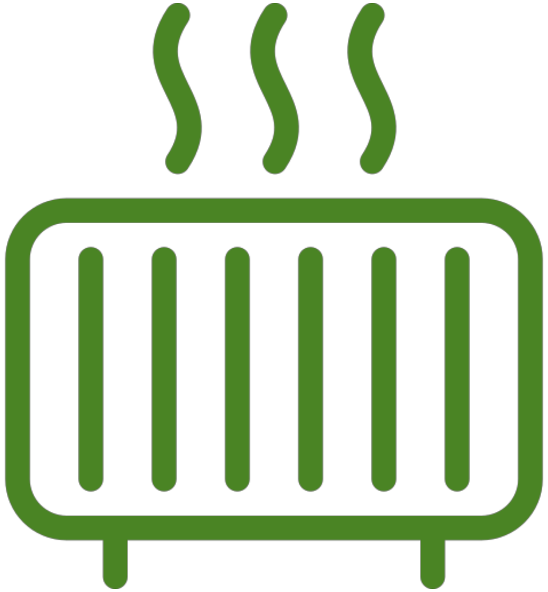
Subsystem Two – Lighting: Light exposure is regulated with solar powered bulbs.

Control Subsystem: Temperature.

Lighting Control with UV Bulbs

↳ **Taper to Ambient**



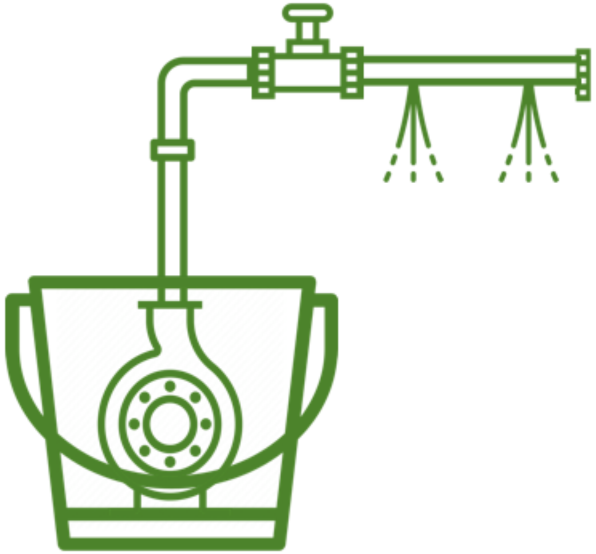


Temperature Control with Heating Element

↳ **72˚F – 85˚F**
22˚C – 30˚C

Humidity Control with Misting System

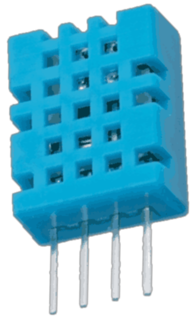
↳ **85% – 95%**



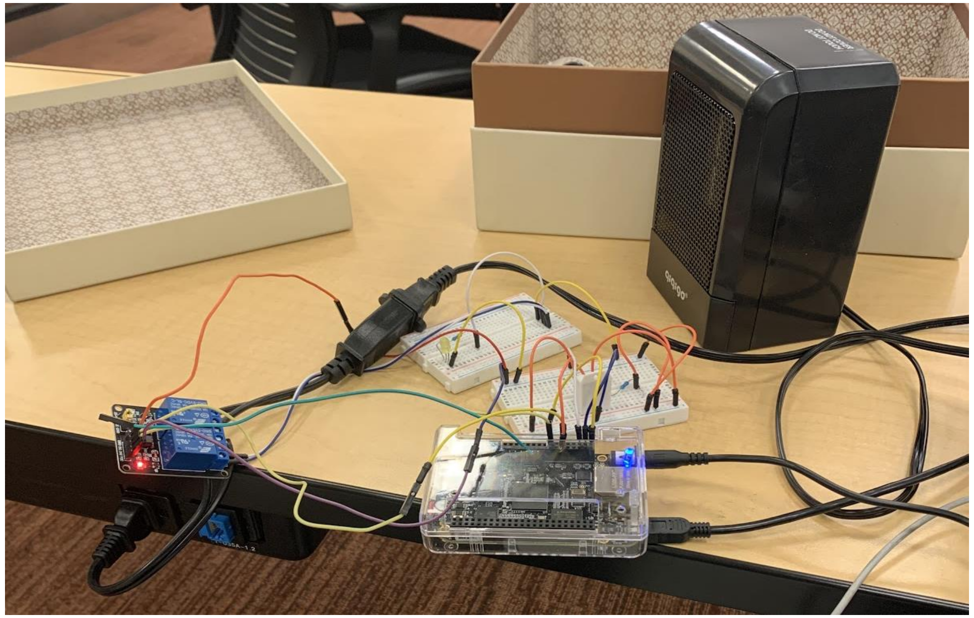
Subsystem Three – Temperature Control: Thermal regulation is achieved with a space heater, Digital High Technology (DHT) sensor, and relay.

Space Heater

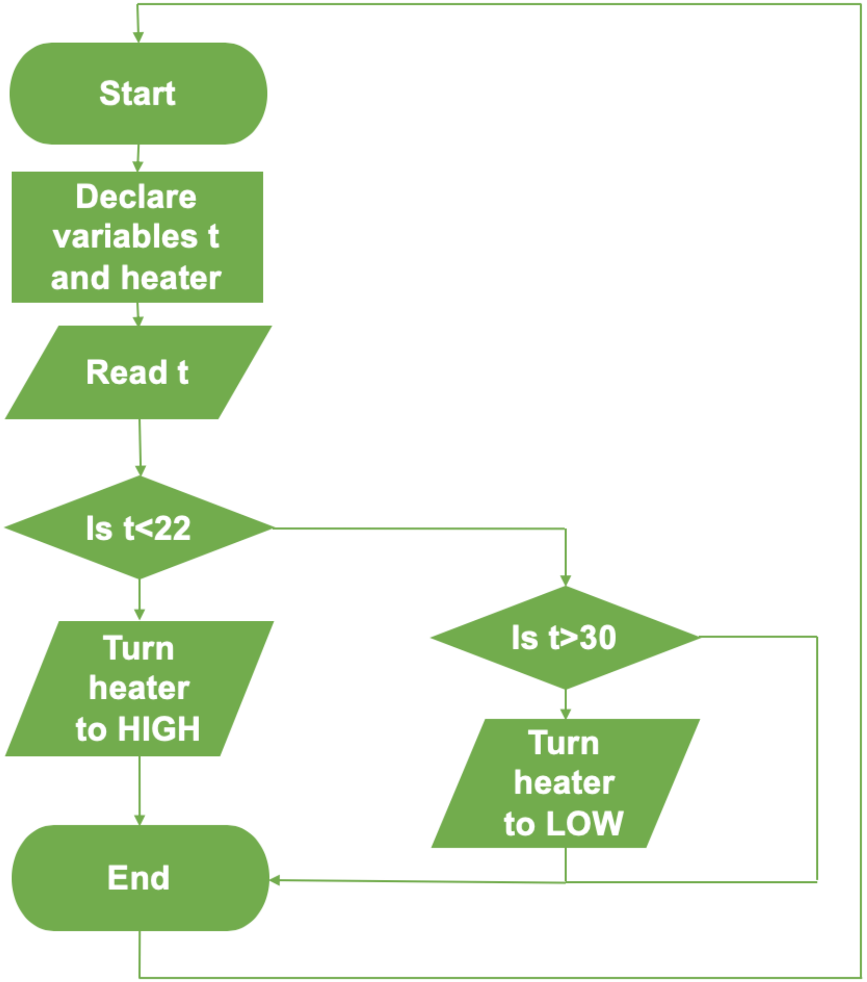
DHT Sensor



5V Relay



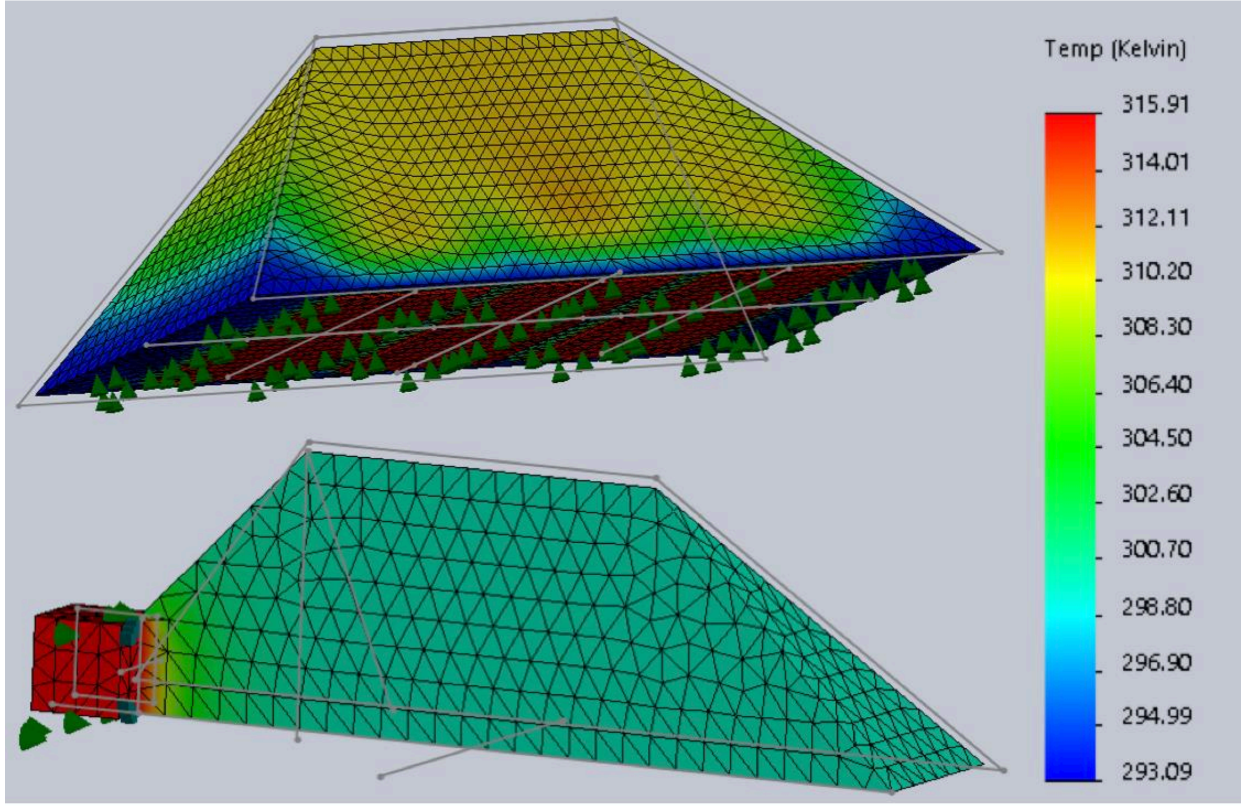
Temperature control system prototype.



Temperature control, initial logic.

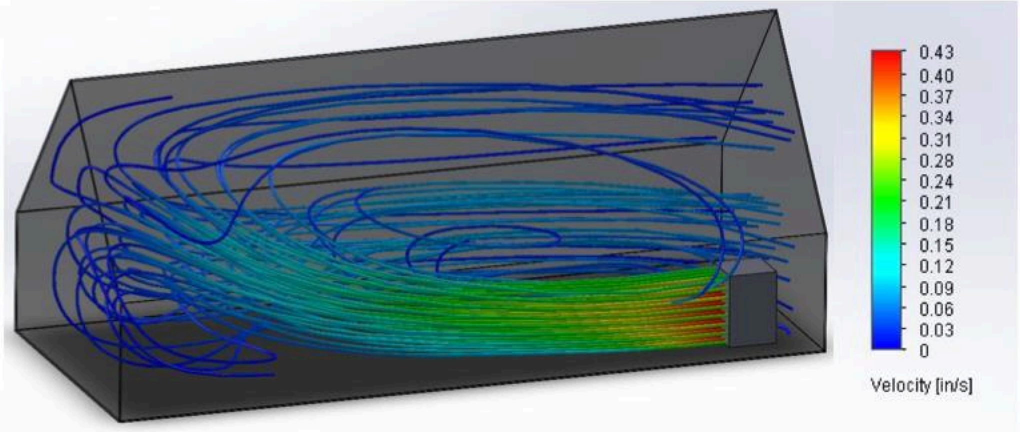
Finite Element Analysis: Simulation using SolidWorks, FlowSim, and COMSOL Multiphysics modeled temperature distribution, airflow within the chamber, and heat loss through the chamber walls.

Temperature Distribution



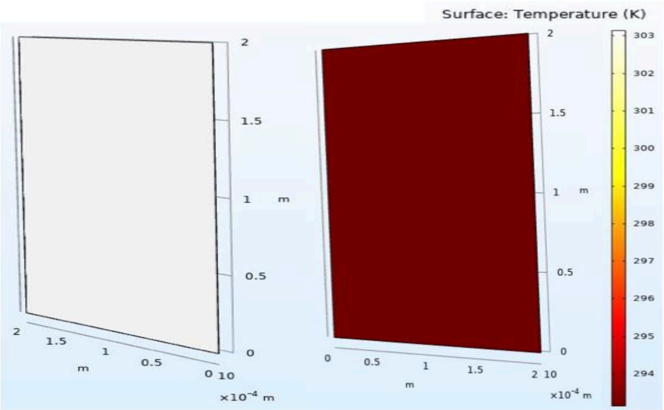
Heating mats (top) and space heater (bottom).

Airflow



Chamber airflow, integrated fan only.

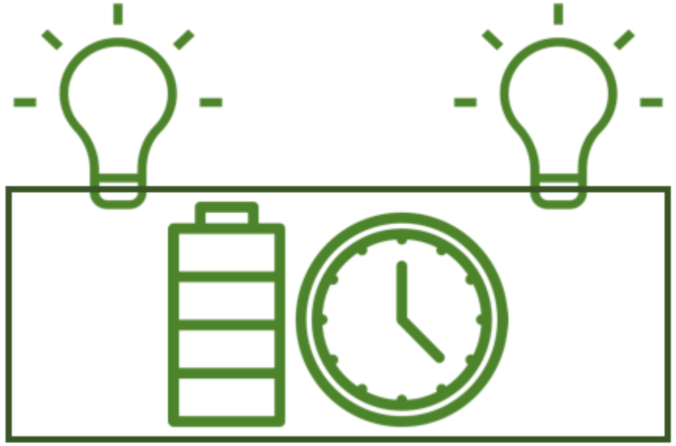
Heat Loss

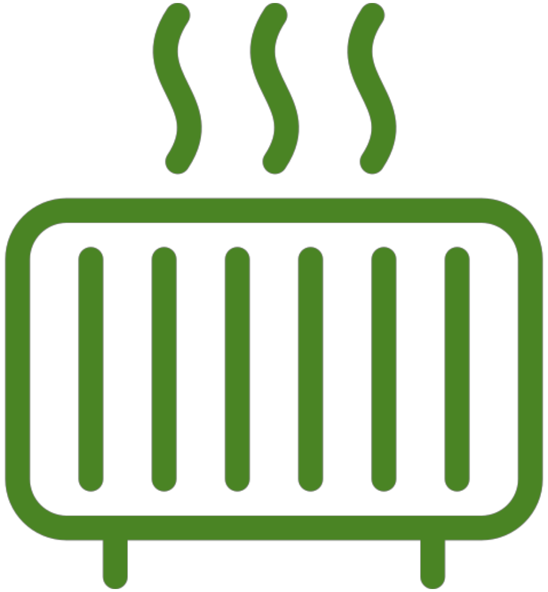


Control Subsystem: Humidity.

Lighting Control with UV Bulbs

Taper to Ambient





Temperature Control with Heating Element

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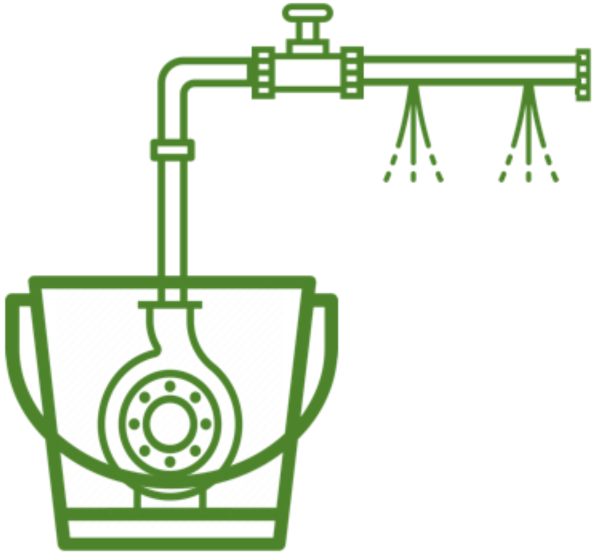
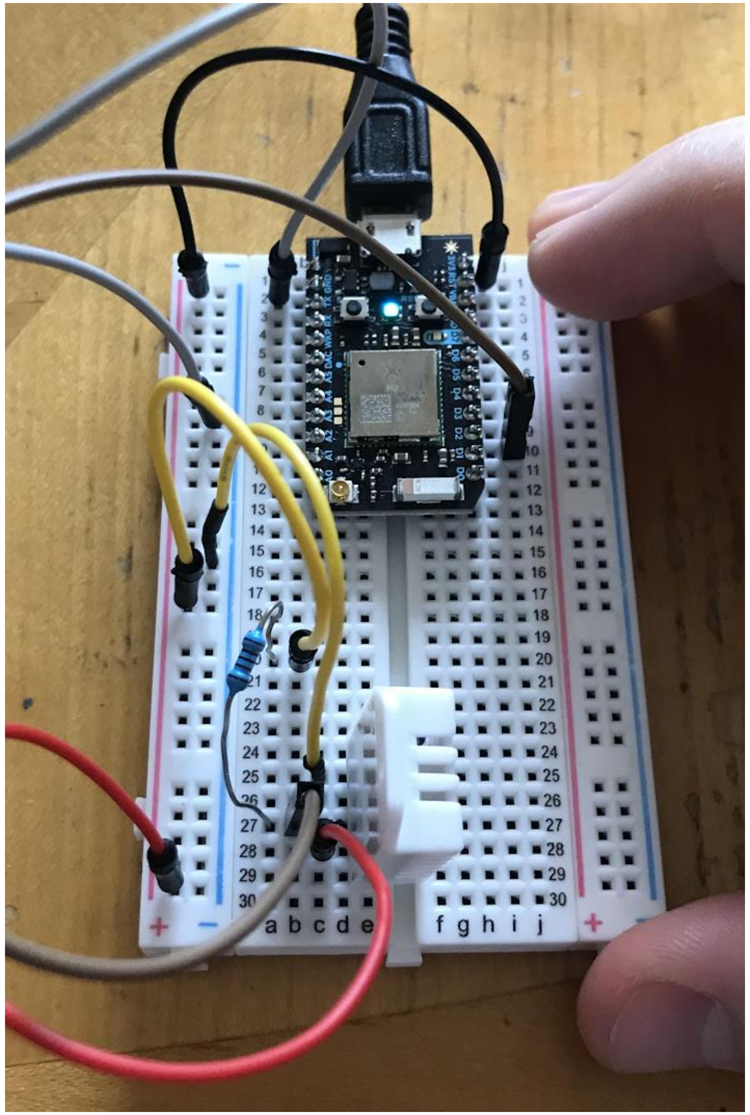
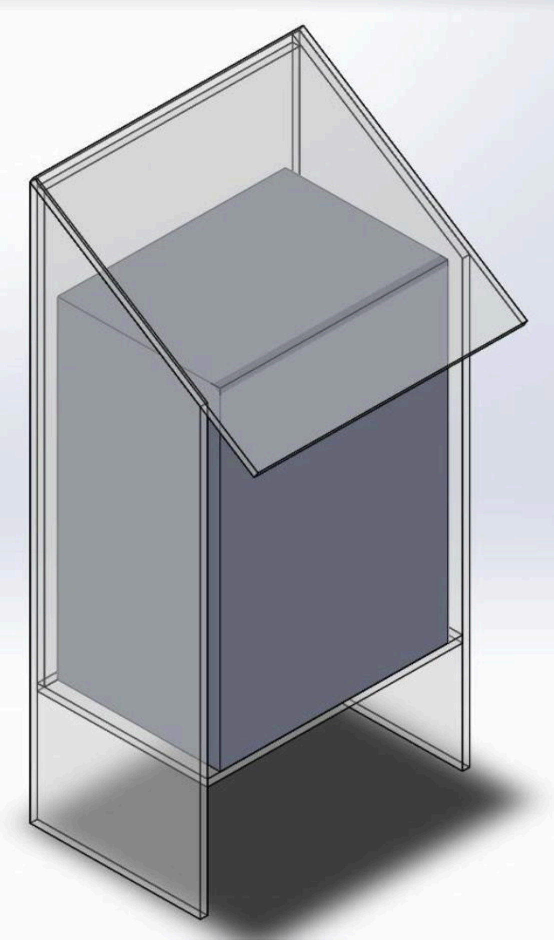
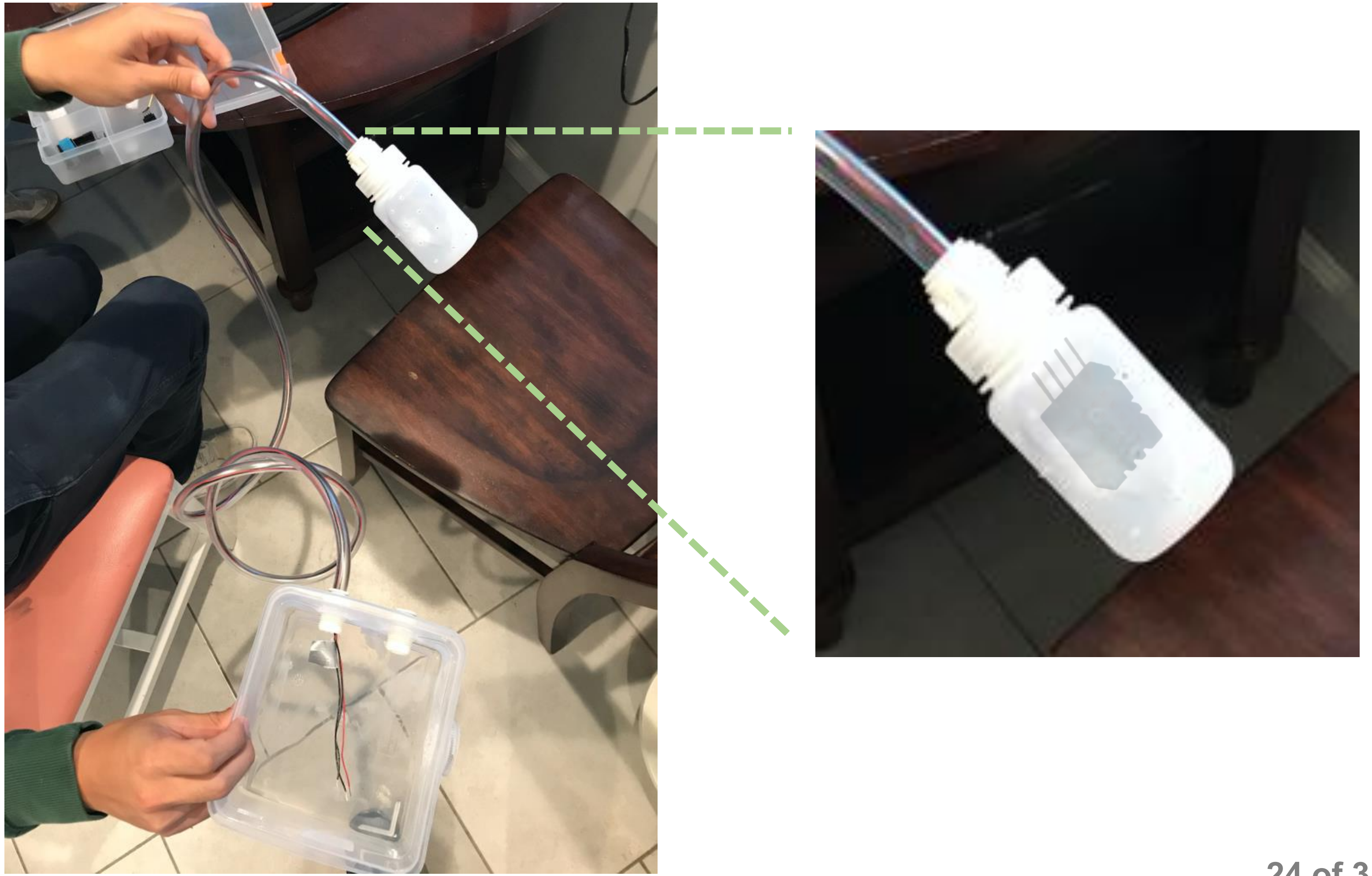


Subsystem Four – Humidity Control: Target humidity is achieved with a misting system, DHT sensor, and electronically controlled valve.



Data Collection: Chamber conditions and environmental uniformity are measured via a waterproofed sensor array.



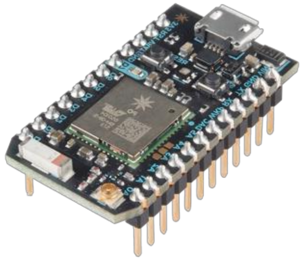


Microcontroller Selection: Evaluation of microcontrollers included criteria such as cost, Wi-Fi capability, and compatibility with additional hardware components.

Arduino Uno

BeagleBone Black

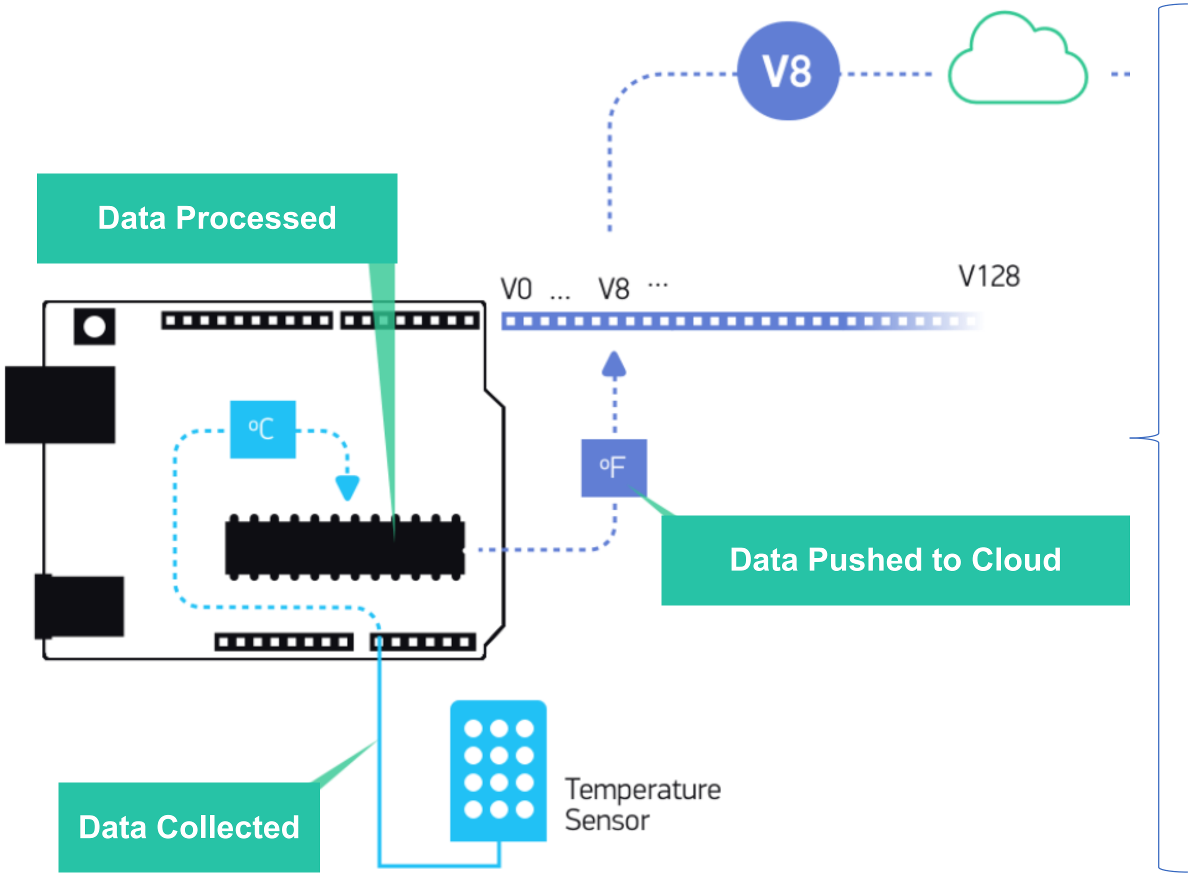
Particle Photon



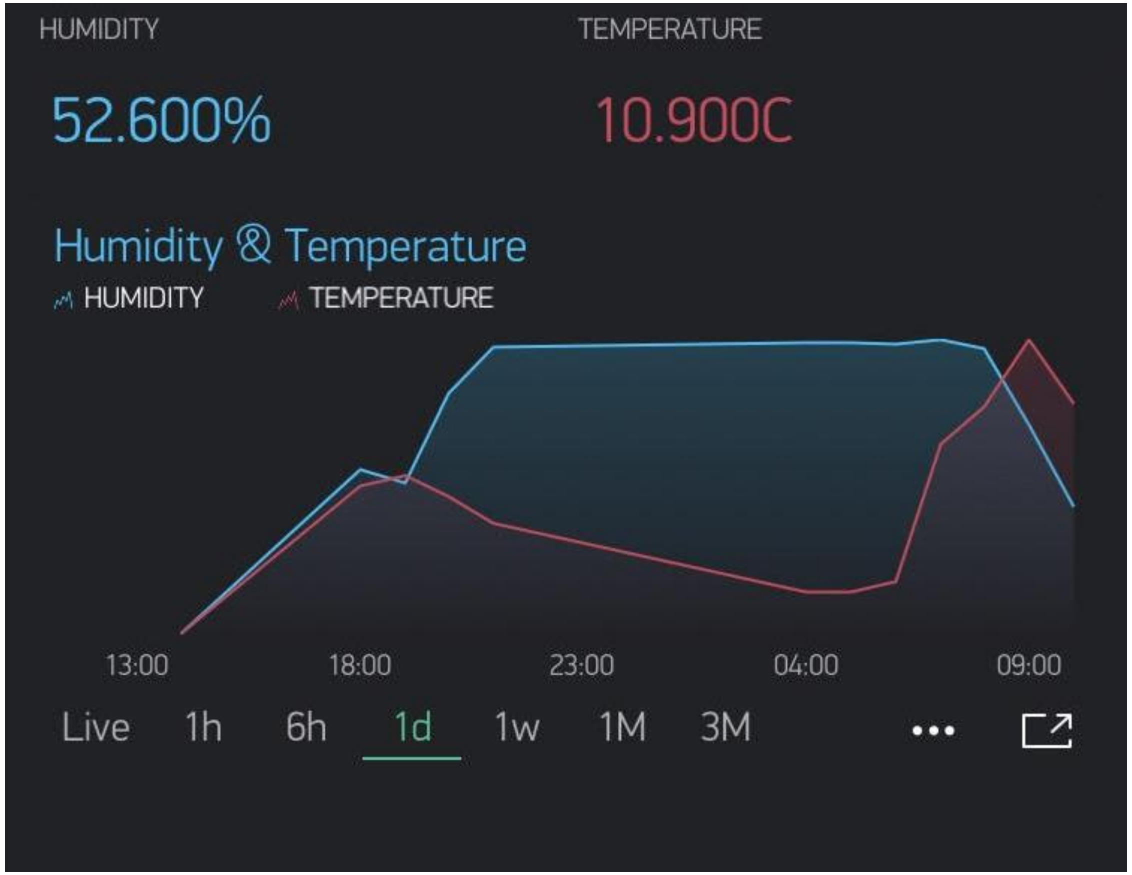
Comparison of microcontrollers for grafting chamber project.

Evaluation Criteria	Arduino Uno	BeagleBone Black	Particle Photon
Integrated Wi-Fi Capability	No	No	Yes
Cost	$	$$$	$
Significant Local Storage	No	Yes	No
Processing Power	Low	High	Medium

Remote Monitoring: Using the Blynk app, we have been able to remotely monitor environmental conditions inside the grafting chamber during testing.



How it works.[1]



Blynk sample interface.

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[1] https://blynk.io/en/getting-started

Testing Methodology: Individual subsystems were tested as they developed, with the goal of demonstrating the superiority of active control at environmental regulation.

No Control

Baseline test – empty chamber.

Passive Control

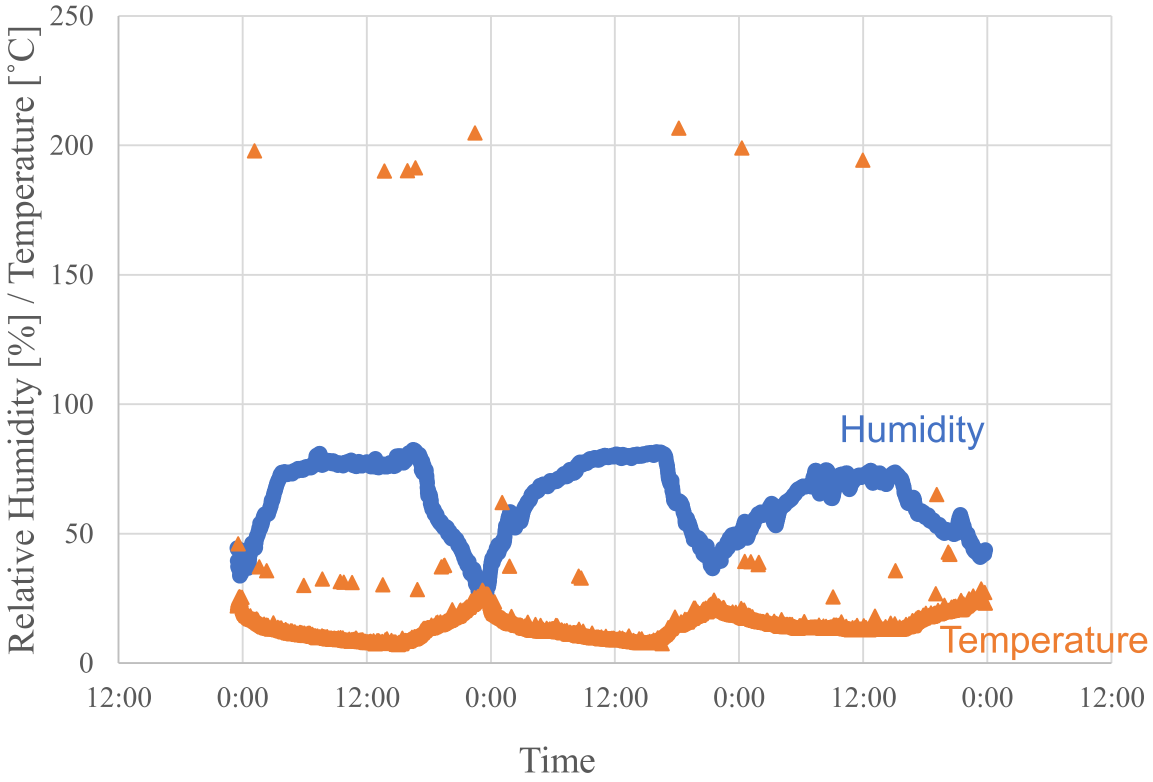
Constant heat: floral foam, Humidipaks, and water tray.

Active Control

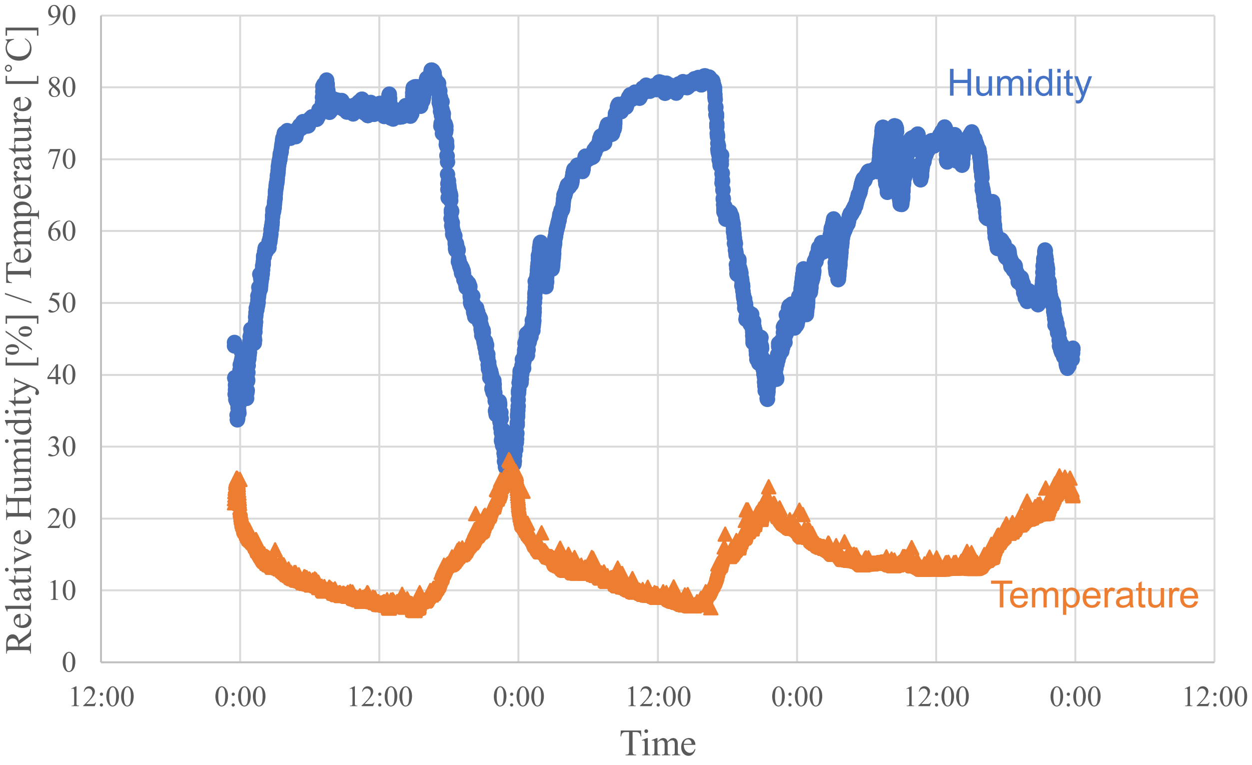
Active heat: water tray and daily sprays.

Grafting chamber: preliminary test setup.

Addressing Errant Measurements: Our data processing model identifies and eliminates false readings and outliers.



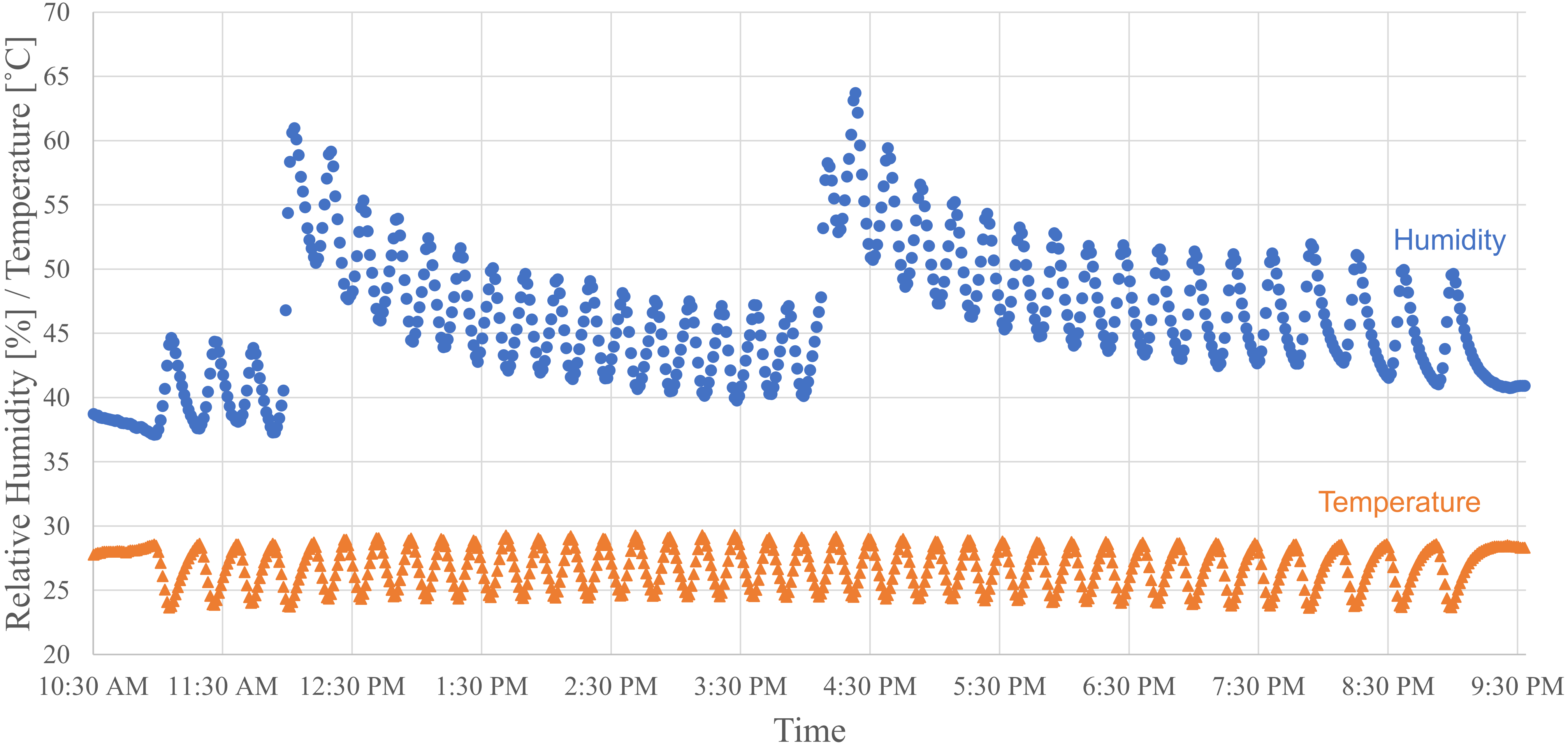
***Without* anomaly detection.**



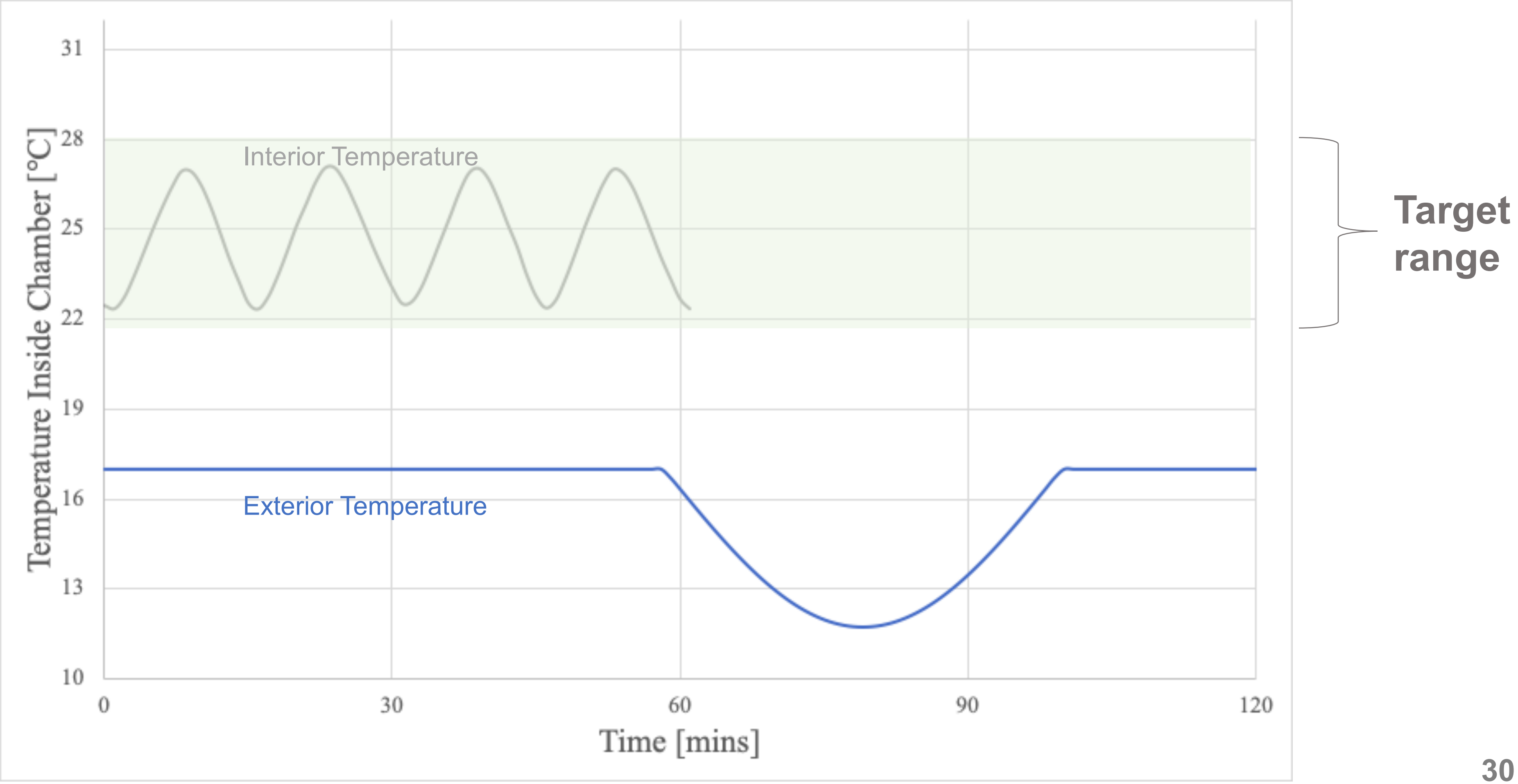
***With* anomaly detection.**

measured value < 2 x (std. dev. of previous 10 values)

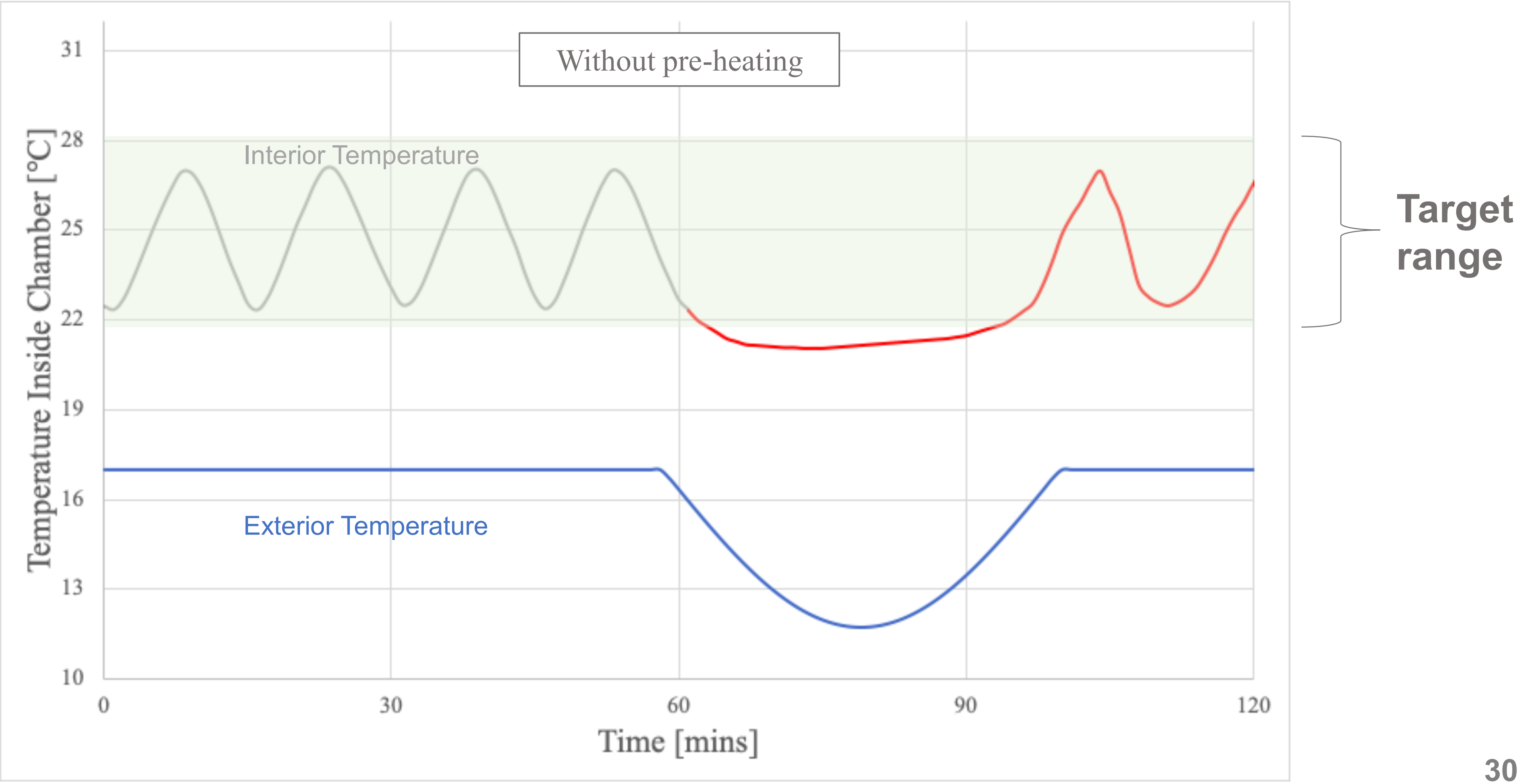
Sample Data: Test results indicate that the implemented active control methods create a more suitable recovery environment than passive control.



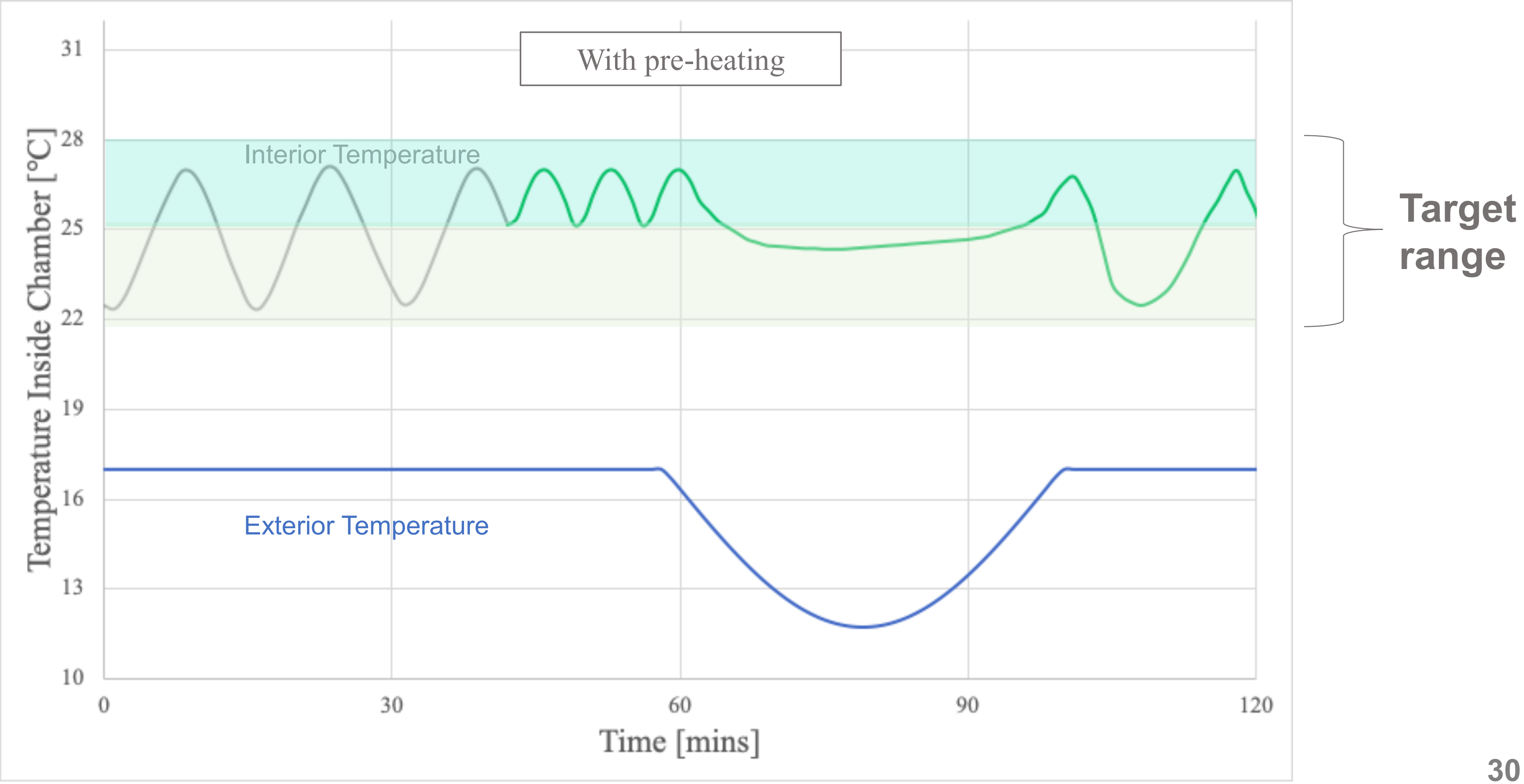
Improvement Opportunity: By pre-heating the grafting chamber in anticipation of temperature drops, a more consistent temperature profile can be achieved, reducing shock to healing plants.



Improvement Opportunity: By pre-heating the grafting chamber in anticipation of temperature drops, a more consistent temperature profile can be achieved, reducing shock to healing plants.



Improvement Opportunity: By pre-heating the grafting chamber in anticipation of temperature drops, a more consistent temperature profile can be achieved, reducing shock to healing plants.



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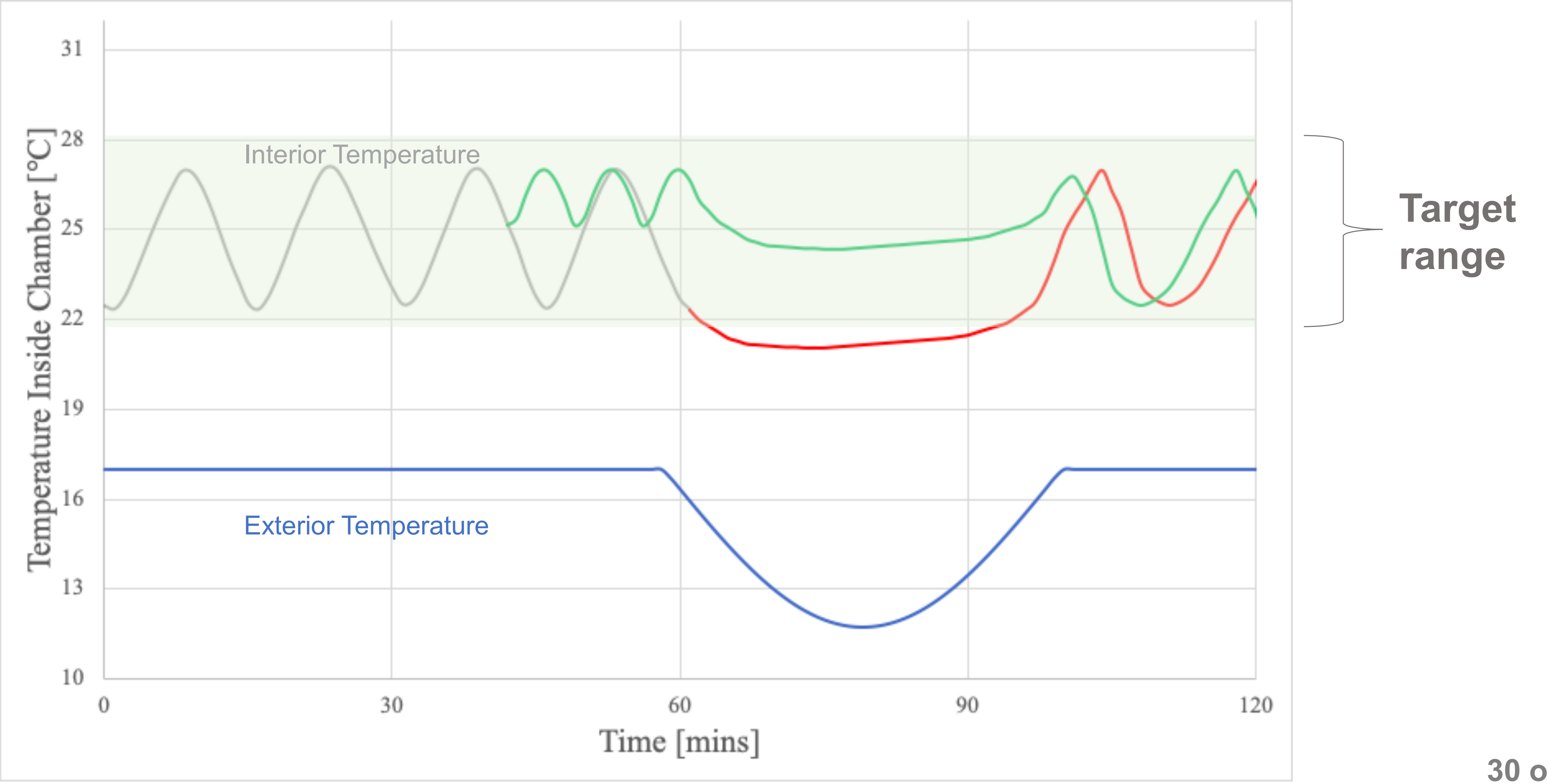
Improvement Opportunity: By pre-heating the grafting chamber in anticipation of temperature drops, a more consistent temperature profile can be achieved, reducing shock to healing plants.



Machine Learning: To optimize chamber temperature, a machine learning algorithm was developed to predict temperature values and facilitate pre-heating of the chamber.

Kaleb

Description	3 Days Before	2 Days Before	1 Day Before	Today (0 days Before)
1:00pm	T(3,1)	T(2,1)	T(1,1)	T(0,1)
2:00pm	T(3,2)	T(2,2)	T(1,2)	T(0,2)
3:00pm	T(3,3)	T(2,3)	T(1,3)	T(0,3)
4:00pm	T(3,4)	T(2,4)	T(1,4)	T(0,4)
5:00pm	T(3,5)	T(2,5)	T(1,5)	T(0,5)
6:00pm	T(3,6)	T(2,6)	T(1,6)	T(0,6)
7:00pm	T(3,7)	T(2,7)	T(1,7)	T(0,7)

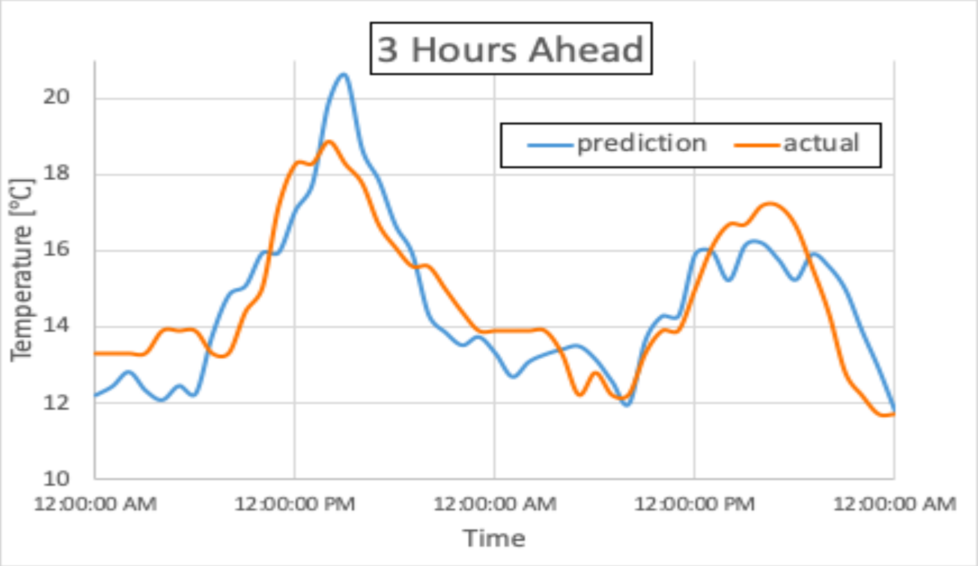
- **Using the green values the red values are predicted in accordance with linear algebra:**

$$Y \times P = U$$

- **To do this, the values that make up the P matrix are needed:**

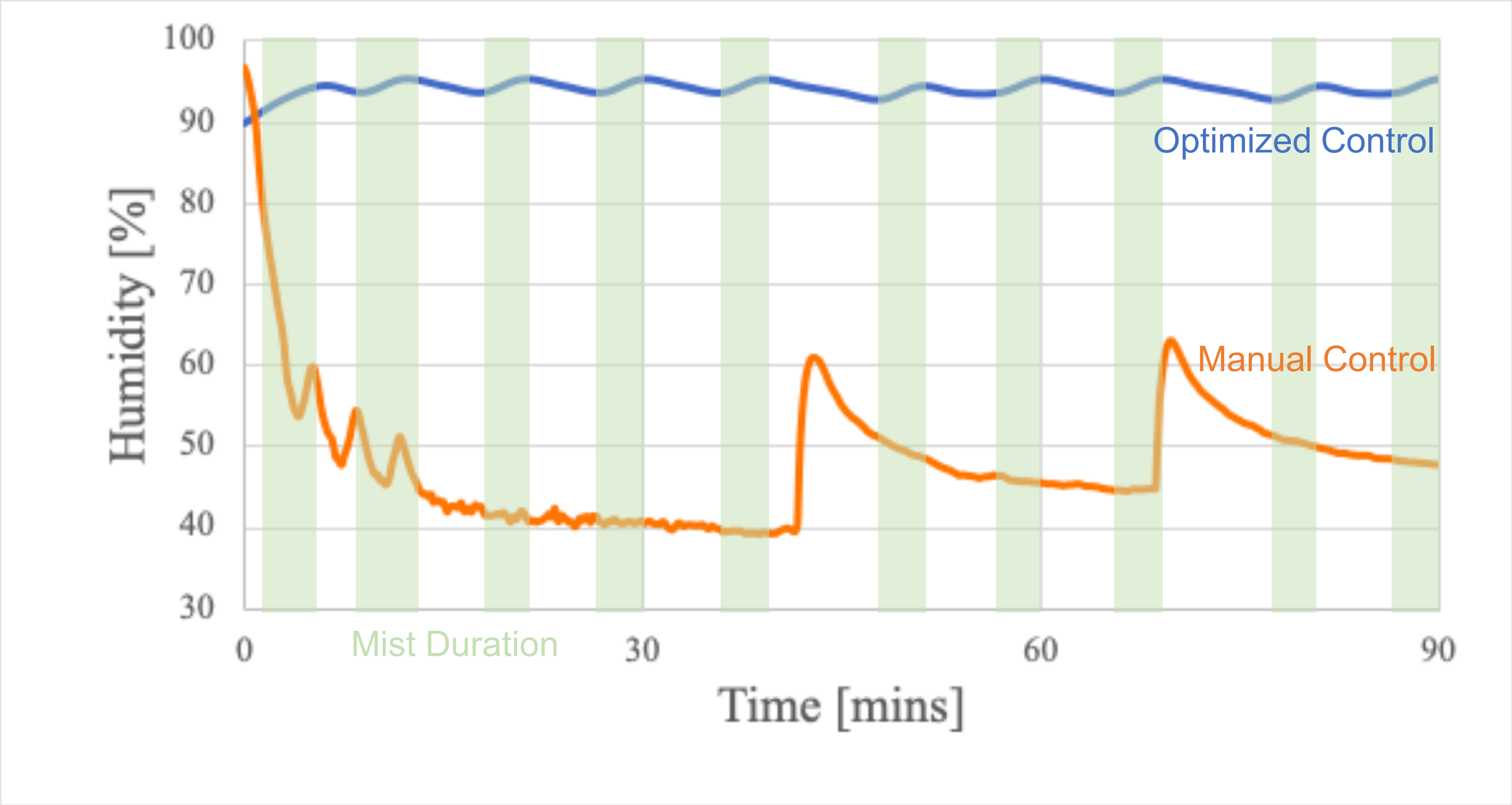
$$\underbrace{\begin{pmatrix} Y(1,1) & Y(1,2) \ldots & Y(1,12) \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ Y(n,1) & Y(n,2) \ldots & Y(n,12) \end{pmatrix}}_{n \times 12} \underbrace{\begin{pmatrix} P(1,1) & P(1,2) & P(1,3) \\ P(2,1) & P(2,2) & P(2,3) \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ P(12,1) & P(12,2) & P(12,3) \end{pmatrix}}_{12 \times 3} = \underbrace{\begin{pmatrix} T(1,4) \ldots T(n,4) \\ T(0,5) \ldots T(n,5) \\ T(0,6) \ldots T(n,6) \end{pmatrix}}_{n \times 3}$$

Linear Algebra Gives: $P = (Y^T Y)^{-1} Y^T U$



Days of Inputs	7 days	5 days	3 days
Mean Error [℃]	0.7466	0.7408	0.7516

Predictive Humidity Control: To determine the best misting schedule, a model to calculate the humidity change in the chamber was created based on the GNR non-linear solving method which optimized chamber humidity and water usage.

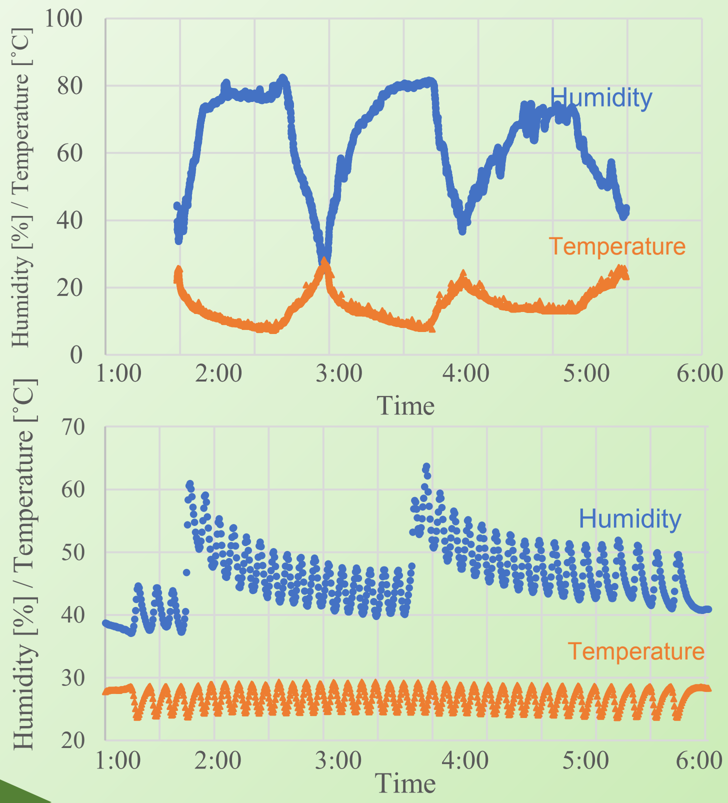


- Humidity inside the chamber is mainly a function of time
- Need an optimized misting schedule to maintain desired conditions
- Excel Solver – Non-linear optimizer

Synopsis: This year our team identified a problem, designed a solution, and demonstrated the feasibility of that solution.

Problem identification

Solution Design



Feasibility Demonstration

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Thank You