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DESIGN OF AN URBAN GARDEN AQUAPONICS SYSTEM

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Design of an Urban Garden Aquaponics System

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SENIOR THESIS

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Abstract

The project objective is to create a durable, off-the-grid, large-scale aquaponics system consisting of over 90 sq. ft of growing space, a 650-gallon fishpond, and four types of sensors to transmit water quality data to the internet for remote water quality monitoring. The end goal of the project is to supplement produce grown in the garden to further increase fresh, nutritional options available in meals cooked and distributed by Loaves and Fishes Family Kitchen to combat food insecurity in San Jose. This report presents the need for a system, details the various subsystems, and the rationale for the designs. It serves as a comprehensive guide to all the work that has been completed, provides an outlook for future iterations, and demonstrates the viability of aquaponics as an efficient method to grow food.

Acknowledgements

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List of Abbreviations

- A: amperes
- AC: alternating current
- AGM: absorbed glass mat
- ASME: American Society of Mechanical Engineers
- AWG: American wire gauge
- CAD: computer aided design
- CFD: computational fluid dynamics
- CNG: Certified Naturally Grown
- DC: direct current
- DO: dissolved oxygen
- dS: deciSiemens
- EC: electrical conductivity
- FDA: Food and Drug Administration
- FEA: finite element analysis
- ft: foot/feet
- GFCI: ground-fault circuit interrupter
- GHG: greenhouse gas(es)
- GJ: gigajoules
- gph: gallons per hour
- gpm: gallons per minute
- IBC: Intermediate Bulk Container
- IEEE: Institute of Electrical and Electronics Engineers
- in: inch
- IoT: internet of things
- IP: internet protocol
- kg: kilogram
- kWh/Wh: kilowatt-hour or watt-hour
- lb: pound
- mg: milligrams
- MJ: megajoules
- MPPT: maximum power point tracking
- mph: miles per hour
- NEC: National Electric Code
- NFPA: National Fire Protection Association
- NFT: nutrient film technique
- NPO: nonprofit organization
- NPV: net present value
- NSF: National Sanitation Foundation

- psi: pounds per square inch
- ppm: parts per million
- PV: photovoltaic
- ROI: return on investment
- sq. ft: square feet
- TDS: total dissolved solids
- UF-B: underground feeder wire
- USB: universal serial bus
- UN: United Nations
- USDA: United States Department of Agriculture
- UV: ultraviolet
- V: volts

1. Introduction

1.1 Food Insecurity

Food security is defined according to the 1996 World Food Summit as being [1]: "when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life". However, access to food relates to the distribution of food, creating an issue of equality. Food insecurity is often linked to low-income status and location, especially in areas known as "food deserts" where easy access to a variety of affordable fresh produce is non-existent [2]. The metrics for measuring food insecurity include missing one or more meals a day, relying on food banks or food stamps, borrowing money for food, or neglecting bills and rent in order to buy groceries [3]. Inaccessibility to nutritious foods often leads to physical ailments, such as obesity or malnutrition, as well as mental health problems, such as stress in taking care of a family.

The severity of this issue has increased and will continue to increase due to climate change that affects the availability of food produced, access to food due to higher costs, utilization of food due to disease and hunger, and stability of food as more and more areas are impacted [4, 5]. However, food insecurity also serves as an indicator of rising housing rates, unemployment rates, and the increasing population growth, leading more families to enter the low-income bracket, becoming vulnerable to increased chances of food insecurity.

Situated in the heart of Silicon Valley, San Jose is a hub of technology and development; however, an underlying, significant, and often unknown issue in this Valley is food insecurity. In Santa Clara and San Mateo Counties, approximately 10% of people and 14.3% of children experience food insecurity [6]. In addition, the Hunger Study published by Second Harvest Food Bank and Santa Clara University's Leavey School of Business found that 10.2% of people live below the federal poverty line and 12.1% of people are food insecure [7].

According to the United States Department of Agriculture Economic Research Service, several areas of San Jose are considered low income with low access to nutritious foods, demonstrating that there exists the need to create a local impact in reducing food insecurity and alleviating health disparities [8].

1.2 Aquaponics Systems

Aquaponics systems combine growing fish with the soil-less growing of plants. The systems are closed loop and the fish waste acts as fertilizer for the plants and the plants and media clean the water for the fish. An aquaponics system is one of the best options to combat food insecurity for urban communities in need and provides people with more options for nutritious food choices. An aquaponics system provides a soup kitchen, Loaves and Fishes Family Kitchen (abbreviated as Loaves and Fishes), with the ability to give their clients fresher vegetables with less impact on the environment and less reliance on water than traditional farming.

The opportunity to know where one's food comes from is often an overlooked luxury, and the implementation of the aquaponics system gives people a sense of agency over the food they put in their bodies. In this way, growing food locally is both socially and economically empowering. Furthermore, aquaponics can provide the added advantage of supplying the user with a protein source, in the form of fish. While the fish grow slowly, the benefit of protein accessibility adds significant value to the system beyond what existing hydroponic and aeroponic solutions offer.

1.3 Project Background

1.3.1 Benefits of Aquaponics

Aquaponics is an integrated farming system that includes a grow bed for vegetables and a tank that holds fish. It takes advantage of the symbiotic relationship between fish and plants to create a successful nitrogen cycle that optimizes plant growth. Using a pipe and pumping system, the water from the fish tank is cycled through the plants and then returned to the fish tank. This allows for the waste from the fish to fertilize the plants and the plants to remove chemicals while oxygenating the water, providing healthy living condition for the fish. The wastewater is filtered twice, once to remove the solid waste, and once more to remove any dissolved waste. Through a process called nitrification, the first filter uses bacteria that "[converts] ammonia, which is toxic for fish, into nitrate, a more accessible nutrient for plants" [9]. The system and nitrification process can be seen in Figure 1.

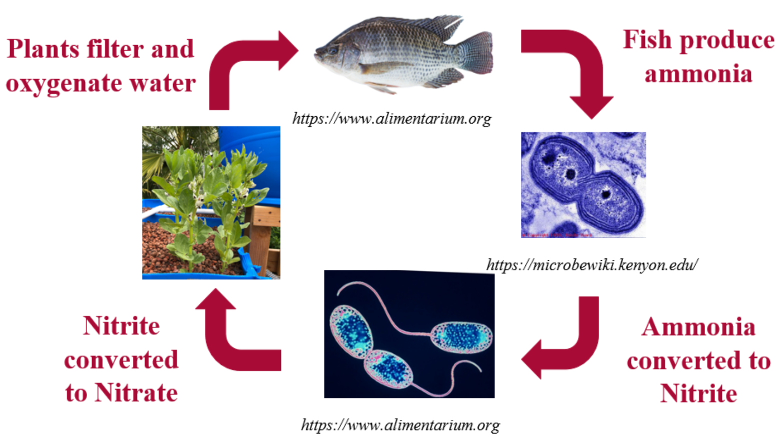


Figure 1. Nitrification cycle within an aquaponics system (Source: alimentarium.org, reproduced without permission)

A successful aquaponics system has the potential to alleviate hunger and the financial burden of having to buy fresh produce, which can be expensive and inaccessible—as is the case with food deserts. Food deserts are areas "vapid of fresh fruit, vegetables, and other healthful whole foods, usually found in impoverished areas" which "is largely due to a lack of grocery stores, farmers' markets, and healthy food providers" [10]. Additionally, the effects of climate change also threaten people's basic right to food. In more rural areas, climate change has led to the high occurrence of crop failure due to droughts, floods, and pest infestation. Aquaponics, therefore, tackles both climate change and food insecurity, as shown in Table 1.

Table 1. Problems solved by aquaponics

Problem	**Solution**
Food insecurity	● Grow high quantities of produce at a potentially faster rate ● Grow a wide variety of vegetables at lower costs ● Be accessible for people in urban areas to grow food ● Return agency to the individual, since the system can be easily maintained
Climate change vulnerability	● Resist drought, since it uses less water that is cycled throughout ● Resist floods, since it can be elevated and/or moved to prevent inundation ● Resist pests, since it can be elevated and natural methods of pest removal (fish) are prevalent

An additional advantage of aquaponics is that it uses a closed loop watering system, a farming technique with the potential to use 80% less water than traditional farming methods. One study demonstrates that "compared to extensive and semi-intensive culture practices where 20–25% of the water is exchanged daily to produce 8–15 kg fish/m^3 of water, the aquaponic system produced 45 kg fish/m^3/crop along with 42 heads/m^2/crop of lettuce with an addition of only 1.4% of total water in the system daily" [11]. This indicates that an aquaponics system can surpass the productivity of traditional aquaculture and hydroponics while reducing water waste and consumption significantly. The system combats drastic changes in water levels by negating the need for irrigation and constant watering. As a result, aquaponics is particularly suited to areas where water is scarce or very expensive.

A comparative analysis between traditional methods and aquaponics is presented below:

Table 2. Comparison of traditional farming techniques compared to aquaponics

Variable to Consider	**Traditional Farming**	**Drip-Irrigation**	**Aquaponics**
Low upfront cost	✓	✓	x
Implementation in urban area	x	✓*	✓
Less labor-intensive	x	✓*	✓
Water-efficient	x	✓	✓
Climate smart	x	x	✓
Incorporation of fish	x	x	✓

✓*: May be able to address variable

Overall, aquaponics provides a sustainable, comprehensive solution to low water resources, climate change, and nutrient-deficient farming that provides more benefits than other traditional farming methods. It has become increasingly popular and practical, catering to a variety of needs across the globe.

1.3.2 Approaches to Building an Aquaponics System

There are many ways to design and build an aquaponics system. It is necessary to consider many factors, specifically the configuration of the system, type of grow bed, the symbiotic relationship between the fish, the type of plants grown, and the timing of the pumping system. One of the simplest configurations to achieve water flow through the system is with a pump to move water from the fish tank up to the grow beds, while letting gravity return water to the fishpond and the rest of the system. Some more information on typical configurations of aquaponics systems can be seen in Appendix A. Additionally, there are also different types of grow beds that need to be considered. Table 3 provides a summary common types of grow beds:

Table 3. Grow bed considerations

Type of Grow Bed	**Visual Representation**	**Main Characteristics**
Nutrient film technique (NFT)	 *(Source:wikimedia.org, reproduced without permission)*	• Plants grow out of holes cut into long tubes [9] • Water from fishpond is flowing through the bottom of the tubes • Each hole is filled with a net to support plant and absorb flowing water • Requires a biofilter to ensure certain chemicals do not reach the plants
Media-filled bed	 *(Source:https://www.farmhydroponics.com, reproduced without permission)*	• Most similar to traditional farming since plants are already grown out of clay pebbles or small gravel [9] • Water floods and drains bed so the plants' roots can soak up nutrient-rich water • Drained grow beds allow root exposure to oxygen • Layer of bacteria grows on media to filter water naturally
Raft	 *(Source: http://www.projectfeed1010.com/, reproduced without permission)*	• Plants suspended by floating raft on top of the water [9] • Small holes on the raft have nets to hold the plants • Easily scalable, but can only grow certain vegetables • Requires a biofilter

Based on the various options available for grow beds, it is important to compare the variables to determine which options perform best under the specific circumstances present.

Table 4. Comparison of aquaponic grow beds

Variable	NFT	Media-Filled Bed	Raft
No filter required	x	✓	x
Options for plants grown	x	✓	x
Simplicity	x	✓	✓
Scalable	x	x	✓
Planting density	✓	x	✓

Table 4 examines different types of aquaponics grow beds with respect to a variety of variables. From Table 4, it is apparent that the NFT method has many drawbacks when compared to the media-filled bed and the raft, as it requires a filter, has limited plant options, is complex, and is not scalable. All these variables must be taken into account when choosing materials for aquaponics grow beds. As a result of the information, raft and media grow beds will both be used in the system.

Finally, another component that is critical to a proper functioning aquaponics system is the pumping rate of the water through the system. The rate at which water flows through the system cannot be so fast that the plants are stripped of nutrients but also cannot be so slow that water lingers for long periods of time, which can cause unhealthy water quality and clogging of the system. Researchers found that "the halving of the pump operation time has a positive influence on both economic and environmental aspects. Most of the papers suggest that between 2.3 and 18 fish tank water recirculations per day with a water flow from 0.8 L/min to 8.0 L/min should maximize aquaponic system performance in terms of fish growth, plant growth and nutrients removal" [12]. This research is significant because it can help reduce the amount of time it takes to deduce the correct pumping and timing cycle.

2. Design Considerations

2.1 Customer Needs

2.1.1 Loaves and Fishes Community Partner

Following the University and the School of Engineering's mission statement to "fashion a more humane, just, and sustainable world", the project was designed and implemented for Loaves and Fishes, a national non-profit organization. In the San Jose location, Loaves and Fishes receives food donations from various food banks around the Bay Area, then uses the donations to prepare 1,800 meals every day for those in need [13]. These meals are then distributed to local soup kitchens throughout Silicon Valley. The aquaponics system will be implemented in the Loaves and Fishes' community garden and will act as a supplemental source of produce for the meals they serve. Loaves and Fishes has designated a 12-ft by 16-ft plot of land for the system. While this system is specifically for Loaves and Fishes, there are many potential users for aquaponics systems which are discussed in Appendix B.

2.1.2 User Expectations

As part of the design process, the team interviewed the volunteers at Loaves and Fishes about their expectations of the aquaponics system. The volunteers at Loaves and Fishes understand that this project is experimental, but a new opportunity for the garden to attract school students and inspire others to visit the farm.

While they are all rather large proponents of traditional farming due to some of the features listed below, they are open to the idea of aquaponics. At the moment, they cannot envision how this system may be more productive than traditional farming, specifically in Silicon Valley, where it used to be called "Valley of Heart's Delight" due to the arable soil conditions, but they are interested in seeing what the benefits may be once the system gets started.

Their main goals are to:

1. Effectively grow a similar yield in the 12-ft by 16-ft plot of land as they would with traditional farming techniques
2. Experiment with different crops to see the efficacy of aquaponics compared to traditional planter boxes, comparing grow time, taste, and productivity
3. Educate and inspire more volunteers and students to learn about farming and its benefits

Their expectations are to:

1. Ensure 98% of the plants grown in the system will survive
2. Have a self-sufficient system that requires very low maintenance on their part

3. Ensure its longevity for over five years and creating this connection with Santa Clara University on future projects to expand the system.

Recognizing the high initial cost and effort, they would not be willing to build the system themselves but would be open to dedicating other plots in the future as needed to expand the system. Depending on its success, other experiments may also take place in the garden as well. Lastly, they understand that the system may require additional maintenance, and they would be more than happy to maintain water level, fix leaks, feed the fish, and complete minor repairs as necessary.

2.2 Project Objectives and Goals

Our system is based off a design by Cristina Whitworth and Lauren Oliver, former Santa Clara University students, who built a small-scale aquaponics system for a cohort of women in rural Uganda in 2018 [14]. It retains certain characteristics from the previous team's design but is larger and tailored to its San Jose location. (For more information on the team's decision to continue with an aquaponics system to address the problem of food insecurity in Silicon Valley, refer to Appendix C) The current team's main objective was to create a custom, off-the-grid, large-scale aquaponics system with 90 sq. ft of growing space, a 650-gallon fish pond, and four types of sensors to transmit water quality data to the internet. The current engineering project team was divided into two sub-teams, mechanical and electrical, and the different objectives of each sub-team are summarized in Table 5 below:

Table 5. Objectives of the aquaponics system for each sub-team

Mechanical engineering	• To arrange system layout and orientation of components through an iterative process and to maximize grow space. • To complete a comparison of produce grown with traditional farming versus aquaponics farming. • To optimize water flow in raft grow bed using computational fluid dynamics. • To perform flow calculations for bell siphons and pump to control movement of water. • To design an IBC media grow bed with two appropriately sized bell siphons that to mechanically empty the media beds at a designated depth. • To perform Finite Element Analysis on a custom-designed solar panel chassis to ensure it can safely hold 10 solar panels at a pitch of 38 degrees, the best angle for year around power generation. • To reduce system connections to prevent possible leaks. • To build engineered system to full scale and integrate all components.
Electrical engineering	• To design an IoT-based sensor system that uses an Arduino to collect data on water temperature, pH, electrical conductivity, and dissolved oxygen. • To transmit this information to the web through LoRa, a long-range wireless communication device, from an area without internet access, enabling anyone to remotely monitor the system through Thingspeak, an online platform. • To ensure 24/7 operation by creating and optimizing the power system to drive the pumps and sensors by using solar panels with a battery.

The engineering team decided to design and create a quality, long-lasting, working system that can be used by Loaves and Fishes to increase food yield, reduce water use, and inspire other farms to adopt similar systems.

Overall, the system provides Loaves and Fishes with a new source of fresh produce by increasing the supply of vegetables produced in their garden. During this first year, the goal was to produce an annual harvest equivalent to traditional farming and to enable the system to exceed this amount in subsequent years. Given Loaves and Fishes’ prominence in the community, a partnership with them helps inspire other farmers, NPOs, and community members to pursue aquaponics as a means of increasing food yield in urban settings where farming density is low and food insecurity is high.

2.3 Rationale for System Specifications

2.3.1 System Level Requirements

Once the specific needs of the individual parts of the aquaponics system were devised and ranked by importance, the corresponding metrics with appropriate units were identified. Not every need has a metric, as some needs are more qualitative. However, the quantitative needs were associated with a metric that helps identify the success of the system based on a marginal and ideal range. These metrics, seen below in Table 6, were translated from the customer needs data, allowing for the direct integration of customer needs into the system through product specifications.

For example, from the interview with fish culturist Debra Grant, the team learned that higher water temperature can lead to accelerated fish growth but higher risk of disease, whereas lower temperatures provide a more stable environment for fish, but slower growth. This required them to specify and integrate a water temperature sensor to ensure a range of 30°F for the marginal value of the temperature, whereas the ideal temperature had to be kept within a 10°F range (see metric 6 below).

Table 6. Metrics for product specifications and units

Metric Number	**Elements/ requirement**	**Units**	**Datum**	**Target Range**
1	Volume flow rate of pump [15]	gph	650	500-700
2	Flow rate of bell siphon [16]	m/sec	0.7	0.4-0.9
3	Flow rate of drain [16]	m/sec	0.4	0.2-0.6
4	Flood and drain cycle [17]	Minutes	15	10-20
5	Flow rate through raft grow bed [16]	m/sec	0.3	0.2-0.6
6	Water temperature [18]	°F	80	50-88
7	pH [18]	pH	5-10	6-9
8	Dissolved oxygen [18]	mg/L	3	>3
9	Electrical conductivity [18]	dS/m	2	0.2-4
10	Kilograms of fresh produce	kg/month	15	12-18
11	Fish life span	years alive	2	1-5

As Table 6 shows, qualitative needs were converted into quantitative metrics, with concrete units and value ranges for each need. From this table, along with the interview notes and supplementary tables available in Appendix D, achievable product specifications were discerned from initial customer interviews. The raw data and the information in the tables allowed the team to design a whole system that met the customer needs. The resulting metrics and detailed needs also guaranteed that the aquaponics system will be appropriate for the specific customer.

2.3.2 System Level Issues

There are several potential system level issues that the project could face. These potential issues include material selection for each subsystem. It is important to select materials for the system that are strong enough to be safe under given loading conditions, nontoxic to ensure the food is safe to eat, durable, and long lasting. Another system level issue is determining how the different components of the system will be oriented on the plot to reach an optimal fish to plant ratio. Additionally, this system will be implemented in an area that does not have access to the electric grid and has limited access to Wi-Fi. Lack of access to the electric grid is a major challenge, as the aquaponics systems require energy to pump water through the system and power the sensors. Additionally, the team wanted to monitor water quality, so limited access to Wi-Fi posed a challenge to sending the data to the user.

2.3.3 System Options and Rationale for Chosen System

This project focuses on aquaponics, which is a good solution to combat food insecurity in urban areas. However, there are other solutions that could address this problem. These include aeroponics and hydroponics. In aeroponics, plants are grown in air or mist. Hydroponics is growing plants without soil. In both cases the plants must be supplied with nutrient rich water, so a special nutrient mix must be used. The three possible solutions aquaponics, aeroponics, and hydroponics were compared using a matrix, which can be seen in Appendix C. The results of the matrix show that while aquaponics requires more training to care for the fish, it has clear advantages. Aquaponics systems are closed loop, which reduces the water used and they have the potential to provide the user with a protein source. Hydroponics is a less attractive solution because it wastes a large amount of water, as the user must replace the old water in the system with new nutrient rich water as the plants absorb the nutrients in the water. Lastly, aeroponics is cost prohibitive and requires significant upkeep to be a suitable solution for Loaves and Fishes.

After aquaponics was identified as the best innovative solution, in order to ensure the system meets the user expectations and minimizes risk of system level issues, the team looked into two different systems. One system uses a sump tank and the other does not. A sump tank is a tank that holds extra water and is used to flood and drain the system. Images of these two types of systems can be seen in Appendix A. The team decided to not use a sump tank as it does not add any extra grow space to the system and the flooding and draining of the media beds can be accomplished with other methods, like bell siphons, which will be described in Section 8.2.

2.4 Engineering Standards and Constraints

The system created met engineering standards and constraints. These include organic standards, laminar water flow, National Sanitation Foundation 61, National Fire Protection

Association standards, certified naturally grown standards, and the Electric Building Code. The constraints are presented below and will be revisited in the testing and analysis section.

Organic Standards

The Organic Standards set by USDA Organic must be followed in order to continue Loaves and Fishes' Garden's organic certification [19]. The urban farm uses organic compost and avoids chemicals to treat plants and the aquaponics system must do the same, necessitating that the design satisfies the following criteria:

- The fish food must be organic, which may be more expensive than conventional products
- The media needs to meet organic standards.
- The seeds that are used to start the plants must be organic.
- The fish, if they are edible, must be organic.
- Any additives used to alter the system cycling must be organic.

Given these constraints, the organic standard is met if there are no harmful chemicals introduced into the system.

Certified Naturally Grown

The requirements for an aquaponics system to be considered Certified Naturally Grown (CNG) relate most strictly to water treatment and filtration in the nitrogen cycle [20]. The conversion of ammonia to nitrate is a key process in an aquaponics system, and the CNG code has specific criteria for meeting the degassing and biofiltration requirements. Following the guidelines is necessary not only for obtaining the certification, but also for implementing a good nitrogen cycle without which, the aquaponics system is just a glorified hydroponics system.

Laminar Water Flow

Laminar flow of the water, within the pipes and inside the raft grow beds, is important, as turbulent conditions could cause damaging effects to the system components and connections. Turbulent flow within the PVC and pump pipes could decrease the longevity of the piping and irrigation system, causing a need for repair and maintenance. Turbulent water flow could also mean that vital nutrients are stripped from the roots of the plants as water is throttled through the piping system. To avoid this, large pipe diameters, proper drainage systems, and secure bonds and connections were used to guarantee that the system flow stays laminar.

National Sanitation Foundation 61

It was imperative that the design follows National Sanitation Foundation (NSF) 61 guidelines because the water in the system is used to grow food [21]. Any chemicals that would leech from the PVC or Intermediate Bulk Container (IBC) components would impact the growth of, or poison, the vegetables and fish. These chemicals could render the vegetables and fish inedible, making the entire project irrelevant. The guidelines for NSF 61 stipulate a certain standard of the materials to be drinking water safe. Therefore, the design followed the NSF 61 guidelines to ensure that the produce and fish are safe to eat.

National Fire Protection Association

The National Fire Protection Association (NFPA), to reduce the risk of fire, requires systems to meet the NFPA 70 code, otherwise known as the National Electrical Code (NEC), and the system was designed to comply [22]. The wiring to the entire system were designed to follow the NEC standards to prevent the chance of fire. This is especially important because of the proximity of the electrical equipment to the water sources.

Building Code for Solar Panel Installation

In order to install the solar panels on top of the shed, the team adhered to guidelines set by the International Building Code, the International Fire Code, and the National Electric Code. The long list of specific requirements is laid out in Appendix E.

3. Analysis of Alternatives

3.1 Existing Solutions

Currently, there are several aquaponics systems on the market ranging in size and cost. The variety of systems is summarized in Table 7 below.

Table 7. Summary of aquaponics systems

Name	Manufacturer	Price	Fish tank size (gallons)	Grow bed size (sq ft)
Aquasprouts Garden [23]	AquaSprouts	$165.95	10	1
Springworks Microfarm Aquaponic Garden [24]	Springworks	$249.00	10	1
Mr. Stacky Indoor Vertical Hydroponics Tower, 6-tier tower [25]	Mr. Stacky	$600.00	N/A	2
Sanctuary Series System [26]	Endless Food Systems	$2,895.00	275	24
Genesis Series System [27]	My Aquaponics Garden	$2,995.00	140	48
Aquabundance Home Aquaponics System [28]	The Aquaponic Source	$5,095.00	200	45

One system in Table 7, the Aquabundance Home Aquaponics System, is the most similar to the created system. It is large and fits either a 200 or 300-gallon fishpond with modular grow beds of 9 sq. ft of grow space each. This system, designed for either personal or school use, can grow a variety of vegetables, herbs, greens, and decorative plants. Some of the main benefits of this system are its modularity--ability to add or subtract grow beds, the combination of both media and raft grow beds, raised grow beds, easy setup, and free lifetime support. This system is pictured in Figure 2, which shows different configurations of what the system looks like.

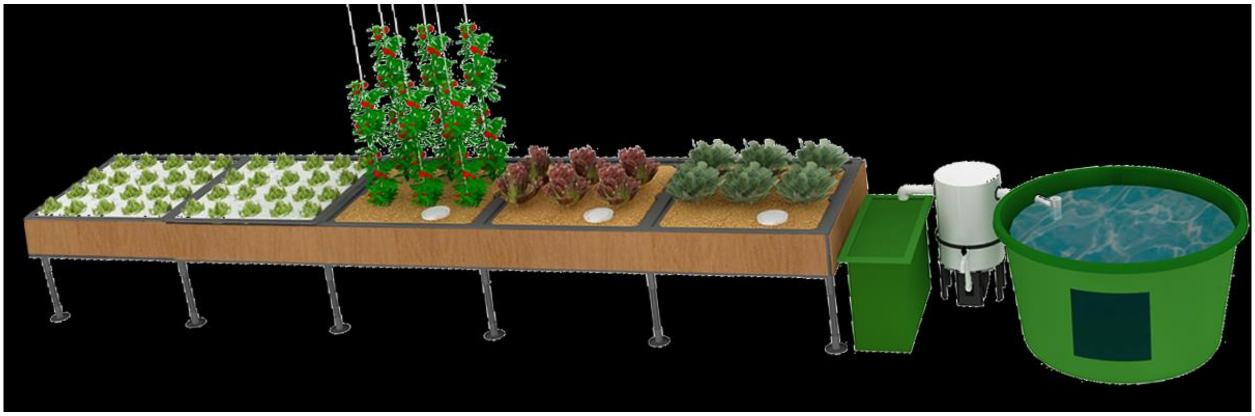


Figure 2. Aquabundance Home Aquaponics System (Source:https://www.theaquaponicsource.com/home-aquaponics-system/, reproduced without permission)

Another aquaponics system the team analyzed is the Genesis Series System, which has the potential for more grow space than the Aquabundance Home Aquaponics System at half the cost. The Genesis Series can be expanded up to 48 sq. ft. of grow bed space and is connected to a large 140-gallon insulated fish tank with an internal radial filter and easy drain / clean-out valve system. One benefit of this system is that its larger size increases produce yield. Additionally, its modularity fits the sizing needs of customers and its filters prevent clogging. The basic Genesis G-24 system is shown in Figure 3.

Figure 3. Genesis G-24 (Source:https://www.endlessfoodsystems.com/genesis-series/, reproduced without permission)

The Genesis G-48 system contains the same components as the Genesis G-24; however, it incorporates two more raft grow beds with the metal stands.

Although both the Aquabundance Home Aquaponics System garden and Genesis Series System have many positive features, they also both have significant drawbacks. For example, they cost $5,095.00 and $2,995.00 respectively, corresponding to $113.22/sq. ft of grow space and $62.40/sq. ft of grow space respectively. Additionally, both systems must be close to a power outlet to run the pumps and lack monitoring devices, such as sensors to see if water conditions are suitable for the fish and plants to live. Therefore, there is much room for improvement, including the addition of sensors to monitor water quality and an off-the-grid power system.

3.2 System Cost

This project was funded by Santa Clara University's School of Engineering, the Xilinx Fund, and an IEEE Epics Grant. It was initially estimated that the project would cost $8,319.90 for fixing the existing system in the Forge Garden, building a new system on campus, and building the system for Loaves and Fishes (a breakdown of this budget can be found in Appendix F).

However, it was decided the old system would no longer be fixed because of lack of time and because the system was sufficiently different from the current one to preclude their integration. Therefore, a system was only built at Loaves and Fishes and not on campus. The team's sources of funding and the estimated overall prototype cost are displayed in Tables 8 and 9.

Table 8. Sources of funding

Funding Source	Sought	Committed
School of Engineering	$10,421	$2,500
Xilinx	$1,500	$1,500
IEEE Epics	$2,000	$2,000
Total	$13,921	$6,000

Table 9. Overall costs

Category	Cost
Sensors	$866.44
Power system	$1,245.95
Solar panel chassis	$398.44
Fishpond	$675.19
Raft grow bed	$1,225.20
Media grow bed	$645.76
System inputs (seeds, fish, fish food)	$342.94
Prototyping	$202.56
Tools	$78.22
Total	$5,680.70

A breakdown of each subsystem and its costs can be found in Appendix F, along with a comparison of actual costs versus the original budget.

Even though First Solar donated solar panels to help power the system, there were many other costs involved with building the system from the ground up. The main expenses were in the power system and materials for the grow beds.

The vast majority of the costs were due to the exploratory nature of this prototype project. Additional costs were incurred due to adding in different components to make the project more unique and user-friendly, such as the renewable energy source for off-grid capabilities and the added benefits of off-site monitoring through the sensor system. These features also reduce costs in the long term, since there are no monthly electric bills. Other methods to reduce costs require testing different materials and investigating different configurations which will be reduced in the future.

3.3 Benchmarking

To ensure the system was frugal, the team analyzed three main variables: cost, size, and scalability. As the proposed aquaponics system was tailored towards the needs of the community partner, Loaves and Fishes, it was necessary that the final aquaponics system be of more cost-effective than other solutions, large enough to replace one of their grow beds, and scalable. Depending on the success of the initial system implementation, Loaves and Fishes may decide to allocate more land for other aquaponics systems that expand off the current system; the design therefore needed to be scalable.

In order to compare the created aquaponics system to the commercial competitors, two commercial systems were ranked using the product specifications in Table 10. Although the proposed aquaponics solution has a greater total cost, the large size of the system reduces the cost per sq. ft, which is the general metric evaluated between the three products.

Table 10. Benchmarking

Criteria	**Competitor 1 Aquabundance Home Aquaponics System** [28]	**Competitor 2 Genesis G-48** [27]	**Our Proposed Aquaponics Solution**
Wholesale cost ($)	$5,095	$2,995	$2,440*
Area of grow space (sq. ft)	45	48	90.6
Volume of fish tank/pond (gallons)	200	140	650
Weight of fresh fish grown (lbs)	28.57	20	92.86
Cost per area of plant grow space ($/sq. ft)	113.22	62.39	28.70
Cost of energy after 1 year ($)	81.90	82.08	1125**
Cost of energy per plant grow space ($/sq. ft)	8.19	1.71	13.68
Cost of energy per plant grow space after 10 years ($/sq. ft)	21.53	20.19	20.14
Ratio of fresh fish to grow space (lb: sq. ft)	0.63	0.42	1.02

* The wholesale cost represents the cost of materials used to create the base system which other competitors have. It does not include any inputs such as fish, seeds, power system, or sensors.
**This price represents the initial investment for solar, which includes electronic parts and wires. It does not include the price of solar panels, which were donated, nor the price of installation
***For explanation of calculations, please refer to Appendix G

Table 10 clearly indicates the differences and issues with the systems currently available for purchase. It is interesting to note that the aquaponics solutions exceed the values of both competitors in every aspect, which can mainly be attributed to its large size. Not only does the designed system have twice the grow space as both competitors, but it is also more cost-effective per sq. ft of grow space.

Over time, it is important to note that the longer-term total cost of ownership is lower than that of the other competitors, especially due to the power system which requires a large upfront cost and a battery replacement every five years. The following graph demonstrates that after 10 years, this system begins to save money for the end-user.

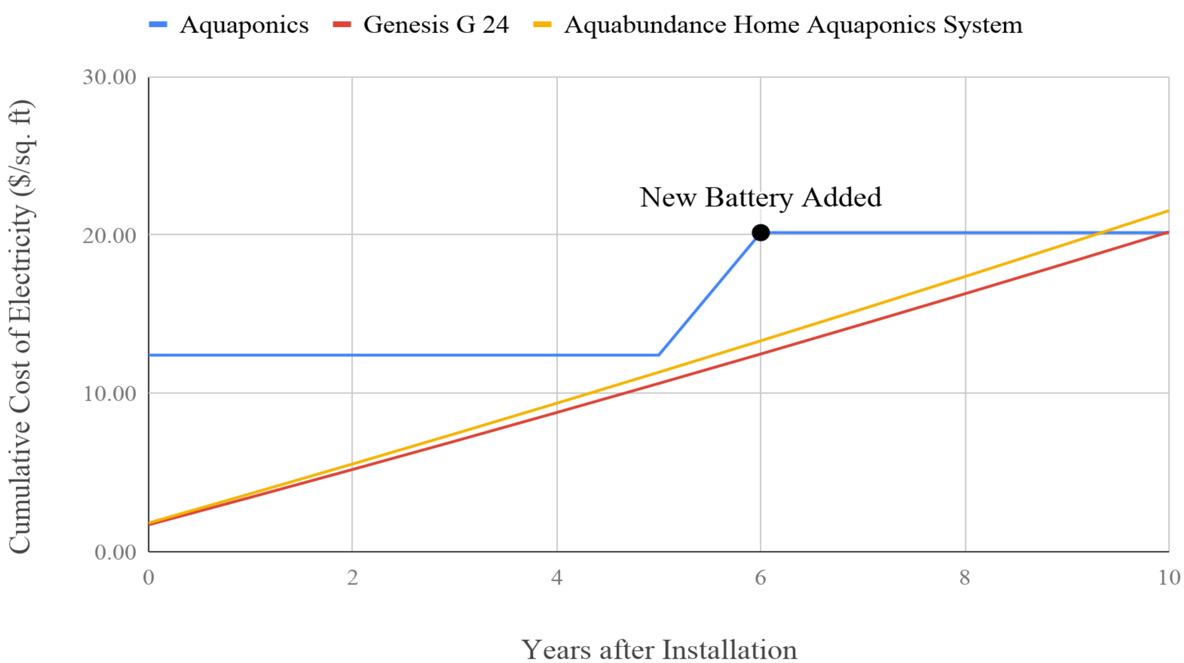


Figure 4. Cumulative cost of electricity per sq. ft of grow space

However, using solar energy also saves money that would otherwise be spent on electricity. A comparison of the amount of electricity saved by using solar is shown below, comparing two cases. One in which the battery is not replaced, and the other, where the battery is.

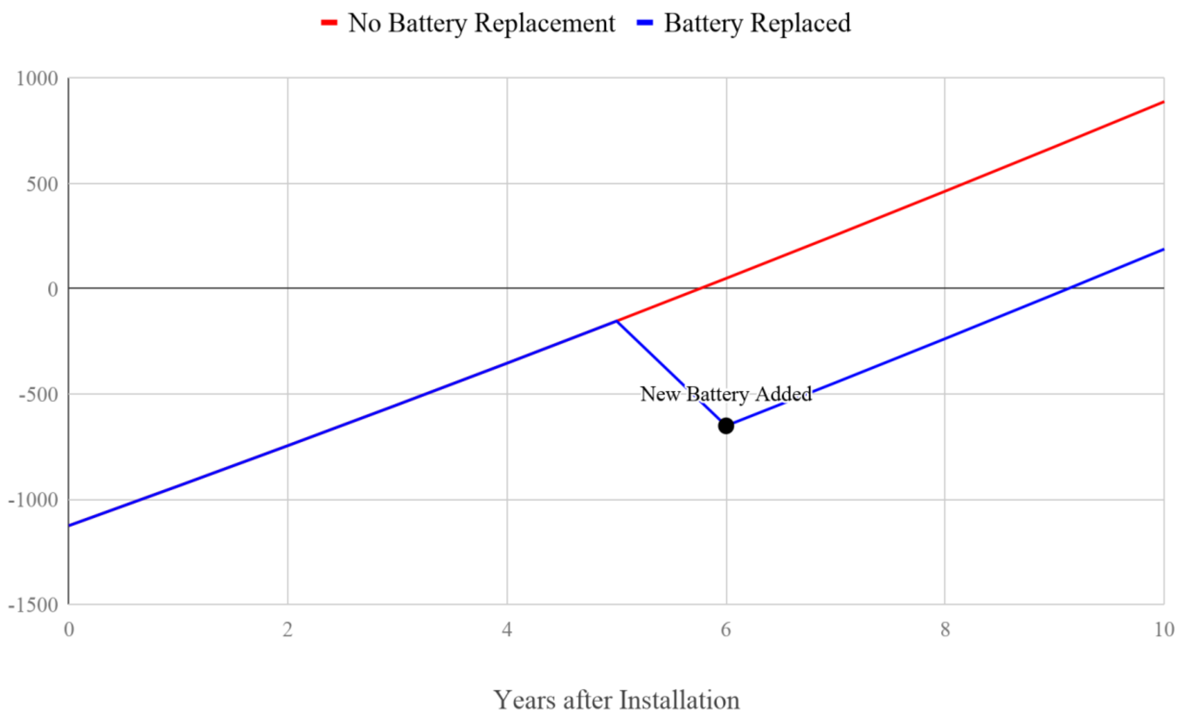


Figure 5. Cost savings of using solar energy rather than using electricity from the grid

This system demonstrates that if the battery manages to last over 5 years, cost savings will occur after six years. If a new battery needs to be added, which will most likely occur after 5 years, the cost savings will occur after 9 years. In either case, the system will be productive in the long-term.

In future systems, to cut down costs, organizations can request donations, as Loaves and Fishes currently does for materials on the farm. Because of the slow rate of donor response given the tight timeline of the project, the team decided to purchase materials instead. For more information regarding the cost benefit of the system, please refer to Section 13.10.

4. System Overview

4.1 System Layout

This aquaponics system was optimized to make the most out of the 12-ft by 16-ft plot allocated by Loaves and Fishes. It is composed of six subsystems including the fishpond, media grow bed, raft grow bed, irrigation system, power system, and sensor system. A physical sketch of the system is shown in Figure 6:

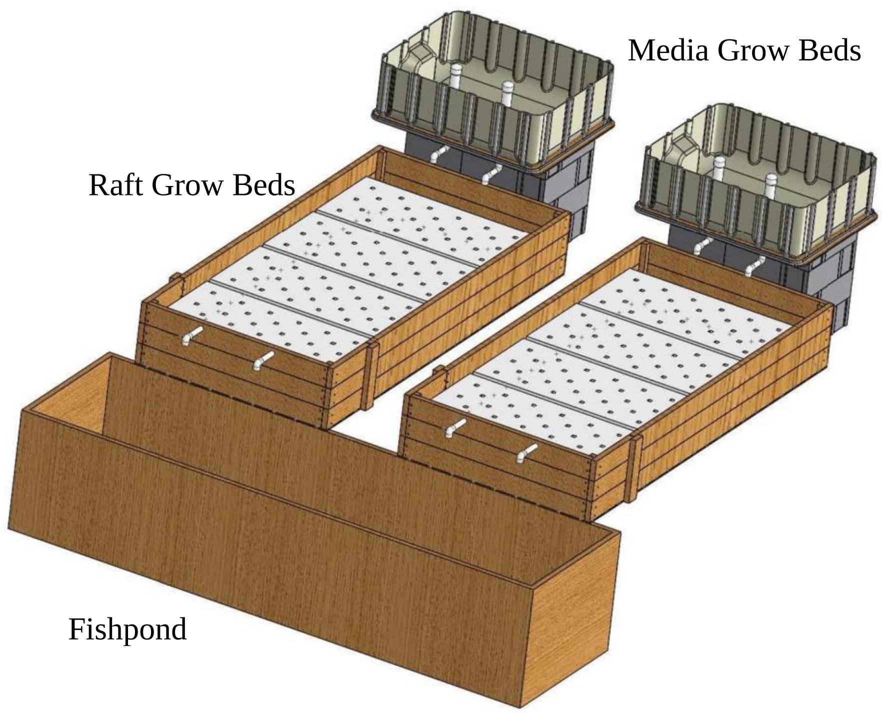


Figure 6. Physical sketch of aquaponics system

Now that the system is constructed and running, the system is easy to use and user friendly. It will be used and maintained by the volunteers at Loaves and Fishes. The system requires the user to add water due to losses from evaporation and the plants, new seeds or seedlings, and fish food. Additionally, they will plant seedlings in the media beds, which are 4-ft off the ground, making it more ergonomically friendly. Moreover, they will also plant seeds in the rafts, which are easily removable for easy planting and harvesting. The two raft grow beds have a 2-ft walkway in between them to allow for easy access to the plants as well.

The fishpond, media grow bed, and raft grow bed subsystems relate to the irrigation subsystem, as shown in Figure 7. The irrigation system includes a submersible pump to move the water from the fish tank to the media grow bed and an air pump to ensure the water is oxygenated.

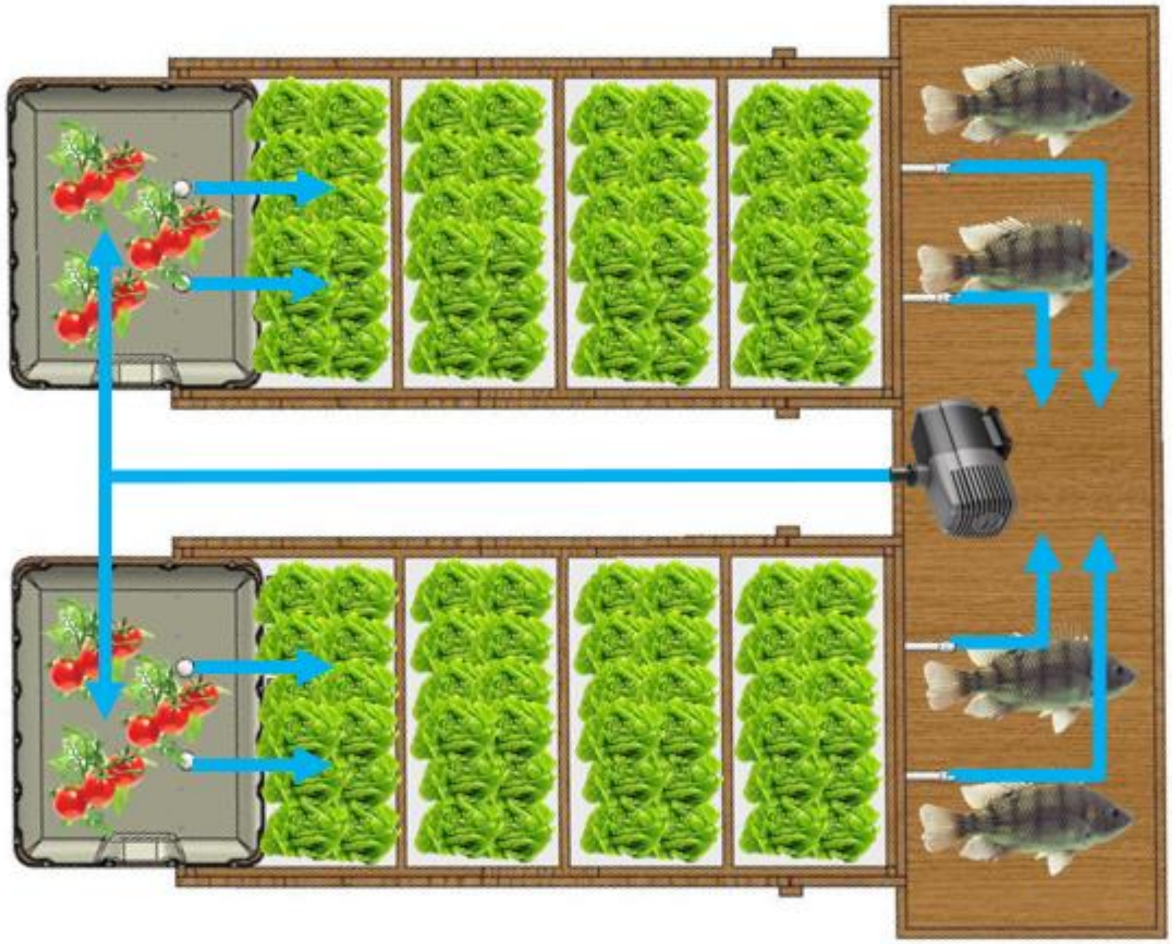


Figure 7. Visual representation of aquaponics system

The grow bed will have a bell siphon to drain water out of the media grow bed and directly into the raft grow bed via gravity. The water will then flow through both of the raft grow beds and back into the fishpond also using gravity.

A broader aerial view of the farm in Figure 8 shows the relationship between the plot and the solar installation.

Figure 8. Aerial view of Loaves and Fishes' Garden

Figure 8 shows the 12-ft by 16-ft plot that the aquaponics system was built on. The air pump to oxygenate the water and the water pump to cycle the water are powered by 8 solar panels. Given the large size of the system and the lack of space to mount the solar panels, Loaves and Fishes agreed to have the team install solar panels atop their shed, which is a 20-ft long by 8-ft wide by 8.5-ft tall shipping container. A trench was dug to run the electrical wires from the shed to the system. Figure 9 below shows the state of the system as of June 2019.

Figure 9. Aquaponics system at Loaves and Fishes

4.2 Design Process

Designing this system took many different iterations and the team went through many different steps to reach the current design.

This project was inspired by a senior design project from last year that implemented a family sized system in East Africa, and as a result, their paper and the information that they gathered were reviewed. Additionally, a literature review and review of current solutions was conducted to narrow down the goals of this system and determine existing solutions. With the research in mind, the team brainstormed and drafted different ideas for the overall design and subsystems. These ideas were then narrowed down using the matrices which shown in Appendix H. With the best idea selected, a CAD model of the system was then created:

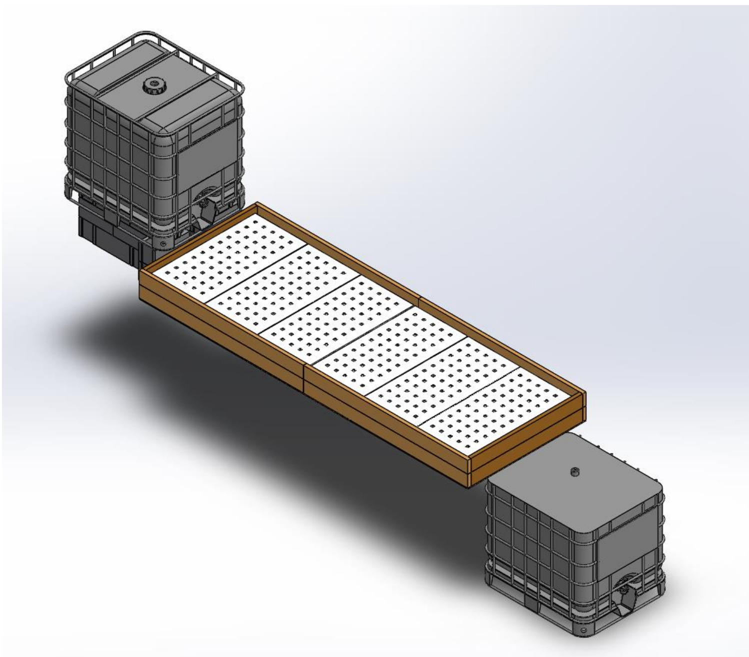


Figure 10. Preliminary design given matrices and plot allotment at the garden

This model was shared with the client, Loaves and Fishes, to receive their feedback. Initially the plot of land that this system could be built on was 10-ft by 20-ft so the system was designed to be less than 5-ft wide and 20-ft long, so that there is the possibility to add another system.

However, the plot of land changed to 12-ft by 16-ft. As a result, the configuration of the system needed to be altered. Concerns regarding the small size of the fish pond also led to a second iteration of the system:

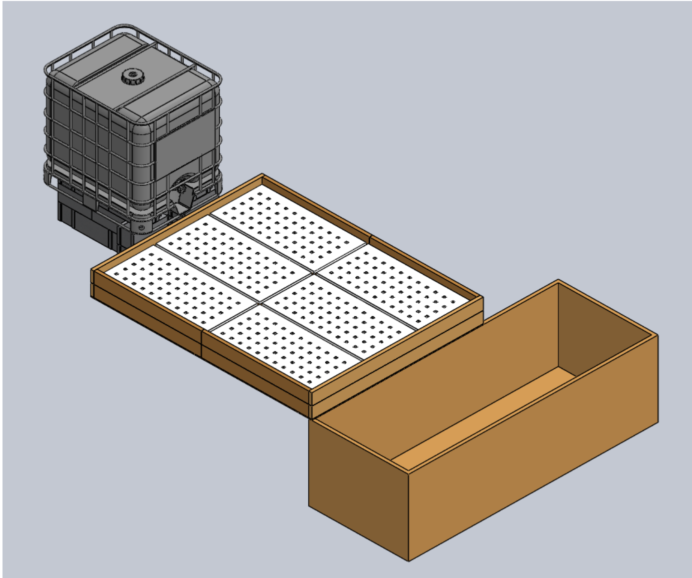


Figure 11. Second iteration of aquaponics system

As one can see this second system took into account the feedback that Loaves and Fishes provided. First, it features a larger fish tank and the grow bed length is shorter to fit within the 16-ft long plot provided. However, this system had a major drawback in that it did not maximize the use of the land and could not easily be scaled.

Consequently, a third model with the client's feedback was created and shown to the client as demonstrated below.

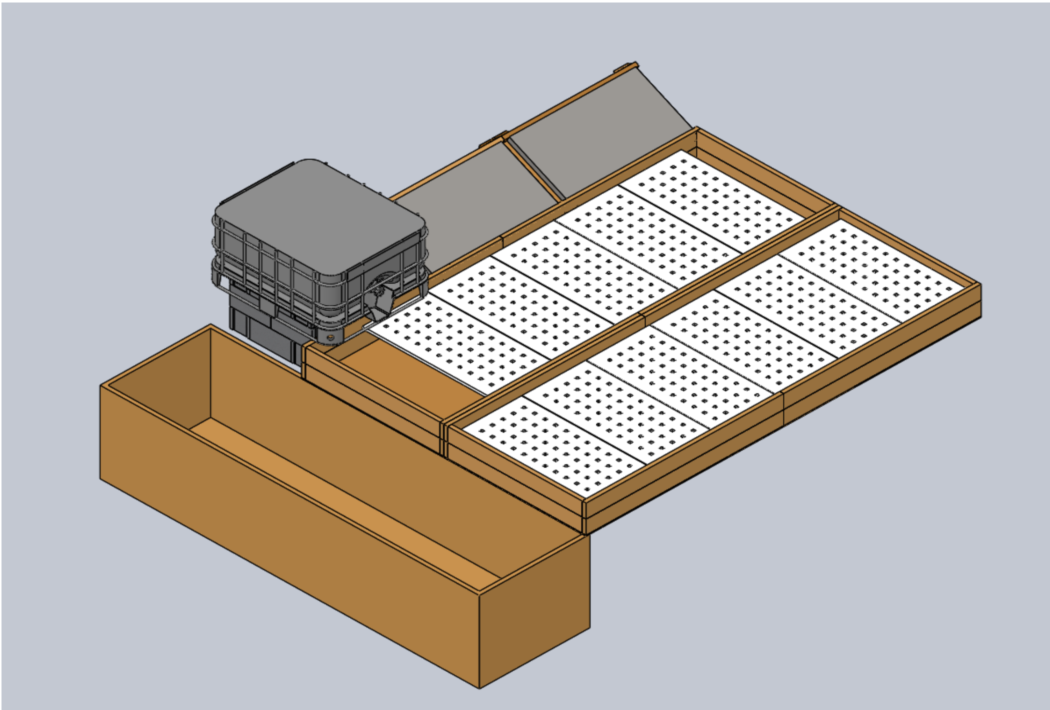


Figure 12. Third iteration of aquaponics system

This model consists of one media grow bed, two raft grow beds, a fish pond, and has two solar panels on the ground. This model also had significant drawbacks as the water would not be able to flow easily through the system, as seen in the flow diagram in Figure 13.

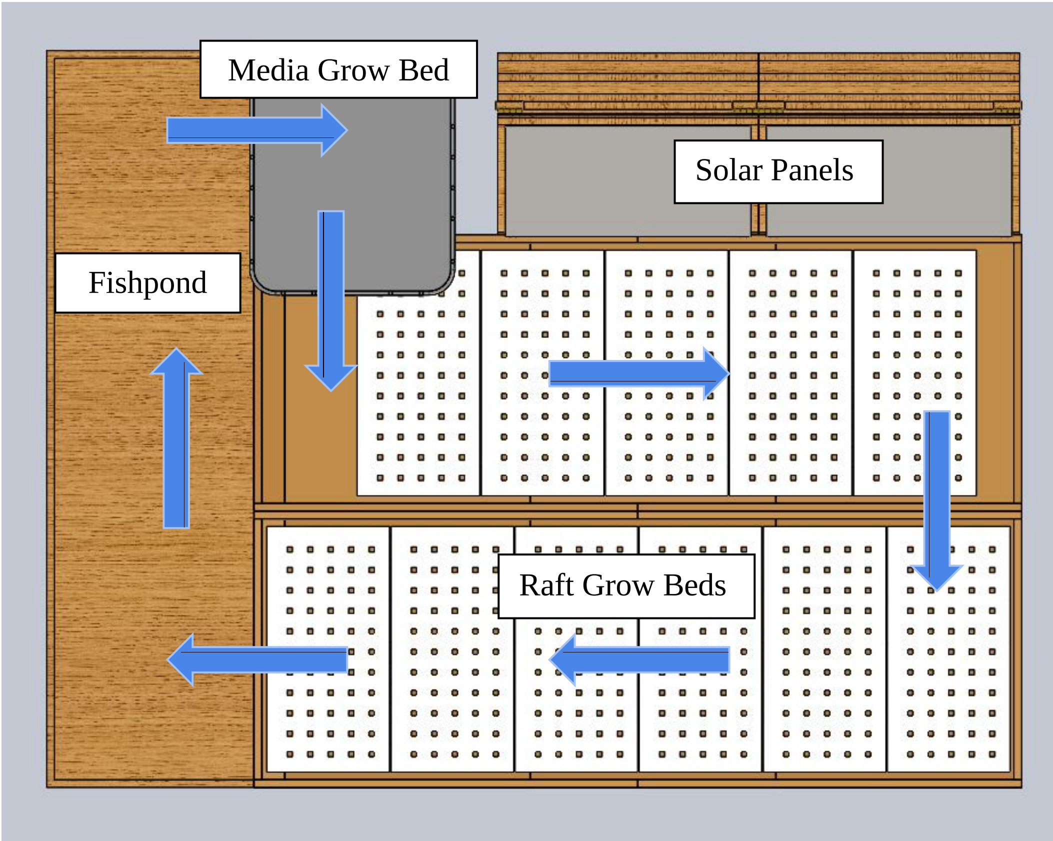


Figure 13. Water flow diagram of third iteration of aquaponics system

In order for water to flow through the system, the water would need to turn 180 degrees when flowing from the first raft grow bed to the second raft grow bed. This would be a very difficult transition. Additionally, having the solar panels on the ground inhibits people from accessing the plants grown on the raft grow beds. Therefore, based on these concerns, feedback, and design restrictions, the model discussed in Figure 6 was created and is the final design of the system.

Additionally, one part of the team's design process was determining how the 12-ft by 16-ft plot should be allocated between the grow bed, media beds, raft beds, and walking space. To determine this some standard practices of aquaponics were used. First, it is industry standard to have a ratio of 1-lb fish per sq. ft of grow bed surface area, and each pound of fish needs 7 gallons of water [29]. This standard resulted in Equation 1.

$$V_p=4A_p=0.93(A_m+A_r) \quad (1)$$

In this equation, V_p is the total volume of the pond, A_p is the surface area of the pond, A_m is the surface area of the media grow bed, and A_r is the surface area of the raft grow beds. For this analysis, the pond is assumed to be 4-ft deep, shown as the factor before A_p in the equation. As a result, the volume of the pond is equal to the surface area of the pond multiplied by the depth. This depth of 4-ft was assumed because it would allow the fish to hibernate in winter. The factor of 0.93 comes from converting 7 gallons to cubic feet. The second industry standard is that a "bacteria-based filter". the media bed in this case, needs to be at least one quarter the size of the fishpond in order to adequately filter the water [30]. This was translated into Equation 2.

$$V_p=4A_p=4A_m \tag{2}$$

The industry standard compares the volume of the fishpond to the volume of the media grow bed, but since the grow bed is 1-ft deep, the surface area of the media bed can replace the volume of the media bed in Equation 2. The next constraint is on area. Loaves and Fishes allocated a 12-ft by 16-ft plot for the system, and this space must equal the sum of the surface area of the media bed, raft bed, pond, and walkways. Of the 192 sq. ft, 36 sq. ft are allocated to a walkway, leaving 156 sq. ft for the various subsystems, as seen in Equation 3.

$$156=A_p+A_m+A_r \tag{3}$$

36 sq. ft of the plot are used for a walkway between the raft grow beds so that the user has easy access to the plants. Using the equations 1, 2, and 3, the three surface areas of the subsystems can be solved for. The results are that the fishpond and media bed should be 30 sq. ft and the raft grow bed should be 97 sq. ft. With these areas a cost analysis can be completed to estimate the cost of the system. The team did research into the cost of each subsystem and determined the cost per sq. ft of each subsystem. Table 11 shows the cost per sq. ft of each subsystem, the cost of each subsystem, and the total estimated cost.

Table 11. Estimation of cost of system

Subsystem	**Surface Area (sq. ft)**	**Cost per sq. ft ($)**	**Cost of subsystem ($)**
Fishpond	29.58	14.21	420.18
Media grow bed	29.58	27.32	808.04
Raft grow bed	96.85	15.52	1502.78
Total cost			2731.00

The cost per sq. ft of the fishpond considers the cost of a pond liner, underlayment, and fish. The media grow bed cost comes from media, siphons, and IBC. Lastly, the raft grow bed cost considers the redwood, pond liner, bulkheads, and rafts. Table 12 shows the ideal areas based on these equations with the actual system specifications.

Table 12. Comparison of surface area of subsystems

Subsystem	**Calculated Area (ft^2)**	**System Area (ft^2)**
Fishpond	30	36
Media grow bed	30	27
Raft grow bed	97	86

The discrepancies between the calculated or ideal areas and the areas of the actual system are due to available container, raft sizes, and customer needs. For example, IBC containers are large containers commonly used in aquaponics systems. However, they only have a surface area of 13.3 sq. ft, so using two of them resulted in a media bed surface area of 27 sq. ft. In other words, the team was constrained by the container chosen. This area is lower than the ideal area but is relatively close. Additionally, for the raft grow beds, the rafts only come in 2-in by 4-in sizes, so the grow beds had to be designed to fit these rafts. Lastly, the client was very concerned about the fish having enough room, so the size of the fishpond was expanded slightly.

4.3 Functional Decomposition

There are three types of inputs into the system and two types of outputs. The inputs include initial inputs, continuous inputs, and intermittent external inputs. The outputs are categorized into final outputs and continuous outputs.

The initial inputs into the system include the water into the fishpond and grow beds. Once the system began to operate, there are fewer external inputs as the outputs of one subsystem become the inputs for the next one. These are continuous inputs. For example, the water from the fishpond is the input into the media grow bed, flows as an output into the raft grow beds through the bell siphons, before returning into the fishpond. In addition, solar energy is a continuous input that will power the system. The last type of input are additional intermittent external inputs that occur when an item needs to be replaced at the subsystem level. This includes the fish, fish food, water, and plants as they are consumed.

In terms of outputs, there are two types: final and continuous. Final outputs constitute the fish and the plants once they are grown and ready to harvest and provide the main products of an aquaponics system. The second type of output involves continuous outputs that match with the continuous inputs of the system: electricity generated from the solar energy to power the pumps and the water (along with the fish waste) that is outputted into other sections of the system.

All these inputs and outputs are constrained by the size of the plot, which determines the size of the system and the amount of water, fish and plants, and energy needed to run the optimal size system. A table of the various inputs and outputs is summarized in Appendix I. Additionally, the figure below is a flow chart of the system that shows the inputs and outputs of the system. Lastly, since there is a sensor system implemented to monitor water quality, there is a continuous output of water quality data. This data will be sent to the user and they will be responsible for correcting problems with the water. There is no control feedback system to automatically fix the water quality.

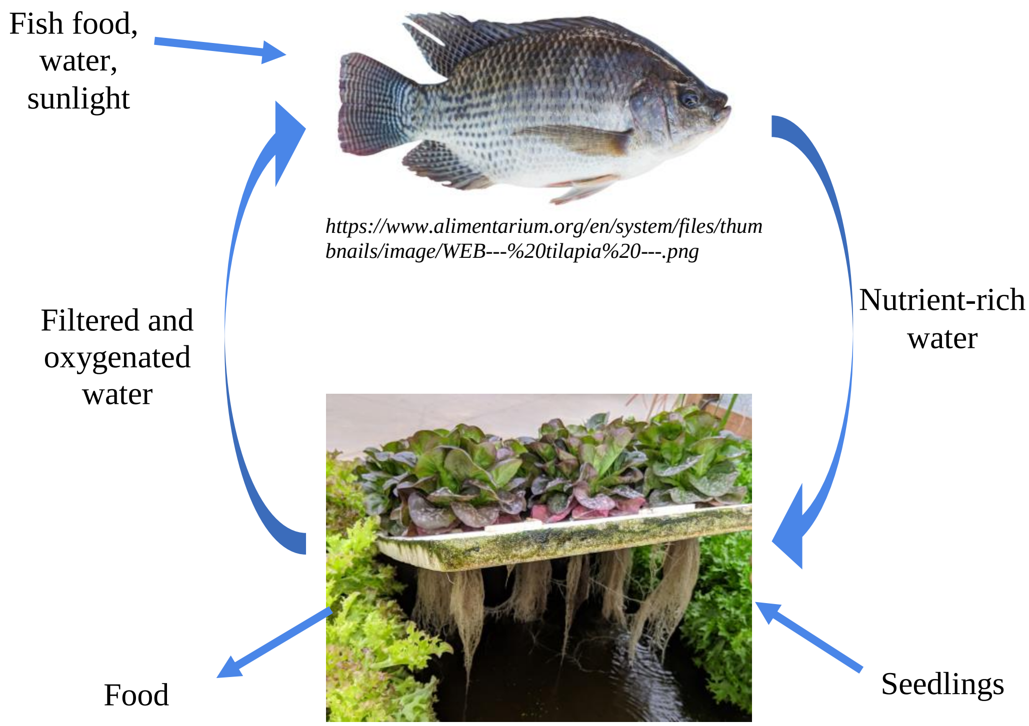


Figure 14. Flowchart of system (tilapia photo reproduced without permission)

This flowchart shows that one must add fish food, water, and seedlings to the system which are external inputs, resulting in vegetables that can be harvested as the final output. Additionally, there are continuous inputs and outputs, which are the nutrient-rich water and the water that is cleaned and oxygenated by the plants that cycles continuously from one subsystem to another.

5. Fishpond

5.1 Pond

The main objective of this pond is to be large enough to hold a significant number of fishes that produce adequate nutrients for the plants. The pond is stocked with tilapia that are fed pellet food twice a day by an automatic fish feeder. The automatic fish feeder is essential because the volunteers at Loaves and Fishes are only there four days a week. A small fishpond size could mean overcrowding and build-up of bacteria and waste. Loaves and Fishes wants to have at least 40 fish that are all around 12-in long in the system.

Based on this specification, a fish tank of at least 480 gallons is required. The team decided to build a 650-gallon fishpond to ensure that that fish have enough room and to allow for more grow beds to be added in the future. There are several possible designs for the container, including 55-gallon barrels, 275-gallon IBC containers, and an in-ground pond. These possible designs were evaluated using a selection matrix, which can be seen in Appendix H1.

55 gallons barrels and IBC containers are too small to hold the number of fishes needed, as 11 barrels or three IBC containers would be needed. Although these containers are rigid and are unlikely to leak, they are not cost effective, do not provide fish with enough space, and require each tank of fish to be fed separately. The other alternative was an in-ground pond. This design has the possibility of leakage, as pond liners can tear and leak; however, this allows the pond to be large enough to meet the client's requirements.

Having one large pond is preferred because it eliminates the need to have multiple automatic fish feeders. Having an automatic fish feeder is essential because the volunteers at Loaves and Fishes do not go to the garden every day even though the fish will need to be fed each day. Additionally, this solution is unusual in aquaponics systems, as most systems do use a 55-gallon barrel or IBC container for the fish tank. Having the tank in ground has many advantages, as the dimensions of the pond can be selected to fit the plot of land well. Additionally, having the pond in ground will help with water temperature regulation.

The fishpond is in-ground and measures roughly 12-ft long, 3.5-ft wide, and 4-ft deep. The pond is 12-ft long to take advantage of the whole width of the 12-ft-wide plot of land. Additionally, the pond is 4-ft deep, which gives the fish room at the bottom hibernate during the winter. When the water is cold, fish will hibernate at the bottom of the pond and they will survive, as long as the water continues moving. The pond is lined with an underlayment of thick fabric and a pond liner to make the hole watertight. The underlayment acts as a barrier between the dirt and sharp rocks and the pond liner, so it helps prevent the pond liner from tearing. Figure 15 shows the empty fishpond.

Figure 15. Empty fishpond with underlayment

Additionally, the aquaponics system is in an area with cats, birds, and other animals that could pose a risk to the fish. The fishpond is covered with wire netting to keep these animals out. The cover is hinged to allow access to clean the pond.

Computational fluid analysis was also completed on the fishpond to determine the optimal location of the pump. Two pump locations were simulated in COMSOL. The figure below shows the two possible locations on the pump.

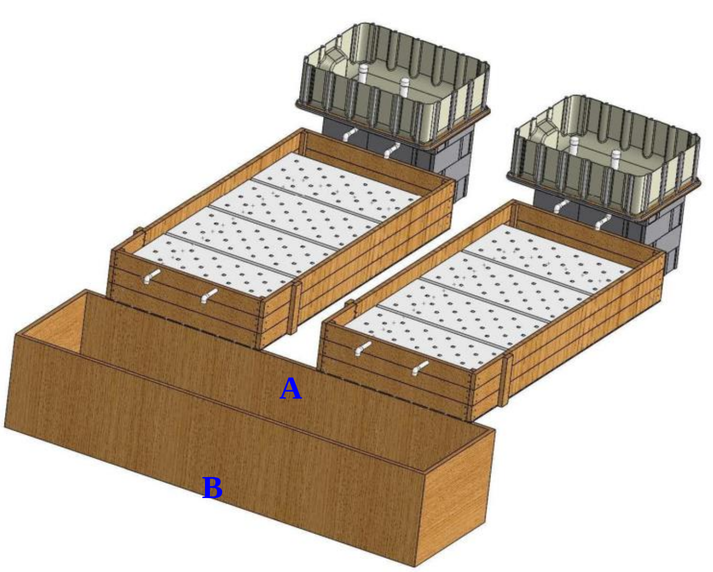


Figure 16. Pump locations in fishpond

Figure 16 shows that the first possible location, location A, for the pump is near the surface of the pond and closest to the raft grow beds. The second position, B, is at the bottom of the pond on the side opposite of the raft grow beds. These two pump locations were analyzed because they both offer unique benefits. Placing the pump near the surface of the pond, position A, will reduce the required head of the pump, allowing the pump to have a higher volume flow rate. On the other hand, having the pump at location B allows for better circulation of water. One concern that the team had was that having the pump in location A would only circulate the clean water draining out of the raft grow beds and the water at the bottom of the pond would be stagnant, reducing dissolved oxygen (DO) concentrations at the bottom. Additionally, this analysis is useful as it shows how much the water draining out of the raft grow beds will mix the water in the pond. The results of the computational fluid dynamics (CFD) analysis can be seen in Figure 17 and 18 below. The simulations show a two-dimensional cross section of the pond, with the water entering from the raft grow beds in the top and the water exiting through the pump. This model assumes that no water moves lengthwise in the pond.

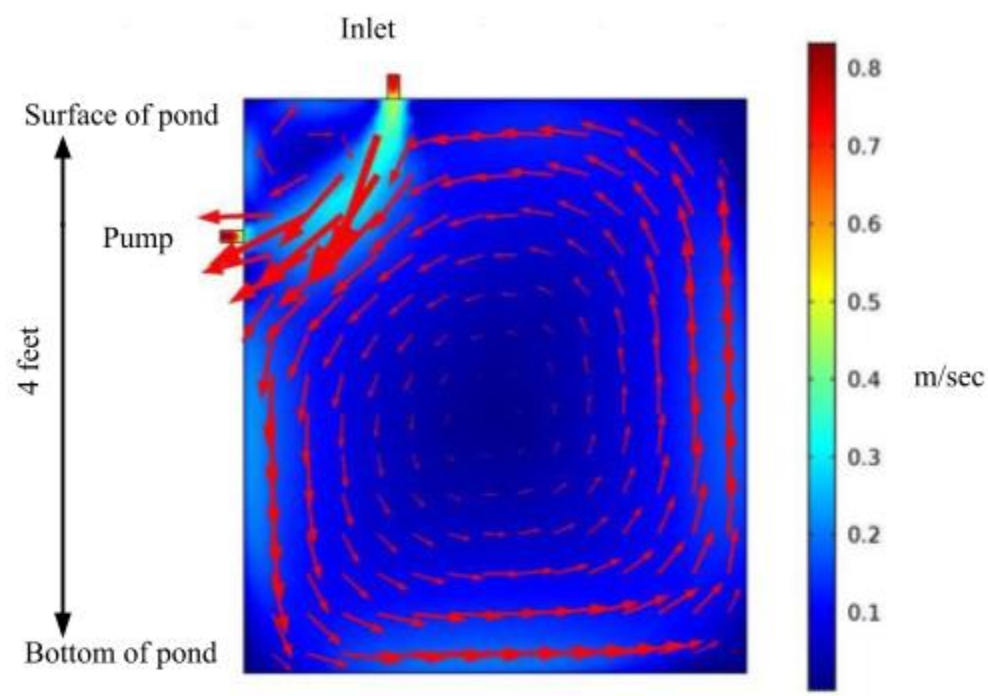


Figure 17. Position A, analysis when the pump is near the surface of the pond

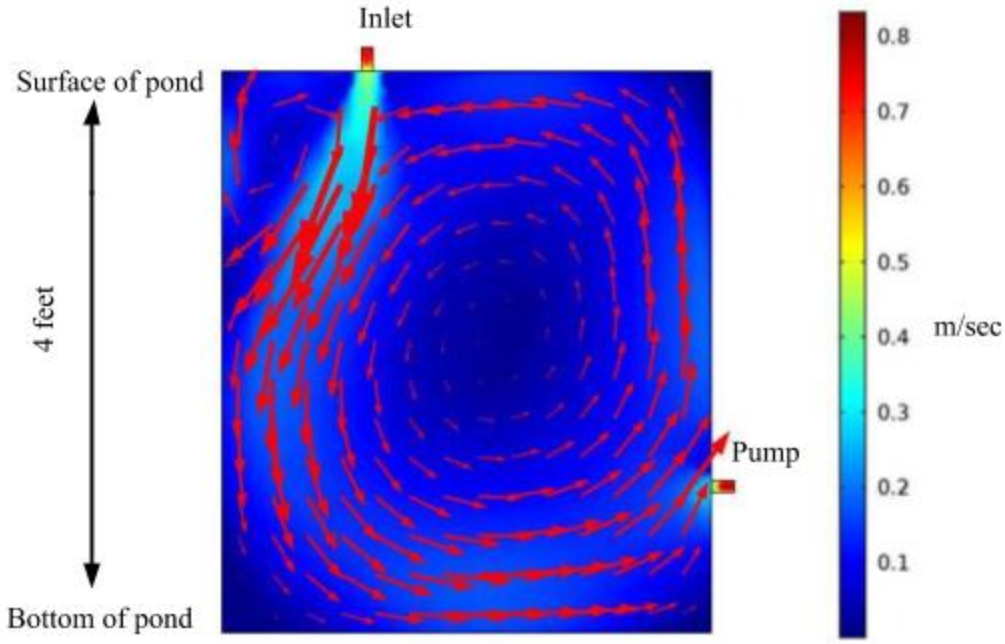


Figure 18. Position B, analysis when the pump is on the bottom of the pond

As Figures 17 and 18 show, having the pump at position A or B both allow for flow of water vertically throughout the pond. As a result, it can be concluded that the flow of water into the pond from the raft grow beds will mix the water in the pond. However, for position A, much of the water draining out of the raft grow beds is immediately pumped out of the pond. This is not ideal as most of the clean water from the plants is being pumped immediately out of the pond, instead of the water with a large concentration of fish waste in it. As a result, the plants will not be receiving as much nutrients. In contrast, having the pump at position B allows for greater circulation of water throughout the pond. This is the ideal pump location, as water with a large concentration of fish waste will be pumped to the media grow beds and plants. Additionally, these figures show that the water is flowing at a safe velocity of around 0.3 m/s, as it is recommended that the velocity of the water in aquaponics grow beds and ponds remains below 0.5 m/s [16].

5.2 Fish

There are many different types of fish that can be used in aquaponics systems. Some of the most popular types of fish are koi fish, goldfish, and edible fish such as tilapia. The table below compares the various fish the team was considering for the aquaponics system with different variables such as cost, life span, and adaptability.

Table 13. Comparison of fish

Variable	Koi	Goldfish	Tilapia
Life span	✓	x	x
Cost	x	✓	✓
Ammonia produced	✓	x	✓
Adaptable	✓	x	✓
Edible	x	x	✓

As one can see from the table, koi fish have the main drawback of cost, but are often very successful in aquaponics systems due to the large amount of waste they produce, their long life span, and their adaptability to changing water conditions. Goldfish have a smaller temperature range than koi fish and produce less waste than koi, but they are still a good option because they are inexpensive and can adjust to different water conditions. Lastly, even though the client is not interested in using the system as a protein source, edible fish such as tilapia are a good choice for this system. Tilapia are low cost, produce a lot of waste, and are adaptable to various water temperature, pH, and DO conditions. Additionally, considering the large size of this system, several hundred goldfish would be needed due to their small size, which is not feasible. In comparison, only 30 to 40 koi or tilapia are required. Overall, tilapia will be used in the system since they are significantly less expensive than koi. Below is a picture of the completed fishpond.

The fish will be fed two times a day by an automatic fish feeder. The fish food is called Premium Quality Tilapia Fish Food and is sold by Aquaponics USA. They recently switched their brand to make the food domestically, rather than in China to prevent harmful chemicals, such as Melamine to be present in the food. The new food is a mix of Marine and Vegetable protein, since tilapia are omnivores. While the fish are fingerlings, they are fed fingerling crumble. The specific 1/32-in crumble purchased have a 50% protein content and 17% fat content. The large amount of protein enables the fish to grow at a faster rate. The specific ingredients are fish meal, wheat flour, brewer’s yeast, fish oil, and a vitamin mix. The vitamin mix contains vitamins A, C, D, and E which helps with disease resistance and digestibility. This food sinks which allows for fish at all water levels to find food and this food should not impact water quality or clarity.

As the fish continue to mature and grow past 4-in, they will be fed pellets. The protein content in this fish food is decreased and the pellets will float, helping the team monitor the amount of food the fish are eating. Protein remains an important part of their diet because these levels may help with reproduction rates to sustain the system but lowering fat content will help prevent liver failure and early mortality. In the future, the farm may switch from fish food to duckweed, a more natural source of food [31]. Additionally, the fish may be fed scraps of vegetables. Both duckweed and vegetable scraps are good options once the fish mature because the fish food is not organic.

Additionally, the pond is equipped with an air pump and three air stones to ensure that the fish have enough oxygen. Specifically, the pond has a Vivosun Air Pump that pumps 950 GPH and uses 32W.

Figure 19. Completed pond with cover, aeration, and fish

6. Media Grow Bed

The media-filled grow beds act as one of the two types of grow beds in the system, the two grow beds together providing 26.7 sq. ft of growing space. The team chose this system because it acts as a natural filter to balance nutrients through nitrification, so harmful chemicals will not enter the water flow of the grow beds. The figure below shows the media grow bed at the garden.

Figure 20. Media bed setup

As the figure shows, an IBC container was used, and it is placed on cinder blocks so that the bell siphons can drain directly into raft grow beds. Many different containers were considered for use; however, an IBC container was chosen for many reasons (See Appendix H3 and H4 for details).

A specific benefit of using an IBC is its rigid container, which prevents leaks. A wood box with a liner was considered, but the rough media could cause tears in the liner. In addition, the IBC containers are 275 gallons, making the containers a perfect size for the system, since the "bacteria-based filter" needs to be at least one quarter the size of the fishpond in order to adequately filter the water [30]. Lastly, the IBC sits on raised cinder blocks that can support the weight of the container, especially when it is full of media and water.

In addition to container selection, another important aspect of media bed is selecting the media. There are various types of media including clay pebbles, lava rocks, and pea gravel. All these options are porous, which allows for the nitrogen fixing bacteria to grow in the beds and pH neutral, which is important for plant and fish health. However, the various types of media do differ, and these differences are highlighted in Table 14.

Table 14. Comparison of aquaponics media

Variable	**Clay pebbles**	**Lava rock**	**Pea gravel**
Cost	x	✓	✓
Size	✓	✓	x
Drainage	✓	✓	x

From Table 14, the cost, size, and drainage of each media type is selected. Clay pebbles are used in most aquaponics systems since they are a good size of around ½-in in diameter and allow for good drainage and since most aquaponics systems are relatively small. However, this system needs one cubic yard of media, and if clay pebbles were used over twenty 40-liter bags would be needed, equating to $800 worth of media. Lava rock and pea gravel are less commonly used in aquaponics system. While pea gravel can be used, it is not commonly used due to its small size, which can negatively affect the water flow through the grow bed and is small enough to get into the media guard on the bell siphons. Even though lava rocks are not commonly used in aquaponics, they are a good trade-off, as they are affordable and are a good size. Additionally, lava rock is a good choice because it is pH neutral, which is important for plant and fish health, and it is porous, which is vital for the nitrogen fixing bacteria. This system uses ¾-in red lava rock, which are sold in bulk and are large enough not to infiltrate into the bell siphons. The lava rock costs $198.29, which is significantly less expensive than the clay pebbles.

7. Raft Grow Bed

In addition to two media grow beds, the system will have two raft grow beds, where the plants are suspended by a raft that floats on top of the water. The raft has small holes cut into it with nets on the inside that support the plant as it develops into a seedling and the root system matures.

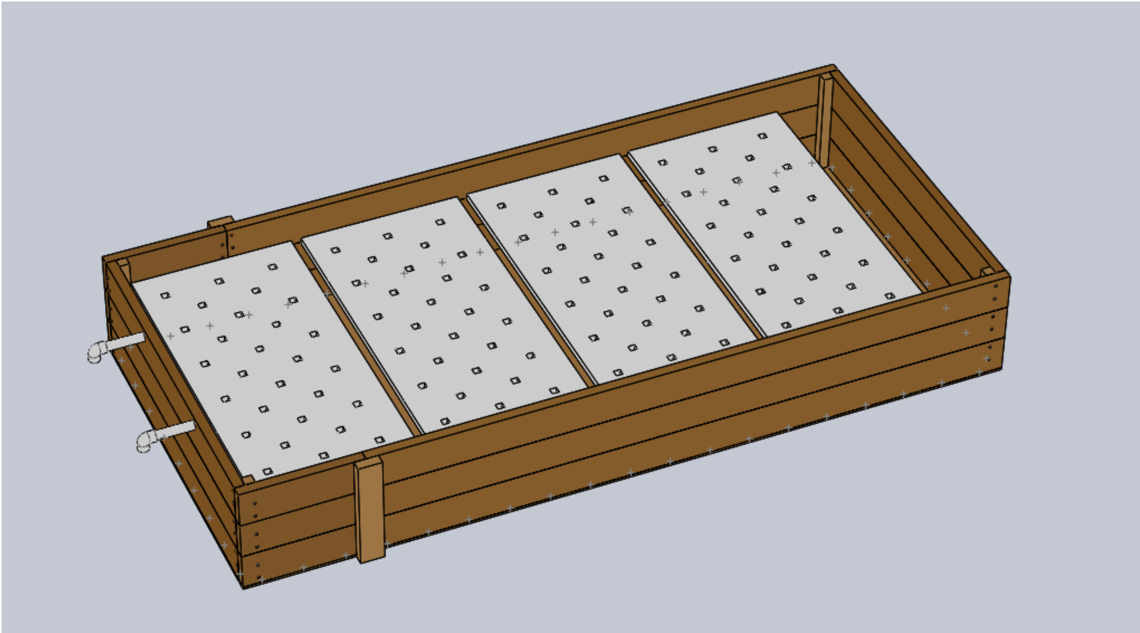


Figure 21. Model of raft grow beds

The system is using rafts that are each capable of holding 72 plants. With the system's 8 rafts, the raft sub-system can grow 576 plants at once. This number of plants corresponds to 9 plants per sq. ft, which is greater than the planting density of traditional farming, which is 2 plants per sq. ft. Furthermore, raft systems are advantageous because they are easily scalable; however, rafts can only grow lightweight vegetables.

Each raft bed is 9.5-ft long and 4.5-ft wide. Each bed is filled with 12-in of water, the industry standard, and the rafts float on top of the water and hold up the plants. The beds were designed using standard wood sizes to help with manufacturability. The grow bed is made of wood panels screwed together to form the sides with plywood sheets that are in turn screwed underneath to support the bottom of the structure. Appendix J shows the detailed part and assembly drawings for this subsystem. In order to make it watertight, a 5mm thick pond liner was placed inside and secured to the wooden frame. Because there was no optimally sized container commercially available, it was decided (using the scoring matrix in Appendix H4) to build the raft grow beds out of wood and a pond liner.

Each of the raft grow beds can grow 288 plants at once, so most of the plants will be grown in the rafts. Since the raft beds grow most of the vegetables, it is imperative to promote proper health and growth of the plants, so the raft system requires nutrient-rich water, free of large matter, and a good drainage system. The movement of the water provides nutrients for the roots which help filter and further oxygenate the water before it is drained back into the fishpond.

7.1 Water Flow Analysis

CFD was used to determine how the water will flow through the raft grow beds. The rafts are rigid foam sheets that float on the surface of the water and hold the seedlings and larger plants as they grow. Water flow through all four rafts collated together is displayed below:

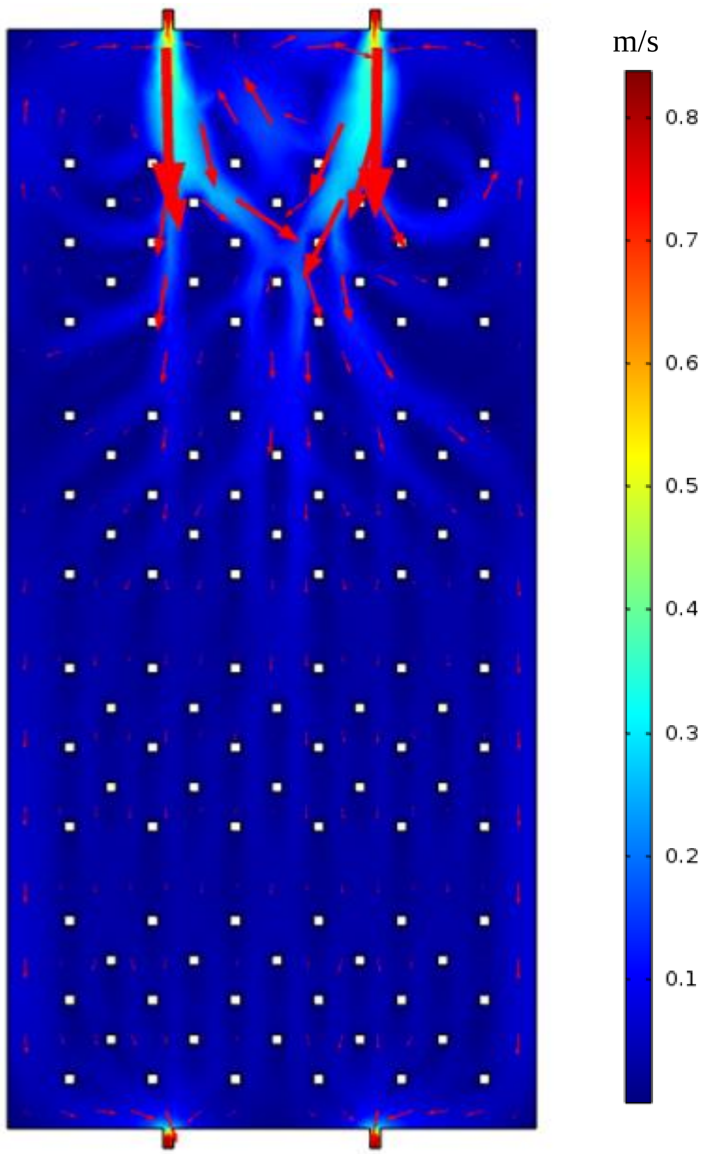


Figure 22. Top view of grow bed, showing location of holes in rafts and water inlets and outlets

The holes represent the plant roots, where water flows around. The water flows in through two 1- in pipes and exits through two 1-in pipes downstream.

The red arrows show the magnitude and direction of the flow, indicating that all of the plants do receive fresh water under this configuration. The maximum velocity occurs at the inlets and outlets with 0.7 m/s. This velocity is safe, as the greatest velocity recommended for drainpipes in aquaponics systems is 0.7 m/s [17]. Additionally, there are two eddies that circulate at the top of the raft system, which encourages mixing and circulation at the far corners. The water then descends through the rafts and around the holes in a patterned way with steady low-flow around 0.3 m/s before it exits the grow bed.

Given a velocity limit of 0.5 m/s in the grow beds, this CFD shows a reasonably safe water flow of less than 0.3 m/s. Therefore, the configuration of these rafts should be kept the same, and the inlet and outlet pipes should be kept at 1-in diameter.

In addition to analysis on the top of the raft beds, analysis was also completed on the side of the raft beds. Two models of the root structures are compared below in Figure 23 to investigate the positioning of more mature plants in the raft grow beds. The models show a side view of the raft grow bed and compare CFD analysis on root positions. The roots are represented by the rectangles in the water, as the plant roots hang below the rafts that float above. More mature plants are assumed to have longer roots, whereas the seedlings have shorter roots. The same 1-in pipes are assumed for the inlet and outlets as above for the raft CFD. The top CFD analysis, Configuration A, shows the most mature plants, with the longest roots closest to the inlet of the water, and with plant roots getting shorter and shorter as the water goes down stream. The inverse of this root layout was analyzed in the bottom configuration, Configuration B, with the shortest plant roots towards the upstream inlet, and the longest plant roots downstream towards the drain. In this analysis the red arrows show only the direction of the flow.

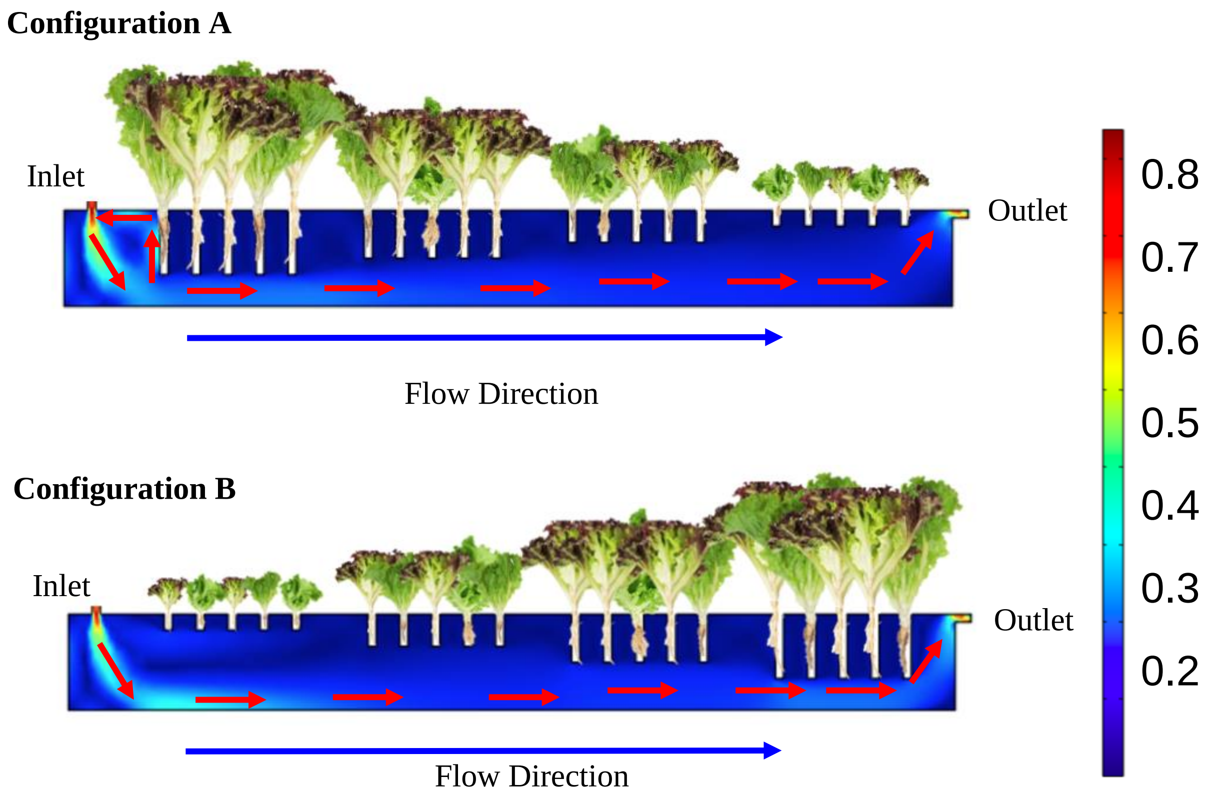


Figure 23. Comparison of two possible root configurations with water velocity vectors to show water flow and velocity

It can be seen from the CFD analysis that configuration A has more turbulent flow with a maximum velocity of 0.5 m/s seen at the inlet, which is at the top limit of the recommended velocity in raft beds [17]. Additionally, long roots create a large eddy at the inlet of the grow bed, which is not ideal, since it prevents the water from flowing smoothly to the exit. Configuration B, in contrast, shows the water flowing smoothly from the inlet to the outlet, with a maximum flow velocity of around 0.3-0.4 m/s, which is within the velocity limit. Therefore, configuration B results in a safe and reasonable design.

This analysis helped the team learn that there is a strategy to the configuration of rafts placed in the grow bed. Furthermore, the team learned that having younger plants near the inlet and more mature plants closest to the outlet, Configuration B, would be ideal to allow for a smooth flow of water through the beds. This information will be passed along to the user to ensure that the system is operating as efficiently as possible.

7.2 Finite Element Analysis

Finite element analysis (FEA) was also conducted on the long side of the grow bed in order to verify that the wooden grow bed frame would not break under the distributed pressure load of the water:

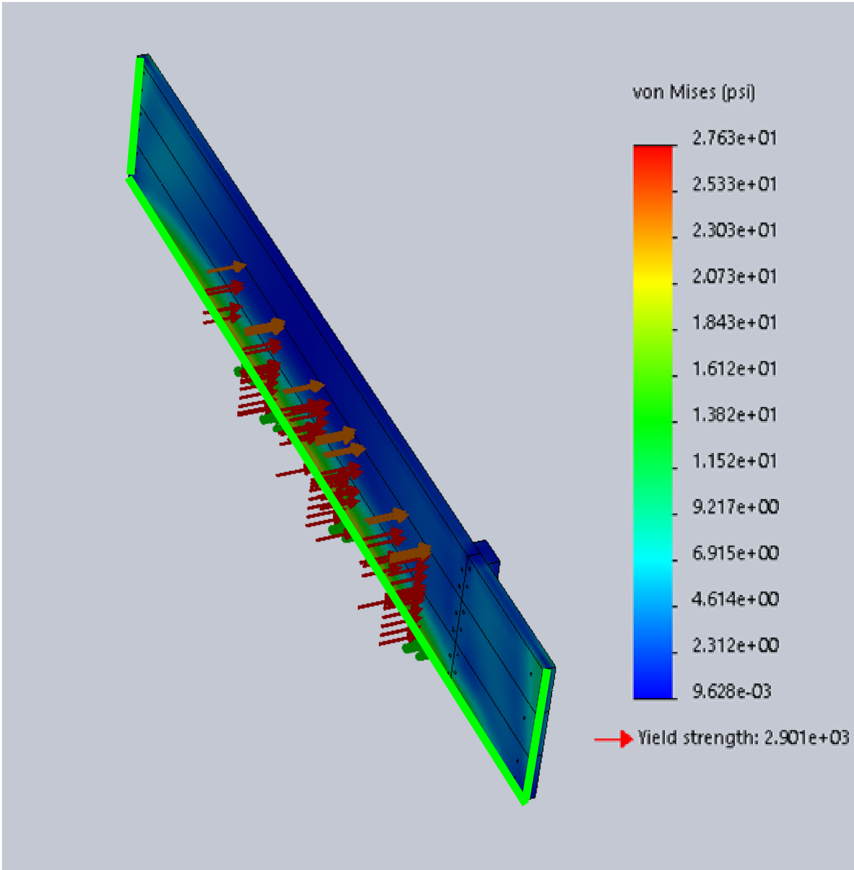


Figure 24. Von Mises analysis on the long side of the wooden raft grow bed, with distributed load from water pressure when the grow bed is full of water

Since the side of the grow bed is comprised of three separate 5.5-in deep horizontal panels of wood, a separate load due to the distribution of water pressure was applied to each beam. The top beam, which only has the bottom in under water, has a distributed pressure of 0.018 psi. The middle beam has a total pressure of 0.14 psi, and the bottom beam, with the largest distributed pressure load from the full weight of the water, has a load of 0.33 psi. The horizontal bottom edge of the grow bed and the side of the grow beds, highlighted in green in Figure 24, are assumed to be fixed, since they are screwed into other parts of the bed.

The location of failure was expected to be at the bottom of the grow bed, where the pressure would be greatest, or at the wood joint, since the wood is not one continuous piece and is held together by screws. However, given the grow bed design and material choice of redwood, it was expected that the grow bed would not fail due to stress or large displacement. While many different types of wood, like pine, would be safe under these conditions, redwood was selected because of some of its other qualities. Redwood is easy to use in construction projects and is weather resistant. It was important to the team to select a wood that is weather resistant, so it requires little maintenance for the client and does not need to be replaced frequently.

Figure 25 below shows the displacement analysis that resulted from the distributed pressure load against the wood panels, using the pressures described above.

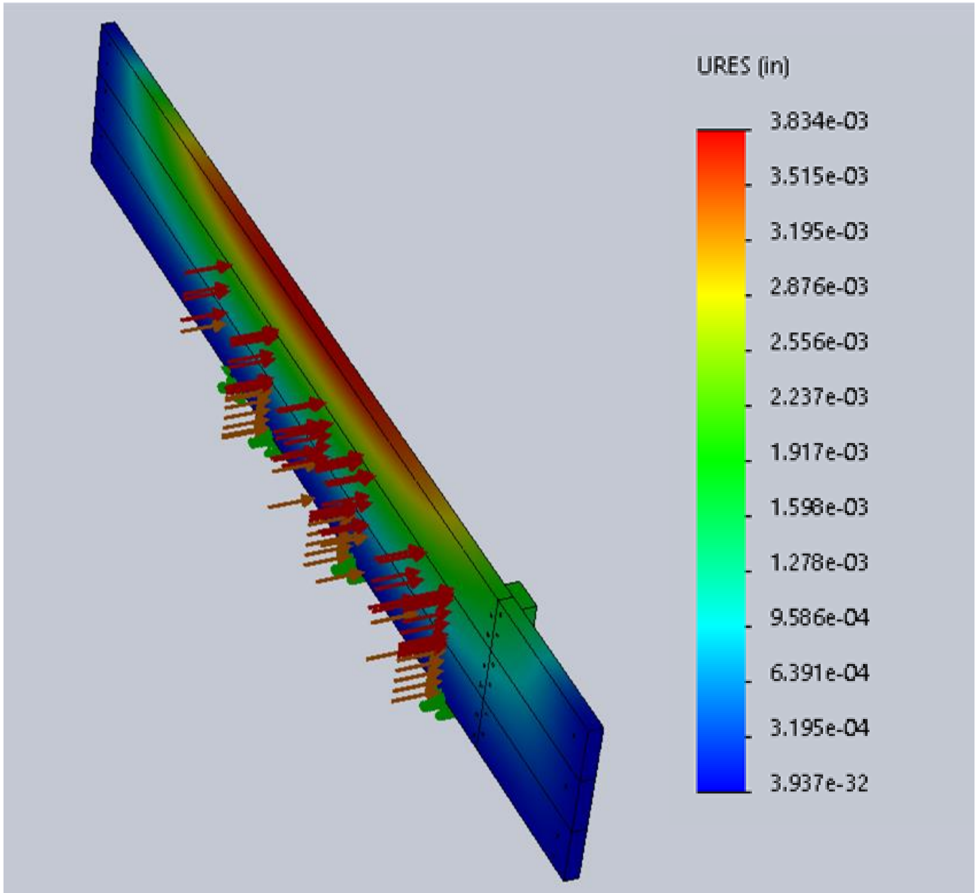


Figure 25. Displacement analysis on the long side of the grow bed from the distributed load of the water when the grow bed is completely full of 12-in of water

From Figure 25, the maximum displacement that the wood will experience will be 0.00384-in along the top of the grow bed. In Figure 24, the maximum stress the wood will experience is 2.763 psi, at the bottom of the grow bed. This stress is significantly less than the maximum yield strength of 2901 psi. It should also be noted that the entire analysis was completed assuming the wood is balsa, since the finite element analysis software used, SolidWorks, could not run the simulation with redwood as the material. Since balsa has a lower yield strength and is weaker than redwood, it can be concluded that the grow beds will be safe when made out of redwood, since they are safe when a weaker material was used in the simulation.

Overall, from the finite element analysis, one notices that the wooden grow bed, despite the large amount of water flowing through it, will have a negligible amount of deflection and a minimal stress applied at the bottom of the grow bed. Therefore, the grow bed is a sound design.

8. Plumbing

In addition to the media grow bed, raft grow bed, and fishpond subsystems, another important subsystem is the irrigation system. The objective of the irrigation system is to move the water from the fishpond to the media grow bed, then to the raft grow bed, and finally back into the fish pond, completing the cycle. This cycle can be seen below:

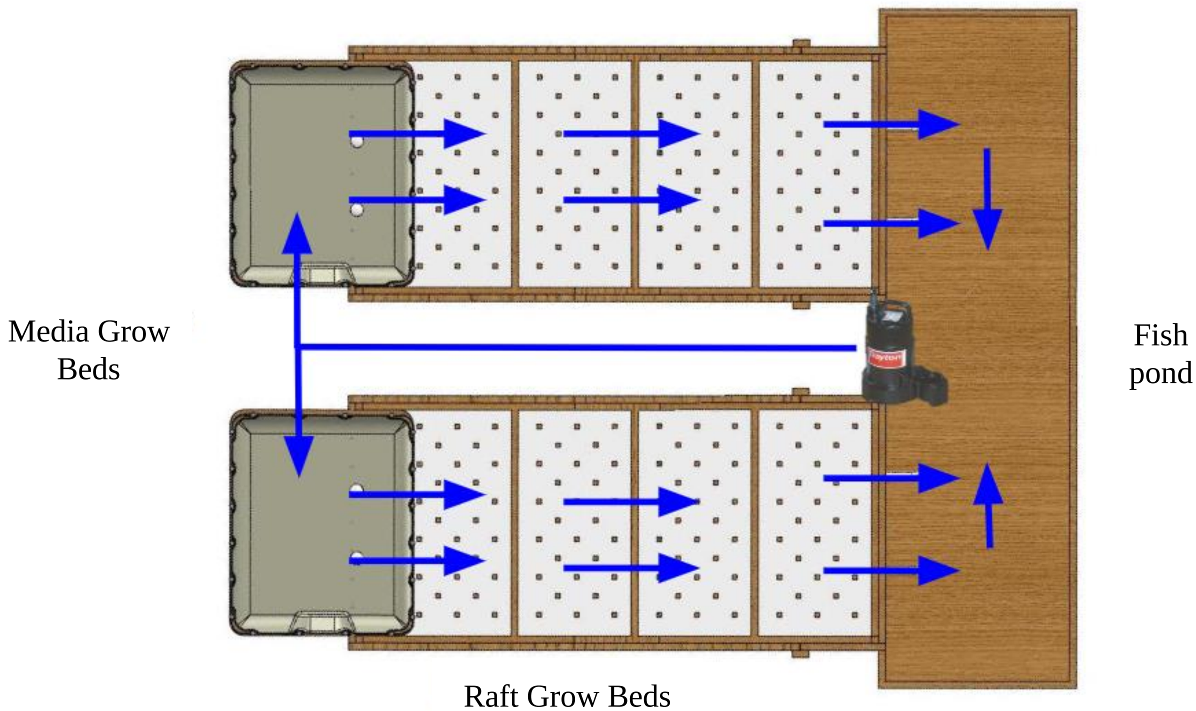


Figure 26. Water flow diagram of aquaponics system

The blue arrows indicate how the many different parts of the irrigation subsystem move water throughout the different subsystems. Although gravity is the main driver of water flow, other mechanisms are utilized as well.

Additionally, throughout the irrigation system 1-in PVC and bulkhead unions were chosen in order to provide adequate water flow and drainage, which is controlled by the angle of tilt of the raft grow beds. Based on research of the drainage angle applied to roadway designs, a tilt of 1.5% is applied to the raft grow beds [32]. This encourages the water to flow from the raft grow bed back to the fishpond.

8.1 Pump

The system includes a submersible pump, which pumps water from the fishpond into the media bed. A submersible pump was chosen over a non-submersible pump because submersible pumps are less likely to overheat and stop working. Ideally, the total volume of the fish tank, 650 gallons for this system, will be cycled through the system each hour [15]. Figure 27 shows a side view of the aquaponics system.

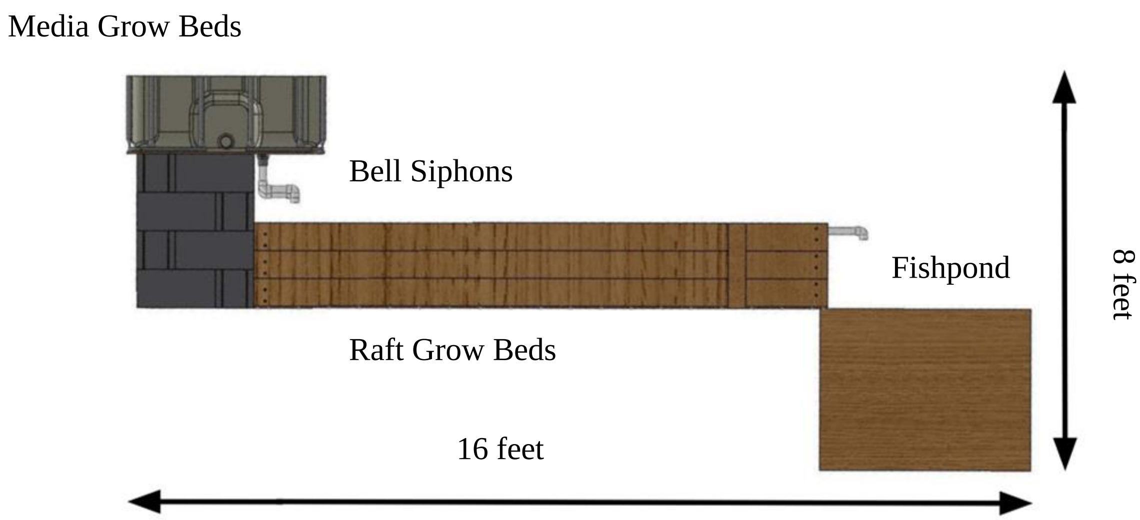


Figure 27. Side view of aquaponics system

This side view of the aquaponics system shows that water must be pumped from the bottom of the fishpond up 8-ft to the top of the media beds. With these flow rate and head requirements a calculation was completed to determine what size pump was needed. First, the desired flow rate, Q, must be selected along with the hose diameter, d. The cross-sectional area of the hose, A_c, can be calculated using Equation 4.

$$A_c = \frac{\pi d^2}{4} \tag{4}$$

With the cross-section area of the hose, the velocity of the flow, V, can be determined using Equation 5.

$$V = \frac{Q}{A_c} \tag{5}$$

Next, the Reynold’s number is calculated with Equation 6.

$$Re = \frac{Vd}{\nu} \tag{6}$$

In Equation 6, ν is the kinematic viscosity of water and is assumed to be 1.0035 x 10^{-6} m^2/s for water at 20 degrees Celsius [33]. The roughness of a hose, ϵ is assumed to be 0.3 mm, and a value of ϵ/d can be determined [34]. This value is then used to determine the friction factor, f, of the pipe. Since the flow is turbulent, Equation 7 can be used to determine the friction factor.

$$\frac{1}{f^{1/2}} = -1.8 \times log(\frac{6.9}{Re} + (\frac{\epsilon/d}{3.7})^{1.11}) \qquad (7)$$

Next, the head loss due to friction in the pipe can be calculated with Equation 8.

$$h_f = \frac{8Q^2}{\pi^2 d^4 g}(\frac{fL}{d}) \qquad (8)$$

In Equation 8, L is the length of the hose and is assumed to be 5 meters. Lastly, the total head loss h_t can be calculated with Equation 9.

$$h_t = h_f + h \qquad (9)$$

Equation 9 shows that the total head loss is equal to the sum of the head loss due to friction and the head loss due to pumping the water to a different height, which is 8-ft.

With the total head and flow rate determined, an appropriate pump can be selected. Using a flow rate of 650 gallons per hour (gph), or 10.8 gallons per minute (gpm), and a pipe diameter of 1-in, a pump must be able to pump 10.8 gpm at a head of 10.3-ft. Figure 28 shows the maximum head versus flow rate of the HydroFarm Active Aqua submersible water pump with a maximum head of 12-ft and a maximum flow rate of 18.5 gpm.

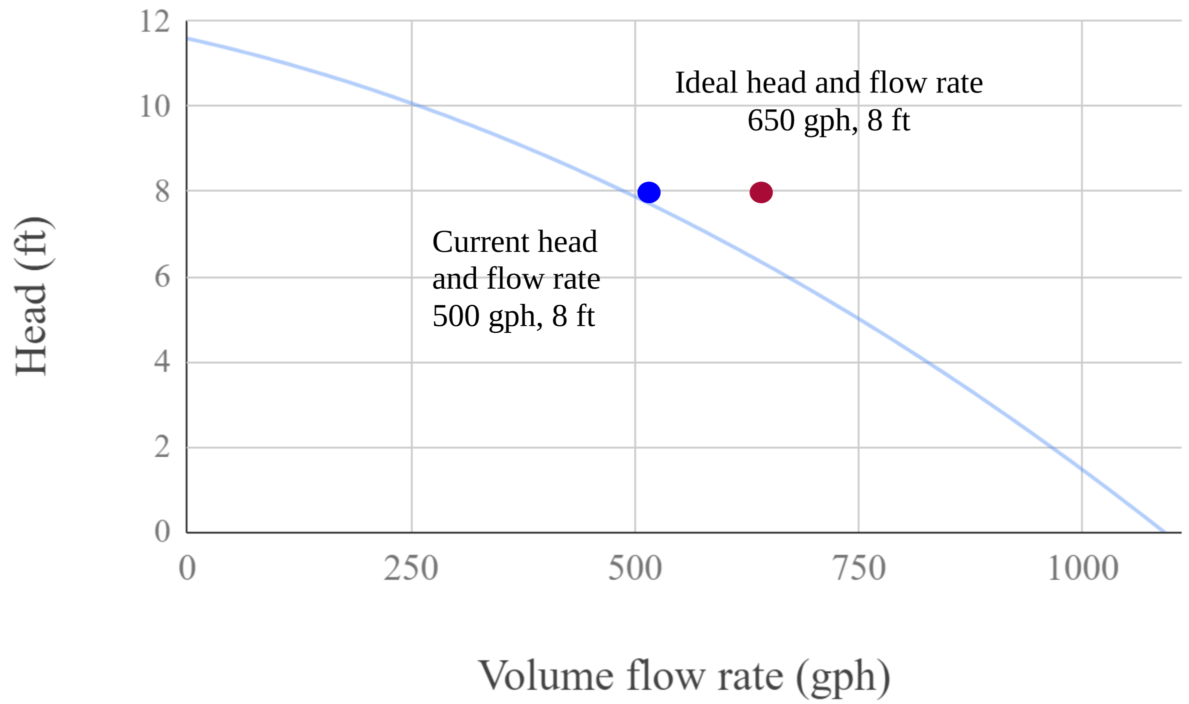


Figure 28. Pump curve from pump calculation of fishpond pump

This pump curve shows that the pump is slightly undersized for the given requirements of 650 gph and 8-ft of head. The pump selected can only pump 500 gph at the required head. However, this pump was still selected because of the limitations on power consumption, which are discussed in the next section. An undersized pump will cycle the water slower than the ideal rate. However, this is okay since the pump is not significantly undersized. It will still cycle the water at a reasonable rate, which will allow the fish to receive clean water and the plants to get nutrients out of the water. One significant downside is that the media bed will flood and drain less frequently, which means that the plants and nitrogen fixing bacteria will receive less oxygen.

8.2 Bell Siphons

To allow for flooding and draining of the grow beds, bell siphons are used in the media grow beds. A bell siphon is a mechanical timer that uses hydrostatic principles to allow the water in the media bed to flood and drain directly into the raft grow bed through gravity. This mechanical timer was chosen over other electric timers due to its simplicity and lower chance of failure. An image of a bell siphon is shown in Figure 29.

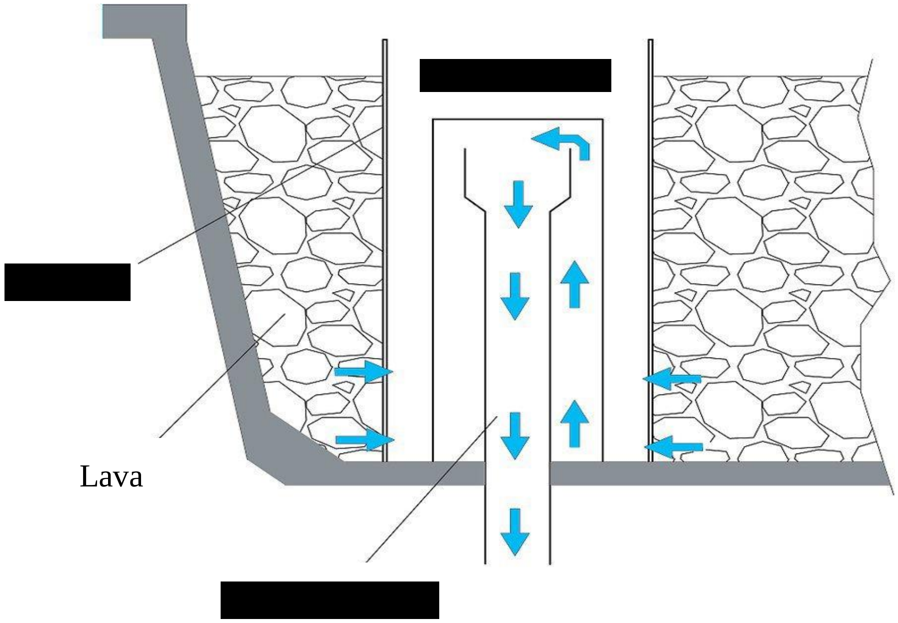


Figure 29. Bell siphon in media bed (Source https://worldwaterreserve.com/wp-content/uploads/2018/10/bellsiphon.jpg, reproduced without permission)

Bell siphons consist of a standpipe, a bell siphon that goes over the standpipe, and a media guard. Bell siphons can be easily constructed using PVC and are made watertight using Uniseals. Water is pumped from the fishpond into the media beds, and when the water reaches the top of the standpipe, water begins to drain down the pipe. This creates an area of low pressure in the bell that encourages more water to flow into the bell and down the pipe. At this time the siphon is fully initiated, and the water drains out of the bed at a faster rate than the water is being pumped into the media bed, so the water level decreases. The water continues to drain until the water reaches about ½-in and air beaks the low-pressure zone in the bell. The water will then stop draining and the media bed will fill up with water again. Ideally this flooding and draining cycle occurs every 15 minutes so the plant roots can get fresh air, but not so long that the roots dry out. Additionally, the standpipe in the bell siphon should be 1 to 2-in below the top of the media. If the water level rises to the top of the media the plants in the bed will be soaking in the water, which is not ideal. Finally, and importantly, the media guard prevents the media from interfering with the siphon.

9. Power System

The power system ensures that the system is operational and off-the-grid by providing a renewable energy source and energy storage for constant power. The many different components help to maximize power input and energy necessary to run the different loads: water pump, air pump, and Arduinos. An overview of the system is shown below:

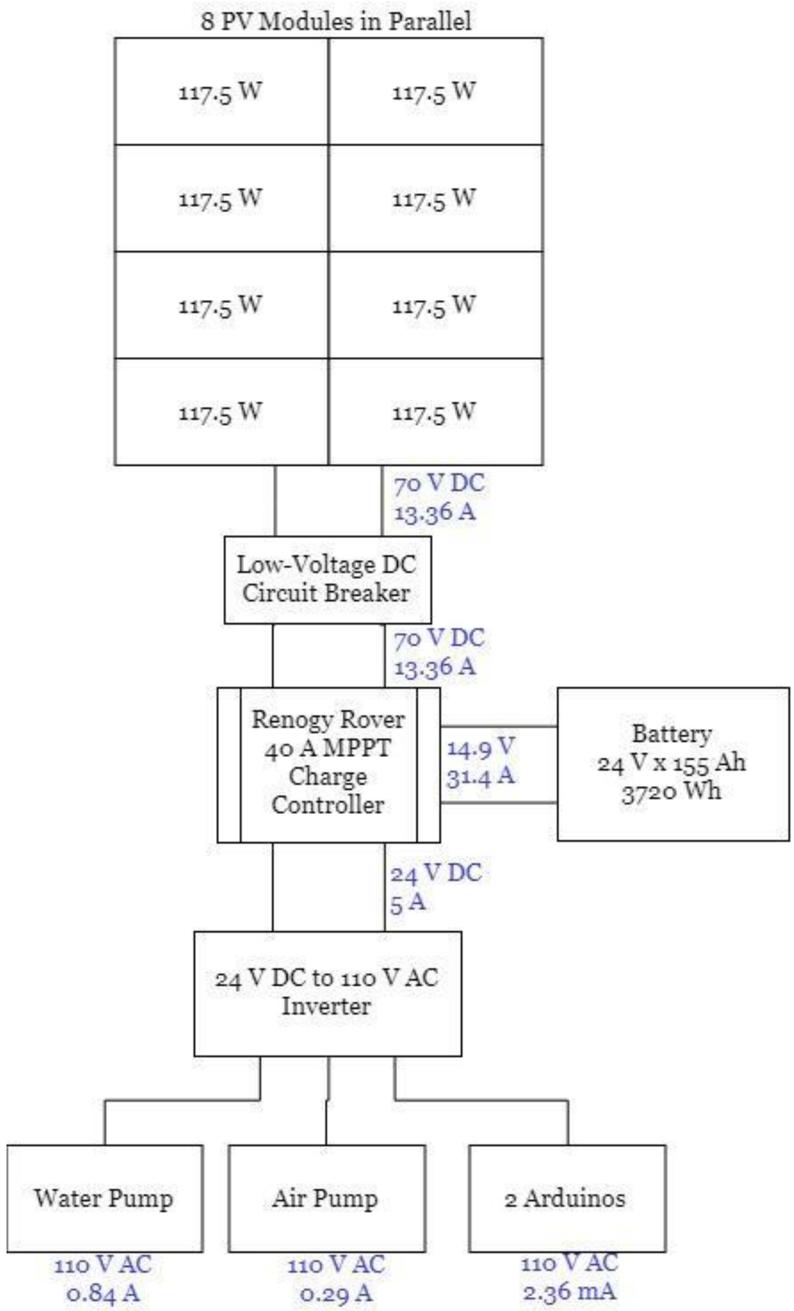


Figure 30. Power train for the entire system

The solar panels generate electricity which feeds into the Maximum Power Point Tracking (MPPT) Charge Controller. The circuit breaker in between acts as a safety precaution to disconnect the energy source from the rest of the system. Energy from the solar panel is fed directly into the inverter, which changes the direct current (DC) to alternating current (AC) necessary to power the pumps and the Arduinos. The battery is also connected to the charge controller and will be charged up by the excess electricity generated. It will discharge when the solar panels are no longer generating electricity to continue to power the inverter and the individual loads.

In the following sections, a breakdown of each component will demonstrate power calculations and reasons for sizing each one.

9.1 Load Requirements

It is imperative to determine how much power and energy is necessary for the system given the amount of energy each load will absorb or consume. In a 24-hour day, the total load will be 2982.2 Wh, since the system is intended to operate continuously 24/7. However, the different components, mainly the charge controller and inverter, also have power loss that needs to be factored in.

To calculate energy absorbed, Equation 10 was used.

$$E = P * t \qquad (10)$$

E represents the total energy, P is the total power that each load consumes, and t is the amount of time that the load is consuming. Using Equation 10, the table below breaks down the amount of energy consumed by each load.

Table 15. Total energy consumed by each load

Load	Power (W)	Time (hours)	Energy (Wh)
Water pump	92	24	2208
Air pump	32	24	768
Arduino and Sensors*			6.2
Charge controller	1.4	24	33.6
Inverter	12.4	24	298.2
Total			3314

*The Arduino and sensor calculations are broken down in *Table 22*

From the table, the total required energy each day is approximately 3314 Wh, which will serve as the baseline for determining the sizing of the other components.

9.2 Solar Panel

The solar panels were generously donated from the company, First Solar. Each First Solar Series 4 Thin-Film PV Module (FS-4117-2) is rated at 117.5 W if operating at maximum capacity. Field testing at different angles indicates that maximum ratings will have a voltage output of 70 V, a current rating of 1.6 A, and about 112 W. This will serve as the basis for future calculations.

Assuming a worst-case scenario when there is the least amount of sunlight—December—and positioning the arrays at a Southeast angle, the next step was to determine the angle level for the solar panels. The two options were either raising the solar panels at the optimal angle for winter (38 degrees) or laying them flat. If inclined, more power could be generated; however, it would have been less cost-effective and much more difficult to mount the modules.

Theoretical energy calculations for the total energy in kWh generated each day is determined by Equation 11:

$$E = A * \eta * H * PR \tag{11}$$

E represents the total energy generated, A is the total area of each solar panel, η is the efficiency of each module, H is the average solar insolation, and PR is the performance ratio which takes into account other external and environmental factors.

Each solar panel has an area of 0.72 m^2, an ideal efficiency of 16.3% which will be assumed for testing purposes, and a default performance ratio value of 0.95 because there are no trees or shade from the surrounding environment. The solar insolation varies based on position of the solar panels. An online Solar Irradiance calculator from the 2019 Edition of the Solar Electricity Handbook created estimates of average solar insolation in San Jose during December for different solar panel angles [35]:

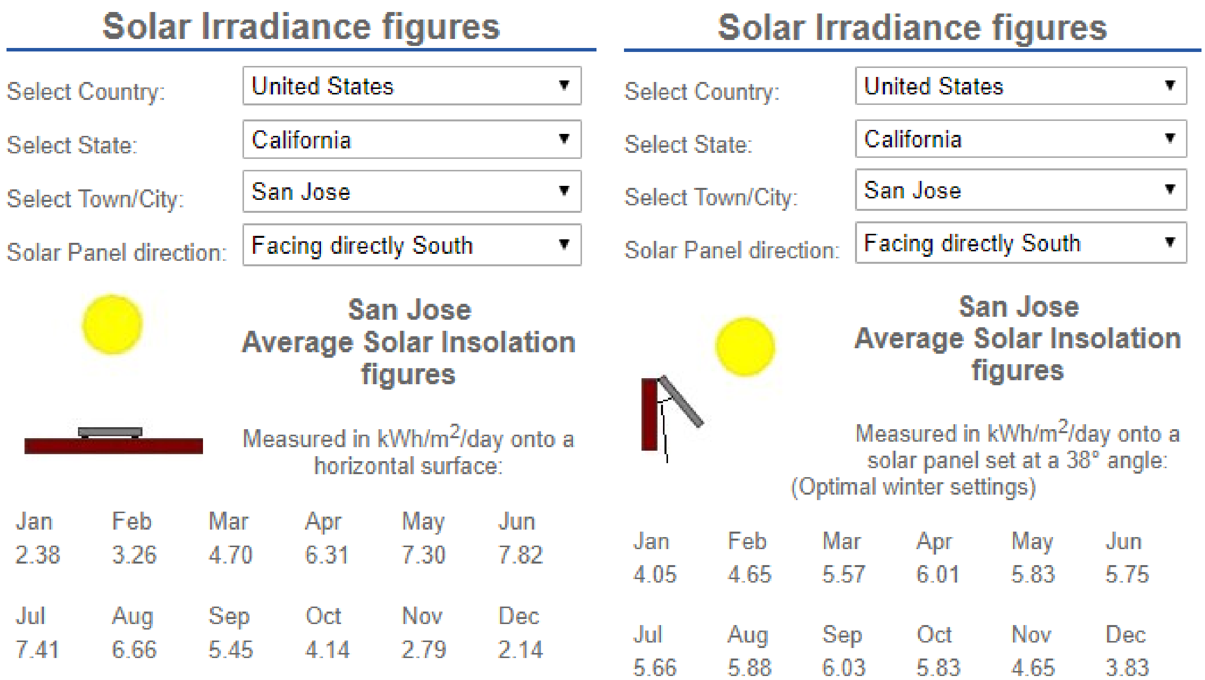


Figure 31. Comparison of solar insolation between solar panel positioning (Source: http://www.solarelectricityhandbook.com/solar-irradiance.html, reproduced without permission)

Based on Equation 11 and the solar insolation charts, the following table compares the energy generated by each individual solar panel and the number needed in the array to generate enough energy to satisfy the load requirements

Table 16. Comparison between solar panel position and number of panels needed

Position (relative to horizontal)	Dec. Solar Insolation	Energy of 1 Panel (Wh/day)	Energy Needed for Load (Wh/day)	Number of Panels Needed
0°	2.14	226	3314	13.89 ≅ 14
38°	3.83	394		7.98 ≅ 8

The results indicate that in December, the system either requires 14 solar panels laid horizontally or 8 solar panels that are inclined at the optimal angle of 38°. The second case is more ideal, given that the team only has 10 solar panels; however, installing the 8 solar panels is the bare minimum. However, other limiting factors for the number of solar panels that can be installed are the maximum input rating of the charge controller as well as the size of the roof, or in this case, the size of the shipping container. Based on both these factors, the team decided to install 8 solar panels in parallel to ensure voltage is maintained at about 70 V and the current at 13.36 A, with a peak power of 935.2 W.

Considering different solar insolation values at the 38° angle, one notices that the electricity generated by solar energy each day will always be greater than the load at any month throughout the year.

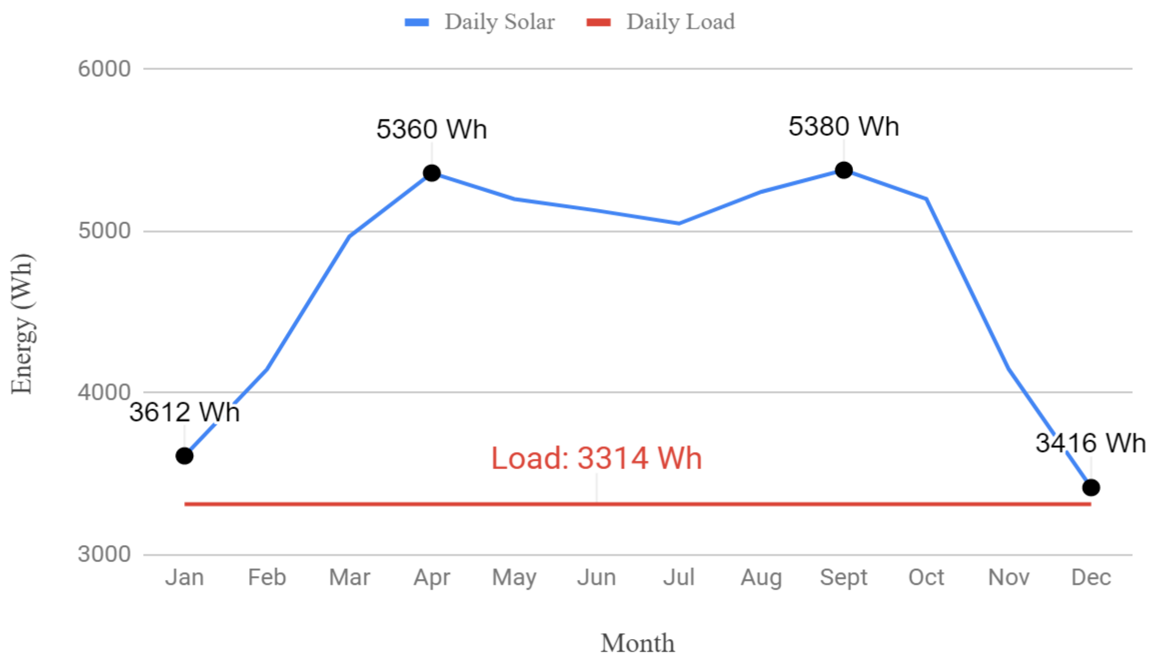


Figure 32. Average daily electricity generation each month compared to energy consumed

Although in December, the energy generated is only marginally higher than the energy consumed, it is still possible that under real conditions, the system may generate more power than the load requires, since these calculations are all theoretical. Given that the system was installed after the winter months, new data will be collected regarding its operation during the winter months.

Since the weather can change drastically, consecutive days of low solar insolation may result in the system shutting down. In such occurrences, a contingency plan was created, as outlined in Section 9.8.

9.3 Charge Controller

An MPPT charge controller is added to maximize the peak voltage and peak current from the solar panels. The MPPT function enables the use of a battery rated at a lower voltage than that generated by the 70 V output from the solar panels while also optimizing the electricity that flows into the load. When the solar panels are not generating electricity, the role of the charge controller shifts to managing the rate at which the battery discharges into the load. Essentially, the charge controller acts to ensure electricity is flowing smoothly where it needs to go and connects the solar panels, the battery, and the load.

Therefore, the charge controller needs to be able to handle the voltage and current from the PV array, the battery, and the load. Smaller-scale charge controllers can only manage up to 1040 W from the PV array when a 24 V battery is connected, ensuring that the number of PV modules cannot exceed eight and the battery cannot exceed 24 V. To ensure the load and PV array criteria are met, the charge controller chosen is the Renogy Rover Li 40 Amp MPPT Solar Charge Controller. The table below demonstrates how the technical specifications of the charge controller compare to the system needs.

Table 17. Technical specifications of charge controller compared to system specifications

Criteria	Charge Controller Rating	System Specification
Solar input voltage	100 V	70 V
Solar input power	1040 W	935 W
Battery voltage	32 V	24 V
Battery current	40 A	31 A
Load current	20 A	5 A
Nominal system voltage	12V/24V	24 V

Table 17 demonstrates that the charge controller is rated perfectly for the system specifications and ensures that technical operation should work perfectly. Originally, the battery current specification tolerance of 40 A is close to the maximum battery current of 39 A (assuming maximum efficiency); however, the battery has a higher charging voltage which will decrease the current needed. The PV Overcurrent auxiliary feature will also help to reduce the charging current to the specification of the battery

Other auxiliary features provided by the charge controller protect the system from different risks that occur either during operation or installation:

Table 18. Protection mechanisms of the charge controller

Protection Mechanism	Potential Risk	Resulting Action
PV array short circuit	Short circuit occurs in PV array	Controller will stop charging
PV overvoltage	PV voltage exceeds 100 VDC	PV will be disconnected until voltage falls below 100 VDC
PV overcurrent	Battery charging current too high if system oversized	Battery charging current will be limited to battery current rating
PV reverse polarity	PV positive and negative wires are switched	Controller will not operate
Battery reverse polarity	Battery positive and negative wires are switched	Controller will not operate
Load overload	Current exceeds maximum load current rating of 35 A	Load will be disconnected
Load short circuit	The load wiring short circuits	Controller will automatically fault
Over-temperature	Temperature exceeds 150°F	Controller reduces charging current

Not only does the charge-controller aid in mitigating potential risks of electrocution that may stem from the system, but as a further precaution the team also added a DC circuit breaker for manual shut-off.

9.4 Energy Storage

The energy storage method stores extra charge generated by the solar panel and ideally, has enough energy in reserve to power the system between sunset and sunrise. So that the system could still function even if the PV array was unable to generate enough electricity for an entire day, the system needed to be 24 V and hold over 3314 Wh of energy.

The original intent was to purchase a more sustainable battery, especially Lithium, but an in-depth cost-benefit analysis demonstrates that a sealed AGM lead-acid battery was the better option:

Table 19. Comparison of battery options

Factor	Lithium	Lead-Acid			Saltwater
		Flooded/Wet	Gel	AGM	
Economical	x	✓	✓	✓	x
Sustainable	-	x	x	x	✓
Deep cycle	✓	x	✓	✓	✓
Non-spillable/non-hazardous	✓	x	-	✓	✓
Lightweight	✓	x	x	x	x
Maintenance-free	✓	x	✓	✓	✓
Heat and weather resistant	x	✓	✓	✓	✓
Resists vibration	-	x	x	✓	✓
High cycle life	✓	-	x	x	✓
High charge/discharge rate	✓	x	x	✓	✓
Low self-discharge rate	x	✓	✓	✓	✓

Although the Aquion Energy Saltwater batteries fit the most criteria, it was difficult to determine how to purchase such batteries, especially since they are starting up after filing for bankruptcy. The next best candidate was a lithium-battery, but the high energy density necessary meant pricing outside the cost structure.

Therefore, it was more effective to connect two 12 V by 155 Ah batteries in series to double the voltage rather than purchasing a 24 V by 300 Ah battery. In the end, VMAX MR147-155 12 V 155 Ah AGM Deep Cycle Batteries was implemented in the system. Each one has a charging current rating of 35 A and charging voltage rating of 14.9 V, which means that it has a power charge rating of 1043 W: less than what is generated by the PV array.

9.5 Inverter

As mentioned previously, the loads all operate on AC, while the electricity generated by the PV array is DC, necessitating implementation of a 24 VDC to 110 VAC inverter. The inverter also needed to have at least two AC outlets for the water and air pump and at least two USB ports for the Arduinos. A power switch was also recommended so that the load could be safely disconnected.

Based on these criteria, a Yinleader 1500W/3000 W DC 24 V to 110 V AC Power Inverter was selected. Although its maximum power rating is much higher than the team's needs, it has the necessary components to complete the job.

9.6 Attaching Solar Panels

Attaching the solar panels is one of the most difficult aspects in the power system. Originally the team wanted to install the panels close to the aquaponics system, for convenience, but due to limitations on space, it was necessary to install the panels on the roof of a nearby shipping container used as a shed by Loaves and Fishes. Installing the panels on the roof of the shipping container also provided added security, as they are less likely to be broken or stolen. The figure below shows the location of the solar installation and the aquaponics system.

Figure 33. Aerial view of solar panel installation and aquaponics system

As the image shows, the solar panels were intended to be oriented 28 degrees from the end of the shipping container, so that they face directly south, which allows them to generate as much energy as possible. The solar panels are about 100 ft away from the aquaponics systems, so underground wire is used to connect the solar panels to the loads, represented by the yellow line in Figure 33 above.

These eight panels were installed using a custom designed Unistrut racking system and the panels were installed at a 38-degree angle with respect to the horizontal. This 38-degree angle optimizes the solar panels for winter, when there is the least amount of sun.

The team decided to use a Unistrut racking system because it can be easily modified to fit specific needs. The safety plan for this solar panel installation is shown in Appendix K. Hand calculations for the solar installation can be seen in Appendix L. Additionally, the figure below shows a SolidWorks model of the chassis, and part drawings are shown in Appendix J.

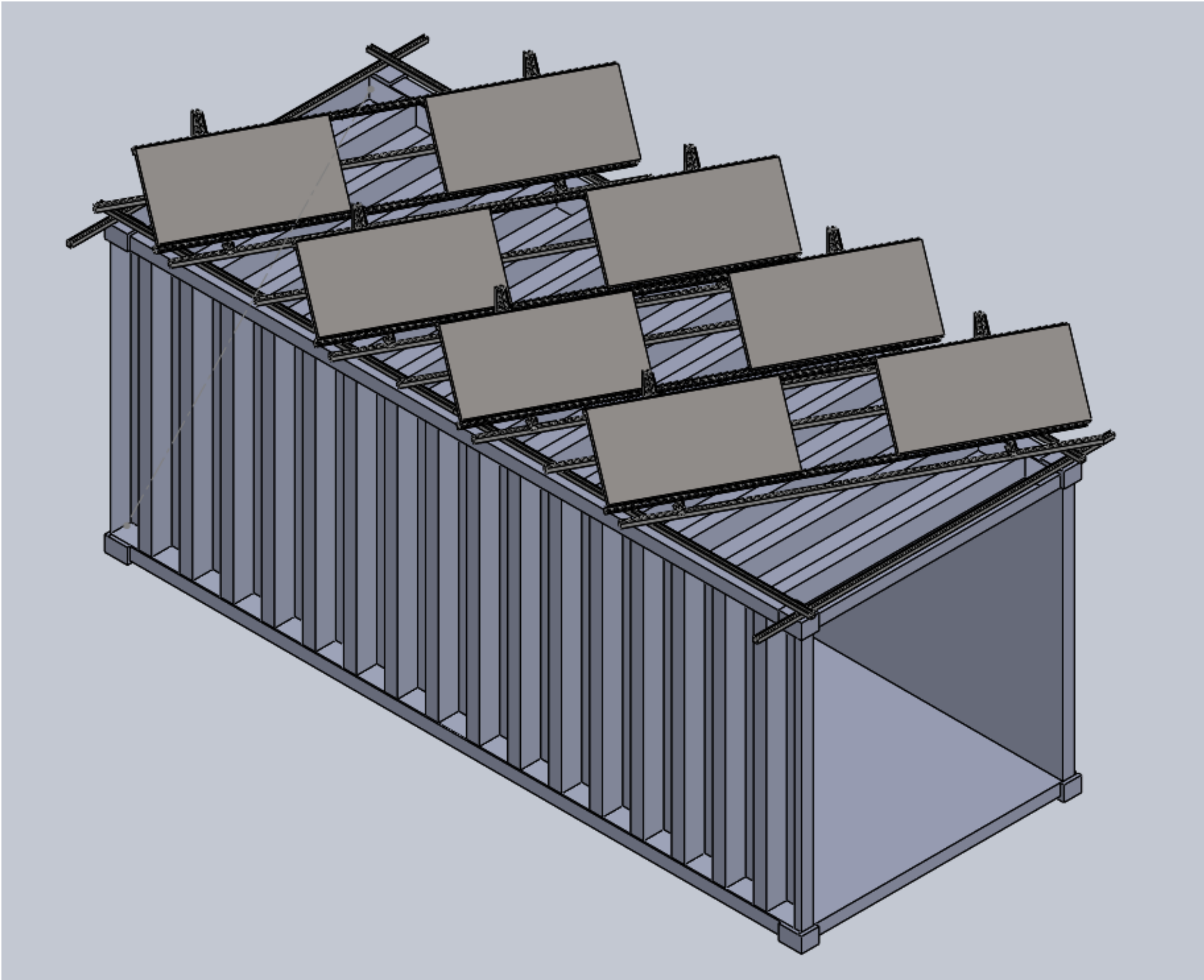


Figure 34. CAD model of the solar panel chassis

Unistrut was donated by CBF Electric and the installation process is composed of five steps. Laying down the base frame, attaching diagonal beams, adding triangular frames, creating solar panel mounts, and lastly, clamping the solar panels.

The entire structure was created using P1000T Unistrut, which will subsequently be referred to as struts. The base layer consisted of two 8-ft long struts along the width and two 20-ft long struts along the length of the shipping container. To secure the frame, specific corner fittings, ISO Shipping Container Nuts, were ordered to fit into the specific holes within the shipping container. Each of these corner fittings would then be secured to the frame that was positioned above it. UniPiers, as shown below, were used to support the strut along the length of it.

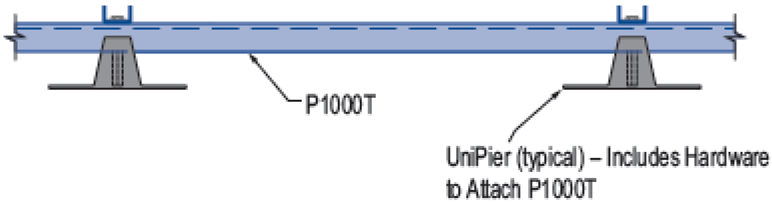


Figure 35. Layout of how the UniPiers connect to the P1000T Unistrut (Source: www.strutandsupply.com/index.php/download_file/view/255/, reproduced without permission)

Figure 36. Images of the frame set in place with the use of UniPiers

All 16 UniPiers were placed strategically under each of the spots where the weight of the solar panel would, to prevent stress from the overhead weight.

Next, eight 10-ft long struts were attached to the base Unistrut frame, diagonally positioned to face directly south. An aerial diagram of the layout is shown below:

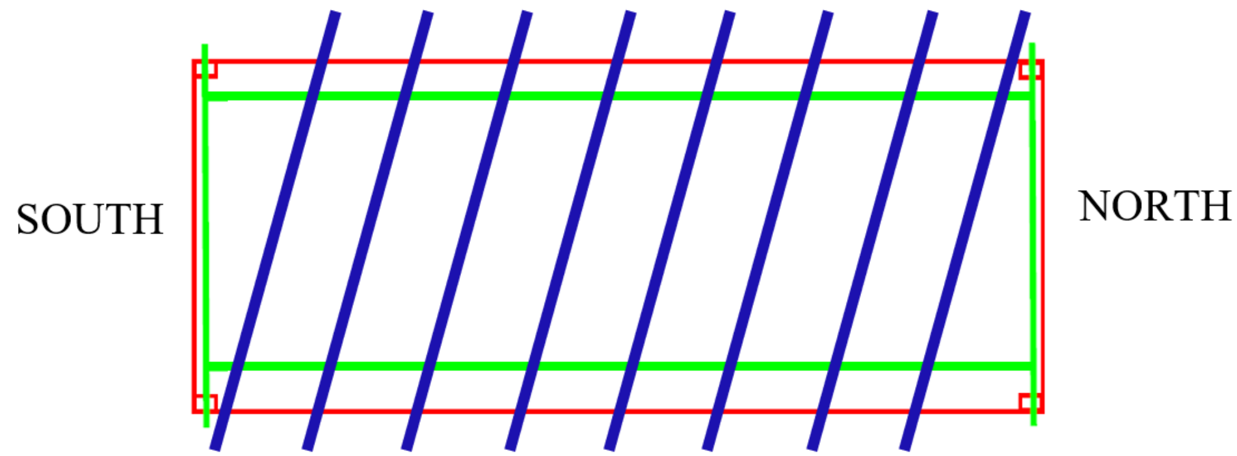


Figure 37. Aerial diagram of the strut layout

The green represents the bottom frame atop the shipping container outlined in red. The blue are the diagonal struts that provide the base for the rest of the solar panel frame.

Although the goal was to position these struts at a 28-degree angle, the current angle is approximately 23 degrees. The team accepted this slight shift mainly because the nuts were securely fastened at this angle. However, this slight shift only marginally shifts the generation potential.

The third step was to create a specific triangle frame by using a hinge connection to connect two struts: the vertical support and the diagonal "hypotenuse" strut. This helped the team to create the specific tilt necessary to optimize the sunlight during winter. Calculations to determine the size of the strut for this angle are shown below:

$$sin(\theta) = \frac{Vertical\ support}{Hypotenuse}$$

$$Vertical\ support = sin(\theta) * Hypotenuse$$

$$= sin(38°) * 34\ in$$

$$= 20.93\ in$$

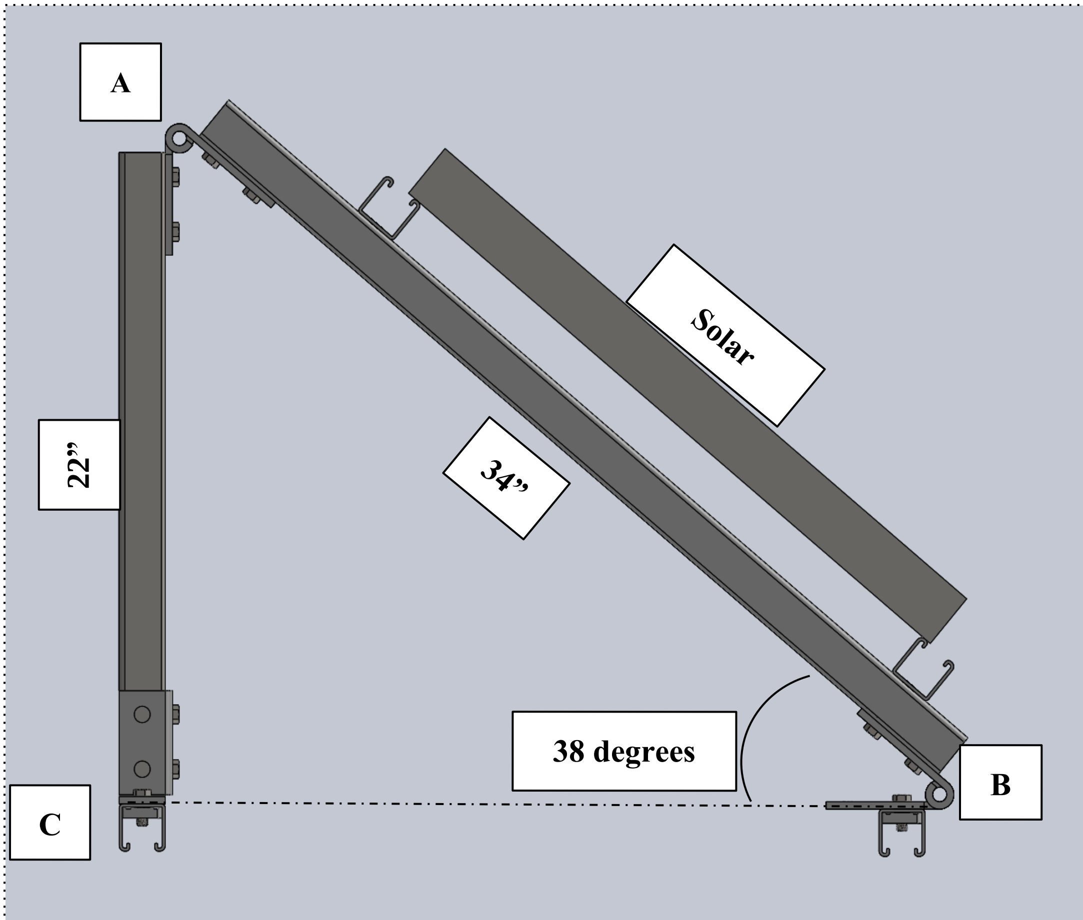


Figure 38. Side support of solar panel chassis

The diagonal hypotenuse strut was calculated to be 34-in to ensure that the 24-in-long panels would be able to fit onto the beam. The team also needed to account for the 2-in width of each beam that would be placed on top and bottom of these smaller triangle frames. The last 6 in was additional room to be able to reposition the specific locations of the solar panels as needed. The vertical support was cut longer than the 21-in to account for errors in measurement while cutting, so they were each 22-in long.

Besides the angle bracket attached at A to connect the hypotenuse strut to the vertical support, another angle bracket was used to connect the hypotenuse strut to the diagonal strut already attached. On the other end, a wing shape fitting was used to attach the vertical support to the other diagonal strut at point C.

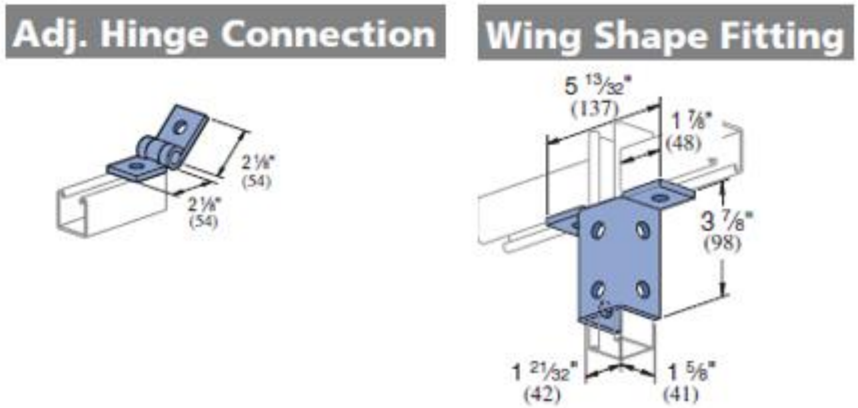


Figure 39. Unistrut connections
(Source: www.strutandsupply.com/index.php/download_file/view/255/, reproduced without permission)

Figure 40. Completion of step 3, attaching the triangular frames

The fourth step is to attach two struts on both the top and the bottom of the hypotenuse strut which will hold the solar panels. This is an important step because the solar panels do not have a built-in frame.

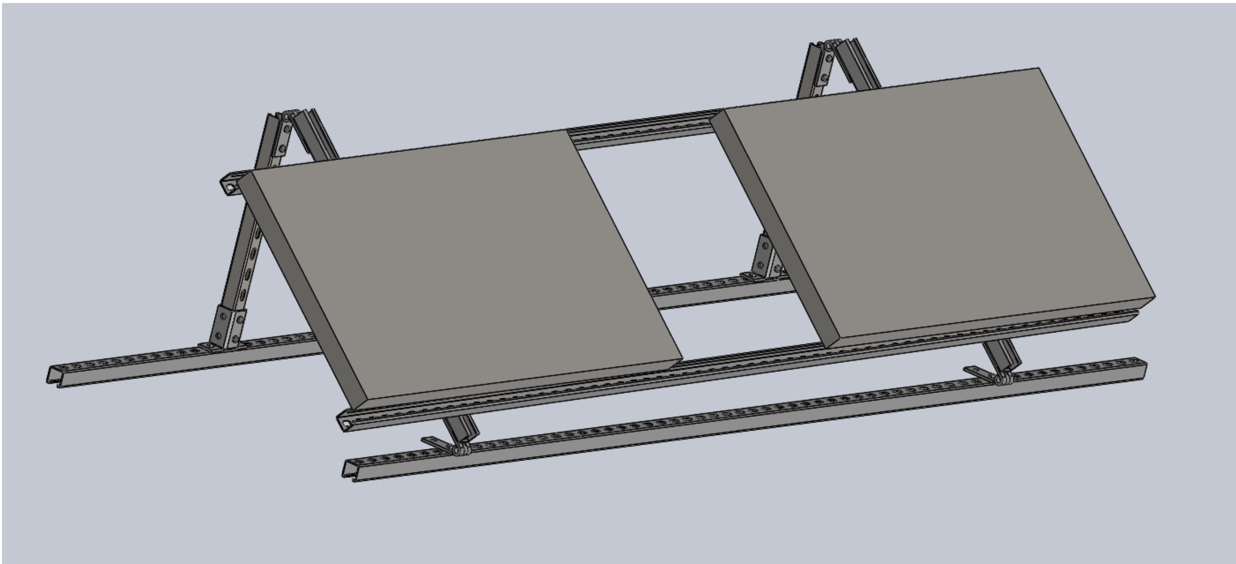


Figure 41. Solar panel flat roof mounting system

Instead, adapting this set-up, the team horizontally attached two struts at the top and bottom of the hypotenuse strut to create the frame from which the solar panels could be mounted.

Finally, the mounting of the solar panels used thin film solar clamps as pictured below:

Figure 42. Sunpreme thin film solar panel end clamp (Source: https://www.solarpartscomponents.com/frameless-pv-module-mid-end-clamps-installation, reproduced without permission)

The solar panel would fit into the mouth of the clamp, while the screw could enter through the back and into one of the holes within the strut. Each of the solar panels had four clamps at each of the corners.

Figure 43. Mounted solar panels with the end clamps

Rather than place each of the solar panels directly next to each other, a 2-ft gap was created such that anyone working on the system had easy access to all the panels. The team considered cutting the struts in the middle, such that someone accessing the farthest panels would not have to step over these 2-ft tall struts; however, they decided against it due to lack of structural support.

A final side view and back view of the system can be seen below:

Figure 44. Side view of completed solar panel system

Figure 45. Back view of solar panel system

9.6.1 Solar Panel Chassis Analysis

The system analyzed in this section of the report is the solar panel chassis. Each chassis is designed to hold two 26.4-lb solar panels that measure 2-ft by 4-ft. The chassis is pictured in Figure 45 above and is composed of two side supports, which are constructed out of P1000 Unistrut. In order to accurately simulate the loads on the chassis, the force from the weight of the solar panel was split into its x and y components. Additionally, since the four chassis are on top of a shipping container, wind is a factor. For the worst-case scenario, the team assumed a maximum wind speed of 100 miles per hour, which corresponds to 0.1778 psi or 204.8-lbs on each solar panel [36]. The force from the wind was also split into its x and y components. These component forces were then applied to the vertical Unistrut pieces that lift the panels to the desired angle. Using the worst-case scenario, when the wind is 100 mph, in the SolidWorks simulation and hand calculations is essential to ensuring that the design is safe under all conditions. Lastly, each chassis has two side supports and holds two solar panels. For this analysis, only one side support is analyzed, and it is assumed that each side support can withstand the forces due to one panel.

To aid in the hand calculations and finite element analysis, a free body diagram was made. Figure 45 below shows this free body diagram, which is of a side view of the solar panel chassis and shows the two loads due to the weight of the panel and the wind.

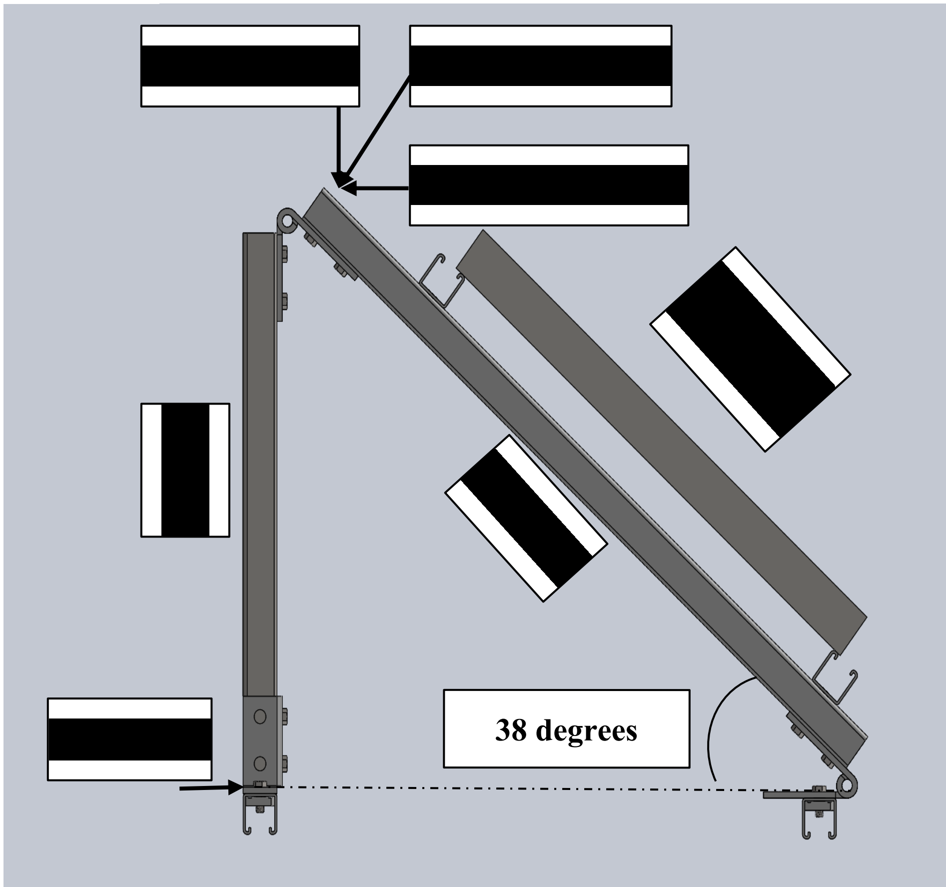


Figure 46. Free body diagram of solar panel chassis

The sum of the two forces are 231-lbs, which can be divided into their x and y components of 182-lbs and 142-lbs respectively using trigonometry. It is assumed that these forces act on the top of the vertical support, which is 22-in long. Additionally, Point A is the most critical point.

For the finite element analysis and hand calculations, it was assumed that the Unistrut and bolts were made from steel. The yield strength of the Unistrut is 42000 psi, and the yield strength of the bolt is assumed to be 36550 psi [37]. Additionally, the moment of inertia of the P1000 Unistrut is 0.185 in^4 and the cross-sectional area is 0.555 in^2 [38]. A cross-sectional view of the Unistrut is demonstrated below.

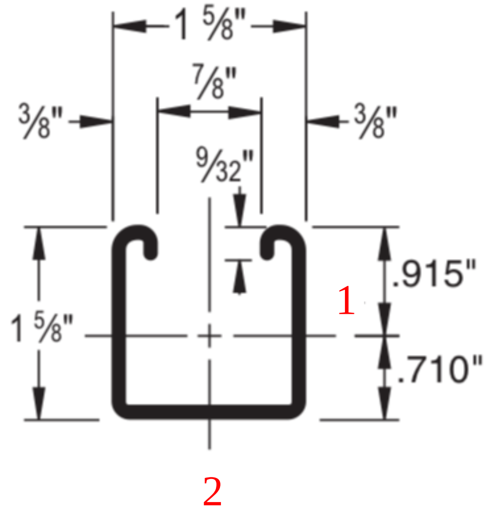


Figure 47. Cross-sectional view of P1000 Unistrut (Source: https://www.unistrutohio.com/wp-content/uploads/unistrut-general-engineering-catalog-17A.pdf, reproduced without permission)

As one can see from Figure 46, the distance from the neutral axis to the closed side of the Unistrut is 0.710 in. This is an important dimension for the stress analysis when the Unistrut is in bending around axis 1, in red in the image above. This value will be used in the calculation below in Equation 13.

For the chassis, the model's expected critical point is the base of the vertical support, as that point carries most of the force from the solar panel and from the wind. The expected mode of failure would be possible bending stress or deflection from the load applied at the top of the vertical support. Additionally, column buckling was another suspected mode of failure due to the applied load at the top of the vertical supports. Even though these two expected modes of failure exist, it was not predicted that the vertical support would fail under the applied loads. All of the components on the chassis are made of sturdy and rigid materials with robust dimensions that prevent buckling and large deflection.

Other potential modes of failure are from shear stress in the bolts. However, the chassis was designed so that it is strong enough to hold the solar panel, and as a result, the system will withstand the predicted worst-case loading.

9.6.2 Combined Loading

It is assumed that the critical point, where the maximum stress occurs, is at point A based on Figure 45. At that point, the vertical force of 182.8-lbs creates a compression stress, the horizontal force of 142.3-lbs creates a compression stress due to bending.

In order to determine the stress due to both these forces, the following equations were considered. To calculate the stress due to the vertical force Equation 12 was used.

$$\sigma_y = \frac{F_y}{A} \qquad (12)$$

In Equation 12, $\sigma_y$is the compression stress, F_y is the vertical force of 182.8-lbs, and A is the cross-sectional area of the Unistrut of 0.555-lbs. Additionally, Equation 13 is used to calculate the stress from the horizontal force.

$$\sigma_y = \frac{F_x l y}{I} \qquad (13)$$

In Equation 13, σ_y is the compression stress, F_x is the 142.3-lbs horizontal force, l is the length of the support of 22-in, y is the distance from the neutral axis to the edge of the strut, and I is the moment of inertia.

Since these two stresses at point A are both compression stresses, they can be summed together, and this is the maximum stress that the Unistrut experiences. The vertical support experiences compression stresses of 256.5 psi and 13,753.2 psi from the vertical and horizontal loads respectively. Overall, at point A, the stress is 14,009.7 psi, which corresponds to a factor of safety of about 3, since the maximum yield strength of the Unistrut is 42,000 psi. The vertical support is not expected to fail. This calculation assumes that the slots in the Unistrut are negligible. The full hand calculation can be seen in Appendix L.

In addition to completing a simplified calculation for the combined loading on the vertical support, finite element analysis on the support was carried out. For the analysis, it was assumed that the base of the support was fixed. Additionally, two loads were applied to represent the vertical and horizontal loads. The results of the analysis are shown in Figure 48 below.

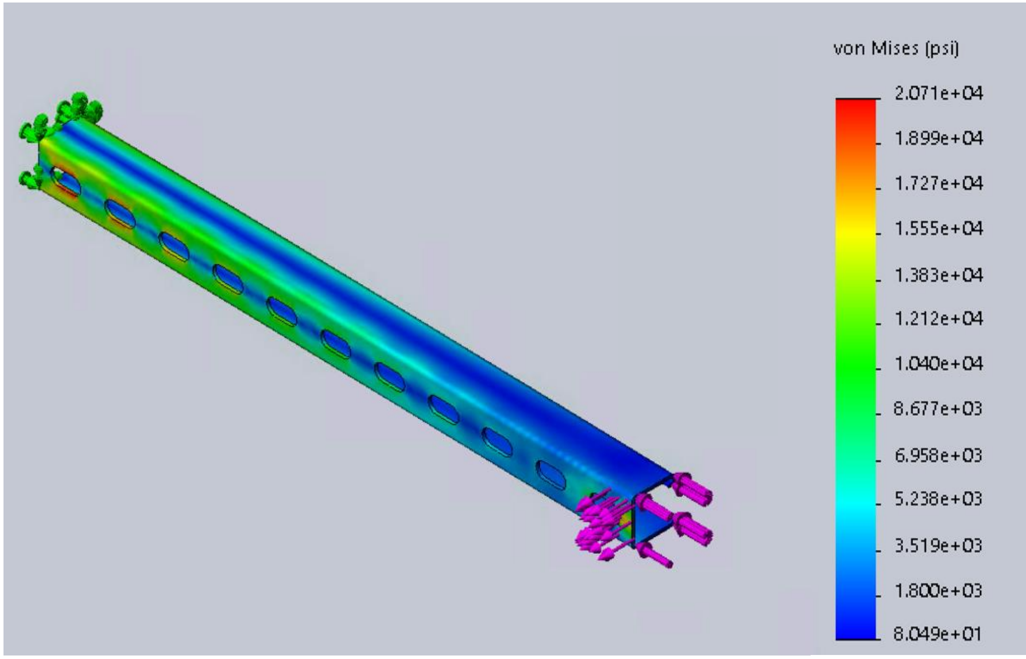


Figure 48. Finite element analysis of vertical support in combined loading

One can see that the maximum stress that the vertical support experiences is around 20,700 psi. This stress corresponds to a factor of safety of over 2. As a result, it can be concluded that this support is safe. Both the simplified calculation and finite element analysis come to the same conclusion that this piece is safe.

9.6.3 Shearing

Lastly, to ensure the safety of the bolt under the applied loading conditions, a calculation and finite element analysis were performed to predict the outcome of shearing on the bolt. This calculation estimates the needed load, P_{max}, to shear the bolt using Equation 14 below

$$P_{max} = \frac{3\tau A}{4} \qquad (14)$$

In Equation 14, τ is the shear stress in psi, and P_{max} is the load needed for the bolt to fail in shear in pounds, and A is the tensile area of the bolt. τ is the shear stress, which is equal to the yield strength of the bolts divided by the square root of 3, which is 21,101.2 psi. The bolts are ⅜-in, so they have a cross sectional area of 0.44 in^2. With this information, P_{max} is calculated to be 1,748-lbs. This maximum allowed load of 1,748 is much greater than expected maximum vertical load of 182.2-lbs, so the bolt is safe. The original hand calculation can be seen in Appendix L.

Besides completing a simplified calculation on the bolt, finite element analysis in SolidWorks was also completed to ensure that the bolt is safe. For the analysis, the threaded part of the bolt was fixed and a 182.2-lbs force was applied. The results of this analysis can be seen in Figure 48 below.

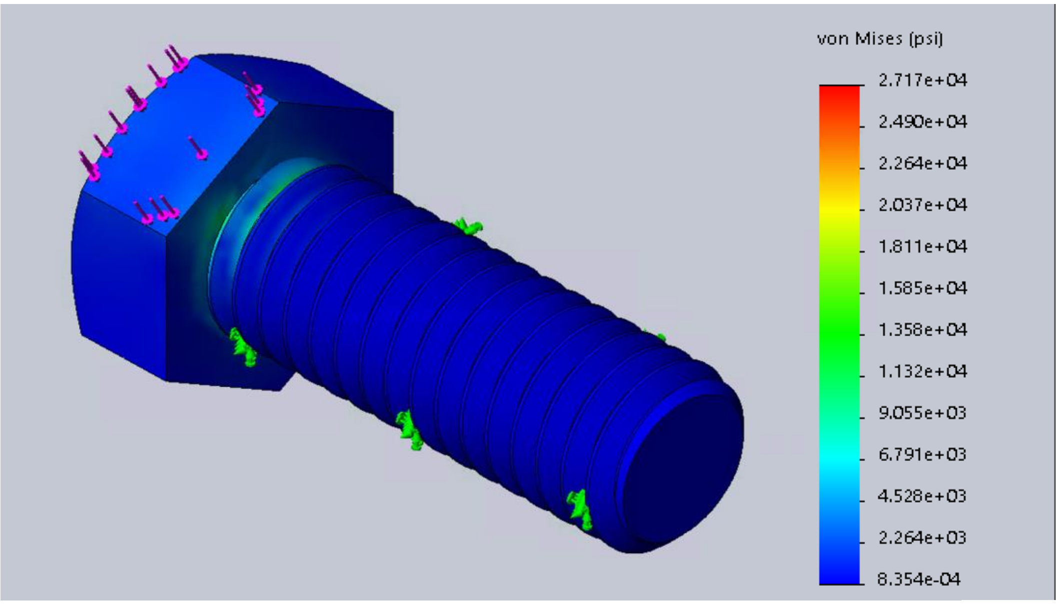


Figure 49. Finite element analysis of bolt

As Figure 48 shows, the maximum von Mises stress on the bolt is around 16,000 psi. This stress is significantly less than the maximum yield stress of the bolt of 36,550 psi, so the bolt will not fail. Overall, both the calculation and analysis show that the bolt is not expected to fail under these loading conditions, so the bolt is safe.

9.7 Wiring the System

In order to connect the different components, different size wires are necessary to meet the standards of the NEC:

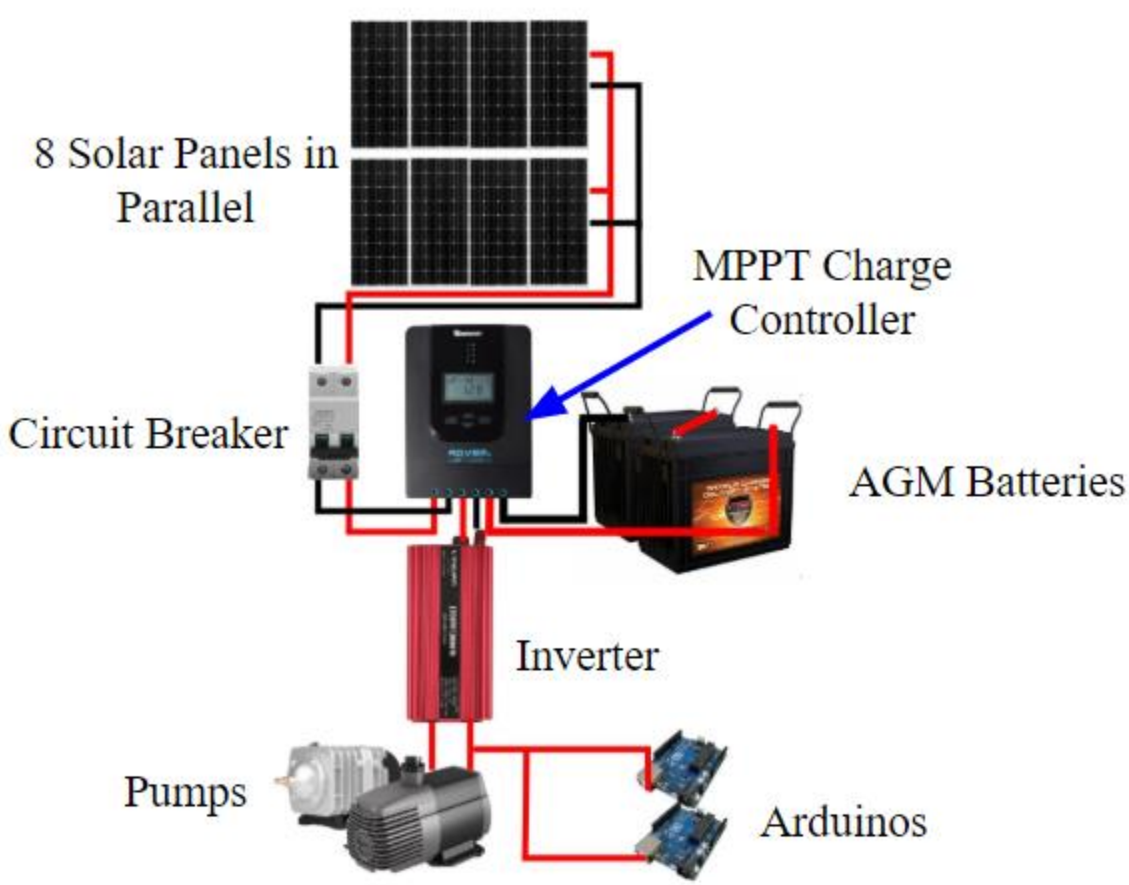


Figure 50. A visual schematic of how the components will be wired in the power system

The PV array, DC circuit breaker, charge controller, and battery are all located on top or mounted to the side of the shipping container, so a short length of wire is needed to connect these parts and power loss due to wire resistance is neglected. The connections between the PV array and the charge controller have current ratings at 13.3 A, so 14 AWG wire with a rating of 20 A was used. The connection between the charge controller and the battery has a current of 31-35 A, so 8 AWG wire with a rating of 40 A was used.

On the other hand, the inverter is located 100-ft away from the shipping container, so underground wire running beneath the farm connects it to the charge controller. However, due to the long distance that the current will travel, it is important to reduce resistance along the line by using higher gauge wire even though the connection between the charge controller and the inverter has a low current rating of 5A. Data from the NEC and the Handbook of Electronic Tables and Formulas for American Wire Gauge for determining the ideal wire gauge size, and the following equation for power loss, were used:

$$P = I^2 * R \tag{15}$$

P represents the power lost, I represents the current, and R represents resistance

Table 20. Wire size in relation to power loss and cost

Wire Size (AWG)	**Maximum Current***	**Resistance per 1000 ft (Ω)**	**Resistance for 100 ft (Ω)**	**Power Loss (W)**	**UF-B Wire Cost** [39]
14	20	2.525	.2525	6.3125	$27
12	25	1.588	.1588	3.97	$43
10	30	0.999	.0999	2.4975	$78
8	40	0.628	.0628	1.57	$105

*The maximum current each wire gauge can handle uses the metrics for power transmission rather than chassis wiring.

It appears that there is not a drastic difference in power loss between the different wire sizes since the distance is not that long; however, because the price of the wires differs much more drastically, the 12 AWG wire was decidedly the best candidate.

Since the wire will be buried 12-in deep, underground feeder cable (UF-B) was used. To prevent the use of expensive conduit, the wire has GFCI protection and the voltage never exceeds 120 V and 20 A [40].

Other design considerations include the bundling of wires and the use of solid copper wire rather than stranded wire which is more durable in the long run. The battery and charge controller are both placed underneath the first set of solar panels, which helps prevent overheating. The circuit breaker is attached to a wooden post for easy shut-off access as well. Lastly, a steel rod was buried underground to create a physical ground for the long wire that connects the inverter to the battery and for the solar panel chassis to prevent shocks stored on the metal.

9.8 Power Contingency Plan

Given that the solar panels and battery may not be able to support the system continuously, especially during the winter months when there may not be enough sunlight or after multiple continuous days with rain, it is important to have a contingency plan in place for how the system will operate. The first step is to turn the switch off on the inverter. Although the system should not be turned on and off constantly because this may damage the impeller inside of the water pump, in these extenuating circumstances, it is more important to prevent the battery from completely draining and decreasing its cycle life.

Afterwards, a specific set of corresponding actions and next steps is outlined in Table 21 below depending on how long the system has been turned off. Although it is true that the system can be turned off for different periods of time, to prevent algae growth, stop ammonia buildup, and ensure healthy living conditions for the plants and the fish, the water should not remain stagnant.

Table 21. Actions to take if the system receives no power

Time	**Corresponding Action**
1 hour	Although there is no backup energy source for the pumps, the Arduinos can also be powered by a 9 V battery instead of the 5 V USB port. However, if both power sources are connected, the Arduino will draw power from the 9 V battery first. Therefore, it should only be plugged in when one anticipates rain or low sunlight
12 hours	Monitor water conditions and determine if there appears to be any disturbances that may be negatively affecting the fish and plants (i.e. temperature increase, pH decrease, etc.) It may be necessary to move the water using the pond skimmer in the fishpond or add additional fertilizers or nutrients.
24 hours	Continue to monitor the water conditions. It may be necessary to use a battery-operated air pump to ensure that there is enough DO
48 hours	After this amount of time, it may be necessary to externally charge the batteries. The first option is to bring the batteries to one’s house and charge them with a wall socket. However, since each battery weighs 70-lbs, this is not the ideal solution. Instead, the diesel generator may be used to supply power to the battery to enable the pump to work.

In the team’s testing, they noticed that over time, with no pumps powered, the water will start to turn green as algae begin to grow and the pH rises. To counteract these shifts, one should use Barley Root Extract and mix it in with the system to prevent further algae growth.

However, the likelihood of this event occurring depends on the amount of rain that the farm receives, and despite the theoretical calculations of the power output, in practice, it appears that even in winter, there should be enough sunlight to power the system continuously.

10. Sensor System

To measure different conditions in the water and ensure that values have not exceeded thresholds, every six minutes, four sets of sensors turn on to monitor the water quality. The sensors stay on for two minutes and take measurements. They then turn off for four minutes, before turning on again and repeat the cycle.

These sensors measure temperature, electrical conductivity (EC), pH, and DO. Arduinos collect the measured data, which is then uploaded onto the web. This simple IoT-system enables the client to monitor the system at any time from any location.

Although initially water level sensors were also to be incorporated, attaching them to the underground fishpond required puncturing the pond liner, increasing the likelihood of leaks. A similar issue arose when considering the option of attaching the water level sensors to the grow beds. In the end, the team decided to exclude water level sensors from the initial system prototype.

10.1 Sensors

Except for the DO sensor, there are two of each sensor, to help take multiple data points and ensure they function correctly. Unfortunately, the EC sensor and the pH sensor cannot be operating simultaneously in the same body of water due to electromagnetic interference. To prevent interference and reduce the need for timing and communication between the two Arduinos, the EC sensors are in the grow beds, while the pH sensors will be in the grow beds. The location and specific types of sensors are illustrated in Figure 51 below:

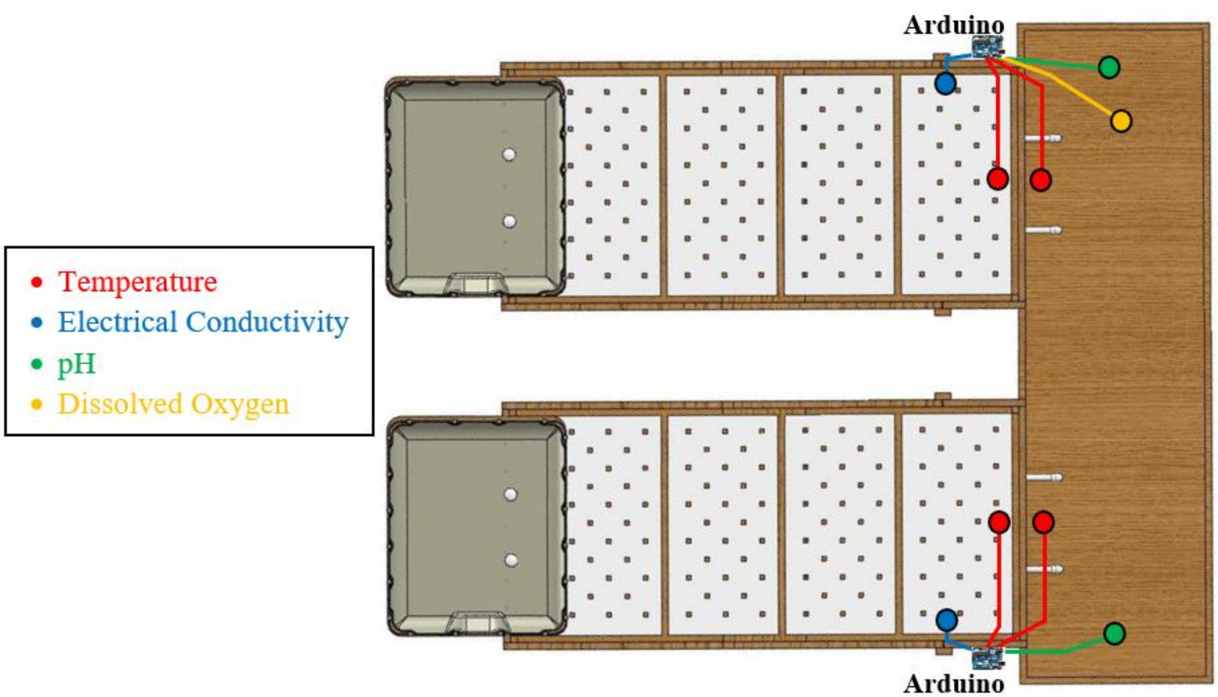


Figure 51. Location of all the sensor placements

All the sensors are fully submersible for extended periods of time apart from the EC sensors that are fixed to a specific location in the raft grow bed where the water will rise and fall above and below the probe to preserve its longevity.

Each of the sensors will be connected to one of the two Arduinos through a BNC connector to a type-specific circuit board. Both Arduinos and all the circuit boards are organized in a waterproof box with holes cut out for the sensors to measure the different parameters, as demonstrated in Figure 51 below.

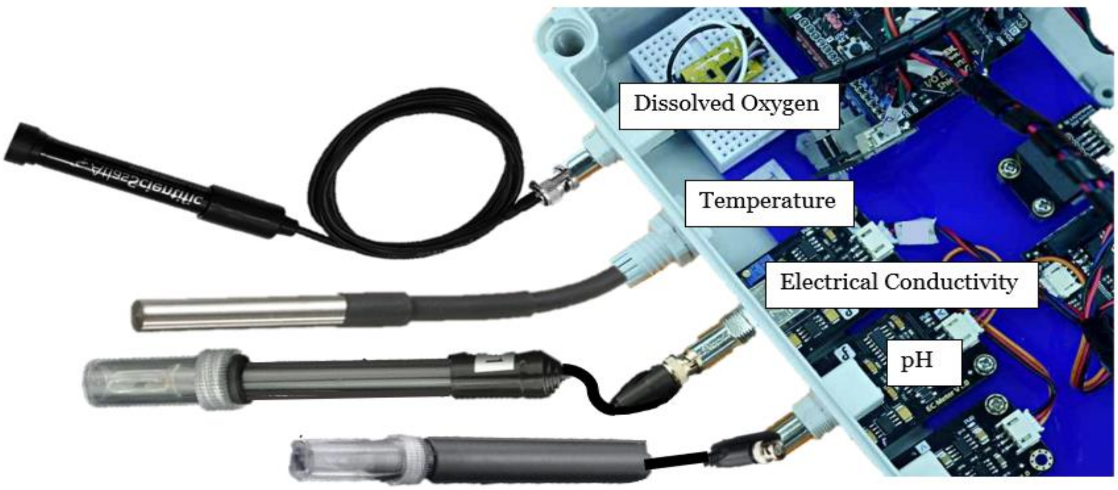


Figure 52. Visual representation of how the sensors will be connected to the Arduinos in the waterproof box

10.2 Power Criteria

To save power, each of the sensors will only turn on for two minutes every six minutes. Each hour, each sensor will record 10 measurements to provide the user with feedback from the two raft grow beds and the fish pond. Power will also be minimized on the Arduinos themselves, which will enter a SLEEP mode when not in use. Both these methods help to reduce the power consumed in the long run:

Table 22. Power calculation of total energy consumed by Arduinos and sensors

Load	Voltage (V)	Current (mA)	Power (W)	Time (hours)	Quantity	Energy (Wh)
EC sensor (ON)*	5	~10	0.05	8	2	0.8
EC sensor (OFF)*	5	~0.5	0.0025	16	2	0.08
pH sensor (ON)*	5	~10	0.05	8	2	0.8
pH sensor (OFF)*	5	~0.5	0.0025	16	2	0.08
Temp sensor (ON)	5	1	0.005	8	5	0.2
Temp sensor (OFF)	5	0.05	0.00025	16	5	0.02
DO sensor (ON)	5	13.5	0.0675	8	1	0.54
DO sensor (OFF)	5	0.66	0.0033	16	1	0.0528
Arduino (ON)	5	35	0.175	8	2	2.8
Arduino (OFF)	5	5	0.025	16	2	0.8

Since the measurement system requires continuous power, as mentioned in Table 21, a 9 V battery will be connected to the Arduinos in the rare case when the main solar system shuts off or when the battery is completely drained. This will allow the system to continue to function normally.

10.3 Communication

In many IoT-applications, Wi-Fi is the optimal solution, since data can be transferred at denser and faster rates at relatively lower costs of transmission. However, since the farm does not have Wi-Fi, communicating the collected data to the web requires additional hardware. Four different solutions were investigated: Ethernet Cable, Bluetooth, Zigbee, and LoRa.

Ethernet cables are a good replacement for Wi-Fi because they transfer and deliver data at faster rates than Wi-Fi. They also have good signal quality because there is less signal interference and ensure a secure connection. However, this is impractical given that the distance between the farm and the nearest port is greater than 500-ft, which could lead to data distortion and possible breaks in the system

Bluetooth is a personal area network for short-range wireless communication, especially for device-to-device file transfers. It employs either a star network or hub-and-spoke model, in which every host is connected to a central hub, or a mesh model, in which data can be transmitted between different nodes that work together to efficiently route data. However, while Bluetooth has lower power consumption; it also lacks sufficient range to store collected data onto a memory drive. Using another phone as a wireless hotspot could remedy the situation, but it would be much more expensive to pay for monthly fees to transmit the data. As such, the Bluetooth solution was unacceptable for the project's scope.

Zigbee is a mesh local area network protocol that, like Bluetooth, also operates across a short-range and has low power consumption. Originally designed for building automation and control, its mesh network enables data to be transmitted through a network of nodes until it reaches the gateway. Certain downsides of this technology are the possibility of high latency if multiple signals are vying to enter the gateway.

LoRa is not only a more long-range solution, but it also consumes low power at a low cost due to the frequency shift keying modulation technique. It has a high network capacity with one gateway having the capability to accommodate 1000 end-node devices [41].

Table 23 shows a decision matrix comparing the viability of the possible solutions:

Table 23. Comparison of methods to transfer data [42]

Factor	**Ethernet Cable**	**Bluetooth**	**Zigbee**	**LoRa**
Cost	x	✓	✓	✓
Ease of installation	x	x	✓	✓
Ease of user data access	✓	x	✓	✓
Low power consumption	x	✓	✓	✓
Range	100 m	77 m	291 m	5000 m
Interoperability/ low latency	✓	x	x	✓
Longevity	5 - 10 years	n/a	3 - 5 years	7.5 - 9 years

Based on recommendations of different technologies, LoRa is the most versatile for use in the system. Due to its low power consumption, the wattage of using LoRa was not included in the calculations in Table 22. However, the small difference should not adversely affect the system.

Figure 53. Aerial view of how the communication system operates

To be able to transfer the data from the sensors and the Arduinos, two Dragino LoRa shields (one of which is pictured above on the right) will be mounted on top of the Arduinos and read in the signals from the sensors. These configurations are referred to as nodes.

Based on the Arduino code, once the information is read from the sensor, it will be transmitted through its antenna and sent to the LoRa LG01 gateway (shown above on the left) which is in the Goodwill facility. This gateway is an open source single channel that serves as the bridge between the two nodes that are sending the signal and constitute the LoRa wireless network and the IP network base, which in this case, is the WiFi. The gateway will then upload information onto the Cloud Server, and although this application only requires one-way communication, in the future, the bidirectional communication scheme allows for a control network to be implemented.

For more information on connecting the LoRa shields with the gateway, please refer to Appendix M. Additionally, the code for the LoRa and sensors is shown in Appendix N.

10.4 User-Interface

The user-interface is an existing online website called ThingSpeak, which is an IoT platform that collects, stores, and graphs data. The Lora shields mounted onto the Arduinos will serve as the IoT device to push data onto the platform. Since ThingSpeak was developed by MathWorks, who also created MATLAB.

Since the team is not sending over 8,200 messages each day, a free account was created for use in this small non-commercial project. The team created a channel to visually assess the four different variables currently being tested. The screenshot below showcases sensor data collected over the course of 3 hours.

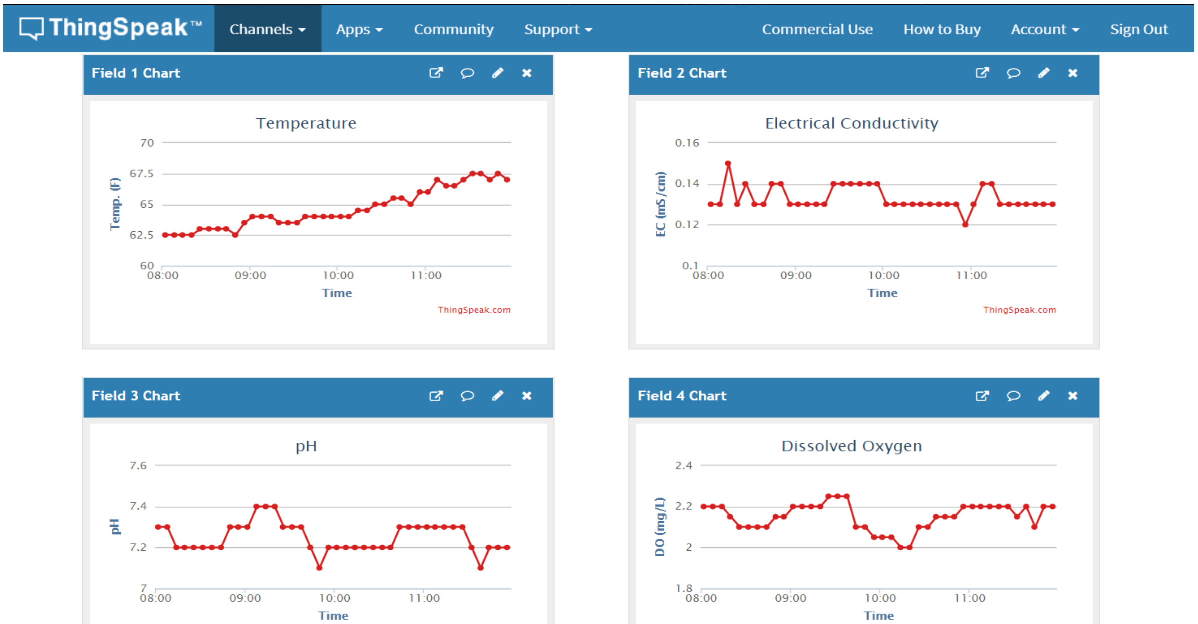


Figure 54. ThingSpeak interface from preliminary data gathered over time

ThingSpeak supports two different types of APIs: RESTFul and MQTT. While MQTT is a machine-to-machine/"IoT" connectivity protocol that is best suited for remote locations where a small code footprint and a small bandwidth are necessary, the team faced issues within the code. Therefore, the team chose a RESTFul API, which was much simpler to implement.

11. Results

There are many product design specifications that were determined from research into aquaponics systems as well as user expectations. These specifications are summarized in Table 6 above. Several tests were completed to determine if the system meets the various specifications. The tests include testing flow rates of various parts of the system and testing the water quality. The results of the tests are summarized in Table 24 below. The experimental protocol for each test completed and more detailed results can be seen in Appendix O.

Table 24. Summary of the requirements and equipment for each potential experiment

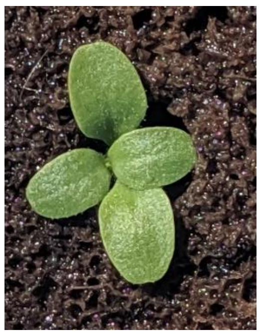
Elements/ Requirements	**Ideal Value**	**Week 1**	**Week 2**	**Week 3**
Volume flow rate of pump	650 gph	178 gph	220 gph	215 gph
Flow rate of bell siphon	0.7 m/s	1.67 m/s	1.70 m/s	1.60 m/s
Flood and drain cycle	15 min	20.82 min	17.54 min	18.22 min
Water temperature	80 °F	60 °F	62 °F	64 °F
pH	7.5	9.5	8.5	9.3
Dissolved oxygen	> 3 mg/L	11.2 mg/L	12 mg/L	10 mg/L
Ammonia	< 2 mg/L	0 mg/L	0 mg/L	0 mg/L
Nitrate	100 mg/L	2 mg/L	2 mg/L	2 mg/L

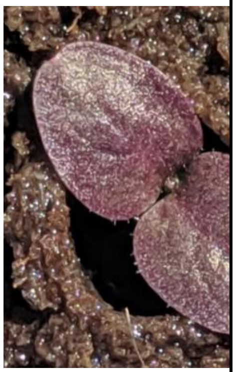
As seen in Table 24, the volume flow rate of the pump is lower than the ideal flow rate of 650 gph. This lower flow rate is necessary so that the water level in the media beds can flood and drain. When the flow rate is above 250 gallons per hour, the water draining from the bell siphons is at a slower rate than the water entering from the pump. This prevents the bell siphons from stopping and does not allow for the water level to flood and drain. The flow rate from the bell siphons is about 1.7 m/s which is also higher than the ideal value of 0.7 m/s. This flow rate cannot be adjusted and will suffice since the water disperse through the raft grow beds and slows quickly to a safer velocity. Additionally, the timing of the flood and drain cycle is approximately 17 minutes. This timing is a good value because it allows the flood and drain cycle to occur multiple times per hour, allowing the plant roots and nitrogen fixing to have oxygen several times per hour.

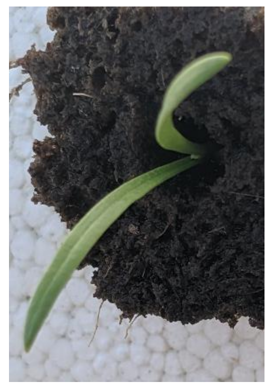
In addition to testing the flow rates and timing of the system, the team also tested the water quality. For temperature, pH, and DO, the test results are in a safe range. However, for ammonia nitrate and nitrogen nitrate, the values are very low. These low values are because the nitrogen fixing bacteria has not had time to start and because the fish are still small and do not produce a lot of waste. These values, as well as the water temperature, are expected to increase and stabilize at a specific equilibrium as the system keeps running and nitrogen-fixing bacteria begin to grow in the media beds. This is normal and expected for aquaponics systems. However, the specifications regarding flow rate and the flood and drain cycle should remain steady over time. The speeds and timing differed due to small changes on the water pump. Finally, the DO content should also remain the same, but the pH should be decreasing as the system stabilizes. Unfortunately, the team ran into a few issues using the EC sensors, so data for the first three weeks was not recorded.

In addition to the tests discussed above. The team is also testing plant and fish growth, which are longer term tests. The team planted a variety of different types of leafy greens as well as tomatoes and are monitoring their growth. Unfortunately, there is no baseline data with which to compare the recorded data; however, the sample data below provides an introductory study for future comparisons. The table below summarizes the growth of various types of lettuces each week based on the height of the plants.

Table 25. Growth of green leafy vegetables in system

Type of Plant	**Percent sprouted after one week**	**Photo after week 1**	**Percent with mature growth after 2 weeks***	**Photo after week 2**	**Percent with mature growth after three weeks***
Iceberg lettuce	100%		71%		74%
Romaine lettuce	65%		74%		65%

Type of Plant	Percent sprouted after one week	Photo after week 1	Percent with mature growth after two weeks*	Photo after week 2	Percent with mature growth after three weeks*
Butter lettuce	94%		16%		44%
Prize lettuce	68%		59%		74%
Red lettuce	88%		66%		63%
Kale	91%		91%		100%

Type of Plant	Percent sprouted after one week	Photo after week 1	Percent with mature growth after two weeks*	Photo after week 2	Percent with mature growth after three weeks*
Bibb lettuce	82%		21%		36%
Spinach	27%		27%		23%

* Mature growth refers to plants that have grown out of the whole

Table 26. Average root length of various types of vegetables each week

Type of Plant	Week 1	Week 2	Week 3
Kale	1.3 in.	2.3 in.	4.7 in.
Spinach	2.2 in.	5.1 in.	12 in.
Iceberg lettuce	0.9 in.	2.1 in.	3.1 in.
Buttercrunch lettuce	1.2 in.	2.5 in.	2.9 in.
Bibb lettuce	0.5 in.	1.6 in.	2.5 in.
Red oakleaf lettuce	0.8 in.	1.8 in.	2.3 in.
Prizehead lettuce	1.1 in.	2.5 in.	3.2 in.
Romaine lettuce	1.0 in.	2.1 in.	2.6 in.

Table 27. Growth rate of the initial Buttercrunch lettuce (N = 53)

Week	Average Root Length	Image
1	1.2 in.	
2	2.2 in.	
3	2.9 in.	
4	3.5 in.	
5	4.1 in	

The team decided not to measure the length of the fish because that would unnecessarily stress the fish, which is not good for their health.

In section 2.4, engineering standards and constraints that the team wanted to meet were discussed. The first standard is USDA organic standards which requires that the fish, fish food, seeds, media and other additives must all be organic [19]. This standard is important because the Loaves and Fishes' Garden grows food under these standards. Unfortunately, the fish food and the barley root extract used to prevent algae growth are not certified as USDA organic [43]. Moving forward, it is advised that the fish are fed organic vegetable scraps when they are fully grown. The barley root extract was used to prevent algae growth, which grows rapidly in stagnant water. To avoid algae from growing in the system the pump should be running as often as possible, therefore obviating the need for the barley extract.

Second, the aquaponics system needs to be considered Certified Naturally Grown. To meet this requirement the system must be designed to allow methane, carbon dioxide, and nitrogen gas to be released [20] . This may occur in a separate degassing tank, through vigorous aeration, or in the process of flowing through the system, if properly designed. This system is vigorously aerated to allow for proper degassing. While the system does allow for degassing, the inputs into the system do not meet CNG standards. For example, the seeds and food used are not CNG.

The third standard is laminar water flow. Since the team used 1-in diameter PVC pipe and the pump cycles 220 gph, the water flow is expected to be turbulent. The Reynold's number of the flow is calculated using Equation 16.

$$Re = \frac{\rho V d}{\mu} \qquad (16)$$

In Equation 16, ρ is the density of the water, V is the velocity of the water, d is the diameter of the pipe, and $\mu$is the dynamic viscosity of the water. $\rho$is assumed to be 62.4 lb/ft^3, d is 1-in, and μ is assumed to be 2.034*10^{-5} lb*s/ft^2 [44, 45]. The velocity of the water is calculated by dividing the volume flow rate in cubic ft per second by the area of a 1-in pipe, which is 1.497 feet per second. With these values the Reynold's number is calculated to be well over 2300, which is the maximum Reynold's number for laminar flows in pipes. However, in the grow beds and the pond, the flow is laminar. A laminar flow in these subsystems is important to ensure that the plant roots are not stripped of their nutrients.

Fourth, the materials used in the system need to follow National Sanitation Foundation guidelines to ensure they are not leaching chemicals into the water and into the produce [21]. The IBC is made of an FDA approved UV Stabilized Plastic that many people use to store wine and other sorts of food. Therefore, it is made of a resin that is NSF 61 approved [46]. In addition, the PVC pipes and fittings are also NSF-rated as well as the pond liners, which is made of a 30 mil fish grade PVC, proven to exceed standards [47].

Finally, the system wiring complies to the NFPA 70 Code, more commonly known as NEC to prevent the chance of fire [22]. This was carried out by ensuring that the wires were sized to carry greater amounts of current as specified in Table 20. During installation, the team followed the safety plan outlined in Appendix K. The chassis and the wire going to the inverter were physically grounded as well.

12. Sustainability

12.1 Environmental Impact

Many non-organic farming methods have a large impact on streams and waterways due to the nutrient runoff that is leading to eutrophication--excessive richness of nutrients in aquatic environments--which leads to a large influx of plant life but kills many of the existing animal and marine life who are deprived of oxygen in the water [48]. Even many organic types of farming can still lead to nutrient runoff as well. On the other hand, an organic aquaponics system creates less impact to the surrounding ecosystem, since all the water is contained, and the nutrients are cycled throughout the system.

These local systems, though scalable, are much better suited for dense urban environments, mitigating the large carbon footprint from traditional farms. With the industrial kitchen from Loaves and Fishes in the adjacent building to the farm, there will no greenhouse gases (GHG) emitted through transportation, unlike more traditional approaches that require fuel for tractors, production wastes (organic waste from the garden will be composted), and shipping emissions. Additionally, aquaponics significantly reduces the amount of water needed to cultivate the plants, and in a place like California, where drought and water insecurity is commonplace, decreased water usage is not only affordable, but also sustainable.

12.2 CO_2 Emissions

The use of solar power for the system drastically reduces the carbon footprint. According to PG&E, 0.435-lbs of CO_2 is generated for every kWh of electricity consumed [49], which indicates that every day, had the system been connected to the grid, the equivalent CO_2 emissions generated would be 1.4416-lbs of CO_2. A comparison of emissions with manufacturing of the solar panels and battery are shown in Figure 55.

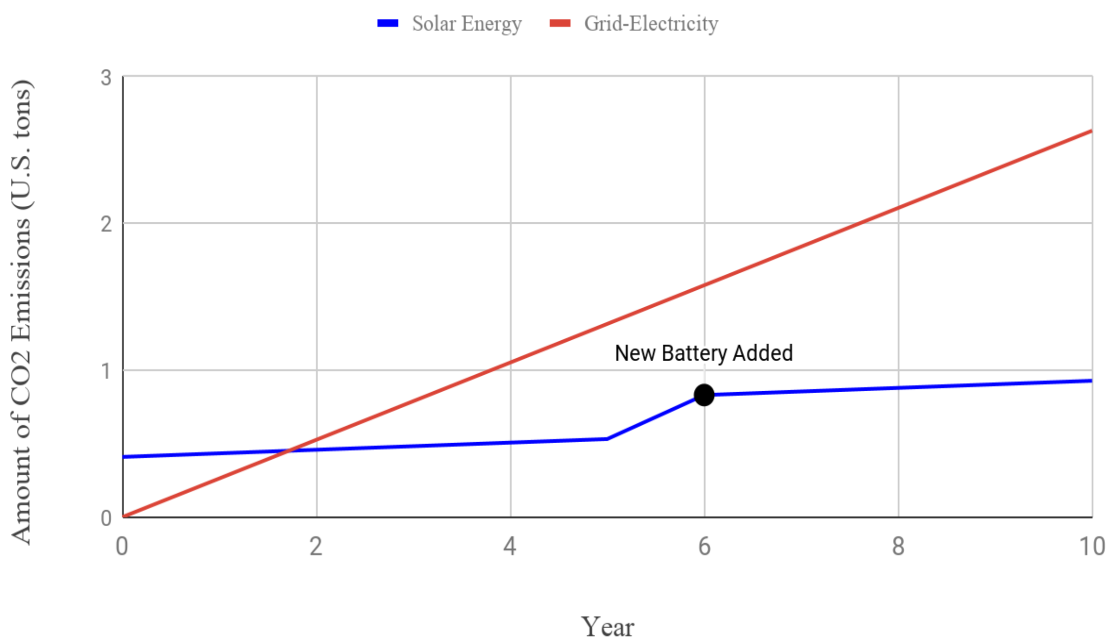


Figure 55. Comparison of CO_2 emissions reduced between solar and grid electricity

First Solar indicates that 0.0265-lbs of CO_2 is generated for every kWh of electricity produced from the panels, which is mainly due to the emissions released during production of these solar panels. Additionally, the production and use of a sealed AGM lead-acid battery generates about 2.26-lbs for every kWh of electricity with an initial 550.4-lbs of CO_2 generated during production [50]. In a given year, assuming that the solar panels and batteries are ensuring sufficient amount to supply the load and operating at maximal efficiency, Figure 55 above demonstrates that even after 2 years of operation, CO_2 emissions from the solar panels will be the same as that generated by the grid. Over 10 years, the amount of CO_2 equivalent emissions will be approximately three times with solar energy.

12.3 Materials

When discussing the sustainability of a project, it is important to examine the building materials used. In this case, the battery, wood, and plastic are the largest concerns. Due to the budget constraint and sizing of the battery, a lead-acid battery was chosen. Compared to a lithium-ion battery, lead-acid batteries require more raw materials during the mining process and have a more energy-intensive processing industry. However, the prevalence of lead-acid batteries has led to a larger recycling industry compared to that of lithium-ion batteries [51].

The specific lead-acid batteries chosen were AGM batteries that are non-spillable and non-hazardous to the environment during operation; however, future iterations should seek to switch out this technology for a more sustainable option such as the cradle-to-cradle (all materials used are completely recyclable) saltwater batteries. The reasoning for not purchasing these batteries is because Aquion Energy, the one company that sells and manufactures them, is in the midst of rebuilding, following a Chapter 11 bankruptcy filing in 2016, and is currently not selling on the public market [52].

Another important component to consider is redwood. Redwood was selected because it is a softer wood, weather-resistant, and requires little maintenance. As a result of these qualities, the wood in the system should be long-lasting, preventing the need to replace components regularly, which creates excess waste. Additionally, the wood does not need to be treated, eliminating the possibility that the produce and fish may be contaminated with toxic chemicals. Moreover, most of the redwood lumber is sustainably sourced, as 90% of redwood forests have been certified sustainable by the Forest Stewardship Council or Sustainable Forestry Initiative [53]. Lastly, redwood is often processed using solar power, which differs from most other products that rely on fossil fuels.

In addition to wood, plastic, specifically polyethylene, is another material that is critical to the design. Wood's embodied energy comes from harvesting trees, chopping the wood to size, preparing the wood, and processing it. Throughout this whole chain, there are a lot of opportunities for energy to be used up. According to a research paper, it estimates that a wood frame of 9600 sq. ft is about 168 to 250 GJ of embodied energy and has 8,345 - 13,0009 kg of CO_2 emissions [54]. Since the amount of wood in the system is approximately 200 sq. ft., it is estimated that the embodied energy and kg of CO_2 emissions is ⅙ of the estimated amount.

Polyethylene is estimated to have about 77 MJ of embodied energy per kg and releases 8.28 kg of CO_2 to manufacture 1 kg of polyethylene [55, 56]. The pond liners used in the system weigh 21.2 kg. A comparison of the two materials' embodied energies and CO_2 emissions are shown in Table 28.

Table 28. Embodied energy and CO_2 emissions for materials

Material	Embodied Energy (GJ)	CO2 Emissions (kg)
Wood (200 Sq. Ft)	3.5 - 5	174 - 271
Polyethylene (21.2 kg)	0.8	175.5

Although the team investigated other materials to replace wood, many other industries have higher GHG emissions than wood [54]. Therefore, it is more feasible to use wood, since it also provides a nice aesthetic and is easy to work with. One concern that may need to be considered is the longevity of the system; however, the use of treated wood will help ensure its durability in the long-term. However, the team did investigate the use of bamboo as a close substitute, but the inability for bamboo to cover wide surface areas and use in mainly vertical applications prevented them from doing so.

On the other hand, it appears that the use of polyethylene is not that energy-intensive or carbon-dioxide heavy. This is mainly due to the small amount of polyethylene being used. While it would be worthwhile to try to figure out a new material for the pond liner, polyethylene provides both the strength and flexibility needed within the pond and is surprisingly, in this case, relatively more sustainable than wood.

13. Business Plan

13.1 Business Plan Background

The creation of a scalable, modular aquaponics system is ideal for anyone living in a dense-urban community to start their own soilless gardening system. Each system can be easily customized and sized to fit the needs of the end-user in any situation. With the growing concerns of food insecurity, healthy food, and climate change, this system will help to address these issues through a cost-effective, low-maintenance system that prioritizes the rising small-scale farming market.

There is a multimillion-dollar market for aquaponics systems that is continuing to grow [57]. The product is less expensive and more customizable than most other aquaponics systems commercially available, giving the team an advantage over competitors.

13.2 Goals and Objectives

Our goal is to combat food insecurity, empower people to retain their sense of agency by choosing what they grow, and explore a new form of farming that is climate smart. Food security is defined as having "consistent access to enough food for an active and healthy lifestyle" by the USDA. Having this system will allow people to have access to fresh nutritious food that they like to eat, which is often unavailable in urban areas with no grocery stores. Additionally, aquaponics systems are climate smart, since they are resistant to droughts, as they use less water than traditional farming, and floods.

Our objective is to provide a cost-effective solution to augment produce yield, particularly in urban settings where there are high levels of food insecurity, enable homeowners to grow produce in their own backyards, and revolutionize farming methods to adapt to the changing climate.

13.3 Key Technology

Given the threat of climate change, lack of arable land within cities, and the rise of water insecurity due to drought, the aquaponics system has the capability to increase agricultural yield around the world, while ensuring that these barriers to farming are overcome. Moreover, it enables any person, regardless of experience, to grow plants, creating the perfect opportunity for everyone to be a farmer.

With this personalized aquaponics system, anyone can

- Conserve up to 90% of water compared to traditional farming techniques [58]
- Save money from buying produce
- Grow plants in a higher density with less area

- ○ Raise fish to either eat or enjoy
- ○ Create your own low-maintenance garden anywhere you'd like
- ○ Know and choose what you are eating for a healthier diet

13.4 Potential Markets

According to a market study carried out by Value Market Research in 2017, the global aquaponics market was valued at $370.5 million based on revenue. This market is expected to reach over $1,501 million by 2024 with a compound annual growth rate of 22.5% [57].

Our customer base targets family homes within the United States. A study by the National Gardening Association determined that 35% of households, or 42 million families, grow their own food [59]. The team estimates that about 5% of this population, or 2.1 million families, would be interested in experimenting with aquaponics as well. Additionally, the team presumes another 10% of the households that do not garden may be interested in starting to garden, corresponding to 7.8 million households. This means that about 9.9 million households may be interested in purchasing an aquaponics system. Given that the market for this product is already rather saturated, the customer base may hopefully be 5% of this market, which would still equate to a little less than half a million customers.

Given the novelty of this innovation, not many studies have investigated the number of sales for aquaponics systems, but many people have started to invest and profit from it. Based on a 2015 study conducted by John Hopkins University that interviewed users and producers of aquaponics systems, it was determined that these systems receive gross sales of $1,000 to $4,999 over the past year [60]. From the study, 71% of the aquaponics systems were personally designed, while the other 29% hired a consultant or purchased a kit. The high percentage of individuals creating their own systems demonstrates that current products on the market are not meeting consumer demands. As a result, the team designed the system to meet more of these customer needs, as it is cost effective and low maintenance.

Our plan would mainly focus on subsidizing the cost for communities and households around the Bay Area, where there is a high percentage of people who are food insecure and could benefit from aquaponics systems. In order to scale the business, the team would open hubs across the rest of the United States, deploying a Hub-and-Spoke model to spread the use of this technology.

13.5 Competition

Since aquaponics systems have started to rise in popularity, many people are beginning to purchase smaller-scale aquaponics systems, such as the Genesis-48 or the Aquabundance Home System, which are both modular in size. However, these two systems are rather expensive compared to the product, as demonstrated in Table 29.

Table 29. Price comparison with competitors

Criteria	**Competitor 1 Aquabundance Home Aquaponics System** [28]	**Competitor 2 Genesis G-48** [27]	**Our Fundamental Package**
Wholesale cost	$5,095	$2,995	$1,600
Area of grow space (sq. ft)	45	48	45.3
Volume of fish tank/pond (gallons)	200	140	300
Weight of fresh fish grown (lbs)	28.57	20	42.86
Cost per area of plant grow space ($/sq. ft)	113.22	62.39	35.32
Ratio of fresh fish to grow space (lbs : sq ft)	0.63	0.42	1.21

As Table 29 shows, the Aquabundance Home Aquaponics System and Genesis G-48 are roughly the same size as the fundamental package. However, both of them are both more expensive than the fundamental system in every aspect. The system also offers the largest fishpond, increasing the potential protein source. Additionally, the system is modular to fit a wide range of spaces.

13.6 Sales and Marketing Strategies

Using a Hub-and-Spoke model, the team will be able to have their headquarters in the Bay Area, where a high percentage of people are food insecure. Based on an increase in revenue and profit, the team would scale the product to other areas of high food insecurity, employing community representatives to work with community leaders to learn about the system, hosting workshops to teach people about the benefits of aquaponics and train them how to maintain a system. Since their goal is to combat food insecurity, an important aspect of their sales and marketing strategy would be to work with non-profit organizations, as this current project has done, to inspire community members and provide as centers of learning.

Furthermore, it would be crucial to hire a marketing manager who would ensure their prominence on social media platforms, television and radio advertisements, and potentially paper flyers around farmer’s markets and community areas.

13.7 Manufacturing Plans

The fundamental package includes two types of grow beds—a 32 sq. ft raft grow bed and an additional 13.3 sq. ft in the media grow bed—and a 300-gallon fishpond, which would preferably be in the ground to reduce heat and save on materials. Since each system can be sized differently based on the size of the pond, it would be possible to create different-sized raft grow beds of the same area; however, the use of the IBC for the media grow bed restricts different sizing for this part of the system.

Our product was handcrafted using power tools to cut the IBC in half, drill holes, and cut the wood to the correct size. The build of the system required precision placement as well. For large-scale manufacturing, it would be important to partner with a manufacturer that would easily be able to create wooden, plastic, or metal containers of varying sizes, which would serve as the two different types of grow beds and the pond, if an inground pond is not possible. Now, everything would be scaled out based on the fundamental package, as mentioned above Depending on the size, the end-user may need to assemble the pieces for the final system.

All the pipes and bell siphons within the system were attached by hand and a few of them were cut to size. The use of PVC was quite prevalent in this endeavor, so it would also be crucial to have these cut-to-size. However, it would be up to the customer to connect the different pieces in the correct spots with the proper sealants.

Finally, the plastic pond liners were a large component of the system, but since each system would be different, the customer can easily cut the liner with an X-Acto precision knife or scissors.

In order to start producing these packages, the team would need 3 months for further research and development, and an initial investment of $1,000,000 to create the kit design, meet industry standards, ensure certification, prototype different designs, market the product, develop the sales channel, patent the design, and pay for other business development needs. The team aims to sell 20,000 units each year, so the team would start with an initial inventory of 2,000 systems. If these packages become popular, the team would increase production by increasing the orders from the manufacturer or partnering with additional manufacturers if necessary. The team estimates that their packages would take the user two days to assemble at their desired location.

13.8 Product Cost and Price

The costs of the system vary based on its size. The system original cost $2,264.14 for materials. However, for the fundamental package, the cost should be about $1,205.76 for materials. A cost-breakdown of all these components is shown in the table below:

Table 30. Cost breakdown of aquaponics system components

Component	Fundamental Package	Our Current System
IBC container for media bed	$100.00	$200.00
Caps for IBC bars	$14.25	$28.50
Media for media bed	$99.15	$198.29
Bell siphons	$85.88	$171.75
Grow bed liner	$69.00	$138.00
Redwood for raft grow beds	$210.17	$420.33
Plywood for raft grow beds	$160.29	$320.58
Rafts	$88.00	$176.00
Bulkheads for drains	$8.80	$17.60
Pond liner	$105.23	$213.52
Underlayment	$24.18	$52.94
Water pump + tubing	$84.70	$84.70
Air pump + air stones	$82.96	$82.96
PVC	$3.00	$18.67
Fasteners	$28.35	$56.70
Raisers	$41.80	$83.60
Total Cost	**$1,205.76**	**$2,264.14**

In addition to the fundamental system, customers may also purchase auxiliary features based on their needs. Each of the auxiliary costs is associated with the fundamental package and are approximate costs.

Table 31. Auxiliary items available for purchase

Auxiliary Item	Added Value	Cost
300-gallon fish tank and raisers	Inability to dig a hole for the fishpond requires external tank	$400.00
Solar panels and power system components	Off-the-grid capabilities to power the two types of pumps 24/7	$1,750.00
Solar panel chassis	Mounting of the solar panels	$900.00
Sensor system	Remotely monitor pH, EC, DO, and temperature	$550.00
	Manual measurements of pH, EC, and temperature (Bluelab Guardian Monitor) [61]	$399.00
Starter	Inputs necessary to begin the system, such as fish, seeds, nutrients, etc.	$700.00

Based on extenuating circumstances for non-profit organizations, many materials may be donated to reduce the cost. It is important for partnerships with local organizations to be formed as such. Furthermore, larger production volumes would reduce the pricing of the system. However, the exact balance between manufactured, for-profit systems and cost-based systems using donated materials would still need to be determined through further analysis of market segmentation and the relative feasibility of these complementary approaches.

13.9 Service or Warranties

All systems would have a 10-year service plan to ensure its functional operation. This would include but is not limited to, repairing leaks, fixing flow rates, providing resources for help, and minor adjustments. The service plan would not be responsible for construction of the grow beds, digging of the holes for ponds, or the wiring of any components. Their business would also not be responsible for the health of the living organisms in the system nor the maintenance of water quality conditions. Guides would be available online to troubleshoot such issues.

The entire system would have a 5-year warranty with individual components and auxiliary items, such as the solar panels, having separate warranties based on the standards set by the manufacturer. Their policies may be subject to change at any time or based on each customer's needs. It is expected that these systems last 10 years and any service required that is covered under the service plan would be paid for by the business.

13.10 Financial Plan and ROI

In order to raise money for this endeavor, it would be important to seek grants from foundations and funding from venture capitalists. Using this initial capital, the team would begin to create multiple sets of the fundamental package, which would include costs needed to acquire the raw materials, hire employees, manufacture the product, and market the system.

Our assumption is that for each product manufactured, a profit margin of 2% would be earned. A cost per unit is presented below

Table 32. Costs per unit

Investments	Per Unit Cost
Raw materials	$1,205.00
Employee salaries	$200.00
Manufacturing and storage space	$90.00
Marketing	$10.00
Overhead	$20.00
Insurance	$5.00
Shipping	$38.00
Total	$1,568.00

With the aim to sell 20,000 systems each year, or 4% of the expected customer base, a return on investment (ROI) is shown below, assuming an initial investment of $1 million.

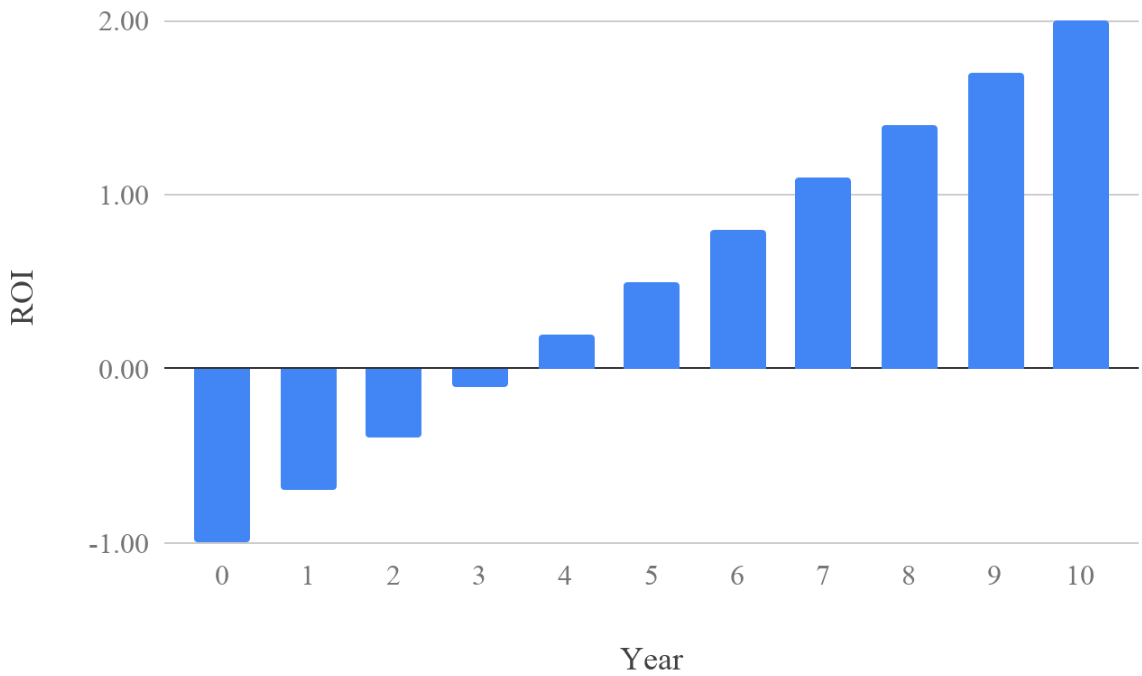


Figure 56. Return on investment of aquaponics business

Based on this ROI curve, one can easily see that their system would be efficient after four years; however, the business could reach this point much sooner based on a variety of factors, such as manufacturing in bulk, heightened awareness of the product, and increased donor support through grants. It is also important to acknowledge that donations and partnerships with different non-profit organizations and businesses may shift the curve.

This projection does not include pricing pressures from competitors. As the team begins developing the market, the goal would be to estimate the impact of those pressures on their pricing power. Even with competition, the team expects to achieve at least 50% of the currently estimated ROI shown in the chart.

The Net Present Value (NPV) of the system takes into account the profitability of the system, as shown below.

$$NVP = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{17}$$

Taking into account the profit margins of each year, to represent the net cash inflows and outflows (R_t), and the general investment rate i to be approximately 1%, the team determined how the NPV shifts over the 10-year period specified, with t representing the number of years since the business started. NPV analysis supports the qualifications of the ROI suggested above.

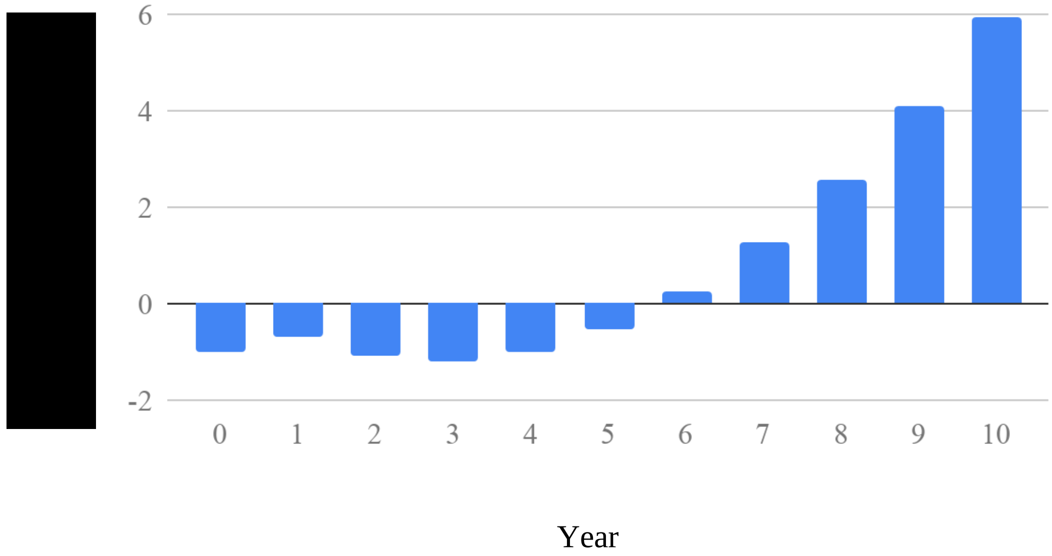


Figure 57. Net present value of business

Based on the graph, one can determine that the profitability would begin around year 6, and increase steadily, assuming that the business only requires the initial investment of $1 million. After ten years, it is possible that the NPV of the proposed business can reach about $6 million.

13.11 Business Contingency Plan

If the business does not reach the set expectations and thresholds within three or four years, the team would reevaluate their value proposition and follow different steps within the contingency plan which is briefly summarized in the table below:

Table 33. Possible risks and actions to take to mitigate risks

Risk	**Course of Action**
Inability to secure initial investment	Continue meeting with other investors and improving business plan. Depending on the amount of money, the team may consider a loan or other sources of funding
Manufacturing plant breaks down or malfunctions	Ensure insurance plan covers damages, but discussion for other manufacturing options would be discussed
Loss of supplier or producer	Investigate other suppliers (who may be more costly) and create partnerships with them
Unable to sell enough product within the first few years	Fund more marketing efforts to increase awareness, availability, and sales

If for any reason, at any time, the business is faring poorly, the last resort option would be to leave the market and file for bankruptcy. To ensure the founders do not enter debt, it would be important to acknowledge when the business is beginning to decline and to cut their losses sooner rather than later.

13.12 Business Plan Summary

In the end, creating an aquaponics business would be highly successful due to the growing market and large need for new forms of farming that are possible in urban settings. However, to ensure the success of the business, it is imperative to start early to acquire funding from initial investors, determine manufacturing sites, ensure a solid marketing plan, and promote a strong distribution channel. Addressing food insecurity would remain at the forefront of all their decision-making since the goal of these systems is to not only scale out through the United States but to also promote healthier foods and agency to choose one's own produce.

14. Ethical Analysis

14.1 Ethical Justification

The intention of an aquaponics system is to provide clean, healthy food alternatives in food insecure areas across the world. As stated above, implementing these systems enables food sovereignty for marginalized communities, making farming accessible in urban settings while minimizing environmental repercussions.

The aquaponics system follows all five sources of ethical standards seen below in Table 34 [62]:

Table 34. Sources of ethical standards

Approach	Reasoning
Utilitarian	Aquaponics is proven to produce higher yields than traditional forms of farming while using less water, demonstrating that the system has a higher utility than traditional farming methods. In this way, by partnering with Loaves and Fishes to distribute the food, the aquaponics system yields the greatest good for the greatest number of people, and the utility of the system is maximized. The utility is also maximized through the intentional reduction of harm as it is drought-tolerant, structurally stable, and low-maintenance.
Rights	The aquaponics system protects the human right to a higher standard of living by improving the quality and quantity of nutrition in people's diets. It also returns agency back to the individual, who now has more options to choose what they grow and eat, which is both socially and economically empowering.
Justice	The aquaponics system advocates for social justice because it is scalable and modular, so all people can be treated equally and gain access to building and using such a system. Although the system designed will only be implemented through Loaves and Fishes, the system will serve as an educational tool to help others understand how they could build a similar system. As well, metrics for reproducibility will allow anyone and everyone to gain access towards building their own.
Common Good	Even though aquaponics requires less maintenance than traditional farming, it can bring a community together by serving as a distinctive feature in any farm or backyard, inspiring more volunteers and people to come out to learn about such a system and participate in the gardening and harvesting process. Furthermore, it creates a community in which people share ideas, techniques, and resources to improve the efficiency of such a system to make it accessible for everyone. But most importantly, aquaponics questions the conditions of large commercial agriculture and the ability for the vulnerable to access food.
Virtue	Aquaponics not only enables the team to expand their engineering skill set and engineering mindset, but it also allows them to improve upon their work as humanitarian-based engineers. Working with Loaves and Fishes has improved their values of generosity and compassion as the team learned from the volunteers at the farm who spend countless hours dedicated to growing food for the vulnerable. Their optimism, patience, and selflessness are all virtues present in their daily lives that the team hopes to emulate and implement to better their characters.

Given these ethical standards, as defined in Table 34, the ethical issues addressed by the aquaponics project will be presented below.

14.1.1 Food Insecurity and Food Sovereignty

As outlined in the UN's Universal Declaration of Human Rights Article 25, "everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food…" [63]. Although food poverty is prevalent throughout the world, especially in developing countries, issues of food deserts and access to healthy food are widespread throughout the United States in large urban settings, such as San Jose, where it is more difficult for people to have access to affordable, sustainable, and locally-sourced foods.

The degradation of agriculture due to large-scale monoculture companies has also led to a lack of biodiversity and available options for small-scale farmers [64]. This has propelled people to advocate for food sovereignty, the idea that people have the right to healthy and culturally appropriate food produced through ecologically sound and sustainable methods.

Moreover, food serves a vital cultural function. It brings people together and is a method of communicating and expressing love. It enables others to learn about different cultures and form long-term relationships. Therefore, it is important for people to have access to foods that are culturally appropriate to provide necessary options for everyone.

It is also important to remember the health aspect. Having healthier food options and increased nutrition will lower health impacts, lower medical bills, and extending lives as increased nutrition and healthy food options decreases the likelihood of developing diabetes, heart disease, or cardiovascular diseases [65].

As an integrated farming system, aquaponics addresses both food insecurity and food sovereignty. On the local level, it provides communities an opportunity to have healthier, culturally appropriate food that is locally sourced and sustainably grown. Even without the use of artificial fertilizers, herbicides, and pesticides, plants in aquaponics systems grow faster, bigger, and healthier than those grown in regular soil [58]. They also require less maintenance than regular farming methods and can be implemented in an urban setting, where traditional farming may not be feasible. Additionally, aquaponics is ecologically sound, since it requires minimal external inputs and produces minimal waste outputs [66].

In addition, aquaponics makes it easier on the farmer to grow plants. The volunteers, who are also their beneficiaries at the Loaves and Fishes farm are retired men who dedicate their weekday mornings tending to this garden. It involves a lot of bending over, weeding, and planting. It is rather labor-intensive and can lead to injuries if one is not careful. The system is off the ground and will require less bending over to inspect the plants, so that these people can continue doing what they love, ensuring that anyone, regardless of age, can employ such a system.

14.1.2 Human and Animal Rights

Many of the electrical components that the team is using are usually manufactured in countries that lack stringent labor laws that allow the employment of child labor, provision of low wages, and the exacerbation of poor working conditions. While this may appear unavoidable in the quest to reduce the end-product cost, some of the companies the team purchased products from have set in place standards of corporate social responsibility. For instance, First Solar has a “conflict minerals” policy to ensure responsible sourcing and operating of a supply chain that revolves around finding ways to avoid these minerals that are linked with human rights abuses and it enforces a Labor and Human Rights policy focused on “protecting human rights and enforcing fair labor practices” [67].

However, it is also important to note that many of the other companies that the team sourced materials from do not showcase their manufacturing standards or labor laws. Given the time constraints imposed by the project, these companies were chosen with price and functionality in mind. Therefore, many of them may lack ethical standards and the team was unable to find documentation that proved otherwise. For the future, fewer materials will need to be purchased to expand the system and the team can ensure that materials are locally and responsibly sourced by contacting companies before purchasing.

Animal rights are also an important issue that need to be addressed with the system. Since aquaponic systems rely on fish to provide fertilizer for the plants, the well-being of the fish should be considered First, some believe that growing fish for human consumption is morally wrong due to the rights argument. Since fish have nervous systems and feel pain, some consider them to have animal rights because they are sentient beings. While this is an important issue for discussion, many aquaponic farmers can choose to keep these animals as pets, with no intention of killing or eating them, which is what Loaves and Fishes has decided to do.

Second, the team needs to determine how much space is needed to keep a fish happy and healthy. To ensure that this was achieved, the team had the following question as their guiding question: do the fish have enough space to grow to maturity without overcrowding? It is important to provide fish with an environment adequate for growth. Besides visually tracking their size, the team is using sensors to monitor water quality to ensure that the fish are living in ideal conditions. Additionally, air stones have been added to the pond to oxygenate the water to ensure the fish have enough oxygen to remain healthy.

One can also argue that compared to conditions on a huge farm, the fish in an aquaponics system are treated much better, since they are grown naturally with no genetic alterations or sex-reversals [68, 69]. They are cared for daily and fed with healthier options rather than pelleted fish food.

14.2 Virtues of a Good Engineer:

As engineers, it is the team’s duty to use engineering for the benefit of others by designing and building solutions to address societal issues through technology. The IEEE Code of Ethics [70] and the ASME Code of Ethics [71] both state that they “hold paramount the safety, health, and welfare of the public” throughout the design and implementation process. However, it is just as important that the team educates fellow co-workers, clients, and partners to ensure they better understand the technology, its capabilities, and its consequences. It is equally important to be honest in expectations set to ensure that the team’s goals align with that of their partner organization and that the team remain competent in the work that they complete, the team addressed this by getting feedback from their partners and maintaining regular, open communication.

14.2.1 Techno-Social Sensitivity

Although many view technologies as solely objective, it has societal consequences and can be heavily influenced by the needs and wants of society. The project started last year to address food insecurity in Uganda, but due to the societal need around Santa Clara University, the team decided to work more locally. Even though the team is only working with one organization, many other schools, community centers, and people have expressed interest in the project, and are very much interested in learning more about this innovation. Through conducting interviews to gather information and customer needs with these different groups, the team was able to create a tailored list of system components that directly addressed the wants and needs of the client. The interviews provided the team with different suggestions from the varying groups, and these opinions helped them to design a system that Loaves and Fishes actual needs.

Moreover, technology may remove people from their immediate experience, which is true for the aquaponics system, since it removes the user from having to continually monitor the system on-site. However, the IoT system does enable anyone to see real-time data, interact with it, and use it to inform decisions about visiting the farm. And the novel use of solar panels and continuous water flow through the system can bring more volunteers and community members to learn about how the systems works, and, in turn, can help lead to suggestions for improvements or new scalable models.

From the completion of the project, the team has learned that nothing is ever fully technical and that there are multiple solutions to every problem. The team drafted many different designs before finalizing their own system, gathering input from their affiliate, their advisors, and professionals working in the aquaponics sector. Although it was a long and tiring process, the team is gratified that the final product will fit the end-user’s needs and create a societal impact.

14.2.2 Respect for Nature

Large-scale, modern farming systems lack the respect, historical and cultural context, and ecological backbone necessary to grow crops. Rather than seeing the inherent beauty in the complexity of nature, industrial farming aims to have large fields of the same crop that do not interact with one another. This monoculture then attracts more pests and weeds, since there is a deficiency in natural deterrents, which then requires the use of chemical preventatives. Although some large farms do practice crop rotation to preserve nutrients in the ground, many companies growing commodity crops, such as corn or soy, continuously plant the same crop on the same land, using artificial fertilizers to provide nutrients instead [72].

The system aims to inspire people to return to the sense of wonderment present in nature. Throughout their work, the team became fascinated by the connections of plants grown in the earth and the complexity required to keep a plant alive. The nutrient cycle between the fish, the nitrogen-fixing bacteria, and the plants demonstrates how all living things are interconnected. It is also incredible to realize the intricacy of nature as the team learned to maintain the proper conditions for fish and plant growth.

Although aquaponics is not as hands-on as traditional farming methods, such systems can be implemented in dense urban settings, providing people with a chance to experience sublimity, despite being cooped up in a concrete jungle. The team especially appreciated being able to work outdoors, even though the garden is in the middle of the city. The team discovered that being able to work with their hands and experience the sensation of farming brought them closer to appreciating how incredible it is for a sapling to become the food on one's plate.

14.2.3 Commitment to the Public Good

Coming into this project, the team wanted to create something that would have a lasting impact on the lives of people. Specifically, the team wanted to work with a community organization that could help feed the most people. Knowing that the project would create a large community impact has inspired the team to make it as user-friendly as possible and to work hard to ensure its successful implementation. The team has continually met and worked with their partner organization to ensure that their project meets the standards that they have and that they know every step of the process. Further documentation will be provided regarding maintenance and operation, such that when the team members graduate, the organization can continue to monitor and ensure the longevity of the system.

The team understands that even though this project will not create a drastic difference in Loaves and Fishes' food production, it is a first step towards addressing food insecurity and creating a difference within the community.

14.2.4 Courage

Courage goes together with open-mindedness. Even though the team fostered a safe space for teammates to voice their opinions, at times, it was hard for the team to talk to the project advisors about certain ideas and suggestions that the team wanted to implement. But having the courage to bring up their concerns helped the team tailor the project towards their own vision and their own set goals. This was important, as the team became more connected and involved with the system, choosing their partner organization, their design, and their scope.

Having the courage to speak up also improved their teamwork and communication. The team knew that if someone was uncomfortable with an idea, they would be able to bring it up at one of their meetings. Then, the team would be able to use their ideas to better improve and optimize the project, since that person would bring an interesting perspective that the others had not thought about.

14.3 Ethical Pitfalls

14.3.1 Safety and Ethics

The main risks the team envisioned for themselves include potential electrocution or burns from touching live wires during the connection with the solar panels, injuries from using the power tools to construct the grow beds, and chemical spillage on skin. For a more complete list, please take a look at Table 35 below.

To mitigate “Fully Known” risks, the team aimed to provide a safety manual outlining steps in case of certain risks or failures that can be expected. The team also embarked in conversation with the volunteers at Loaves and Fishes such that they understand and can address these risks. Explaining to “reasonable people” the safety risks requires signage all around the product to ensure that anybody on the site knows not to touch certain wires or walk in certain places. The team would need a fence surrounding it to prevent anyone from accidentally knocking the grow bed over or stepping in the fishpond.

Since the partner, Loaves and Fishes, consisted of people who, as retired engineers, have experience working with technology, experience gardening, and have worked closely with the team during the building and implementation phase, there are no “settled value principles” that needed to be considered.

Lastly, given that the team will not be able to be on-site to fix each of the problems should they occur, it is imperative that the farmers working at the farm are trained how to maintain and troubleshoot the system. In order to ensure that the farmers are equipped to solve most problems with the system, they will be provided a list of frequently asked questions with answers for them to consult. Additionally, they will be able to follow up with Dr. Laura Doyle, who is conducting research on aquaponics systems and serves as an advisor to the engineering team.

Table 35. Known risks of aquaponics system in daily operation

Risks	Consequence	P	S	I	Mitigation
Fish dying/diseased	Loss of nitrogen cycle	3	4	12	Clean the fish tank; Not overcrowding fish; Maintaining water quality
Nutrient imbalance	Fish and plants are dying	3	4	12	Checking water quality often through pH, EC, and DO sensors
Pump failure	Buildup of nutrients leading to system failure	3	4	12	Choosing a reliable pump
Sensor failure	No water quality data recorded	3	3	9	Backup power source
Lack of sunlight	System shuts down	2	4	8	Sizing the power system with a battery to ensure pump can operate without sunlight
Electrical shock /electrocution	Death or major injury	2	4	8	Disconnect system before modifying; live wires are in areas that are hard to reach
E. Coli/food safety	Health impacts and lawsuits	2	4	8	Washing hands with soap and water; cooking food thoroughly
Plumbing system leaks	Loss of water in plumbing system	4	2	8	PVC pipes properly primed and sealed to create watertight connections
Falling into the fishpond	Minor injury	3	2	6	Creating a fence to prevent unsuspected passerby; gates locked at night
Fish eaten by cat, raccoon, etc.	Loss of nitrogen cycle	2	3	6	Cover fishpond with mesh wiring to prevent animals from eating them
Collapse of grow beds	Loss of plants and water	1	4	4	Tight fittings and load calculations to ensure not exceeding limitations
Leak in pond liner	Loss of water for fish to swim in	2	2	4	Pond liner is kept away from sharp objects
Stolen solar panels	Lack of solar power	1	4	4	Attach solar panels firmly; ensure in location that is not easily reachable
Wire trip hazard	Major injury	1	3	3	Burying wires underground; not placing near walkways

The scale used for Probability (P) is from 1 to 5, where 1 is Improbable and 5 is Frequent

The scale used for Severity (S) is from 1 to 4, where 1 is Negligible and 4 is Catastrophic
The scale used for Impact (I) is from 1 to 20, where 1 is Low and 10+ is High

14.3.2 The Public and Ethics

In the aquaponics system, the “public” will refer to the volunteers who work at Loaves and Fishes Farm, those interested in learning more about aquaponics, and all the food insecure guests who visit Loaves and Fishes’ for the prepared meals.

The population for whom the project hopes to serve is mostly composed of low-income, food-insecure people living in or around San Jose. Since the farm helps to supplement 5% of the meals that Loaves and Fishes provides, this means that in a year, 25,000 meals are sourced from the farm.

We are exposing the volunteers who work at the Loaves and Fishes’ Garden to all the risks mentioned above, except the *E. Coli* and food safety, which can have negative impacts on the guests who attend the meals served by Loaves and Fishes. However, mitigation techniques will significantly lower these risks.

14.3.3 Principle of Informed Consent

Even though all the high impact risks are mainly addressed for the system, a principle of informed consent will ensure that volunteers understand the risks and safety precautions necessary to volunteer at the farm. Loaves and Fishes Family Kitchen will provide volunteers with consent forms outlining in easy-to-understand language the potential hazards. Challenges for consent include language barrier, illiteracy, hunger, complexity of consent form, or unwillingness to sign a form. This will be taken care of by the partner organization, Loaves and Fishes.

Further mitigation of risks will be provided through clear instruction to lead farmers to host in-depth discussions with the volunteers about these risks.

15. Team and Project Management

15.1 Project Challenges and Constraints

The project faced several roadblocks during the design and construction of the aquaponics system. The first set of obstacles dealt with the location of the farm and aquaponics system. The farm is in an industrial area parking lot with no access to electricity or internet. Therefore, the entire system, including all the sensors, needed an off-the-grid energy source and an alternative IoT communication system to upload information online. Both challenges were overcome in the design phase by securing additional solar panels and deciding to use LoRa for data transmission to the internet.

While considerable effort was made to build the system at low cost, certain materials may make this system cost-prohibitive for some communities. Since the project was funded by grant money and community donations, the team had to be creative in choosing materials. For example, the clay pebbles optimal for the media bed cost $350 but this proved to be too expensive so lava rocks at a price of $198 were purchased instead. In addition, this project had a short time frame (10 months) due to the academic school year and with more time, the team could further benefit from local industry partnerships and donations.

In addition, the team faced challenges with working on an outdoor system. It was difficult to build and operate a solar-powered system due to a wet Northern California winter that extended throughout the spring. These delays prevented the team from powering the system continuously, such that the water was not circulating, and algae began to grow, increasing the pH to alarming rates. Furthermore, the low-cost pump has broken down twice due to the impeller losing magnetism when the system was shut off.

Despites these challenges, the team was able to complete the system on time, but future tests of the various inputs will need to occur to compensate for lost time. The timeline will be further elaborated on in the section below.

15.2 Timeline

As mentioned above the team faced some challenges with the timeline, which are mainly due to gathering materials and due to wet weather. A brief overview of the timeline is shown in Table 36 and a more detailed timeline can be viewed in Appendix P.

Table 36. Ideal completion and actual completion dates for major milestones

Task	Ideal Completion	Actual Completion
Research	October 8, 2018	October 15, 2018
Conceptual design	December 7, 2018	December 7, 2018
Media grow beds	January 14, 2019	April 4, 2019
Fishpond	January 21, 2019	April 18, 2019
Raft grow beds	January 28, 2019	April 11, 2019
Solar installation	January 28, 2019	April 30, 2019
Sensors and communication	February 4, 2019	May 2, 2019
Testing	April 18, 2019	May 28, 2019

As shown above, the team ideally wanted to complete the build of the system in the Winter to allow for most of the spring to be devoted to testing. However, the team encountered many setbacks. For example, during the rainy winter, work could not be completed on the project for several weeks due to poor working conditions. Additionally, many large materials needed to be gathered to build the system. The large size of some of the materials presented a large challenge, as they are expensive to ship and difficult for the team to move themselves. Lastly, the system is accessed through a gated parking lot, which is only open on weekdays during typical business hours. As a result, all of the work on the system had to be completed during the week, which is difficult due to class and other commitments. The figure below shows a final project timeline.

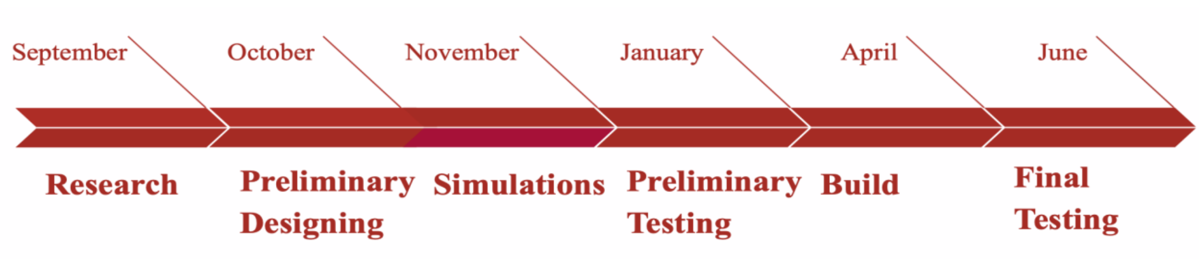


Figure 58. Timeline of project

15.3 Team Management

This team is composed of two mechanical engineers, one electrical engineer, and two public health students. A breakdown of the responsibilities of each sub-group can be seen in Table below.

Table 37. Responsibilities of each sub-group

Mechanical	Electrical	Public Health
• Layout of system • Water flow • Solar installation	• Sensor system • Power system • Solar installation	• Fish research • Plant research • Community impact

The engineers completed the majority of the work on the project, as they designed the system and completed the build. Some issues that the team encountered was communication between the various sub-groups. Additionally, it was difficult to coordinate meeting times between the five members and the advisors on the team.

15.4 Teamwork

Within a team, communication is key. Since the team was interdisciplinary, it was vital that roles were assigned, and each member was held accountable for the completion of their parts. With regular weekly check-ups and a schedule to stay on track, the team members all knew what to expect in order to complete the project.

At the beginning of the year, the team collectively sat down to assess each other's strengths and weaknesses, in order to best utilize each person's assets and value each team member for their contributions. However, in other situations, there was room for growth. If a team member wanted to learn a skill that another team member was competent in, the two would work together on that.

In the end, the team realized that creating the product required all of them to remain vigilant and aware of the end goal and to understand how important each individual's role would impact the project. Although there was a more hands-off approach, this worked out well, since each team member's work ethic and commitment to the project was incredibly high. Because each person worked on different aspects of the system, coming together to build the final product required a lot more coordination, but seeing how much the team could achieve was breathtaking.

16. Future Works

Even though the team accomplished a lot in building this system, there are a multitude of potential improvements, which are laid out in the following table based on importance.

Table 38. Potential future action items

Future Work	**Description**
Pump flow rate	Optimize pump for lower power or for higher durability
Plant experimentation	Carry out experiments to determine the effectiveness of the aquaponics system at growing plants compared to conventional farming techniques
Sensor integration	Implementation of the sensor communication network system
Sensor feedback control system	Maintenance of water quality levels based on high levels of sensor data that are created
Sensor additions	Include additional sensors that measure flow rate, water turbidity, battery level, and PV output
Grow bed	Addition of more grow beds around the fishpond to optimize the amount of fertilizer generated

The top priority is to ensure that the pump is optimized, given that it is the most crucial aspect of the system. Since it has broken twice this year, a new pump or perhaps spare parts, are needed to improve its functionality. Secondly, multiple experiments should measure the different growth rates of different plants to determine which ones would be ideal under different environmental conditions.

Next, the sensors are a large aspect of the system and require more time to integrate into the current aquaponics system for consistent measures of data. Based on this data collected, a feedback control system will aid in the regulation and maintenance of specific water quality parameters. The table below summarizes the variable to be altered and what method could be used to alter the value so that it is within the set parameters.

Table 39. Potential control systems

Variable	**Method**
Too hot	Shade pond, increase aeration
Too cold	Decrease pump flow rate; pond heater
pH too high (basic)	Add phosphoric acid
pH too low (acidic)	Add calcium carbonate/potassium carbonate
Electrical conductivity	Feed fish less, add nitrogen-fixing bacteria
Dissolved oxygen	Turn on/off additional air pump

Current manual solutions on the farm have helped to maintain specified parameters, but since the system is low maintenance, the farmers rarely need to take any measures.

Finally, the fishpond itself is rather large and over time, the tilapia will begin to produce large amounts of ammonia within their waste. Therefore, adding grow beds will help optimize the amount of fertilizer generated and use it to grow and expand the productivity potential of the system.

Since this aquaponics system was designed specifically for Loaves and Fishes, it has many features that are unique to aquaponics systems; however, there are many other potential users for similar systems in the San Jose area such as community centers, schools, or food banks (see Appendix B for more information on potential users in the area). In the future, a more scalable system may be created for other local organizations that are interested in having such a system. This system could then be optimized to be frugal and modular.

17. Summary and Conclusions

In San Jose there are many people of various backgrounds and education levels, who are experiencing food insecurity. There is a need to combat food insecurity on a large scale, and aquaponics presents a good solution to address this problem. By partnering with Loaves and Fishes, a community food distribution center, the team aimed to maximize the number of people positively impacted by the installation of a food growing system. Furthermore, by developing a larger community-sized system, the subsystem efficiencies could be maximized, as was the case for the pump and solar panels.

Although aquaponics is becoming increasingly accepted and commercialized, there is a gap in the market for durable and successful aquaponics systems for low-income, food-insecure people and households. In order to address this, the system is unique in catering to these needs: integrating off-the-grid systems with mechanically efficient siphons, pumps, and materials.

In order to differentiate the proposed system from other commercial systems, information on existing technology and commercial systems was gathered. A benchmark study was conducted to compare the proposed system metrics to those of existing commercial systems. This study indicated that the aquaponics system, besides being less expensive than other large-scale systems, had additional benefits that actually provided a lower-cost, long-term solution due to its durable and sustainable design.

Through interviews with experts, the team was able to define needs and metrics to design the ideal system. The translation of the customer statements into system needs and then product specifications led to a clear project scope. Interviews with fish and plant experts stressed the importance of making the proposed system easy-to-use, easy to understand, and easily accessible for everyday people with no prior plant or fish knowledge.

The created aquaponics system is a community-sized system implemented in a community garden for a local soup kitchen, Loaves and Fishes. The design of the system has gone through many iterations, from the barrel design created last year to an IBC design, and ending with the current design, which is mostly constructed of wood containers with pond liners. The new system has many advantages, including a larger size, monitoring mechanisms, and being low maintenance. The simple design with bell siphons to control water flow and vertically overlapping containers prevents water loss due to leakage. Container space is reduced by having a fishpond dug into the earth and using a raft system both reduces costs for expensive media and increases food yield in a smaller area with less water.

As a result of all these advantages, it is expected that this system will be more accessible and sustainable than those of the competitors and will provide the soup kitchen with more fresh fruits and vegetables than traditional farming.

Many lessons were learned in the design process, especially regarding frugal innovation practices. One of the most important was to remain flexible, since the design of the system changed frequently as new information was discovered and the client provided feedback. This channel of communication was also crucial to understanding client expectations and needs, since the system is a project for them to use and invest.

Although the team does not have enough data based on the difference between traditional forms of farming and the aquaponics system, current results remain positive, since many of the seeds planted have not only germinated but have already started to sprout over the course of the three weeks. Other than the pump breaking two times, the system has operated continuously. It has been completely off the grid for the last month, with the solar panels and batteries providing enough power throughout the course of a day. The only time the system was shut off was over the course of a weekend, when it rained consistently. Since fish were added too early into the system, unfortunately, two of the forty tilapia fingerlings have passed away. The sensor system proved a little difficult to integrate due to the team's inability to connect to Goodwill's Wi-Fi and the numerous moving trailers in the parking lot. However, future work can address this concern.

As with any large-scale system, there have been many challenges. For future iterations, it is advised that aquaponics systems should be installed inside or in areas where the weather is more consistent, especially if the system is off-the-grid and powered by solar panels. A more controlled environment will also help prevent algae growth and ensure that the system runs consistently. Furthermore, the energy storage system could be expanded, which will allow the system to run for longer periods of time when there are consecutive rainy days with little sunshine. Since these specific lead-acid batteries also do not have long life expectancies, fronting the cost for a more sustainable battery may be a future option. Lastly, this system has many parts, which may malfunction or break, so it is recommended that Loaves and Fishes maintains spare parts and understands specified procedures for maintenance.

In the end, the team is proud of creating a physical system for a non-profit organization that they can physically use and experiment within the future. The team hopes the system will be used by Loaves and Fishes for many years to come and that the aquaponics system will produce lots of nutritious vegetables to be served in the soup kitchen and inspire others to create similar aquaponics systems within their own backyards or gardens.

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Appendices

Appendix A: Configurations of Aquaponics System

Table A1. Configurations of aquaponics system

Type of System	Image of System	Main Characteristics
Use of Sump/Flood Tank to hold excess water at the top		• Flood/Sump Tank: holds excess water at the top • Grow beds in middle • Fish tank on the bottom System created out of 55-gallon barrels in Uganda in 2018 by a previous senior design team for small-households made with frugal materials
Typical aquaponics system without sump tank		• Grow bed on top without sump tank • Fish tank on the bottom Popular, cost-effective, and simple setup made from food grade intermediate bulk container (IBC) tank that can grow more fish

Both aquaponics systems presented in Table 3 prioritize the use of strong containers to hold the fish.

Appendix B: Potential Users

The aquaponics system is designed for an urban farm, but similar aspects of the design can be translated for a community center, school, or food bank. Although the team decided to partner with Loaves and Fishes, the team also considered partnering with two other organizations. The first is Sacred Heart Community Center. Sacred Heart focuses on helping the East San Jose community with housing, food and clothing insecurity and the second option is Catholic Charities. Catholic Charities partners with many local organizations and has a large network to help the aquaponics system make the largest difference possible. In providing any of these organizations with an aquaponics system, more money could be spent on buying other food and resources, while saving money on plants that thrive in an aquaponics system.

Appendix C: Deciding between Aquaponics, Hydroponics, and Aeroponics

Table C1. Comparison of aquaponics, hydroponics, and aeroponics

Criteria	Aquaponics	Hydroponics	Aeroponics
Scalability	5	5	3
Upkeep cost	2	3	2
Training	2	3	3
System cost	3	3	2
Waste	4	2	3
Outputs	5	3	3
Total	**21**	**19**	**16**

Table C1 compares three soil-less farming methods, Aquaponics, Hydroponics, and Aeroponics. The three methods were compared using various criteria such as scalability, training, waste and outputs. The three methods were ranked on a scale from 1 to 5, with 5 being the highest. As one can see, aquaponics has the highest score. While aquaponics has the drawback of more training and upkeep costs due to caring for the fish, it uses less water and has the added value of being a protein source. Hydroponics was also considered but was decided against as it wastes a large amount of water and still requires significant upkeep. Finally, aeroponics is not a good solution for Loaves and Fishes as it is too complex and is expensive. From this information, the team decided to pursue aquaponics to help address the problem of food insecurity in San Jose.

Appendix D: Need Finding

D.1 Interviews

<u>Loaves and Fishes Volunteers</u>

Questions and Answers

How do you feel about aquaponics in general?

- Aquaponics is new and exciting, has a lot of possibilities
- Good for school kids
- Requires a lot of maintenance

Do you see any benefits compared to traditional farming?

- Not yet, need to see productivity
- More experimental
- Expensive to start
- Cannot see how it would be more productive that traditional farming
- Would be more beneficial where the soil is bad, but the farm has good soil
- Valley of heart's delight-clay rich soil

What aspects of traditional farming are you unwilling to part with? What aspects are inconvenient?

- Planter boxes make it easier to control weeds
- The guys are from the dirt generation, so this is quite new
- Gardening with dirt is therapeutic and calming
- They like to play in the dirt
- Attune with nature
- Keeps them active
- Loaves and Fishes (not commercial)
- Supplemental food
- Spread Loaves and Fishes message
- Work w/ volunteers and part of the experience to help

What is the most difficult part of maintaining a garden?

- Weeds, but not super convenient to them
- Drip lines also make it easier
- Depends on the crop for raised beds, because some crops need more room
- Rotate crops

Why do they want the system? What do they hope to gain from it?

- Excited to see how it works
- Will experiment with different crops
- Will the crops taste different?
- Good experiment and good for kids if it works

How long do they expect the system to last?

- As long as there is a SCU student

- Out of the box for them
- 5 years
- Very uncertain about it right now
- New classes could modify, refine, or add things

How much "maintenance" do they want?

- Water level
- Fix leaks
- Feed fish
- Willing to do quite a bit

Expectations for how much the system can grow (plants and fish)?

- Want 100% of holes in the rafts

Is the system the right size? Do you foresee scaling in the future?

- Perfect size
- No comparison
- Not going to build it themselves, but open to dedicating another plot in the future if it works

Traditional garden user interview: Jack

Questions and Answers

If you could have a higher yield and larger harvest, do you think you could switch over to an aquaponics system?

Yes

What aspects of traditional farming are you unwilling to part with?

Soil, I am one with the earth

What aspects of traditional farming are inconvenient for you?

Watering and figuring out how much to water
Weeding and maintenance
Don't grow fast enough

What is the hardest part about maintaining your garden/farm?

Weeding
Bending over

Summerwinds Nursery: Kim

Questions and Answers

If you could have a higher yield and larger harvest, do you think you could switch over to an aquaponics system?

Yes, definitely
The basic concept is interesting, but I can't see people using it more functionally. Maybe school children would be really interested.

What aspects of traditional farming are you unwilling to part with?

Aquaponics is more complicated and less traditional
"End results is very important"

What aspects of traditional farming are inconvenient for you?

Depends on what you're doing and on the age of the people

What is the hardest part about maintaining your garden/farm?

Getting the soil prepared correctly is an inconvenient part that

Petco: Paul

Questions and Answers

How many fish can go into one tank?

Generally, one gallon of water is required per inch of full-grown fish

What other requirements are needed to maintain a healthy environment for the fish?

The water must be oxygenated and kept clean

Fish Culturist 1 and 2: Debra

Questions and Answers

How many fish can go into one tank?

It depends on size of tank and the size of the fish

How do we prevent disease?

Do not feed the fish too much

Do not leave fecal matter on the bottom

Warmer water-higher possibility of disease

What is power feeding?

Feeding food multiple times a day smaller amounts so that they grow faster

Other advice?

Buy medicated fish feed if fish get some disease

OnePointOne Meeting:

Meeting Notes

Leafy greens grow best

Useful Resource: Cornell CAA handbook

What are we trying to do

- Feed people?
- Create new technology?
- Make something that lasts a long time?
- What value are we adding?

Problems common with Aquaponics

- Bacteria
- Sick fish

Advice

- Need to train people to keep it running
- Talk to farmers for cost comparison
- Try something new
- Uganda is completely different than locally
- Make sure that you know what they want even if they don't say it explicitly
- If we can't do it for 10% including labor cost, buy it off the shelf

Real core of this problem is to match engineering with humanitarian, include that part in senior design paper

D.2 Need Finding Matrices

In order to learn more about what features need to be included in the system to make a successful aquaponics system, many interviews were conducted, and the results are reported below:

Table D1. Summary of interview responses

Name	Title	Comments
Kim	Summerwinds Nursery worker	● Would use an aquaponics system for its use of less water ● Basic concept is interesting, especially for children ● Could not see it used at homes For traditional farming... ● Enjoyed watching product grow and picking produce ● Disliked soil preparation because she uses steer manure and worm casting to ensure soil fertility
Paul	Fish attendant at Petco	● Fish need certain amount of space to grow and thrive ● Per 1-in of fully-grown fish, 1-gallon water needed ● Regulation of dissolved oxygen above threshold is most important
Debra	Ex-fish culturist for the state government	● Prevent fish disease by not overfeeding to prevent excess fish feed rotting in the tank, lowering water temperature, keeping tank clean, and not stressing fish ● Medicated fish feed can prevent disease from spreading ● Power feeding fish to get fish to maturity faster by feeding fish multiple times a day, but without excess food left over
Sam Bertram	CEO and co-founder of OnePointOne	● Kale, arugula, and lettuce grow well in hydroponic systems ● Discussed some of the challenges that the project may face, including training people to take care of system, having disease circulate around the system, and spread disease from fish to plants. ● Recommended buying parts off the shelf if the team could not produce them for less than 10 percent of the cost ● Think about how the team could be creative with the system, such as implementing a vision system to start collecting data, develop algorithms and create a sequel database.

From these interviews, much was learned about how to farm and the needs of potential customers. The most impactful takeaways indicated that most of the hardships, inconveniences, and difficulties involved with traditional farming could be alleviated with aquaponics. Specific details of aquaculture from Debra and design thinking from Sam helped advance the project most.

From the raw data acquired from customer and expert interviews, the customer statements were recorded in the table below. The customer statements reveal the main points from the interviews, the problems that people face, as well as the parts of a system that they do like. All of this information was then converted into a needs statement which are shown in column two. The needs statements specifically reveal important attributes of a successful system.

Table D2. Customer statements and corresponding needs statements

Customer Statement	Needs Statement
I love the feeling of soil-Jack	System feels intuitive when planting the seeds
I don't want to spend a lot of time maintaining the garden-Jack	System is low maintenance
I am unsure of how much water to give my plants-Jack	System clearly shows how much water needs to be added
Aquaponics is too complex for most-Kim, Summerwinds	System is simple to use and requires little maintenance
Best part is seeing produce grow and picking the produce-Kim, Summerwinds	System grows produce year around and is quicker than traditional farming
Getting soil prepared is most difficult part-Kim, Summerwinds	System clearly shows how much nutrients the water has and if any additional nutrients are needed
My fish need 1 gallon of water per inch of full-grown fish-Paul, Petco	Fish tank is large enough to accommodate enough full-grown fish
My fish need proper oxygen levels and the water needs to be clean-Paul, Petco	System provides adequate oxygen and filtration to maintain water quality
To prevent disease, you shouldn’t over feed the fish, otherwise the extra food goes to the bottom and rots-Debra, Fish Culturist	System is easy to clean to prevent fish disease and the water quality sensor are accurate
The water temperature should be kept lower to prevent disease, but a higher water temperature helps the fish grow faster - Debra, Fish Culturist	System maintains a cooler water temperature to prevent disease but not too cold that fish cannot grow
If you can build it for 10% of the cost of store bought items, including labor, then built it yourself-Sam, OnePointOne	Use most efficient means and methods of producing the system and internal components

D.3 Needs Hierarchy

In order to learn more about what features need to be included in the system to make it successful many interviews were conducted. The people interviewed include an employee at Summerwinds Nursery, an employee at Petco, a fish culturist, Sam Bertram, the CEO and Co-founder of OnePointOne, a company that focuses on aeroponics. From the five interviews, much was learned about aquaponic farming and the needs of potential customers. The most useful takeaways involved alleviating pain and inconvenience involved in traditional farming through aquaponics.

From the raw data, acquired from customer and expert interviews, a needs hierarchy was established to rank the needs of a customer base or client from most crucial to least relevant. This list also included needs that can be implied.

After gathering all of the customer needs statements, including implied needs, the formal needs hierarchy was formed. In Table D3, the first column contains the main categories of needs, ranking from highest to lowest, with the most critical need at the top. These main categories of needs are then broken down into more specific sub-needs. These sub- needs will help in the integration of the customer needs into the system design.

Table D3. Needs hierarchy

Need **System**	**Sub-Need 1** **System**	**Sub-Need 2** **System**
Easy to use	Easy use and maintain	Notifies user of poor water quality
Personal	Can be modified for a specific user's needs and goals	Can be expanded or scaled based on customer need
Reliable	Does not require replacing many parts	Works when it is cloudy
Easy to install	Has small footprint	Can be installed without special tools
Controls are precise	Records temperature, pH, and dissolved oxygen levels accurately	Maintains temperature, pH, and dissolved oxygen levels accurately
Long lasting	Does not leak water	Resists clogging
Good investment	Affordable to purchase	Affordable to maintain water

As seen in Table D3, the designed aquaponics system must be user-friendly, low- maintenance, and long-lasting. These characteristics are all goals for the team and will help ensure that the designed system is something that Loaves and Fishes will continue to use for many years.

The information gathered in the customer and expert interviews was analyzed and translated into needs, as seen in Table D3. In Table D4, these requirements were further dissected into more specific ones, each focused on a unique and singular need, and categorized for ease of comprehension. In the last column, the importance of each need is ranked on a scale of 1 to 5: 5 being of critical importance and incorporation into the design and 1 being least important.

From this table the needs of each part of the aquaponics system can be understood and one can easily gather a holistic view of the system.

Table D4. Needs categorization and ranking

Need Number	Category	Need	Imp
1	Sensors	pH is maintained at safe levels	5
2	Sensors	Dissolved oxygen is maintained at safe levels	5
3	Sensors	Water temperature is maintained at safe levels	5
4	Sensors	Maintain water level at constant level	4
5	Sensors	Electrical conductivity is maintained at saft levels	5
6	Power supply	Solar requires little maintenance and is easy to install	5
7	Power supply	Pumps and sensor systems always on	5
8	Plants	Grows fresh produce	5
9	Plants	Resistant to pests and disease	5
10	Plants	Can grow a variety of fruits, vegetables, and herbs	4
11	Fish	Fish live till maturity	5
12	Fish	Fish are adaptable	5
13	Filtration	Filters solid waste	5
14	Filtration	Filters dissolved waste	5
15	Plumbing	Low maintenance	4
16	Plumbing	Easy to install and maintain	3
17	Plumbing	Pumps water from filtered fish tank to plants	4
18	Plumbing	Doesn't get clogged easily or often	4
19	Plumbing	Siphon drains water from the grow bed	4
20	Nitrogen cycle	Maintains healthy levels of nitrate for the plants	5

Need Number	Category	Need	Imp
21	Nitrogen cycle	Prevents buildup of ammonia	4
22	Nitrogen cycle	Optimize plant growth	4
23	Nitrogen cycle	Optimize fish health and growth	4
24	Size	Scalable	3
25	Size	Modular	3
26	System layout	Grow beds are easy to reach and harvest	4
27	Overall System	Easy to install and maintain	4
28	Overall System	User friendly and intuitive	5
29	Overall System	Does not require special tools to install/maintain	3
30	Overall System	Lasts a long time	5

Appendix E: Building Code for Solar Panel Installation

Table E1. Building code for solar installation

Code	Topic	Requirement	Methods to Address
International Building Code	Flashings and Attachments	1503.2 “flashing shall be installed in such a manner so as to prevent moisture entering [...] penetrations through the roof plane”	Use of sealant around connections
		1507.2.9 “flashing shall be applied in accordance with this section and the asphalt shingle manufacturer’s printed instructions”	Attachments are to flat metal surface, so not relevant
	Fire Considerations	1509.7.2 “rooftop-mounted PV systems must not diminish the fire classification of the roof system.”	Installation onto a metal surface will not diminish the fire classification, since the roof will still contain the same properties
	Structural Loading Considerations	3403 “alterations to the existing building or structure shall be made to ensure that the existing building or structure together with the addition are no less conforming with the provisions of this code than the existing building or structure was prior to the addition.”	Originally intended to have other shipping containers stacked atop, the combined weight of these solar panels about 400-lbs is much less than the average 20-ft container which weighs 5,000-lbs (when empty). Weight will be evenly distributed either through staggering attachments or placing panels in areas with more support

International Fire Code	Firefighter Access	605.11.3.2.1 "modules should be located in a manner that provides access pathway for firefighters."	Modules will be atop the roof in an open parking lot. A 3-ft pathway will be created for firefighter access
	Installation Requirements	605.11.3.2.4 "panels/modules installed shall be located no higher than 3 ft below the ridge to allow for fire department ventilation operations."	The roof is not pitched and does not have a ridge
National Electric Code (Section 690)	Maximum Voltage	690.7.D "live parts in PV source circuits and PV output circuits over 150 volts to ground shall not be accessible to other than qualified persons while energized"	Since the system will not exceed the open circuit voltage of 95.2 V (calculated with correction factor of 1.08), the system should be accessible to qualified persons
	Disconnection of Photovoltaic Equipment	690.15 "The DC output of DC combiners mounted on roofs of dwellings or other buildings shall have a load break disconnecting means located in the combiner or within 1.8 m (6 ft) of the combiner. The disconnecting means shall be permitted to be remotely controlled but shall be manually operable locally when control power is not available."	The load break will be present with the charge controller in case of surges in power. There will also be a way to disconnect from here manually since we are not going to be able to disconnect remotely
	PV System Grounding Configurations	690.41 All PV modules over 50 V have one current carrying conductor connected to ground	This ground cable will also be connected to an 8-ft copper-plated ground rod in the ground as well

	Equipment Grounding and Bonding	690.43 All exposed metal parts of PV systems must also be grounded	8-ft long copper-plated ground rod in the ground will be connected to a ground wire on the chassis and on frames of solar panels when touching. This will also be done for the inverter frame.

Appendix F: Detailed Budget and Bill of Materials

F.1 Estimated Costs

Table F1. Categorization of budget breakdown

Item	Cost	Notes/Rationale
Construction materials to restart existing aquaponics system in Forge Garden for testing	Forge Garden: $500.00	Vegetable farm: vegetable seeds and garden supplies Irrigation system: pumps, spigots, water filters Fish pond: pond liner and fish
Construction Materials for proof of concept (Solar House) and installation of integrated farm in San Jose	Solar House: $2,000.00 San Jose: $500.00	Vegetable farm: media, vegetable seeds, and garden supplies Irrigation system: pumps, spigots, water filters, solar panels, battery Fish pond: pond liner and fish Control System: sensors and raspberry pi
Electrical equipment to provide energy for the system and feedback equipment	$1,000.00	Solar system: solar panel, battery, wiring, charge controller Regulating Equipment: Heat exchange system, fan for cooling, heater, and lights,
Contingency	$1,390.00	
Electrical equipment to monitor the system and create an IoT-based regulation and increase use of sustainable material for building of the aquaponics system (*Xilinx Grant*)	$3,000.00	Sensors: water level, temperature, pH, electrical conductivity Microcontroller: photon particle, data software, IoT web-based platform Picohydro: Alternator, turbine, proof-of-concept materials,
Total	**$8,390.00**	

Table F2. Detailed breakdown of budget

	Description/Model Number	**Unit Price**	**Quantity**	**Total Price**
Automation				
Photon Particle	Particle | Photon with Headers	$19.00	2	$38.00
Arduino	Arduino Uno	$22.42	2	$44.84
Water Level Sensor	KSD301 Horizontal Float Liquid	$2.165	6	$12.99

	Description/Model Number	Unit Price	Quantity	Total Price
Electrical Conductivity Sensor	DFR0300 Analog Meter	$68.00	4	$272.00
Temperature Sensor	DS18B20 LAQIYA Thermistor Thermal Probe	$1.983	6	$11.90
pH Sensor	SEN0161-V2 Analog Sensor/Meter	$37.50	4	$150
Heat Exchanger	BP400-20LP Bell & Gossett Heat Exchanger 5-695-00-020-001	$184.95	2	$369.90
Automatic Fish Feeder	PROCHE Digital Automatic Fish Feeder	$18.99	2	$37.98
Automation sub total: **$937.61**				
Electrical				
Solar Panel	Hyundai HiS-S350TI 350W Polycrystalline	$315.00	4	$1260.00
LFP Deep-Cycle Battery	12V, 15Ah Battery (ABS, BLF-1215AS)	$250.00	2	$500.00
Charge Controller	Morningstar Corporation SunSaver MPPT SS-MPPT-15L Charge Controller	$245.00	2	$490.00
Electrical Misc.	Additional wiring, connectors, converter, picohydro			$500.00
Electrical sub total: **$2,750.00**				
Aquaponics Design				
Plant seeds	Green leafy vegetable seeds, (variety of lettuce, spinach, bok choy and kale)	$4/packet of seeds	8	$32

	Description/Model Number	Unit Price	Quantity	Total Price
Clay pebbles	Hydroton Original 50 Liter (33/Plt) [Item # 714116]	$21.75	42	$913.50
Foam rafts	Deep culture raft boards	$119.95/6 pack	2	$239.90
Fish-Trout	For fish tank	$7.00/fish	36	$252
Fish-Goldfish	For forge garden fish tank	$5.00/fish	12	$60.00
275 Gallon IBC Tank-food grade	Grow bed tank (2), fish tank (2), clean water sump tank (2)	$200	6	$1200
Wood	Grow bed structure 2x4s	$2.82	20	$56.40
Fish Food	Microbe Lift MLLSSXL 14 lb Summer Staple Fish Food	$69.99	2	$139.98
Aquaponics Design Misc.	Varied	Varied		$100
Aquaponics Design subtotal: 2993.78				
Pump and Piping System				
5-gallon bucket-food grade	Swirl filter	$4.48	2	$8.96
Basket	Swirl filter	$1.09	2	$2.18
Submersible Pump	Superior Pump 91250 1/4 HP Thermoplastic Submersible Utility Pump with 10-Foot Cord	$47.38	2	$94.76
PVC Pipe	Piping, fittings, swirl filter, siphon, spigots	Varied		$120.00
PVC primer and glue	PVC primer and glue to connect the PVC pipes together	$7.49	2	$14.98

Silicone Sealant	Sealant to repair leaks	$5.49	2	$10.98
Piping Misc.	Filters, o-rings, bulkheads	Varied		$100
Pump and Piping System subtotal: **$251.86**				
Tax & Shipping		(20% of Budget)		$1,386.65
Total System Budget with Tax and Shipping				**$8,319.9**

F.2 Bill of Materials

Based on donations from various vendors and choosing more cost-effective materials, the cost of the product was reduced from the estimated cost of $8,319.90 to $5,680.69.

Table F3. Detailed bill of materials

Item	Description	Model #	Unit Price	Quantity	Total
Sensors	Arduino Uno	R3	$22.42	1	$43.08
	Breadboard Solderless with Jumper Cables	ALLUS BB-018	$10.99	1	$10.99
	LAQIYA Waterproof Temperature Sensor	DS18B20	$1.98	6	$11.90
	Gravity: Analog pH Sensor/Meter Kit V2	SEN0161-V2	$39.50	2	$79.00
	Gravity: Analog Electrical Conductivity Sensor /Meter V2 (K=1)	DFR0300	$68.00	2	$136.00
	Gravity: Waterproof DS18B20 Sensor Kit	KIT0021	$9.30	5	$46.50
	Atlas Scientific Dissolved Oxygen Sensor Kit	123552297000	$283.00	1	$283.00
	Industrial pH Electrode - Armor Casing	FIT0348	$60.00	2	$120.00
	Dragino LG01-P LoRa Gateway	LG01-P	$79.99	1	$79.99
	Dragino Lora Shield	RFM95W	$27.99	2	$55.98

Item	Description	Model #	Unit Price	Quantity	Total
Power system	Renogy Rover 40 Amp MPPT Solar Charge Controller	RNG-CTRL-RVR40	$180.00	1	$180.00
	VMAX 12V 155AH AGM Deep Cycle Batteries	MR147-155	$350.00	2	$699.99
	Yinleader 1500W/3000W DC 24V to 110V AC Power Inverter		$99.99	1	$99.99
	2P 250V Low-voltage DC Miniature Circuit Breaker	Walfrontg8yz35e1mf-02	$16.39	1	$16.39
	HQST A Pair 5ft 12AWG Solar Extension Cable		$13.99	1	$13.99
	HQST A Pair 10ft 12AWG Solar Extension Cable		$17.99	1	$17.99
	HQST A Pair 15ft 12AWG Solar Extension Cable		$23.99	1	$23.99
	SolarEpic MC4 Y Branch Connector		$7.50	5	$37.50
	Renogy 9in 12AWG Cables		$6.99	1	$6.99
	BougeRV MC4 Connectors Y Branch 1 to 4 Parallel Adapter Cable		$16.95	1	$16.95
	Southwire 250 ft. 12/2 Gray Solid CU UF-B W/G Wire	13055955	$132.17	1	$132.17
Solar panel chassis	ISO Shipping Container Nut + M12 x 60 mm Hex Set BZP		$36.20	4	$144.80
	Sunpreme Universal End Clamp (silver)	75001055	$7.93	32	$253.64
Fish pond	14' x 18' PVC Pond Liner - Black	PVC1417	$213.52	1	$213.52
	Pond Underlayment - 10' x 20'	170301	$52.94	1	$52.94

	Description	Model #	Unit Price	Quantity	Total
Fish pond	Pond Boss PSWP Pump Barrier Bag		$17.50	1	$17.50
	Hydrofarm Active Aqua Submersible Water Pump, 1000 GPH		$52.66	1	$52.66
	Swimline Heavy Duty Leaf Skimmer	8039SL	$13.34	1	$13.34
	TetraPond Pond Tubing, 1-Inch Diameter, 20-Feet Length	19736	$18.70	1	$18.70
	VIVOSUN Air Pump 950 GPH		$38.99	1	$38.99
	25 ft Penn Plax Airline Tubing for Aquariums	ST25	$5.00	1	$5.00
	VIVOSUN Air Stone 2PCS		$12.99	3	$38.97
	VPC 1 in. x 24 in. PVC Sch. 40 Pipe	2201	$2.13	2	$4.26
	DURA 1 in. Schedule 40 PVC 90-Degree Elbow	C406-010	$1.13	2	$2.26
	Charlotte Pipe 1 in. PVC Sch. 40 S x S x S Tee	PVC02400 1000HD	$1.22	1	$1.22
	Charlotte Pipe 1 in. x 3/4 in. PVC Sch. 40 MPT x S Male Reducer Adapter	PVC02110 0800HD	$1.81	1	$1.81
	DURA 3/4 in. Schedule 40 PVC Male Adapter	C436-007	$0.46	1	$0.46
	1/2 in. x 3 ft. x 25 ft. 19-Gauge Galvanized Hardware Cloth	308225EB	$53.39	2	$106.78
	1-1/4in PVC CAP SLIP	49081136 840	$0.96	1	$106.78
Raft grow beds	LIfegard Aquatics 1-Inch Slip Bulkhead Fitting		$4.40	4	$17.60
	Pressure-Treated Plywood Rated Sheathing, 23/32 in. x 4 ft. x 8 ft	261688	$53.43	6	$320.58

	Description	Model #	Unit Price	Quantity	Total
Raft grow beds	1.5INx5.5INx96IN SUPCOM S4S	737164024770	$15.99	19	$303.89
	1.5INx5.5INx96IN SUPHRT S4S	737164024527	$19.41	6	$116.44
	iHort 338 Plug Tray		$43.50	2	$87.00
	72 Hole Beaver Rafts		$22.00	8	$176.00
	Vinyl Pond Liner 20 oz. 22 mil Heavy Duty White Tarp (15' x 20')		$138.00	1	$138.00
	Miscellaneous Fasteners				$65.69
Media grow beds	AquaParts 12" Bell Siphon with Media Guard		$42.94	4	$171.75
	275 Gallon Intermediate Bulk Container (IBC) Food-Grade		$200.00	1	$200
	Prescott Plastics 8 Pack: 1 1/4" Round Black Vinyl End Cap		$5.70	5	$28.50
	3/4" Red Lava "L.C."		$198.29	1	$198.29
	8"x8"x16" Gray Lite-Weight Std Block	0000-728-780	$2.00	12	24
	1" x 10' PVC Class 200 PE Pipe	754826200624	$3.38	1	3.38
	1" PVC Coupling SXS	49081137540	$0.57	1	0.57
	Steel Extension Spring with Loop Ends, 7" Long, 1.5" OD, 0.177" Wire Diameter	9654K788			$19.27
System inputs	8 Heirloom Lettuce and Leafy Green Seeds		$12.17	2	24.34

	Description	Model #	Unit Price	Quantity	Total
System inputs	CrystalClear Barley Extract Liquid 16 oz		$15.21	1	15.21
	35 Mozambique Tilapia		$145.00	1	$145.00
	20 lbs Fingerling Pellet		$80.70	1	$80.70
	AmazonBasics C Cell Everyday 1.5 V Alkaline Batteries (12-Pack)	LR14-12PK	$10.89	1	$10.89
	PetOmatics Automatic Digital Pond Fish Feeder	FF2	$66.79	1	$66.79
Prototyping	1/4-2-2 Sanded Pine Plywood	7701	$5.45	1	$5.45
	DerBlue Horizontal Liquid Float Switch Water Level Sensor		$2.33	6	$13.95
	Particle Photon	PHOTONH	$20.66	1	$20.66
	QLOUNI Pin Housing Connector Pins Adaptor Assortment Kit		$8.99	1	$8.99
	SunFounder IIC I2C TWI Serial 2004 20x4 LCD Module Shield	B01GPUMP9C	$12.99	1	$12.99
	AHS NAT RIVER ROC	191518664393	$4.66	1	4.66
	CRE FOAM SHEETS	400100241073	$1.10	3	3.3
	Proline Easy Grip Sponge	1919	$3.26	1	3.26
	1/2" PVC EL 900 SKFPT	49081141202	$1.14	1	$20.84
	1/2" x 2' PVC PIPE	811000012159	$1.27	1	$1.27

Prototyping	1-1/4"x2' PVC PIPE	81100022 1254	$2.74	1	$2.74
	Description	**Model #**	**Unit Price**	**Quantity**	**Total**
	FC SMOOTH #128 SH	46501011 763	$8.73	1	$8.73
	Timaik Submersible Water Pump 400 GPH		$13.99	1	$13.99
	Acrylic Sheets from Maker Lab		$10.00	3	$30.00
	CPR Aquatic 1" Thread x Thread ABS Bulkheads	BHCPR10 0TT	$15.77	1	$15.77
	Prescott Plastics 50 Pack: 1" Round Black Vinyl End Cap		$23.95	1	$23.95
	Miscellaneous Wood				12.01
Tools	Dewalt 25' Engineers Scale Tape Measure	76174360 660	$8.83	1	$8.83
	Milwaukee 1-1/4" Bi-Metal Hole Saw		$8.67	1	$8.67
	1/2" x 260" PTFE THRD SEAL TAPE (5 PK)		$5.94	1	$5.94
	HANDY PK: RED HOT BLU GLU + PURP PRIMR	44752342 803	$8.98	1	$8.98
	2.8OZ CLR SILICONE II-KITCHEN/BATH	77027002 843	$3.98	1	$3.98
	Miscellaneous Tools				$41.82

Table F4. Estimated budget of donated materials

Item	Donor	Estimated Unit Price	Quantity	Total
2' x 6' Redwood Planks	Economy Lumber	$10.00	6	$60.00
First Solar Series 4 Solar Panels	First Solar	$351.00	8	$2,808.00
Unistrut P1000T	CBF Electric	$45.03	22	$990.75
Unistrut P1842 Adj. Hinge Connection	CBF Electric	$19.48	16	$311.70
Unistrut P2346 Wing Shape Fitting	CBF Electric	$10.24	8	$81.93
Unistrut UniPier UP-BK	CBF Electric	$22.50	16	$21.26
P3008 Channel Nut	CBF Electric	$1.33	88	$116.93
HHCS037100EG 3/8"x1" Hex Head Screw	CBF Electric	$0.21	88	$18.78
Total				$4,409.35

Appendix G: Benchmarking Calculations

Table G1. Explanation of calculations and criteria

Criteria	**Competitor 1 Aquabundance**	**Competitor 2 Genesis**	**Our Proposed Aquaponics Solution**
Wholesale cost ($)	Cost of the physical system, which excludes additional features such as sensors, solar power, assembly time, fish, plants, and water.		
Area of grow space (sq. ft)	Data calculated based on Competitors' websites and measured within proposed aquaponics solution		
Volume of fish tank/pond (gallons)	Data calculated based on Competitors' websites and measured within proposed aquaponics solution		
Cost per area of plant grow space ($/sq. ft)	Dividing the "Wholesale cost" by the "Area of grow space"		
Cost of energy after 1 year ($) $\$ = P * t * Cost$ *t = 365 days * hours of operation*	Average cost of electricity per kWh is $0.1559*		
	60 W pump 24 hours each day	60 W pump 24 hours each day	Solar Power simply requires cost of initial equipment
	$0.06\ kW * 24\ \frac{hr}{day} * 365\ \frac{days}{yr} * .1559 \frac{\$}{kWh}$	$0.06\ kW * 24\ \frac{hr}{day} * 365\ \frac{days}{yr} * .1559 \frac{\$}{kWh}$	$1125
Cost of energy per plant grow space ($/sq. ft)	Dividing "Cost of energy after 1 year" by the "Area of grow space"		
Cost of energy after 10 years ($/sq. ft)	See table below which also accounts for the fact that over 10 years, electricity rates increase, on average, by 15%**		
Ratio of fresh fish to grow space (lb : sq ft)	lbs of fish that can fit in volume divided by sq. ft 1-lb of fish for every 7 gallons of water		
	(200/7)/45	(140/7)/48	(650/7)/90.6

*https://www.electricitylocal.com/states/california/san-jose/

**https://news.energysage.com/residential-electricity-prices-going-up-or-down/

Table G2. Calculations for cost of electricity each year after installation

Aquaponics	Genesis	Aquabundance	Year	Price of Electricity/kWh
12.42	1.71	8.19	0	0.1559
12.42	3.44	16.51	1	0.1582
12.42	5.20	24.95	2	0.1606
12.42	6.98	33.51	3	0.1629
12.42	8.79	42.20	4	0.1653
20.14	10.63	51.01	5	0.1676
20.14	12.49	59.94	6	0.1699
20.14	14.37	68.99	7	0.1723
20.14	16.29	78.17	8	0.1746
20.14	18.22	87.47	9	0.1769
20.14	20.19	96.90	10	0.1793

Appendix H: Selection Matrices and Drawings

There are several subsystems that had many possible designs, which were weighed using decision matrices in order to decide which subsystem design would be best for the overall system. These include filter, grow bed, and material designs. The decision matrices and some drawings of possible subsystems can be seen in the sections below. In all of the decision matrices, the various options were given a score from one to five for each selection criteria, with five being the best.

H.1 Pond

The first subsystem is the pond. There were three possible design that were considered, which include 50-gallon barrels, large IBC containers, and an inground pond. These designs were weighted using four criteria, cost, time, scalability, and aesthetics. The team decided that all of these criteria are equally important, so they are weighted evenly.

Table H1. Pond selection matrix

		Concepts					
		Barrel		**IBC**		**In Ground**	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Cost	25	3	0.75	2	0.50	5	1.25
Time	25	4	1.00	5	1.25	1	0.25
Scalability	25	1	0.25	2	0.50	5	1.25
Aesthetics	25	2	0.50	2	0.50	5	1.25
Total score		2.50		2.75		3.25	
Rank		3		2		1	
Pursue		No		No		Yes	

As table H1 shows, an inground pond is the best option. An in-ground pond is the least expensive, can be easily scaled to create a pond of any size and dimensions, and is the most aesthetically pleasing. However, it does have one downside of being time consuming to install, as a large hole must be dug, but mechanical equipment can make this process a lot quicker. IBC and 50-gallon barrels are not good choices because they are quite expensive and many of them would be required to make a fish pond the size we need.

H.2 Filters

The second subsystem is the filter design. Four possible designs were weighed in the matrix, which can be seen the table below. These include a swirl filter, a box design, sandpaper design, and media filter. They were weighed using five different selection criteria, simplicity, cost, easy to clean, easy to make large scale, aesthetics. Simplicity and easiness to clean are important, as they are both weighted at 25 percent, because the filter needs to be made of simple parts so that it can be easily manufactured and so that it can be easily cleaned, which will have to occur on a regular basis.

Table H2. Scoring matrix for potential filters

		Concepts							
		Swirl		**Box**		**Sandpaper**		**Media**	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Simplicity	25	4	1	4	1	2	0.5	5	1.25
Cost	20	4	.8	5	1	2	0.4	3	0.6
Easy to clean	25	5	1.25	2	0.5	2	0.5	5	1.25
Scalability	20	4	0.8	3	0.6	3	0.6	4	0.8
Aesthetics	10	2	0.2	4	0.4	3	0.3	3	0.2
Total score		4.05		3.5		2.3		4.1	
Rank		2		3		4		1	
Pursue		No		No		No		Yes	

As one can see from the matrix, the media filter is preferable. It is preferable because it is very simple, and it is easy to clean. Additionally, it is easy to scale it. All these traits make this matrix a better choice over the other designs, which are more complex and have various other drawbacks.

Swirl Filter:

- Uses centrifugal motion to filter the water in a swirling motion
- Waste and dirt are pushed to the bottom of the system and cleaned using vacuum
- Beneficial because easy to operate and construct without being costly

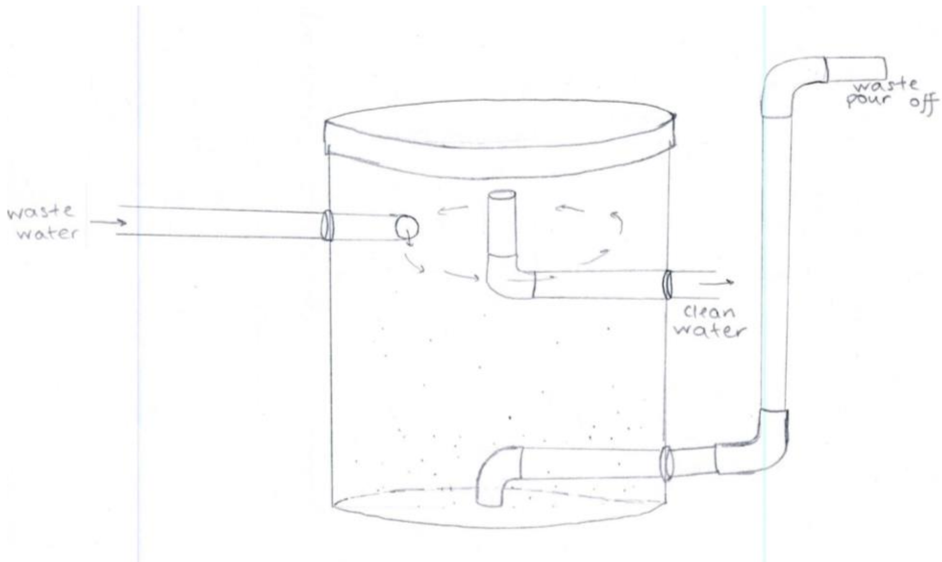


Figure H1. Swirl filter

Box Filter:

- Simple box with foam to separate waste as it falls from the pipes to the drain below
- Beneficial because it is easy to construct and simple

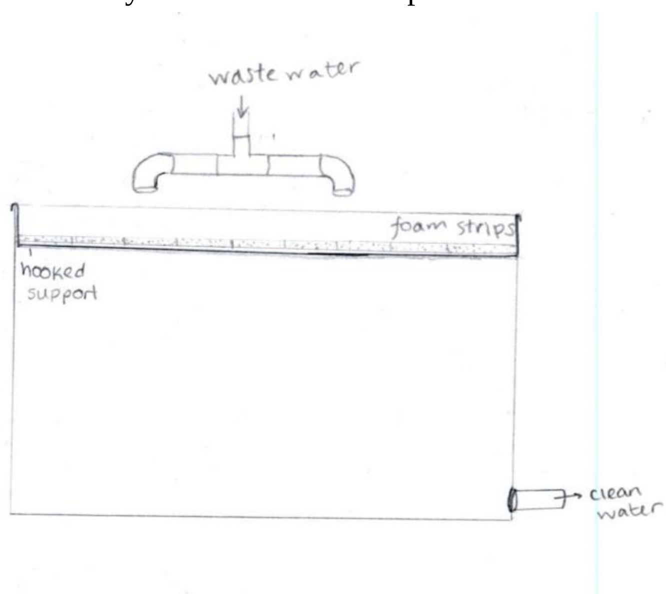


Figure H2. Box filter

Sandpaper Filter:

- Water cycles through the various grades of sandpaper to clear out waste
- Beneficial because it is inexpensive and simple

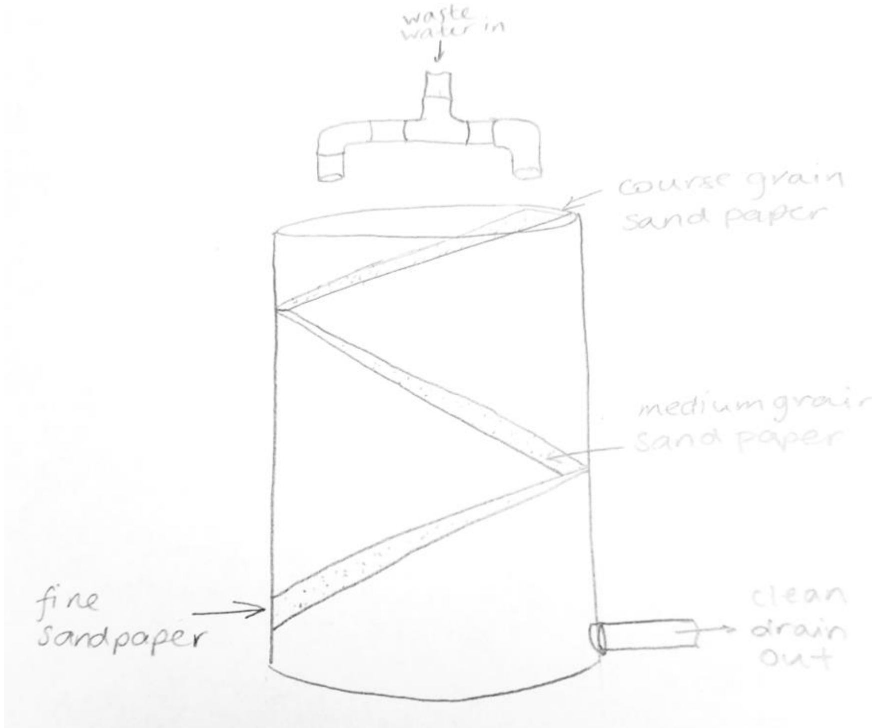


Figure H3. Sandpaper filter

Media Worm Filter:

- Simple box with media and worms to eat solid waste and turn it into food for the plants
- Beneficial because it is easy to construct and simple and has a naturally occurring nitrogen cycle

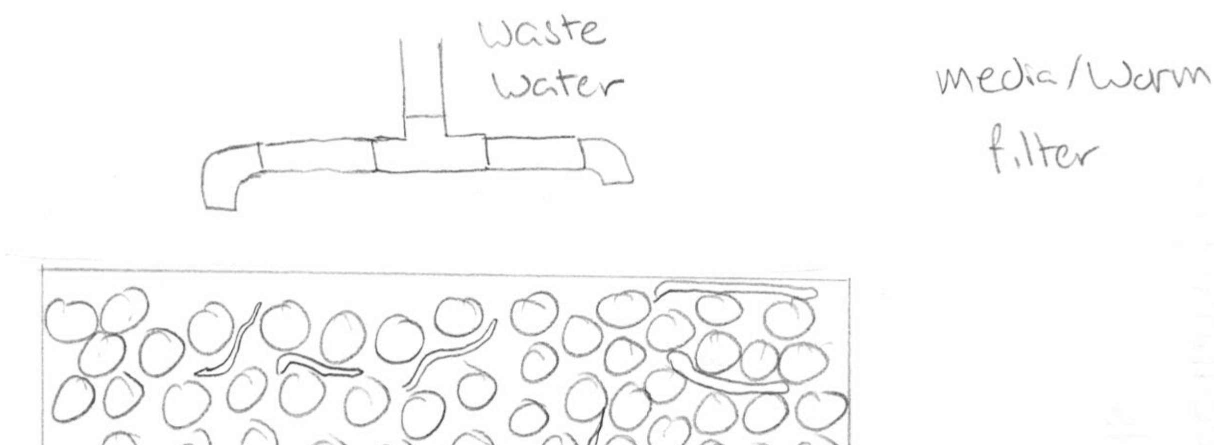


Figure H4. Media worm filter

H.3 Grow Beds

The final matrix is to decide what type of grow bed will be best for the system. The options are nutrient film technique (NFT), media beds, raft beds, or vertical growing. These concepts were selected based on simplicity, filtration required, scalability, plant choices, food production, and cost. Scalability, food production, cost, and filtration were all weighted at 20 percent. These were weighted higher than simplicity and plant choices, because the farm has experienced farmers who have experience growing plants, so they do not require a simple system and because they did not need to grow a wide variety of crops.

Table H3. Scoring matrix for potential grow beds

		Concepts							
		NFT (BCE)		**Media (BC-)**		**Raft (AC)**		**Vertical (DE)**	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Simplicity	10	3	0.3	5	0.5	5	0.5	2	0.2
Filtration	20	3	0.6	5	1	3	0.6	2	0.4
Scalable	20	3	0.6	2	0.4	5	1	3	0.6
Plant Choices	10	3	0.3	5	0.5	3	0.3	2	0.2
Max. Food Production	20	3	0.6	4	0.8	5	1	3	0.6
Cost	20	4	0.8	1	0.2	4	0.8	1	0.2
Total score		3.2		3.4		4.2		2.2	
Rank		3		2		1		4	
Pursue		No		Yes		Yes		No	

Raft and media grow beds received the two highest scores and will be integrated into the design of the system. Media grow beds rank highly because of their simplicity, the fact that it acts as a filter, and because it can grow many different types of plants. The raft grow bed is good in the way that it is simple, scalable, and can maximize food production. By picking two different types of grow beds the system will be more well-rounded. The NFT system was not a good choice because of its complexity and because it is hard to scale and has limited plant choices. Likewise, the vertical design was also not chosen because it is complex, requires filtration, and is expensive.

Nutrient Film Technique (NFT) Grow Material System Design:

- Water is pumped continuously from the fish tank into the grow bed, which is slanted to allow for the water to drain
- Maybe better suited for bamboo or other materials

- Beneficial because it does not use a sump tank, a bell siphon, or media which is expensive

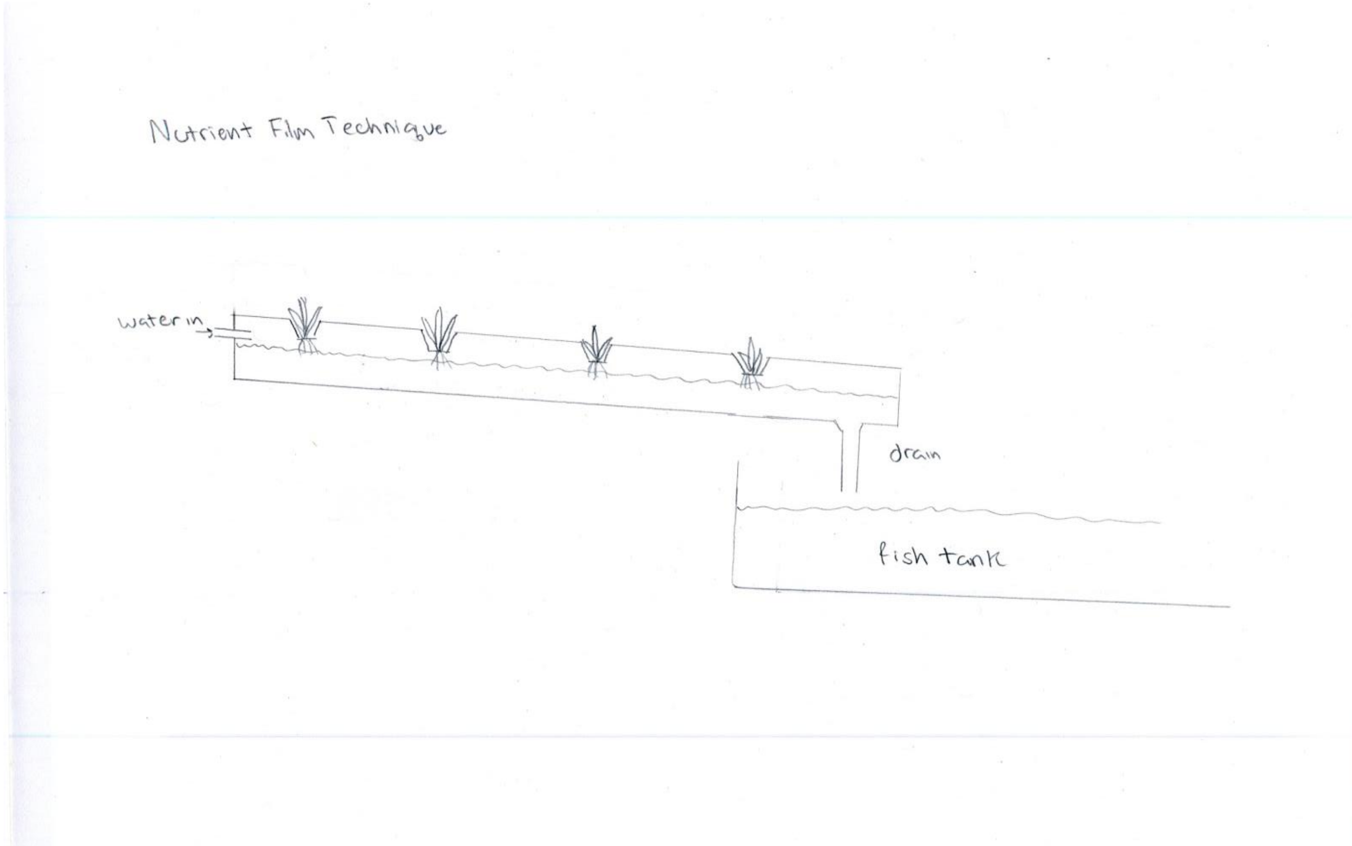


Figure H5. NFT grow bed

Media Grow Material System Design:

- Water is pumped continuously from the fish tank into the grow bed or sump tank, and a bell siphon is used to achieve ebb and flow
- Beneficial because it is intuitive

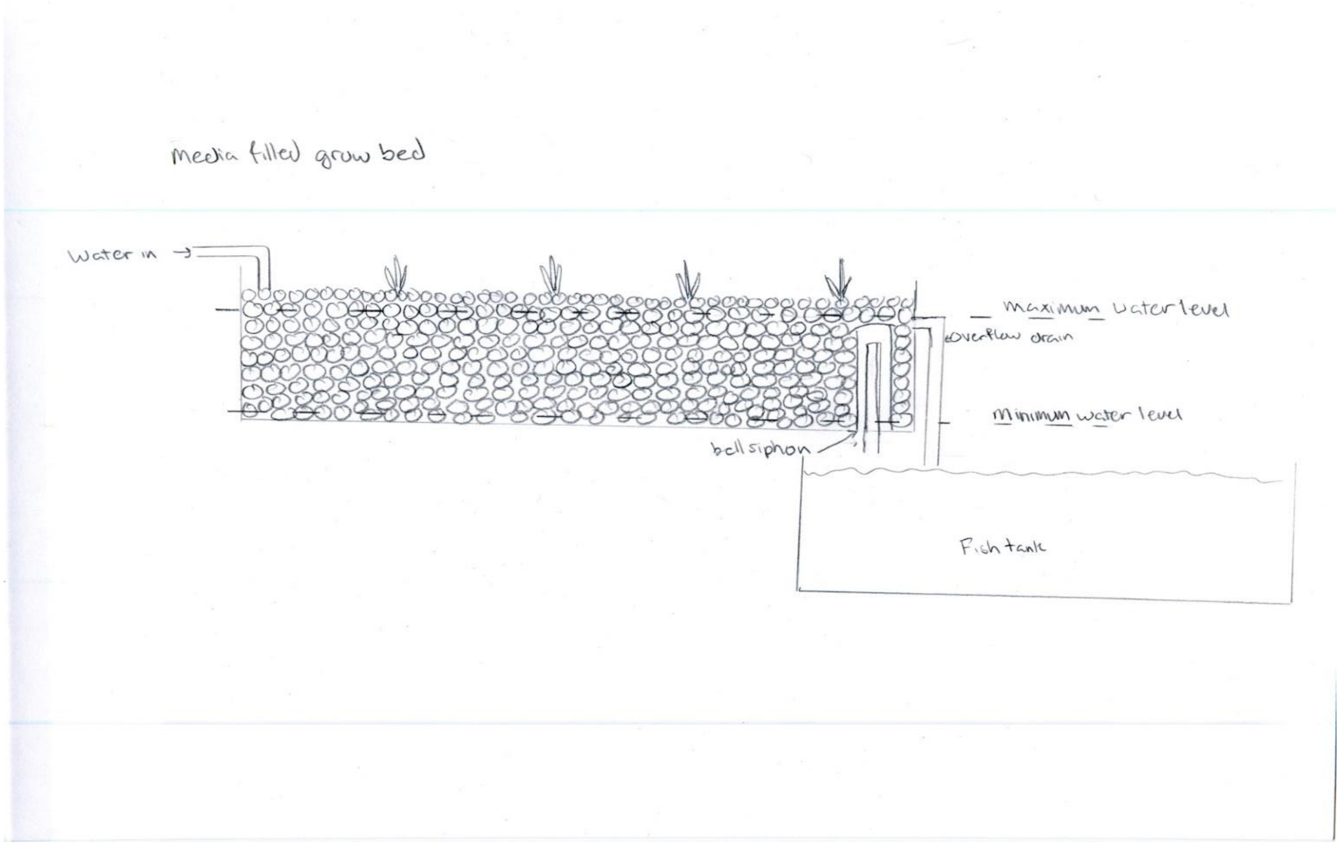


Figure H6. Media grow bed

Raft System Design:

- Beneficial because it is inexpensive than Media and NFT
- Water is continuously cycled through the system
- The foam rafts float on top of flowing water and support the plants

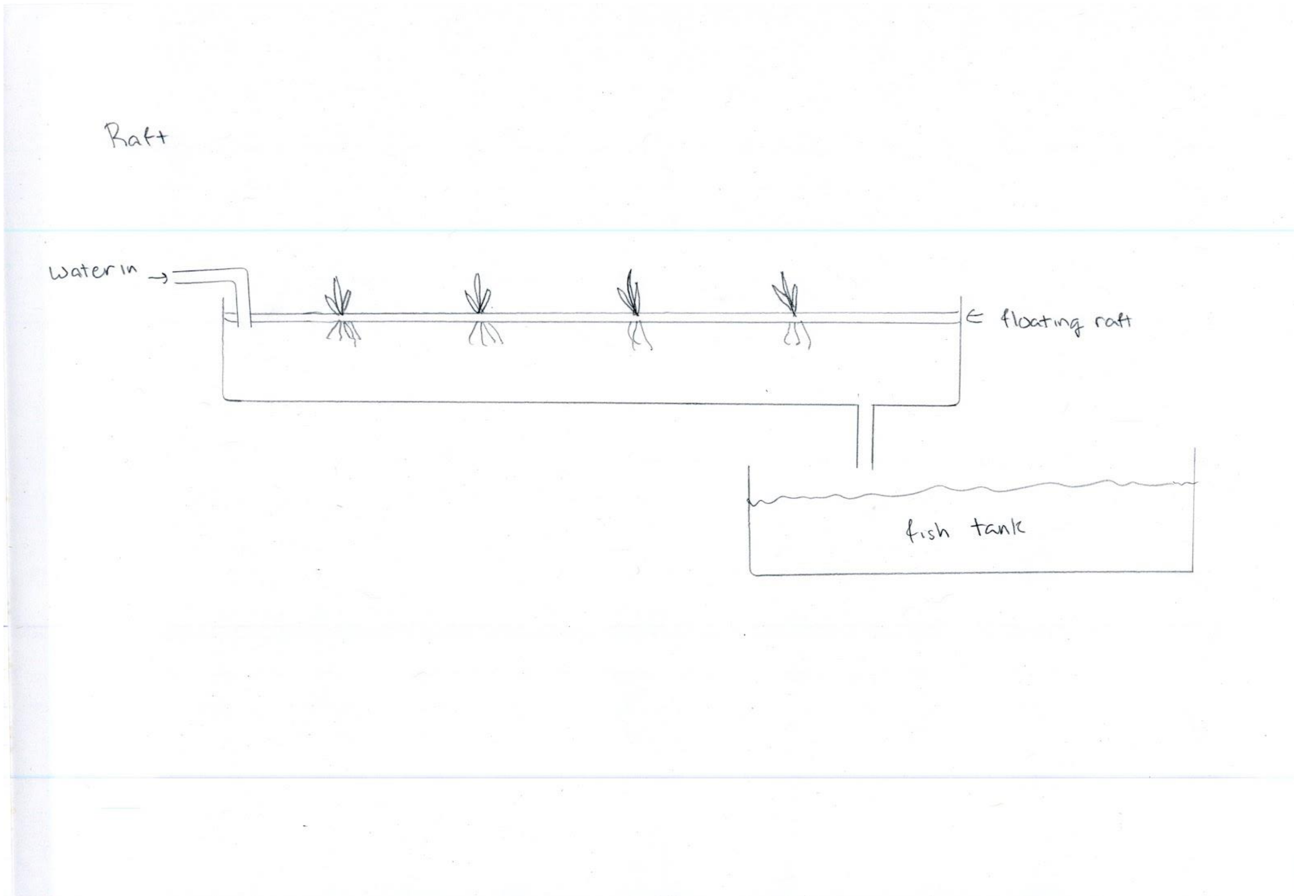


Figure H7. Raft grow bed

Vertical System Design:

- Water will be pumped from the fish tank into the vertical tubes, which will drain back into the fish tank
- Plants will grow out of the holes in the vertical tubes
- Beneficial because of small footprint

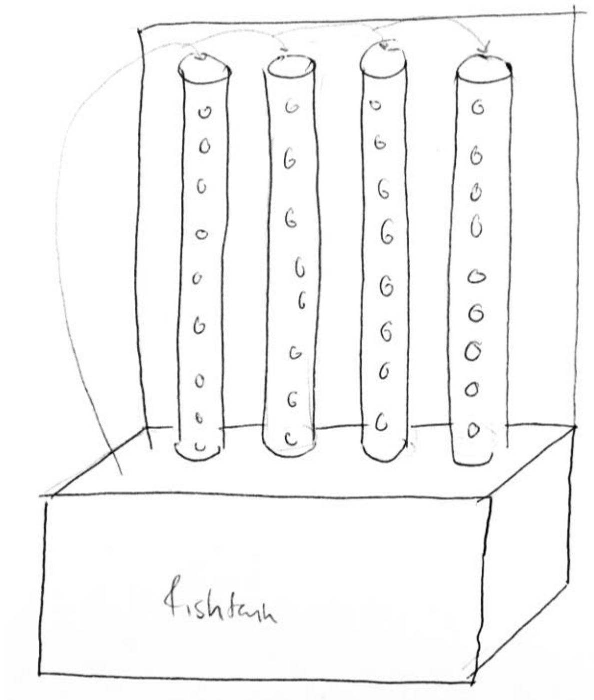


Figure H8. Vertical grow bed

H.4 Materials for Grow Beds

Another subsystem that was examined using a scoring matrix was the materials to be used in the grow beds. The possible designs were barrels, IBCs, bamboo, and wood with liners. The best material for the grow beds was decided based on the access to the material, cost, time to make, scalability, and aesthetics. Access to materials, cost, and scalability were all really important factors. Since the goals of the system were to make a low-cost system and to make the system community sized, these criteria were ranked at 25 percent. Accessibility to the materials is important because of the logistics of receiving the material and constructing the system.

Table H4. Scoring matrix for potential materials

		Concepts							
		Barrell (B)		**IBC (A)**		**Bamboo (E)**		**Wood (FC)**	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Easy access	25	5	1.25	3	0.75	3	0.75	4	1
Cost	25	3	0.75	5	1.25	1	0.25	5	1.25
Time	15	3	0.45	4	0.6	1	0.15	5	0.75
Scalable	25	4	1	5	1.25	2	0.5	4	1
Aesthetics	10	2	0.2	4	0.4	4	0.4	2	0.2
Total score		3.65		4.25		2.05		4.2	
Rank		3		1		4		2	
Pursue		Yes		No		No		Yes	

As one can see from the table, both IBC containers and wood with liners are both good choices. IBC containers are good because they are low cost, require little construction time, and are easy to make large scale. Likewise, wood and liners are also a good choice because of easy access to wood, the low cost of wood, and because wood boxes take little time to construct. The barrels are disadvantages because of their small size and their poor aesthetics. Lastly, bamboo is also not the best material due to the high cost and large time investment to turn the bamboo into grow beds. Overall, both IBC containers and wood will be used in the system.

Barrel Design:

- 55-gallon barrels are used for the fish tank, sump tank and two grow beds
- Beneficial because the material is accessible and lightweight material and inexpensive

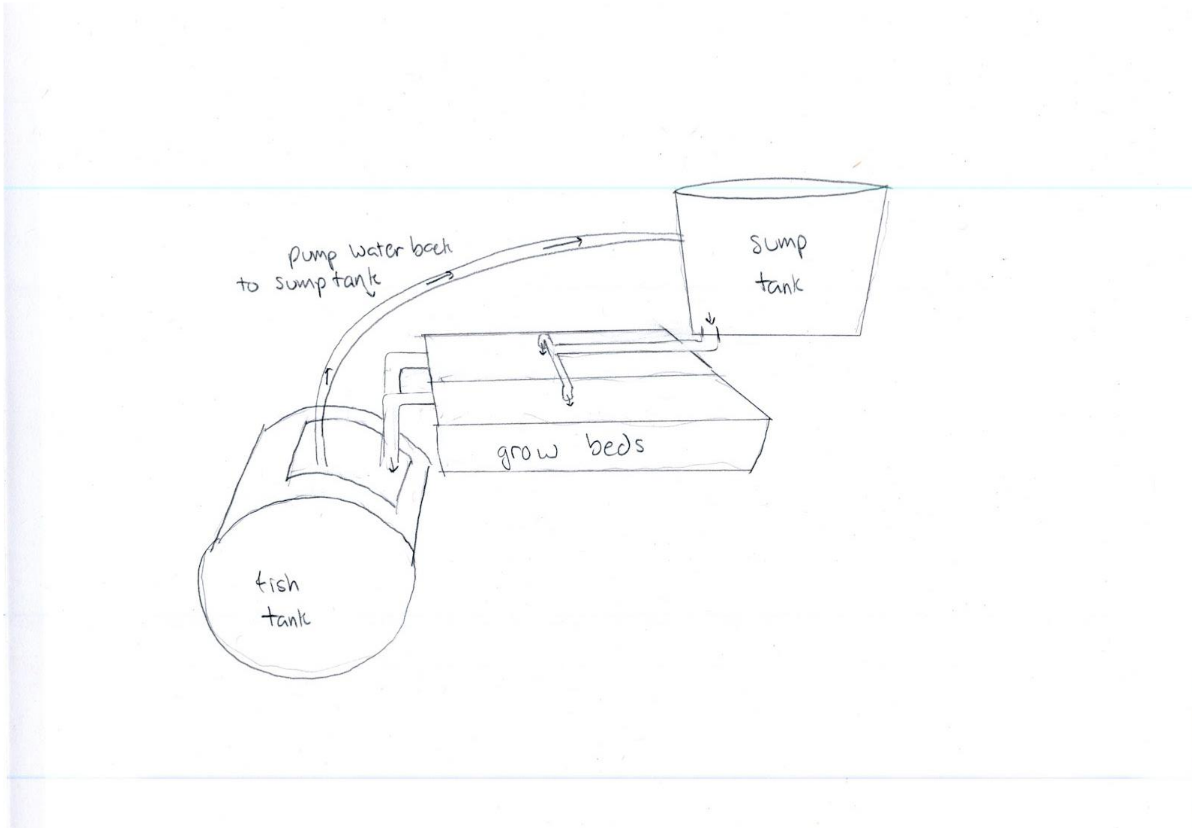


Figure H9. Barrel design

Wooden Tanks with Liners

- The pump will alternate between the two grow beds, allowing for one tank to be filled up while the other is draining. This will result in an ebb and flow system.
- Beneficial because does not include a sump tank or a bell siphon, which makes system simpler

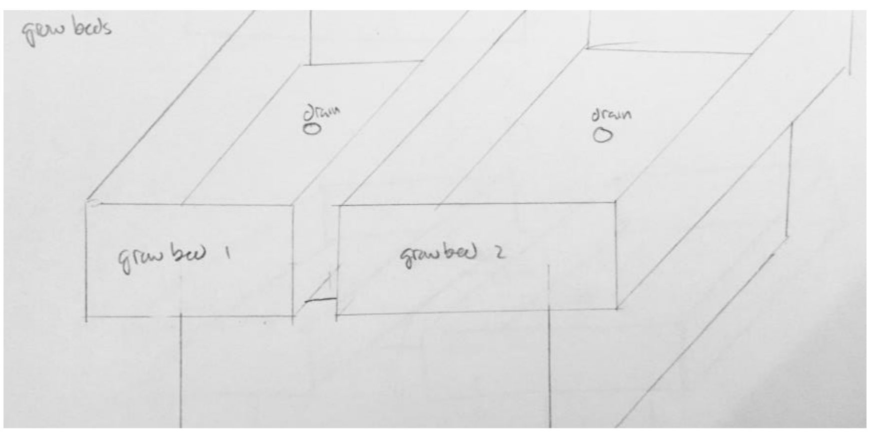


Figure H10. Wood tanks design

IBC Design:

- Large IBC's are used for the fish tank and are cut to provide grow beds
- Beneficial because efficient use of IBC material and aesthetically pleasing

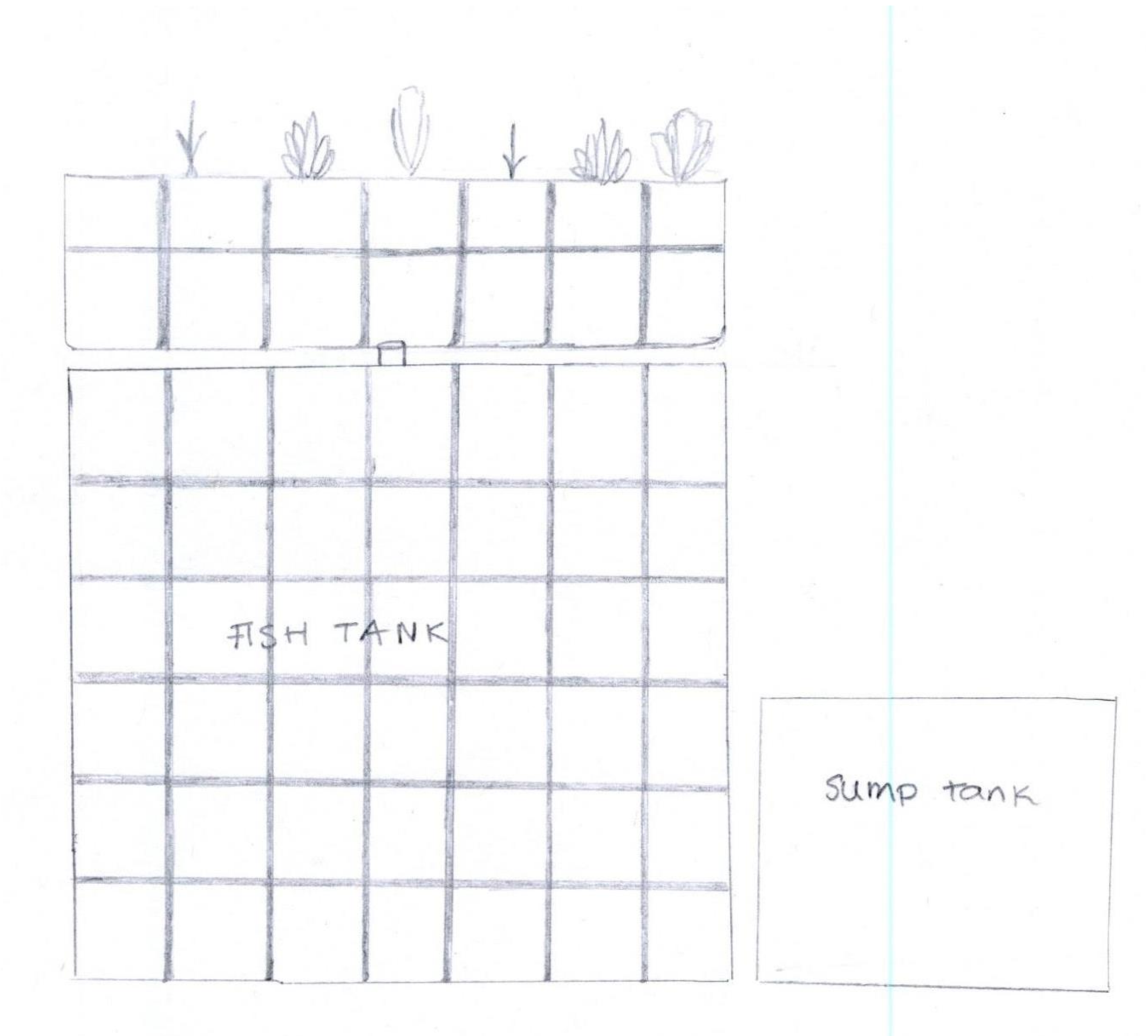


Figure H11. IBC design

Bamboo Design:

- Water will be pumped from the fish tank into the vertical bamboo tubes, with sponges at the first node to filter out waste then drain clean water back into the fish tank
- Beneficial because of small footprint and uses sustainable material

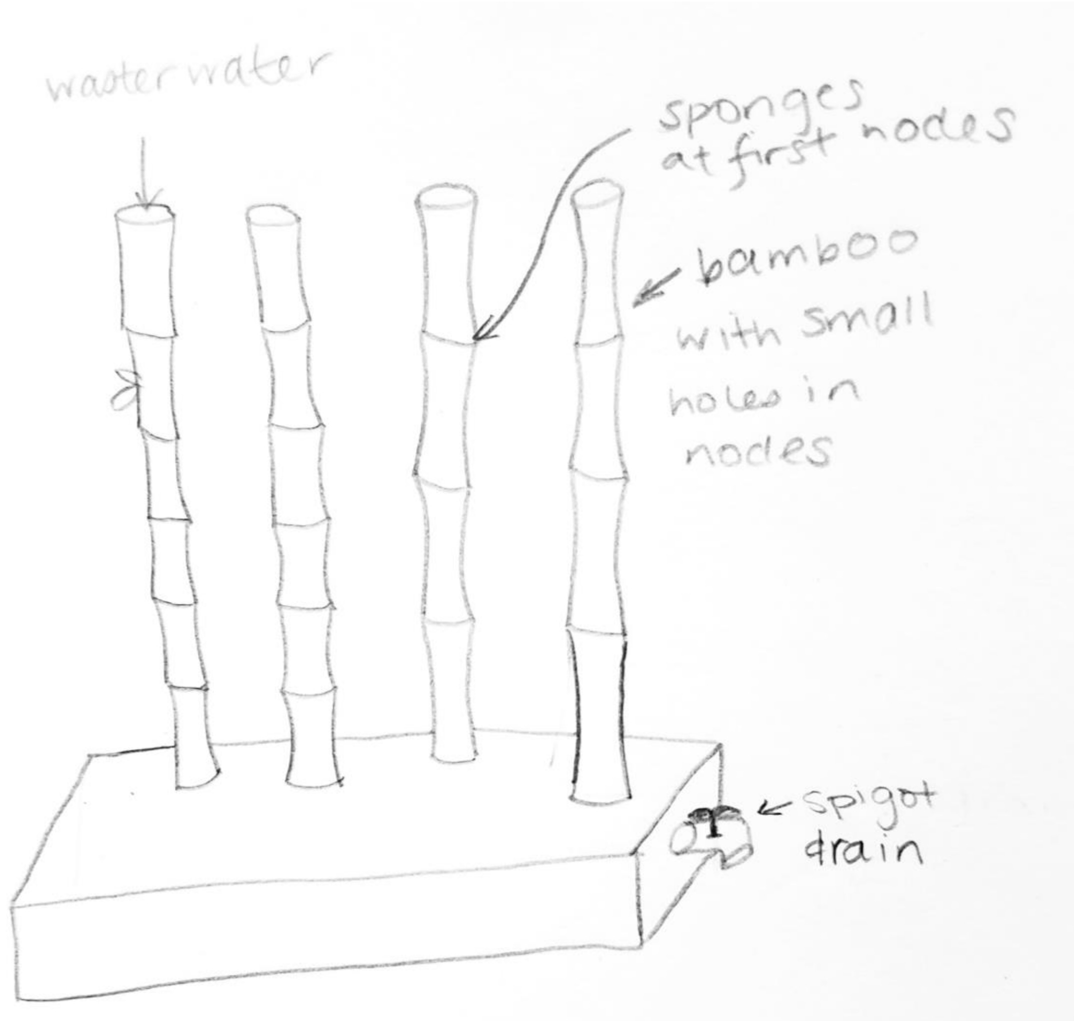


Figure H12. Bamboo design

Appendix I: List of Inputs and Outputs

Table I1. List of inputs and outputs for the aquaponics system

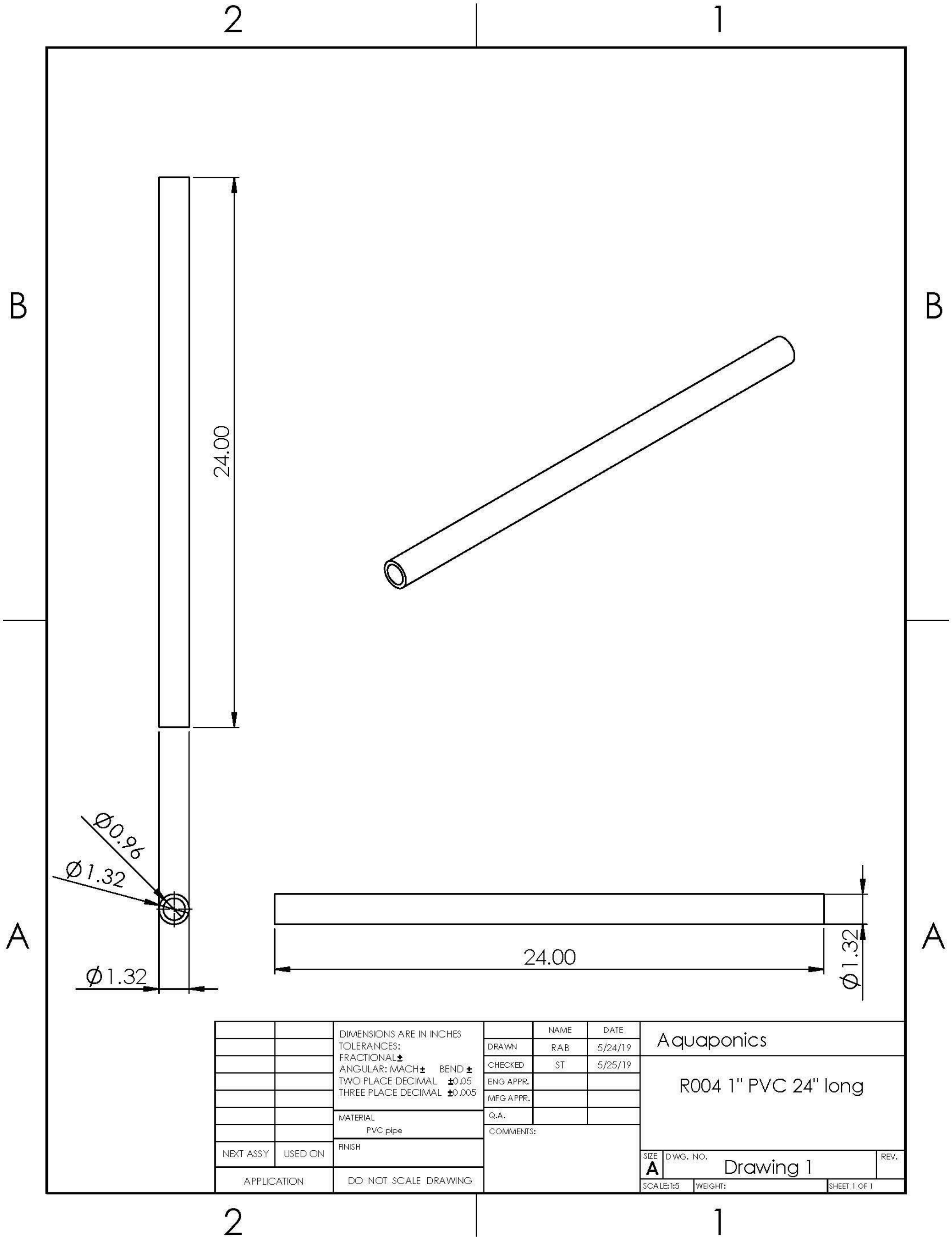
Initial Inputs	**Continuous Inputs**	**Intermittent External Inputs**	**Final Outputs**	**Continuous Outputs**
Water for fishpond	Solar energy	Fish food	Fish	Electricity (pump)
Water for grow beds	Water	Water	Plants	Water (fish waste)
		Fish		
		Plants		

Appendix J: Detail and Assembly Drawings

Attributed Drawings

Riley Albright-Borden -- Drawing 22 Total Aquaponics System

Sydney Thompson -- Drawing 6 Plywood Base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A
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Ø1.32
Ø1.32
24.00
Ø1.32
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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
PVC pipe
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
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CHECKED ST 5/25/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
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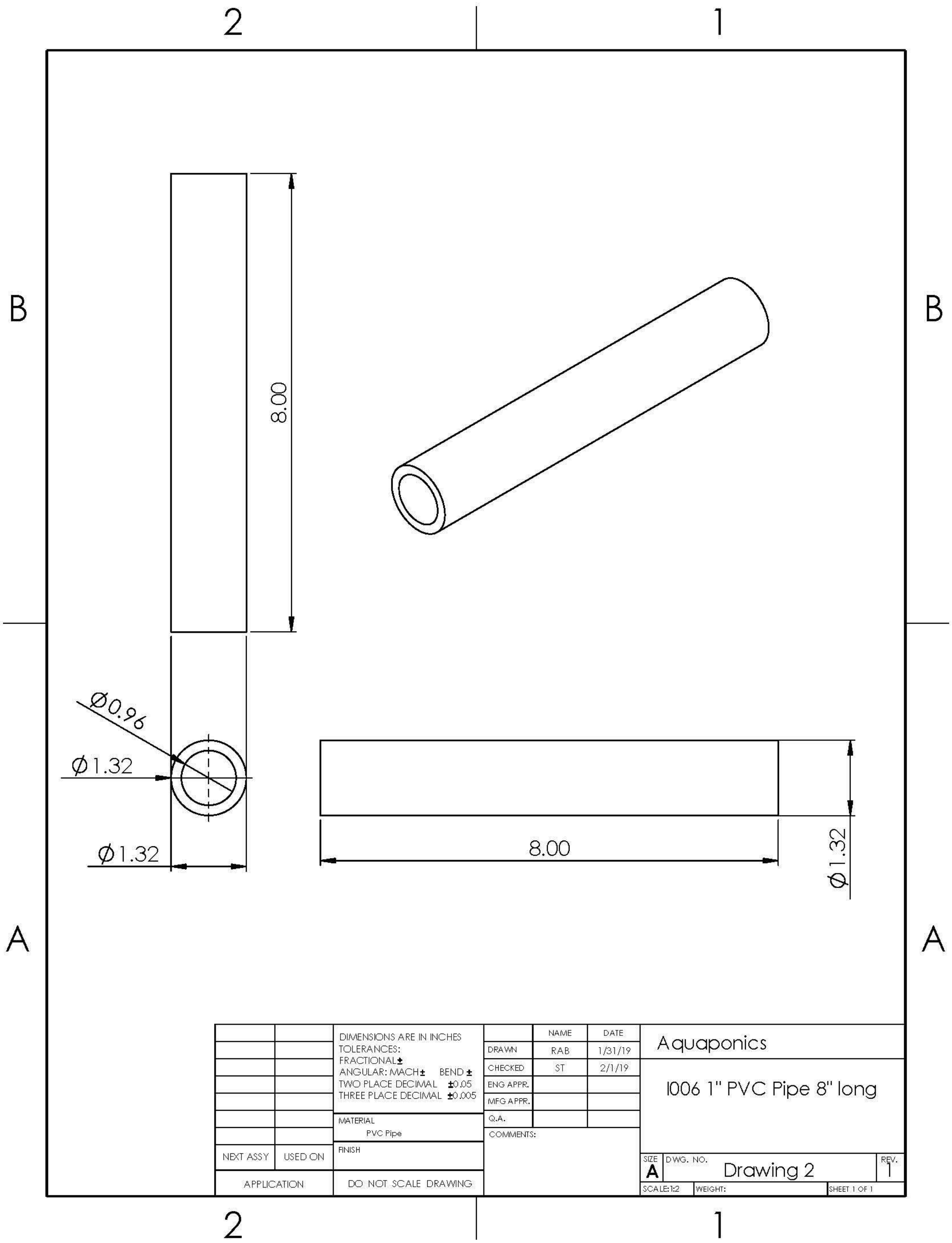
DWG. NO.
Drawing 1
REV.
SCALE:1:5
WEIGHT:
SHEET 1 OF 1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FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
PVC Pipe
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
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CHECKED ST 2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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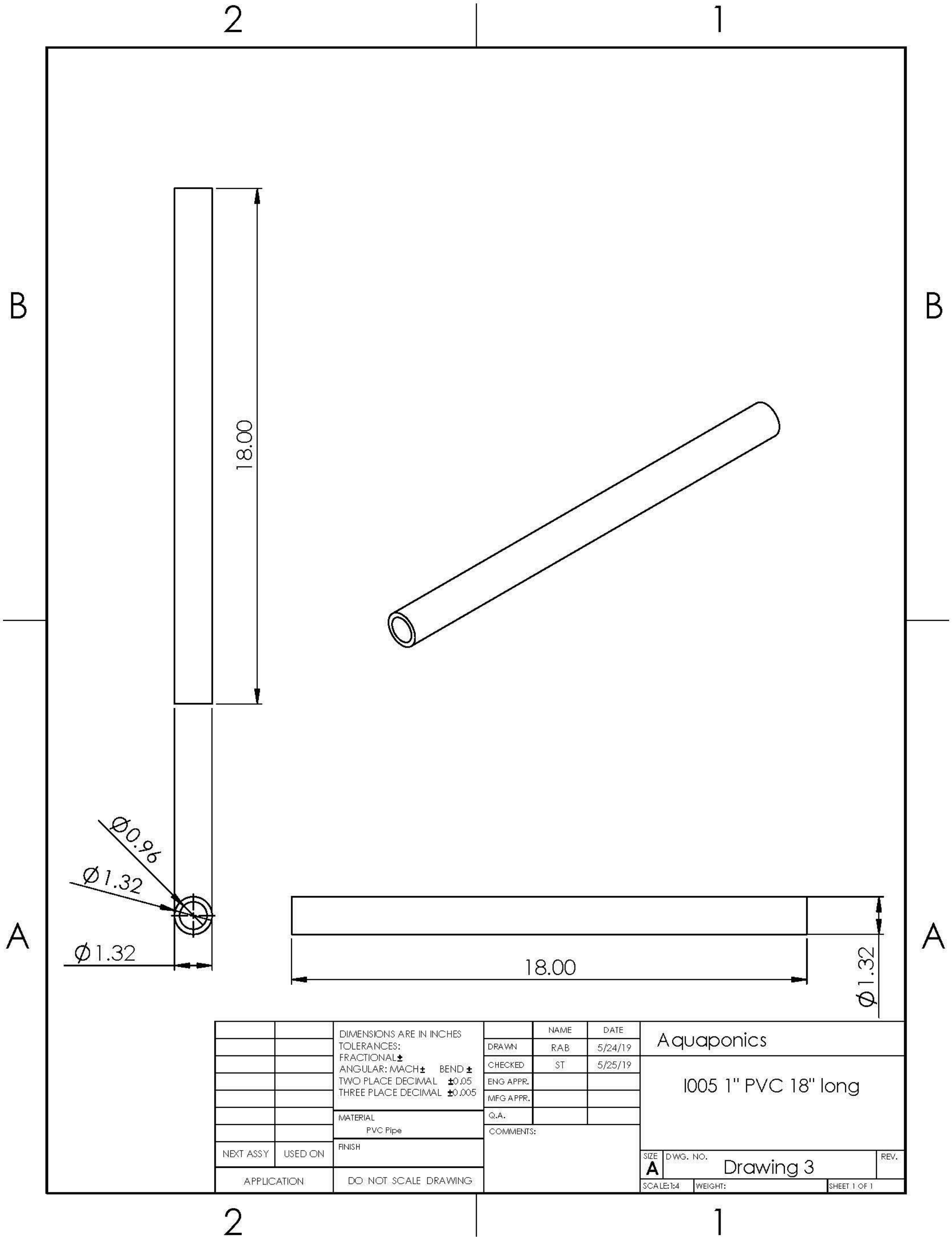
REV. 1
SCALE:1:2
WEIGHT:
SHEET 1 OF 1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Ø1.32
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Ø1.32
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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
PVC Pipe
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
RAB
5/24/19
CHECKED
ST
5/25/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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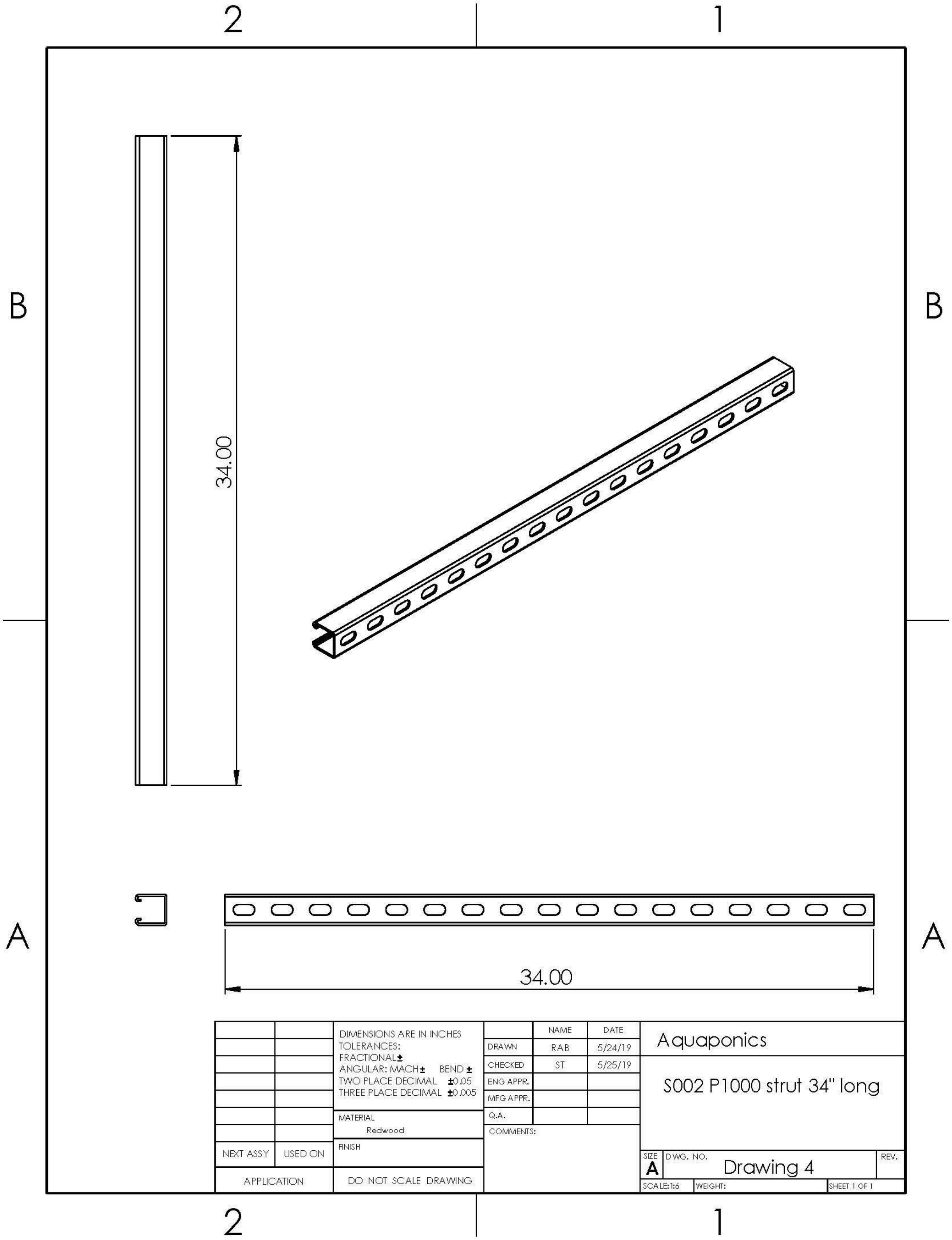
Drawing 3
REV.
SCALE:1:4
WEIGHT:
SHEET 1 OF 1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ANGULAR: MACH± BEND ±
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THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
RAB
5/24/19
CHECKED
ST
5/25/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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SIZE
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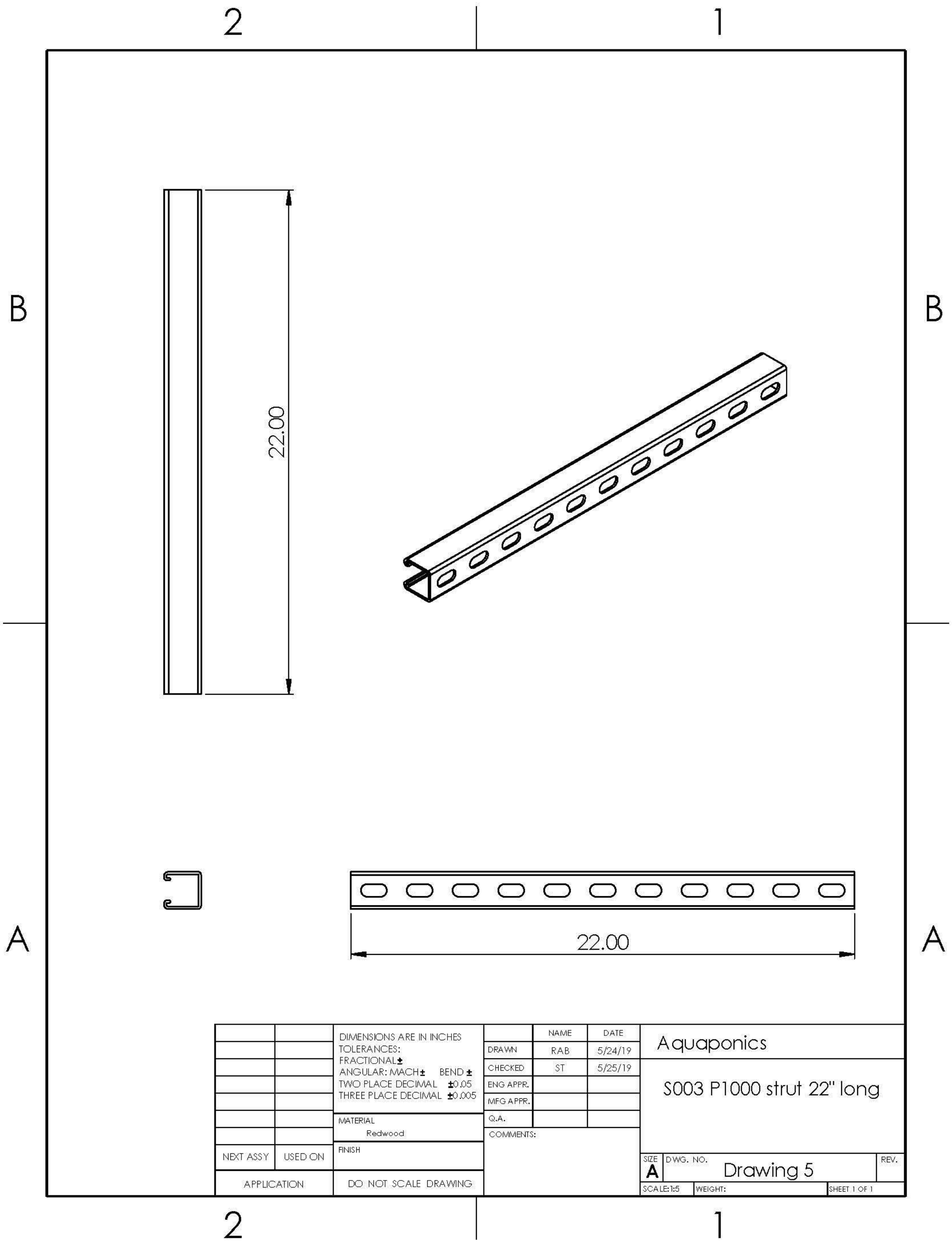
DWG. NO.
Drawing 4
REV.
SCALE:1:6
WEIGHT:
SHEET 1 OF 1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ANGULAR: MACH± BEND ±
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THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
RAB
5/24/19
CHECKED
ST
5/25/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
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SIZE
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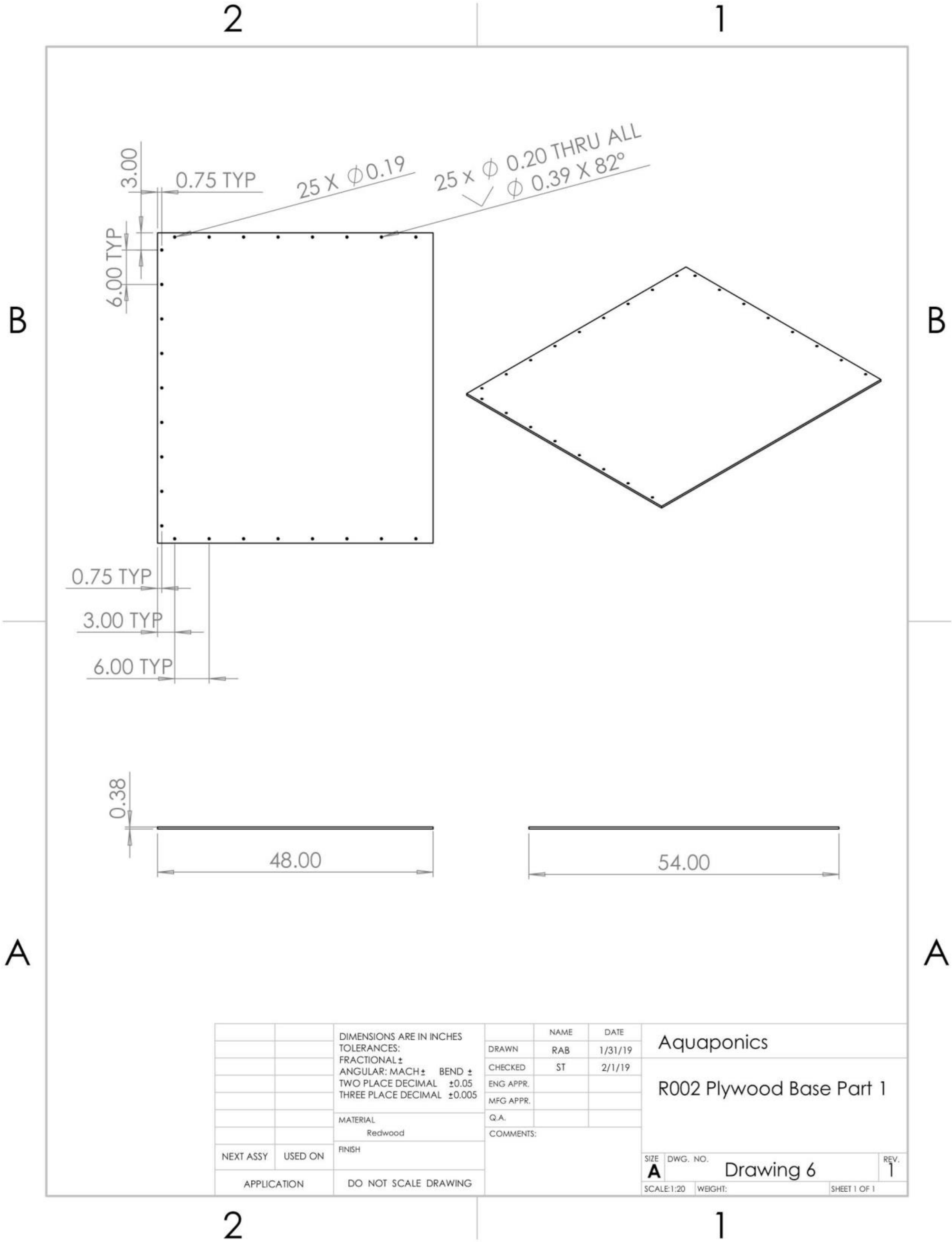
DWG. NO.
Drawing 5
REV.
SCALE:1:5
WEIGHT:
SHEET 1 OF 1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∅ 0.39 X 82°
6.00 TYP
0.75 TYP
3.00 TYP
6.00 TYP
0.38
48.00
54.00
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
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CHECKED ST 2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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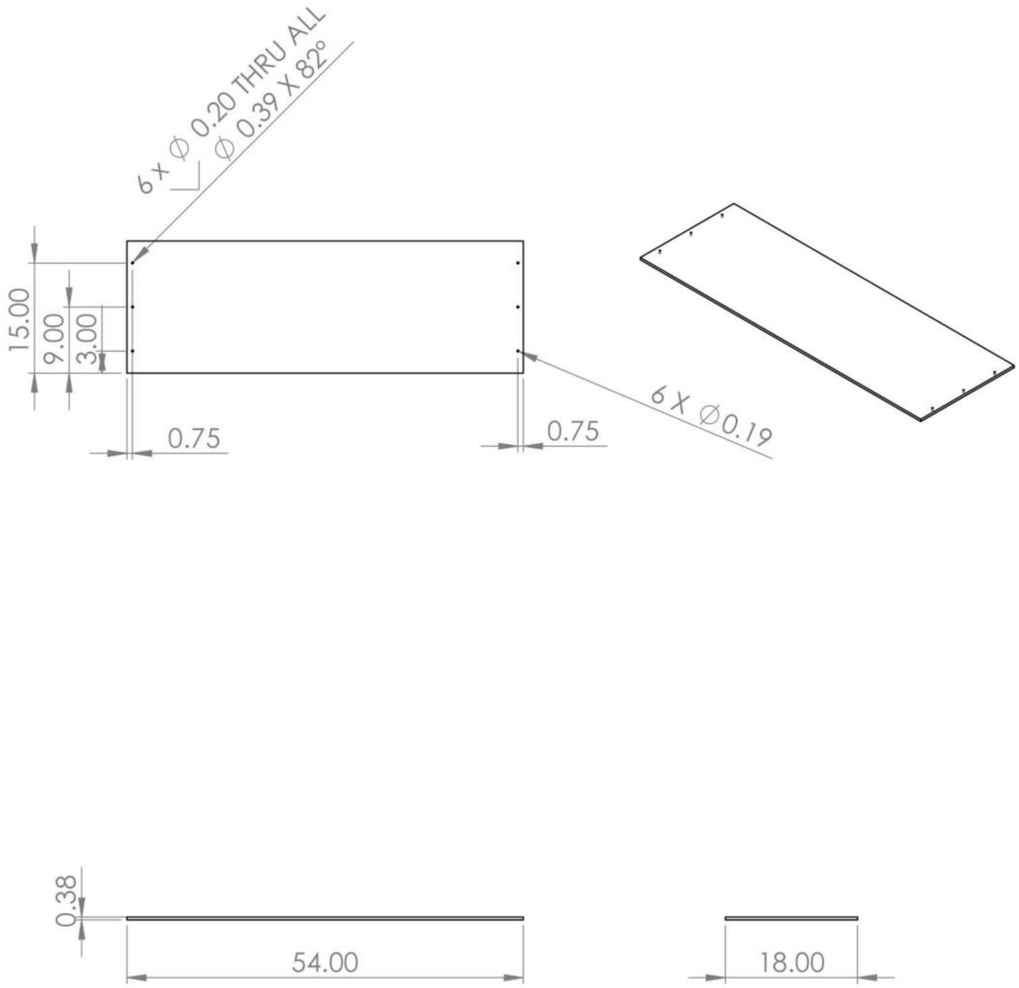
DWG. NO. Drawing 6
REV. 1
SCALE:1:20
WEIGHT:
SHEET 1 OF 1



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		CHECKED	ST	2/1/19	R003 Plywood Base Part 2
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		MFG APPR.			
	MATERIAL Redwood	Q.A.			
NEXT ASSY / USED ON	FINISH	COMMENTS:			SIZE A — DWG. NO. Drawing 7 — REV. 1
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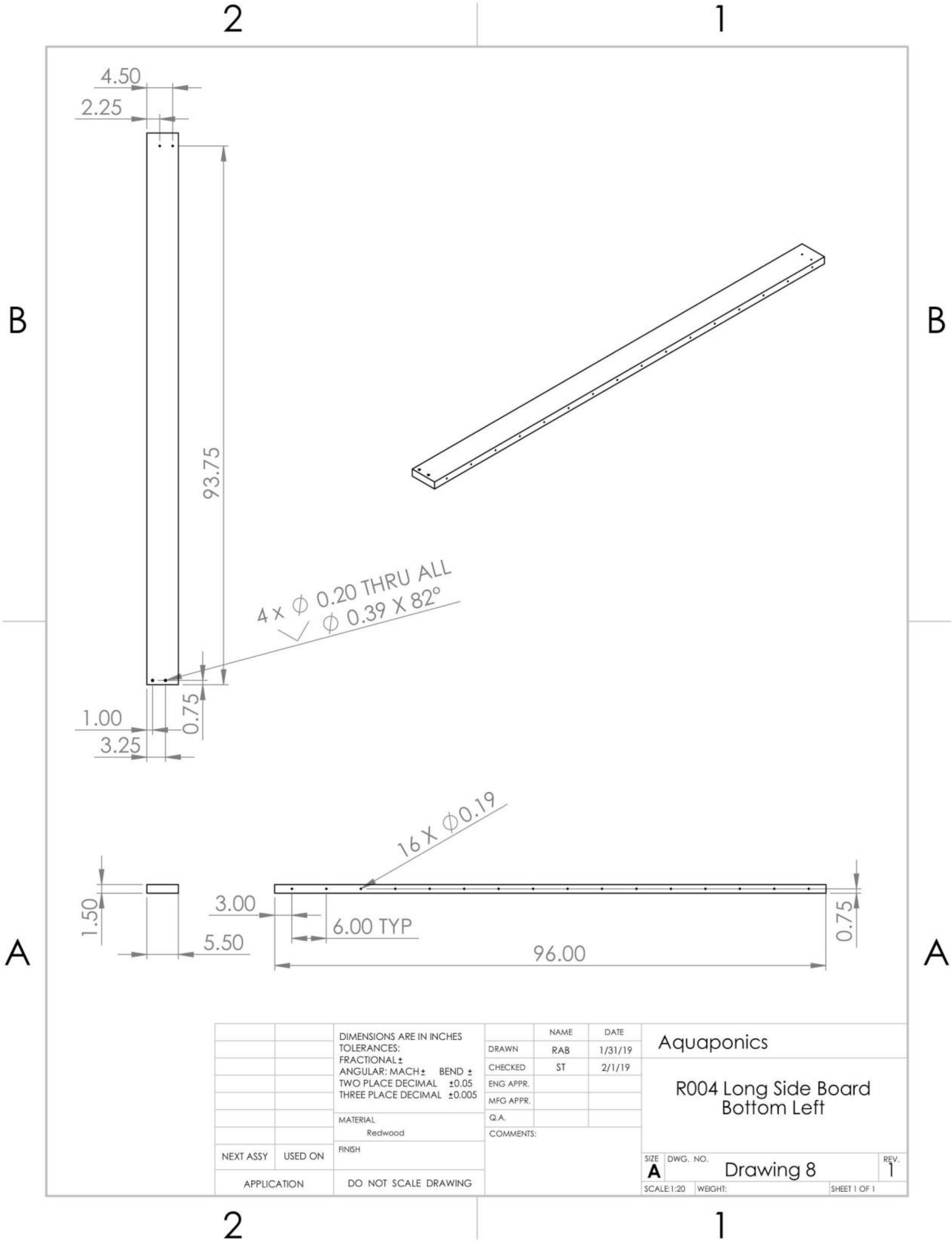
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2.25
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⌵ ⌀ 0.39 X 82°
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3.25
0.75
16 X ⌀0.19
1.50
3.00
6.00 TYP
5.50
96.00
0.75
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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN RAB 1/31/19
CHECKED ST 2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
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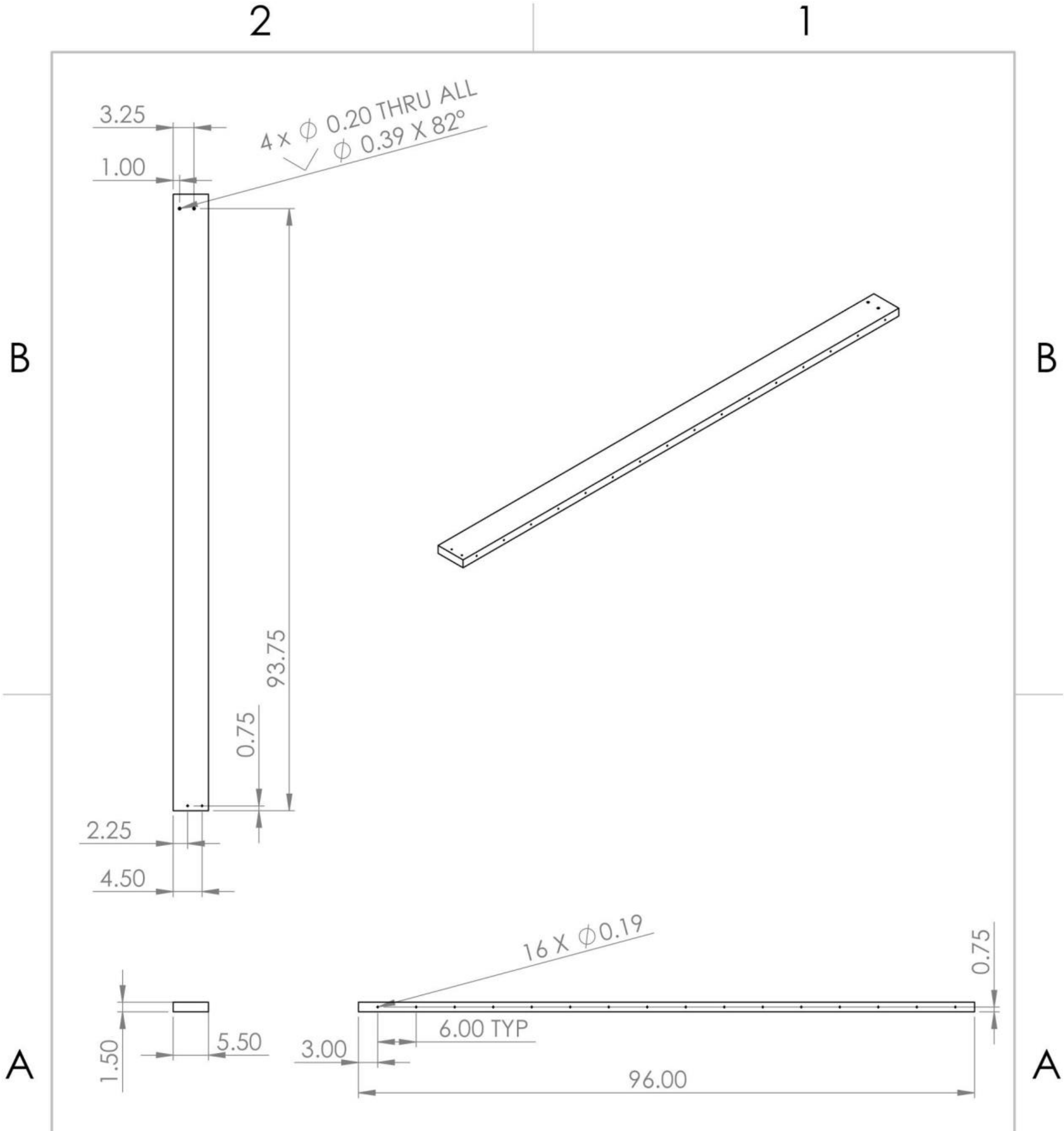
Bottom Left
SIZE A
DWG. NO.
Drawing 8
REV. 1
SCALE:1:20
WEIGHT:
SHEET 1 OF 1



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			CHECKED	ST	2/1/19	
			ENG APPR.			
			MFG APPR.			
		MATERIAL Redwood	Q.A.			
		FINISH	COMMENTS:			
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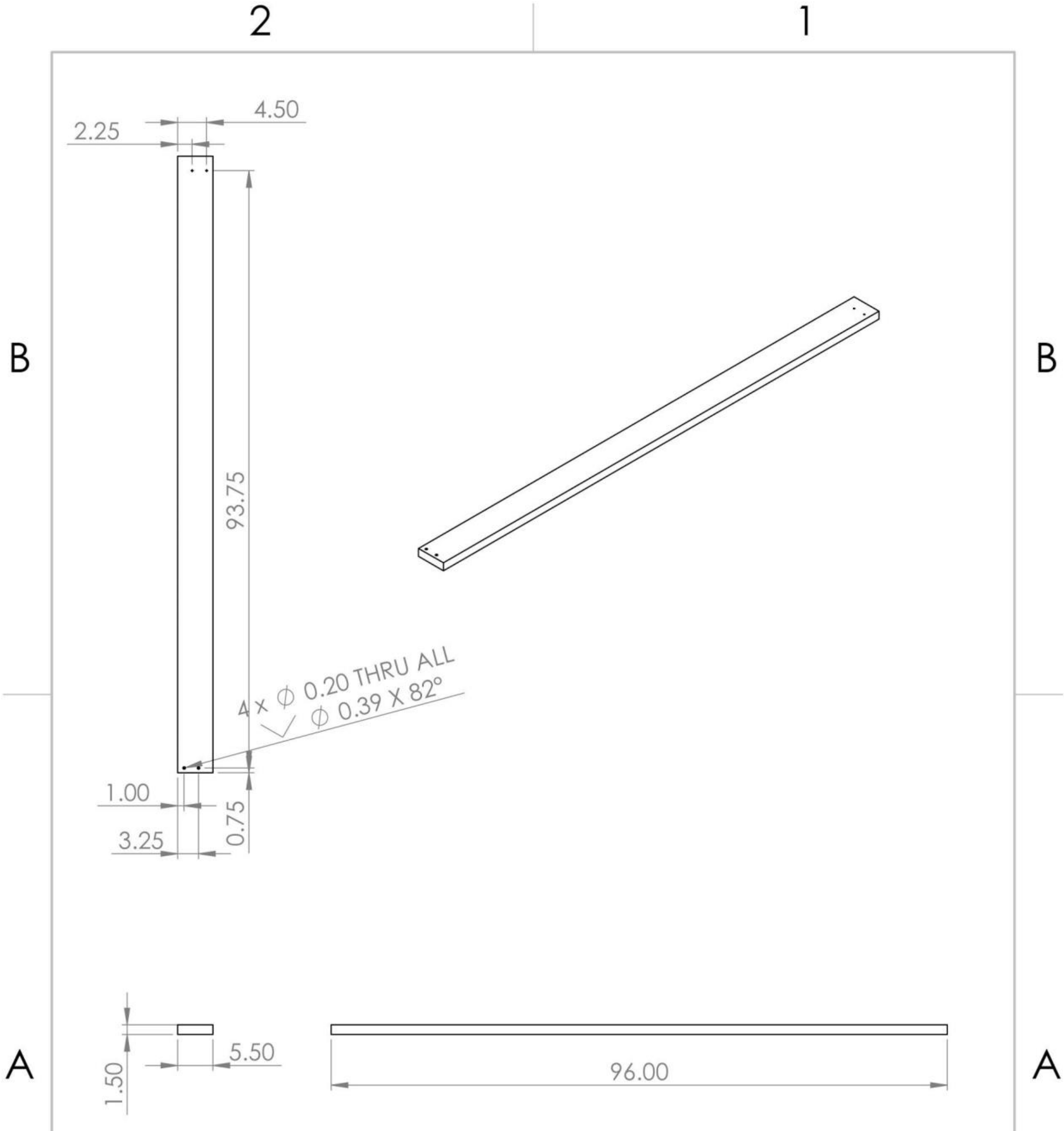

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			CHECKED	ST	2/1/19	R005 Long Side Board Top
			ENG APPR.			
			MFG APPR.			
		MATERIAL Redwood	Q.A.			
			COMMENTS:			
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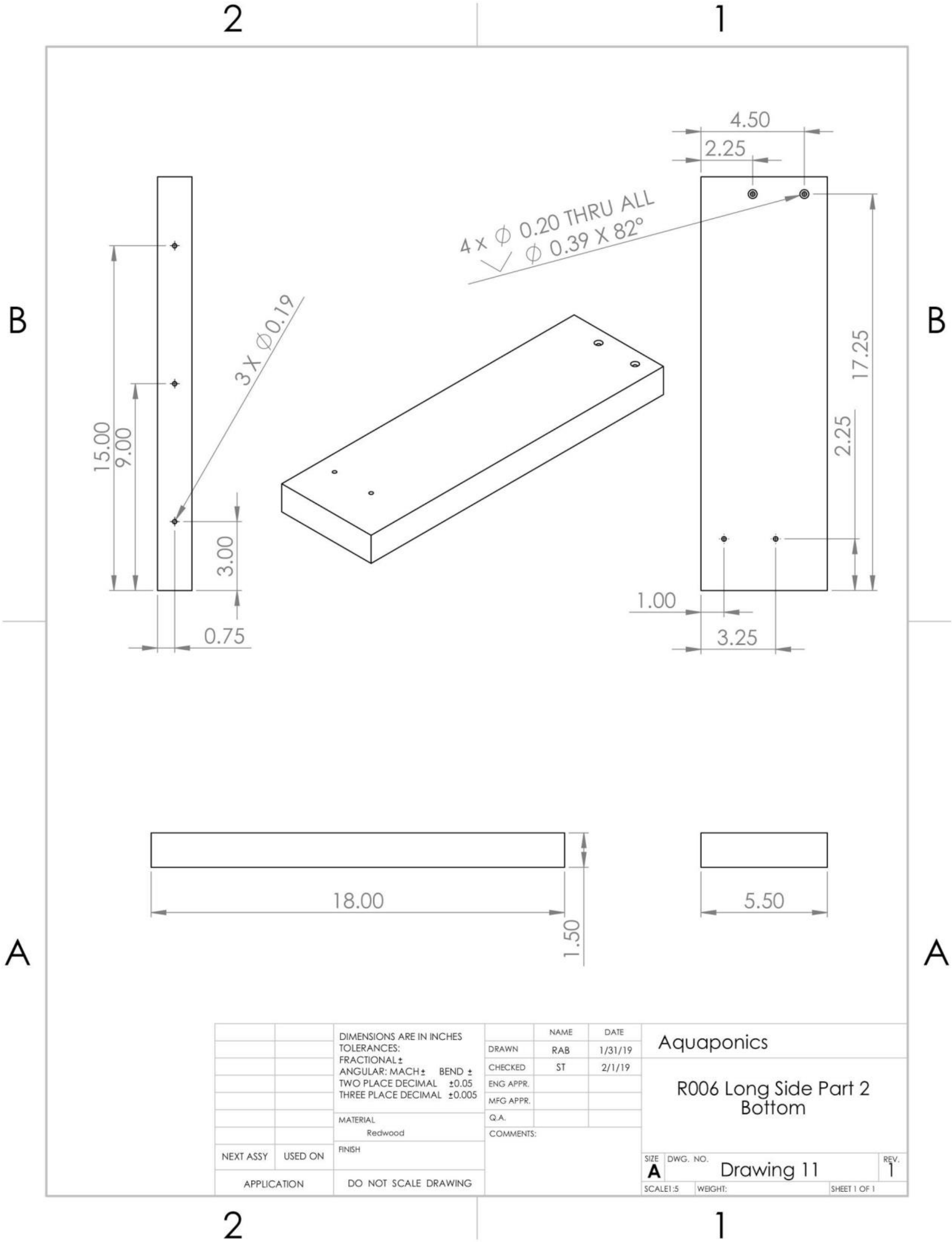
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Ø 0.39 X 82°
3 X Ø0.19
15.00
9.00
3.00
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17.25
2.25
1.00
3.25
18.00
1.50
5.50
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
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CHECKED ST 2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
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Bottom
SIZE A
DWG. NO.
Drawing 11
REV. 1
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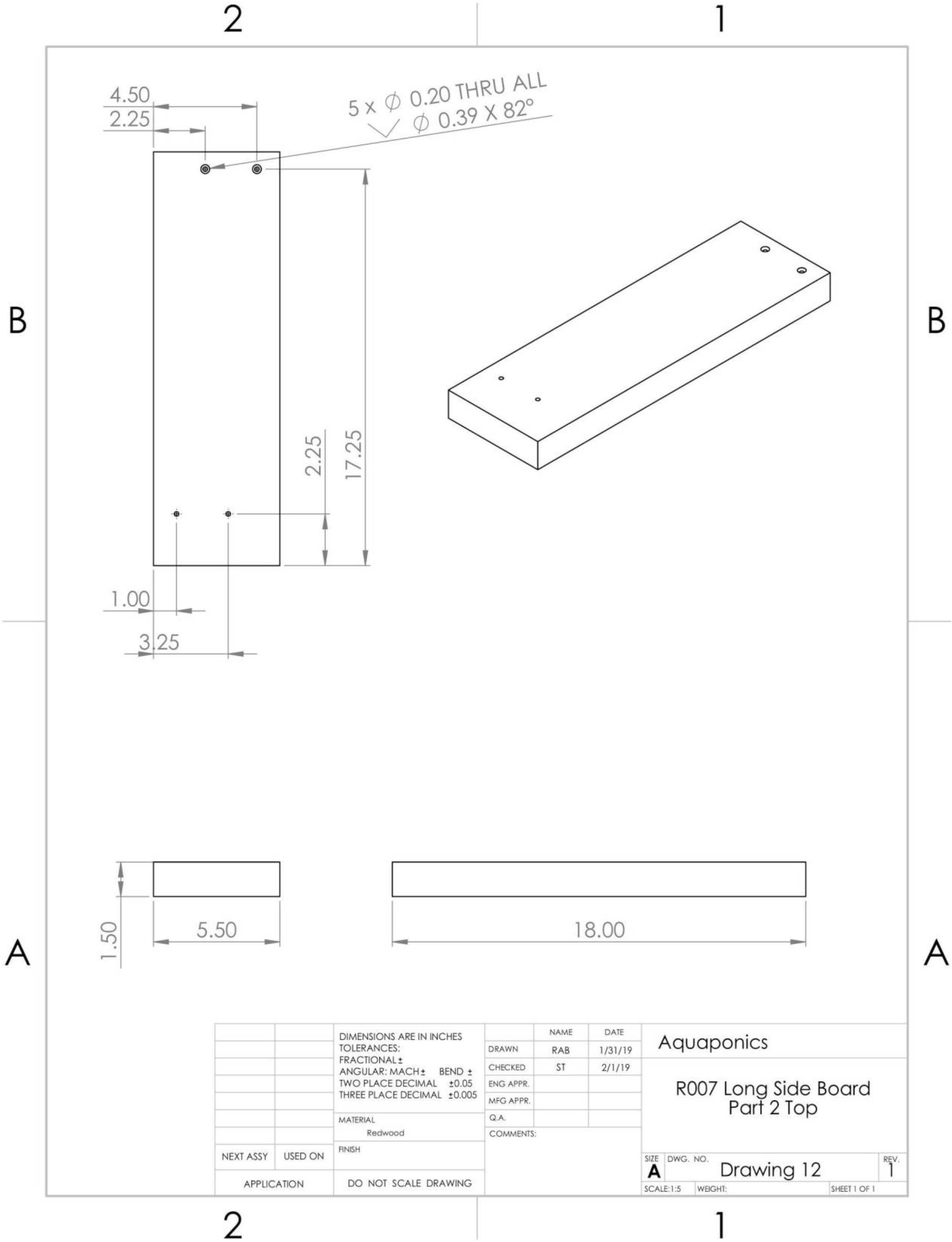
WEIGHT:
SHEET 1 OF 1



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A
4.50
2.25
5 x ∅ 0.20 THRU ALL
∅ 0.39 X 82°
2.25
17.25
1.00
3.25
1.50
5.50
18.00
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
RAB
1/31/19
CHECKED
ST
2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
R007 Long Side Board
Part 2 Top
SIZE
A
DWG. NO.
Drawing 12
REV.
1
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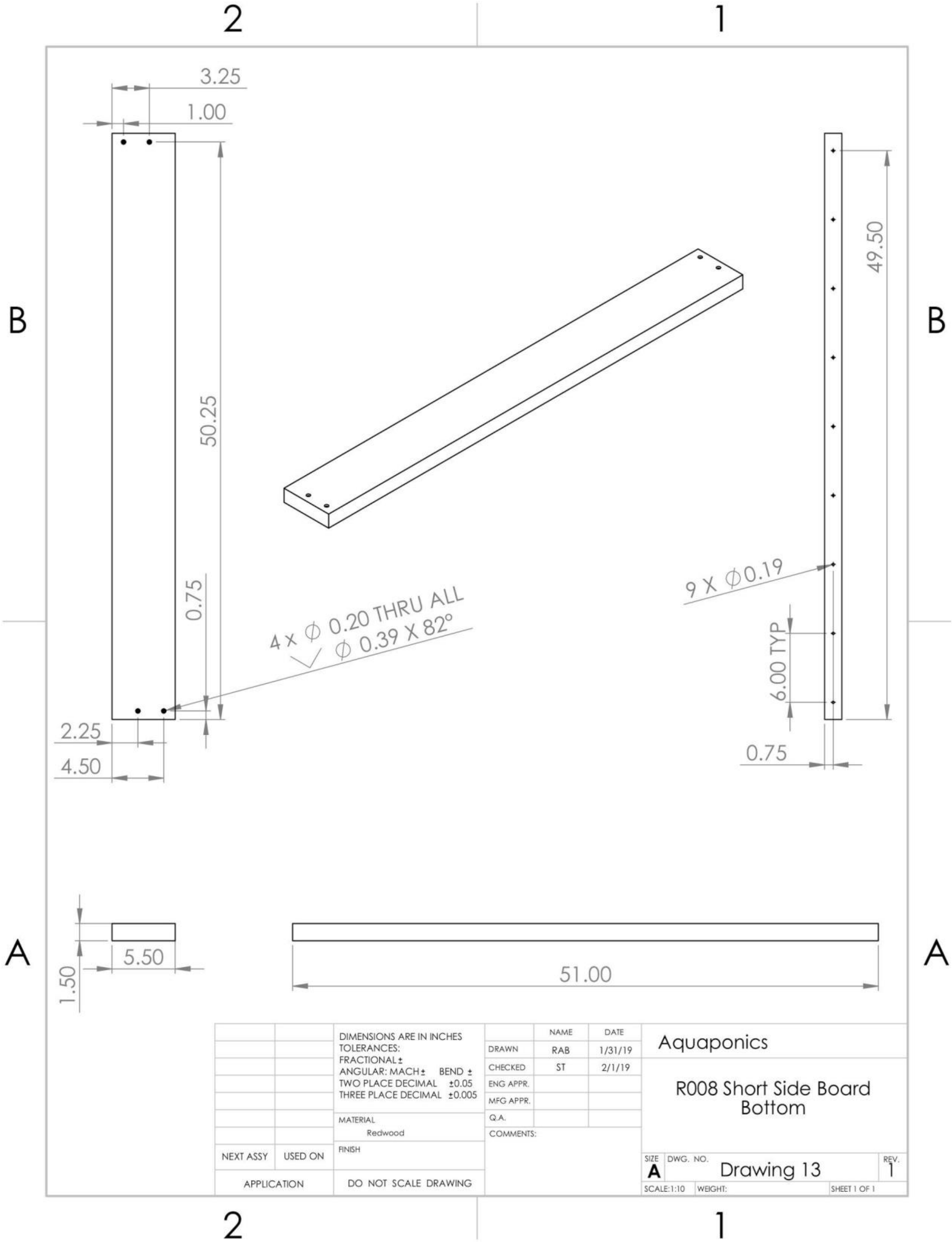
WEIGHT:
SHEET 1 OF 1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3.25
1.00
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0.75
4 x ⌀ 0.20 THRU ALL
⌵ ⌀ 0.39 X 82°
2.25
4.50
49.50
9 X ⌀0.19
6.00 TYP
0.75
B
A
1.50
5.50
51.00
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN RAB 1/31/19
CHECKED ST 2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
R008 Short Side Board Bottom
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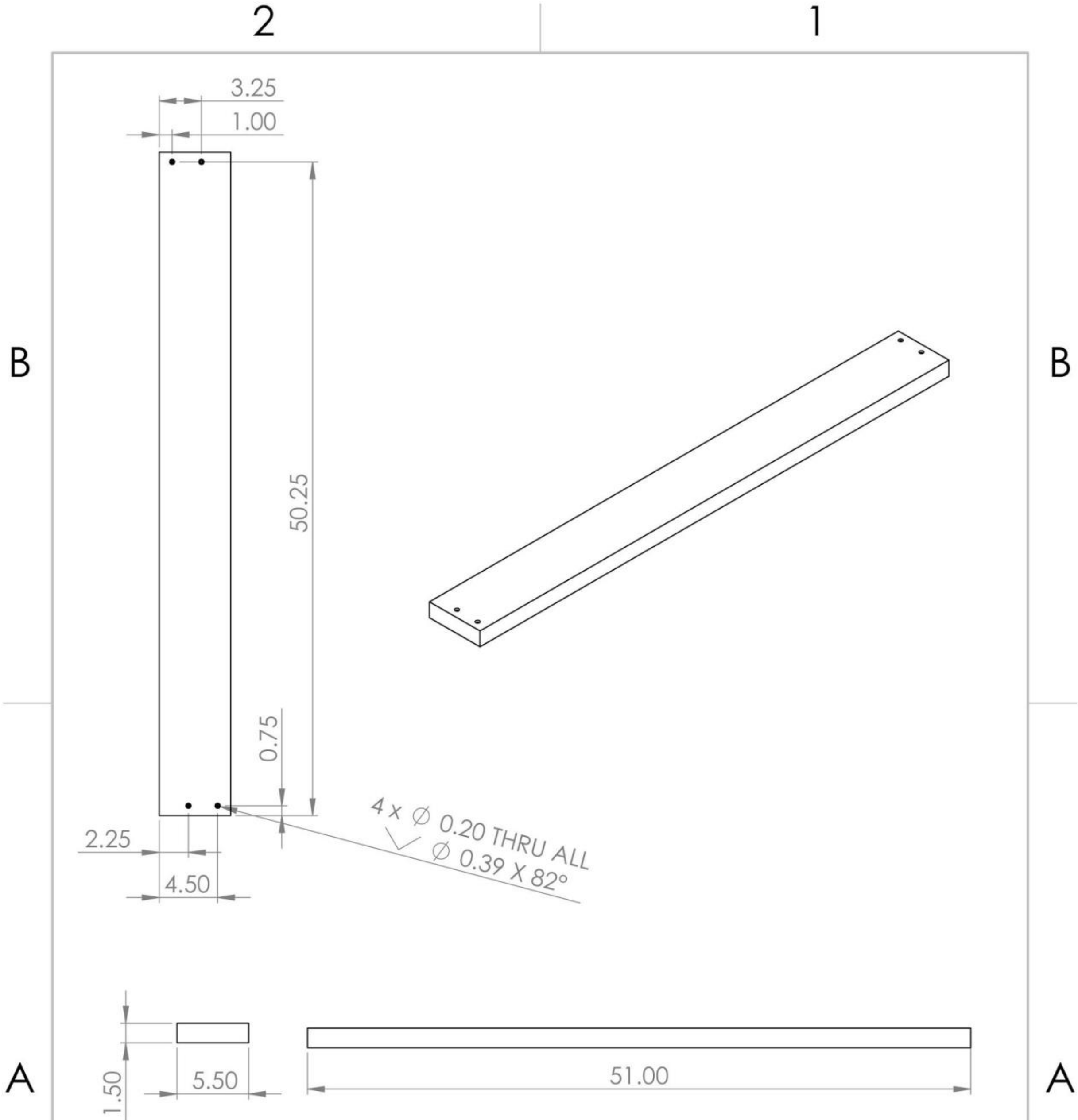
REV. 1
SCALE:1:10
WEIGHT:
SHEET 1 OF 1



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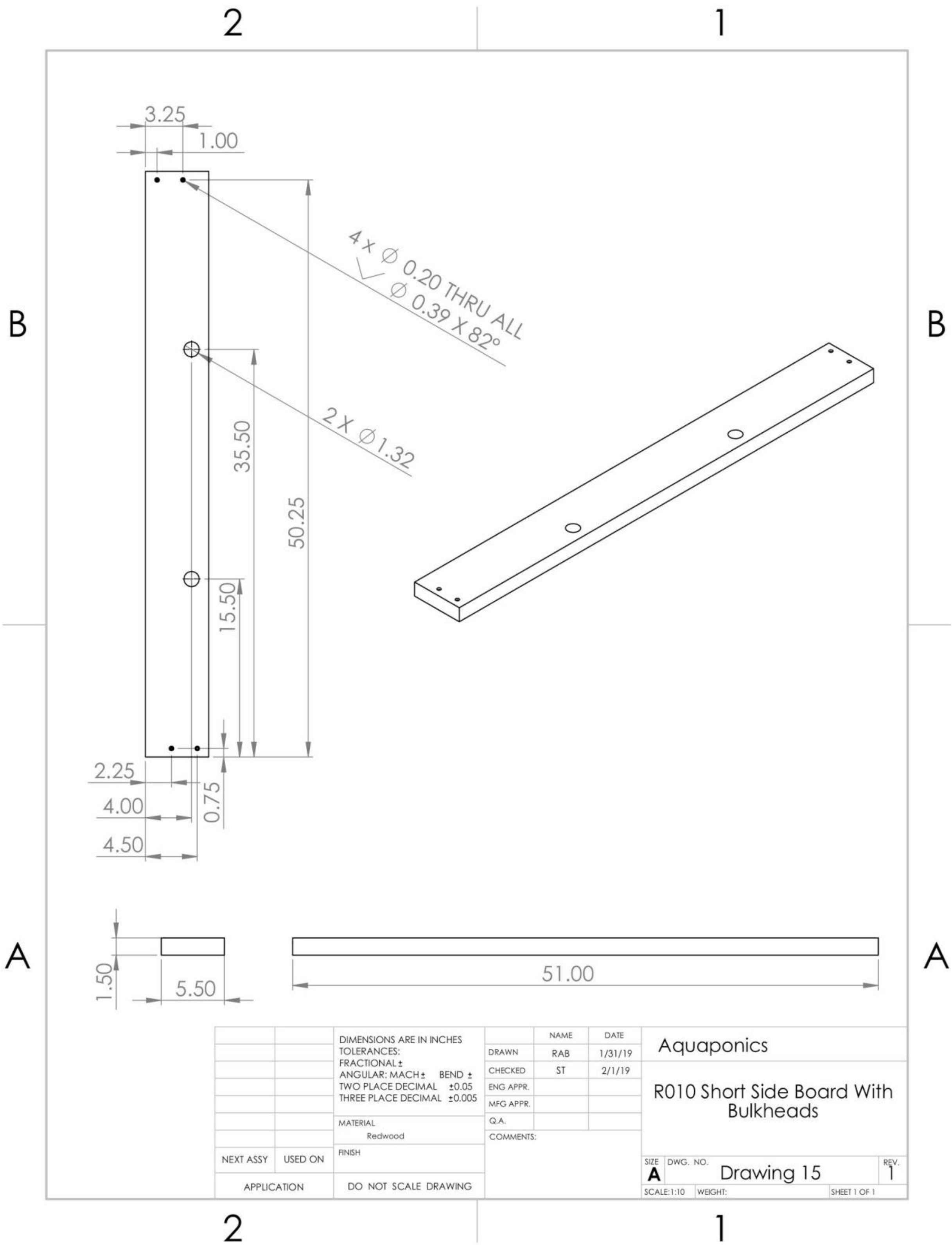
			CHECKED	ST	2/1/19	R008 Short Side Board Top
			ENG APPR.			
			MFG APPR.			
		MATERIAL Redwood	Q.A.			
NEXT ASSY	USED ON	FINISH	COMMENTS:			SIZE A DWG. NO. Drawing 14 REV. 1
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:10 WEIGHT: SHEET 1 OF 1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Ø 0.39 X 82°
2 X Ø 1.32
35.50
50.25
15.50
2.25
4.00
4.50
0.75
1.50
5.50
51.00
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN RAB 1/31/19
CHECKED ST 2/1/19
ENG APPR.
MFG APPR.
Q.A.
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Aquaponics
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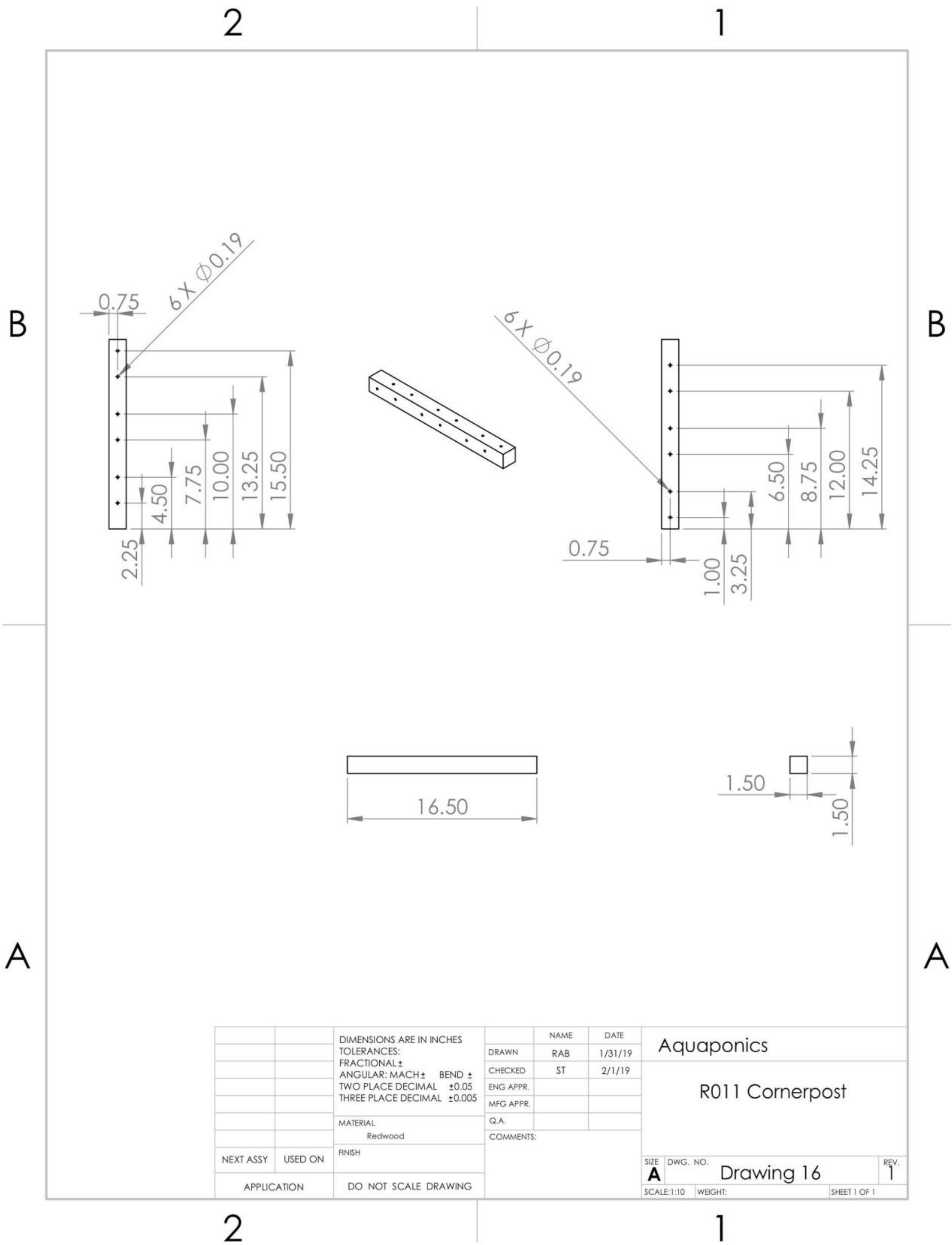
SHEET 1 OF 1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6.50
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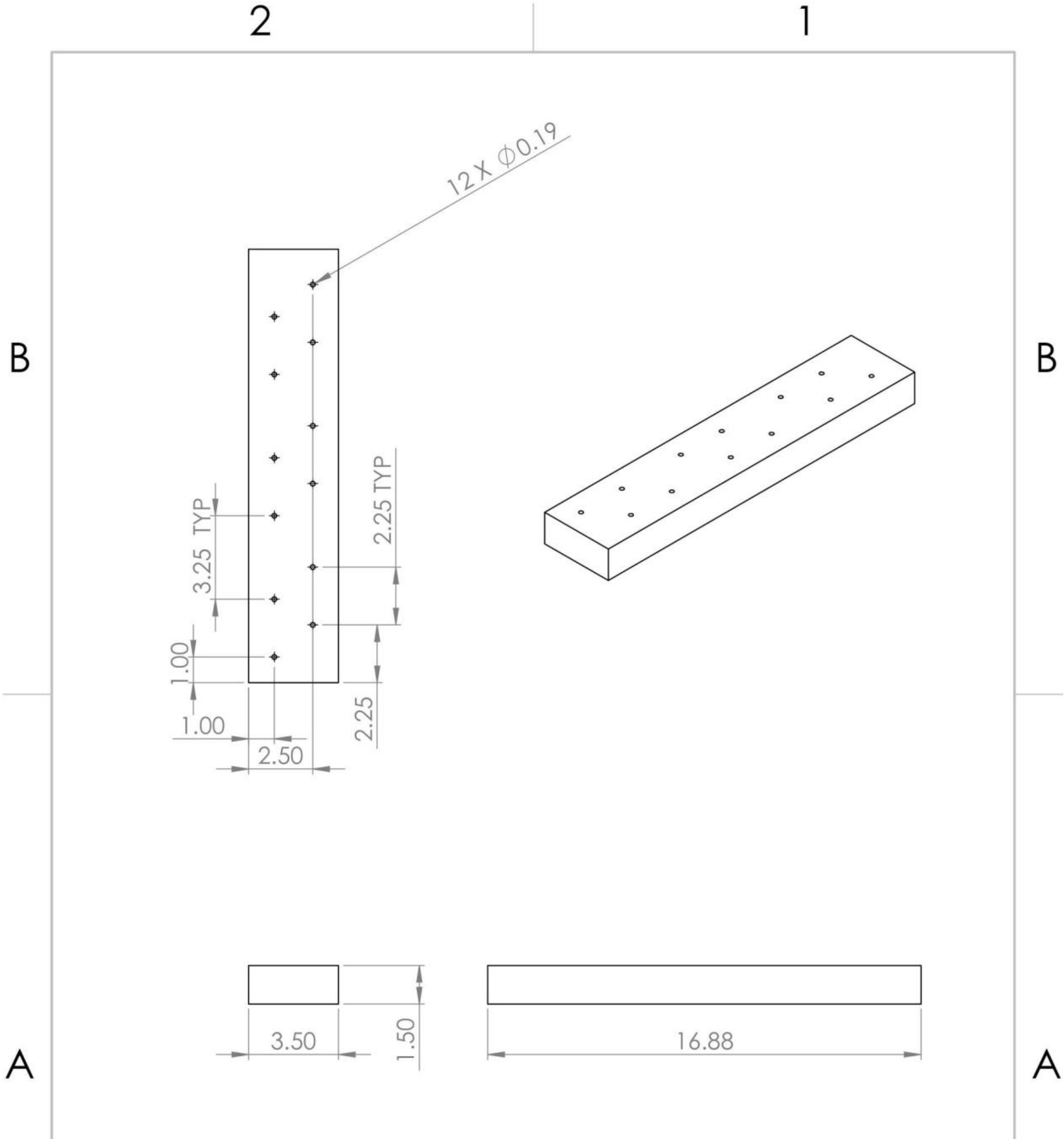
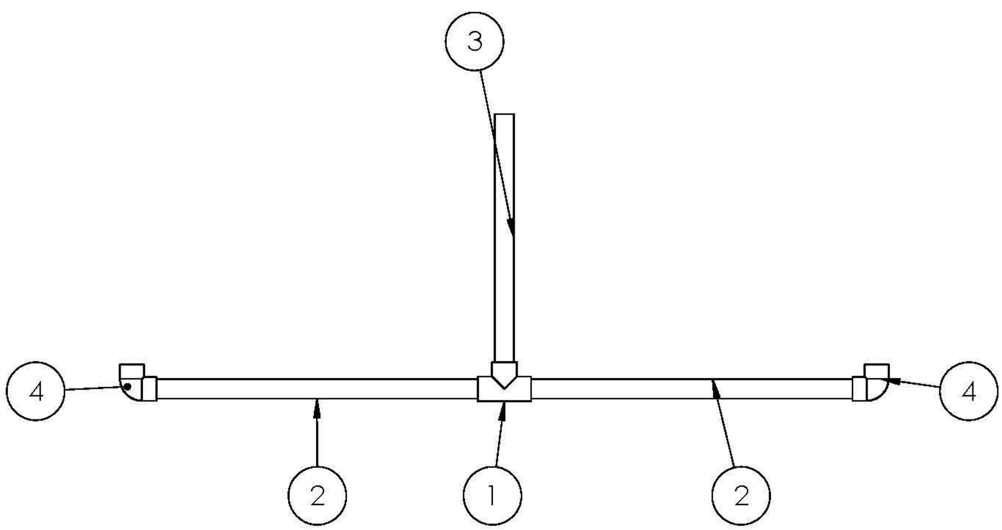
16.50
1.50
1.50
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
MATERIAL
Redwood
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
RAB
1/31/19
CHECKED
ST
2/1/19
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aquaponics
R011 Cornerpost
SIZE
A
DWG. NO.
Drawing 16
REV.
1
SCALE:1:10
WEIGHT:
SHEET 1 OF 1



		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.05 THREE PLACE DECIMAL ±0.005		NAME	DATE	Aquaponics
			DRAWN	RAB	1/31/19	R012 Side Post Tie
			CHECKED	ST	2/1/19	
			ENG APPR.			
			MFG APPR.			
		MATERIAL Redwood	Q.A.			
NEXT ASSY	USED ON	FINISH	COMMENTS:			SIZE A DWG. NO. Drawing 17 REV. 1
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:5 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	I003_1in_Tee		1
2	I004_1in_24in		2
3	I005_1in_18in		1
4	I007_1in_Elbow		2



	NAME	DATE
DRAWN	RAB	5/24/19
CHECKED	ST	5/25/19
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL

FINISH

NEXT ASSY | USED ON

APPLICATION | DO NOT SCALE DRAWING

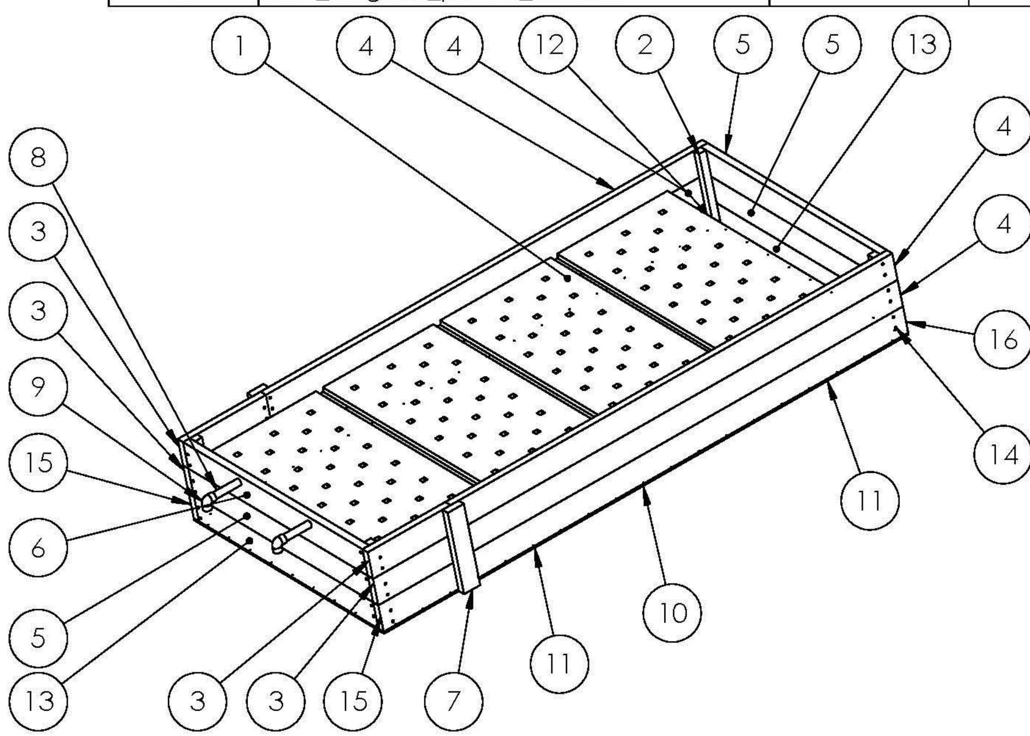
Aquaponics

Irrigation Subsystem

SIZE A | DWG. NO. Drawing 18 | REV.

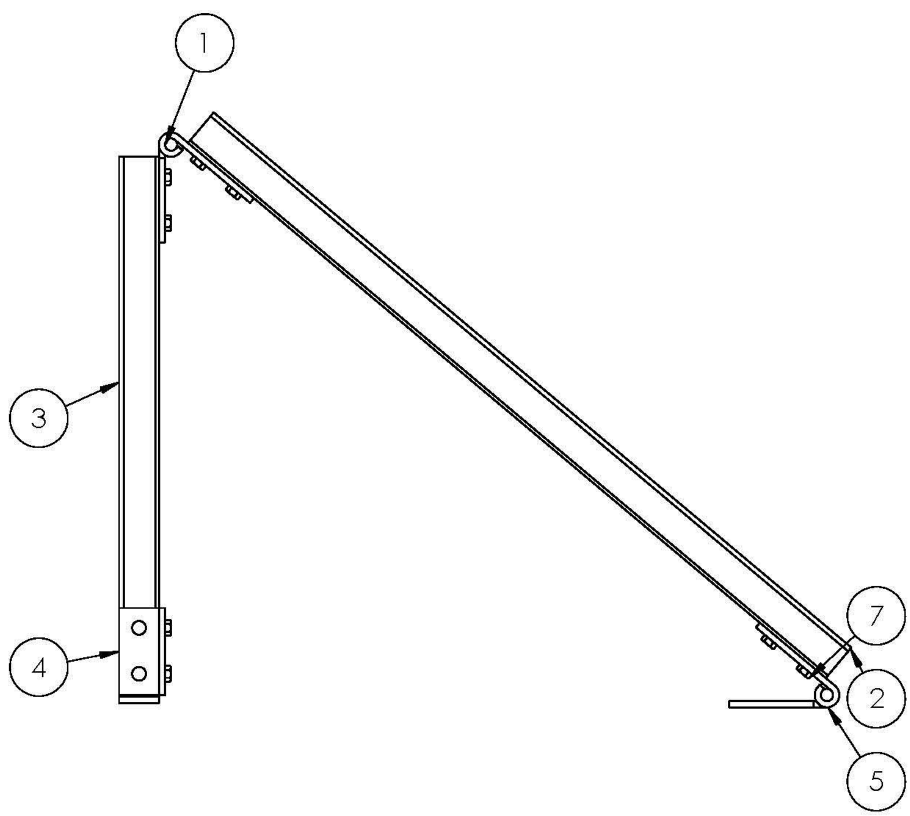
SCALE:1:10 | WEIGHT: | SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R013_rafts		4
2	R011_cornerpost		4
3	R007_longside_part2_top		4
4	R005_longside_part1_top		4
5	R008_shortside_top		3
6	R010_shortside_top_bulkheads		1
7	R012_sidepost		2
8	I006_growbed		2
9	I007_1inElbow		2
10	R003_base		1
11	R002_base		2
12	R004_longside_part1_bottom		1
13	R008_shortside_bottom		2
14	R014_number10_2.5inch_woodscrew		128
15	R006_longside_part2b_bottom		2
16	R004_longside_part1b_bottom		1



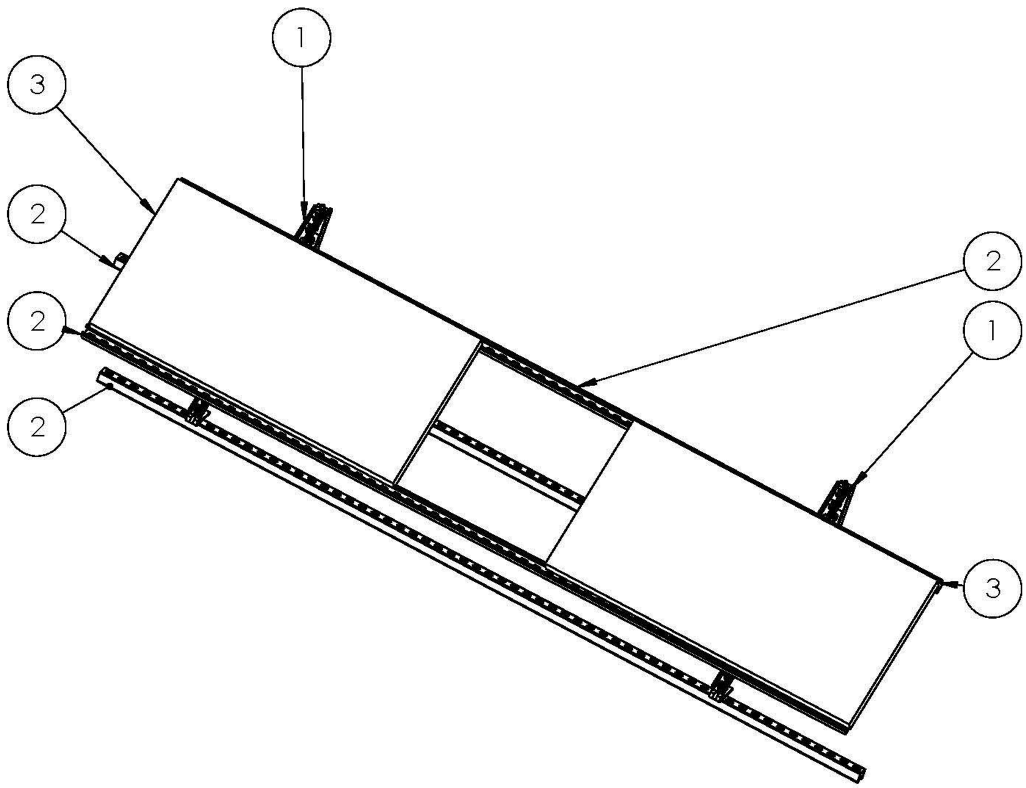
				NAME	DATE	
			DRAWN	RAB	3/10/19	Aquaponics
			CHECKED	ST	3/11/19	Raft Grow Bed Assembly
			ENG APPR.			
			MFG APPR.			
		MATERIAL	Q.A.			
NEXT ASSY	USED ON	FINISH	COMMENTS:			SIZE A DWG. NO. Drawing 19 REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:25 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	S005_hinge		1
2	S002_34in_strut		1
3	S003_22in_strut		1
4	S004_wing		1
5	S005b_bottom_hinge		1
6	S006_nut		8
7	S007_bolt		8



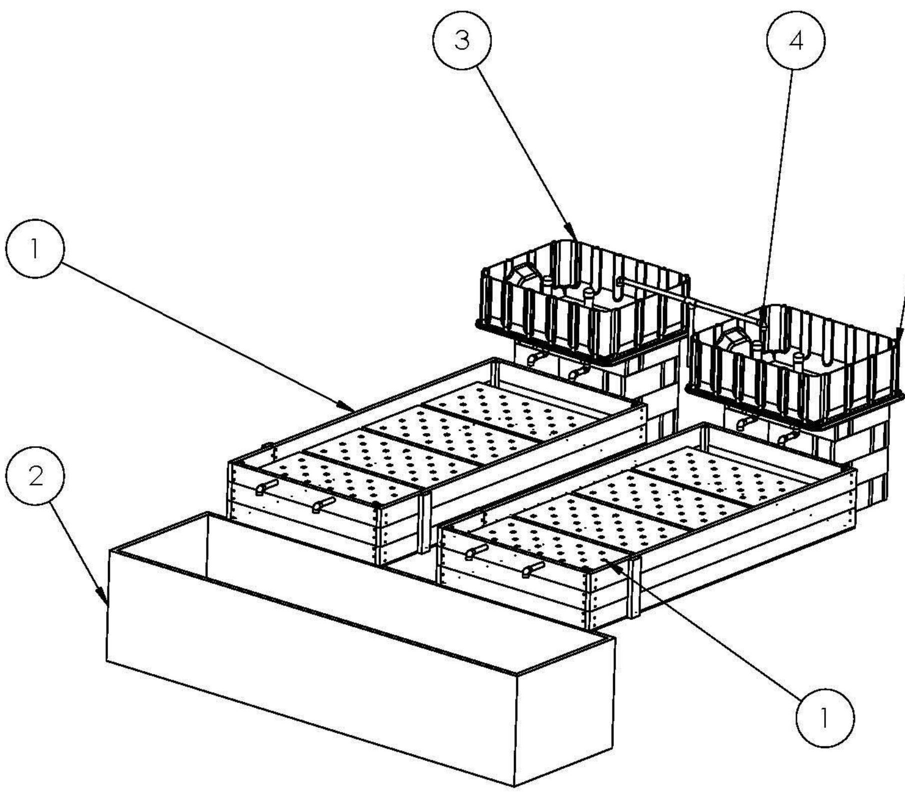
				NAME	DATE	
			DRAWN	RAB	5/25/19	Aquaponics
			CHECKED	ST	5/25/19	Chassis Side Support
			ENG APPR.			
		MATERIAL	MFG APPR.			
			Q.A.			
NEXT ASSY	USED ON	FINISH	COMMENTS:			SIZE A DWG. NO. Drawing 20 REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:6 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	sidesupport		2
2	S001_10ft_strut		4
3	solar_panel		2
4	S006_nut		6
5	S007_bolt		6



				NAME	DATE	
			DRAWN	RAB	5/25/19	Aquaponics
			CHECKED	ST	5/25/19	Chassis Subassembly
			ENG APPR.			
			MFG APPR.			
		MATERIAL	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A DWG. NO. Drawing 21 REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:20 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Raftgrowbed1		2
2	F001_pond		1
3	Mediatank		2
4	irrigation		1



	NAME	DATE
DRAWN	RAB	5/24/19
CHECKED	ST	5/25/19
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

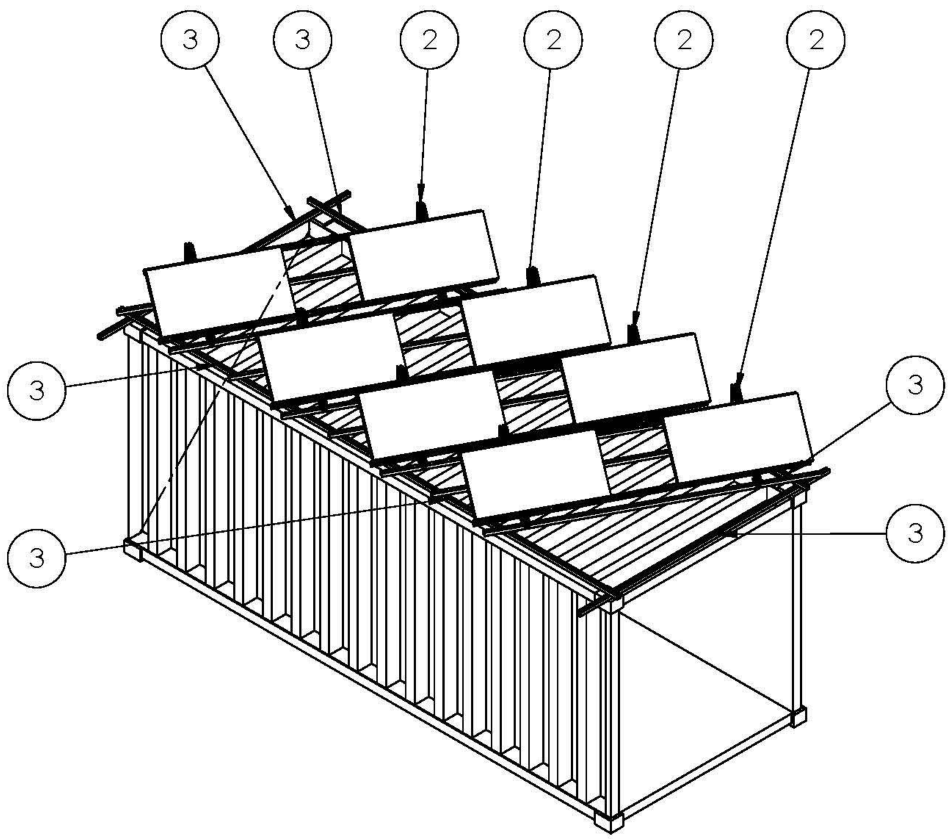
Aquaponics

Total Aquaponics Assembly

SIZE A | DWG. NO. Drawing 22 | REV.

SCALE:1:40 | WEIGHT: | SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	S006, S007		16
2	chassis_subassembly		4
3	S001_10ft_strut		6



	NAME	DATE
DRAWN	RAB	5/25/19
CHECKED	ST	5/25/19
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

Aquaponics

Solar Panel Installation

SIZE A | DWG. NO. Drawing 23 | REV.

SCALE:1:50 | WEIGHT: | SHEET 1 OF 1

Appendix K: Solar Panel Safety Installation Plan

The following report represents a summary of the installation process with a focus on the risks associated with the installation and safety procedures used to mitigate these risks. The whole procedure is separated into different categories to ensure attention to detail for each of the risks is addressed.

A summary of the power train is presented below:

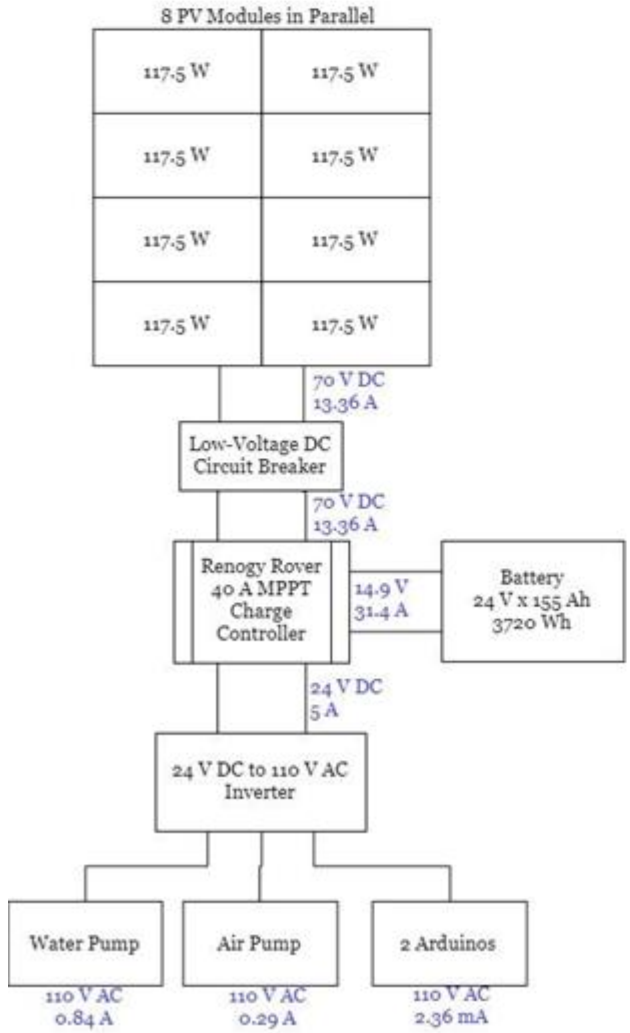


Figure K1. Summary of power train

Within the circuit, a safety disconnect switch (the low-voltage DC circuit breaker) acts to disconnect the power source (the solar panels) from the rest of the system when needed. The inverter will also have a manual switch to disconnect the loads (water pump, air pump, and Arduinos). All wires in the system are specified in accordance to the National Electric Code to ensure they can handle the output current.

Solar Panel Frame

Installation of the solar panels will occur on a standard shipping container located next to the farm as specified below:

Figure K2. Aerial view of solar installation (sketch provided by CBF electric)

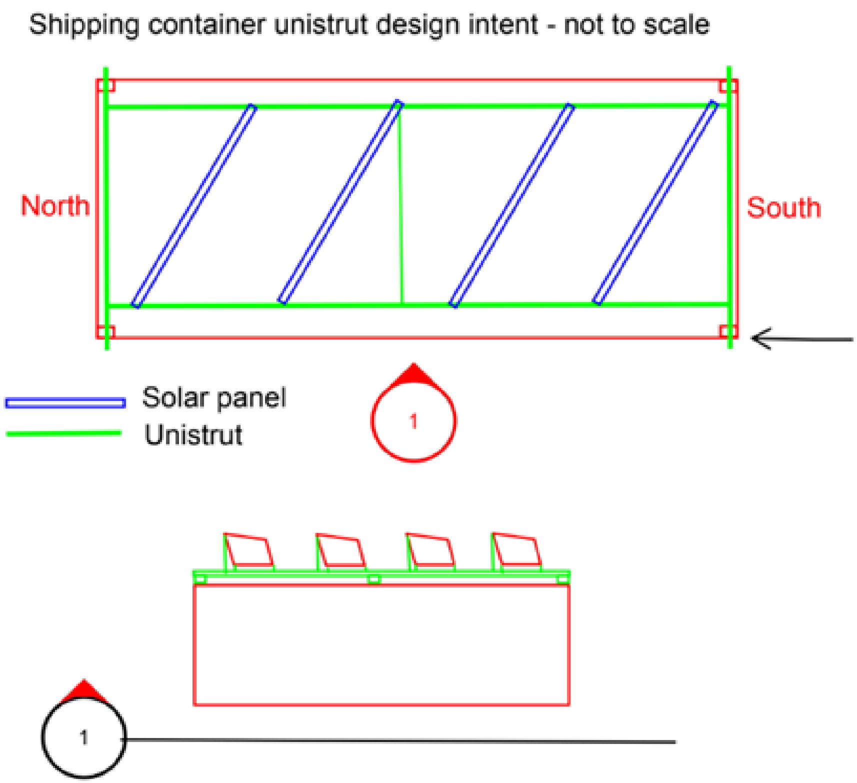


Figure K3. Aerial and side drawings of solar panel installation (sketches from CBF electric)

To install the frame, Unistrut will be used to provide support along the width of the shipping containers and anchored into the fittings on each corner of the shipping container.

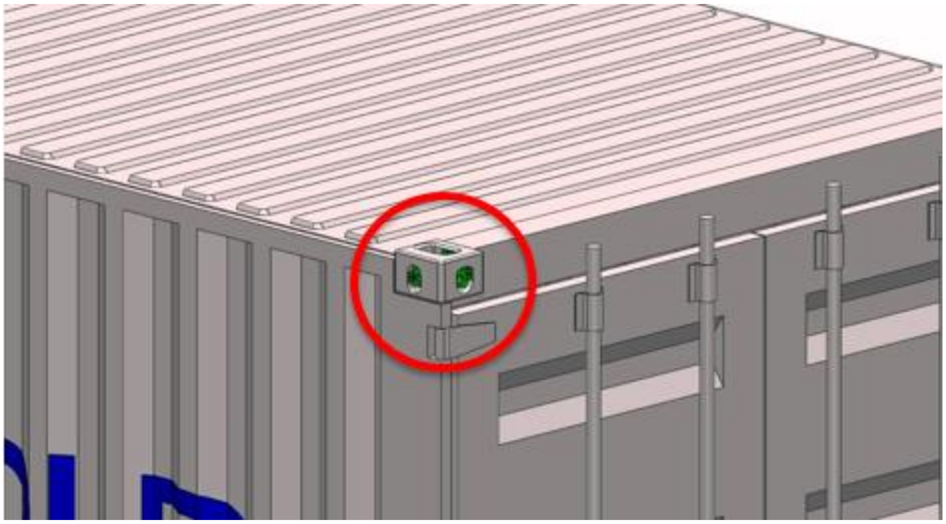


Figure K4. Corner fitting of the shipping container

Unistrut will also be attached lengthwise across the shipping container to reinforce the panels and provide support for the ends of the panels. UniPier supports will provide support from underneath.

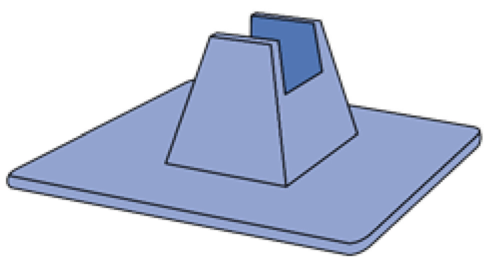


Figure K5. UniPier base support

Each of the solar panels will be mounted onto vertical supports on one end and supported by a clip on the top. The vertical support will be connected to a bottom strut across the two lengthwise Unistrut. At the bottom of each panel, another clip will secure it onto another strut that will secure it in place.

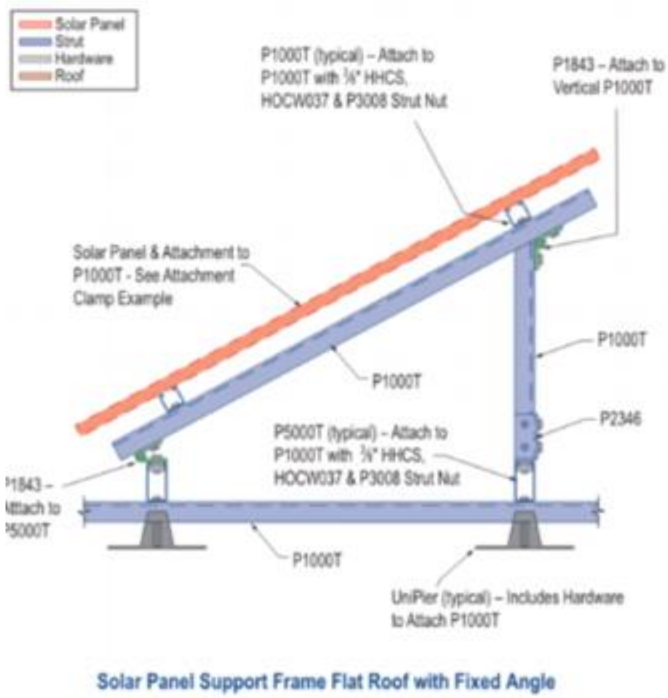


Figure K6. Side view of Unistrut

Throughout the process of the installation, two volunteers will head the manual installation, while the team will monitor activity and provide consolation with a certified electrician from CBF Electric on-site to ensure safety precautions are met. Dr. Sarah Kate Wilson, electrical engineering faculty and adviser for the project will be present and on-site during installation to ensure safety and project compliance.

Given that it is difficult to attach guard rails, since the shipping container is made of metal, and it is difficult to use scaffolding around the shipping container, the best option is to create a "wall effect" by parking trailers in the Goodwill parking lot around the container.

The volunteers will also sign liability waivers in case of any incidents. But to prevent other injuries or detriments, they will be wearing rubber-soled, steel-toed boots, long pants, hard hats, rubber gloves, safety glasses, and have a full walkthrough of the procedure before it begins.

Since the roof is 8 ft up and the solar panels weigh 20 pounds each, each one will be passed up to the roof using the 2-hand carry method, where the two volunteers on top will receive the solar panel from two people hoisting it up from the bottom.

Order of Wire Connection:

1. Charge Controller with Inverter
2. Charge Controller with DC Circuit Breaker
3. DC Circuit Breaker with 4-to-1 Y MC4 Connector

4. Charge Controller with Battery
5. Solar Array to DC Circuit Breaker
6. Loads to Inverter

1. Charge Controller with Inverter
Before connecting the PV array to the DC Circuit Breaker, all the open wires will be installed into the input holes of the charge controller as specified in the bottom.

Figure K7. Picture of charge controller

Since the inverter has no loads, there is no current running in between these two electronics, so this is the safest thing to wire first. It is also one of the more complicated processes, because we will need to use outdoor, underground-rated wire that will carry the current from the battery to the inverter underground.

2-3. DC Circuit Breaker Connections
Next, wiring the DC circuit breaker to the charge controller will be the easiest option, since no current is running through this at the time yet either. And then connecting the 4-to-1 MC4

connector to the DC circuit breaker is the most logical step, since there is still no current flowing throughout the system.

Figure K8. Image of the DC circuit breaker with a 32 A max current

4. Charge Controller with Battery

Even though the battery will be completely discharged before connecting, it should still be connected with care. With the 2 VMAX Marine AGM Deep Cycle batteries rated at 12 V and 155 Ah each, they can store a lot of energy and the open metal hex nuts on the top require handling with care.

Figure K9. Image of the VMAX battery used

Each of the batteries are sealed batteries that are resistant to shocks and vibrations, can be mounted in any direction, and are certified as both “non-hazardous” and “non-spillable”. Handles on each side allow for easy carrying and copper looped insulated wires will ensure they are mounted properly. Use of caps or electrical tape will cover the exposed metal to prevent future potential risks of shock.

5. Solar Array to DC Circuit Breaker

Each of the First Solar panels generates up to a maximum of 70 V and a current rating of 1.68 A. The wires on the back of each panel are insulated with IP64 Waterproof MC4 Connectors (shown below), with no live wires for anyone to touch.

Figure K10. MC4 connectors

Figure K11. Solar panels with wires all enclosed and insulated on the back

All the panels will be covered with sheets of cardboard and blankets to prevent the generation of electricity when the MC4 connectors are connected. Each of the panels will be connected in parallel to reduce the voltage entering the charge controller. Below is an aerial view of the wiring

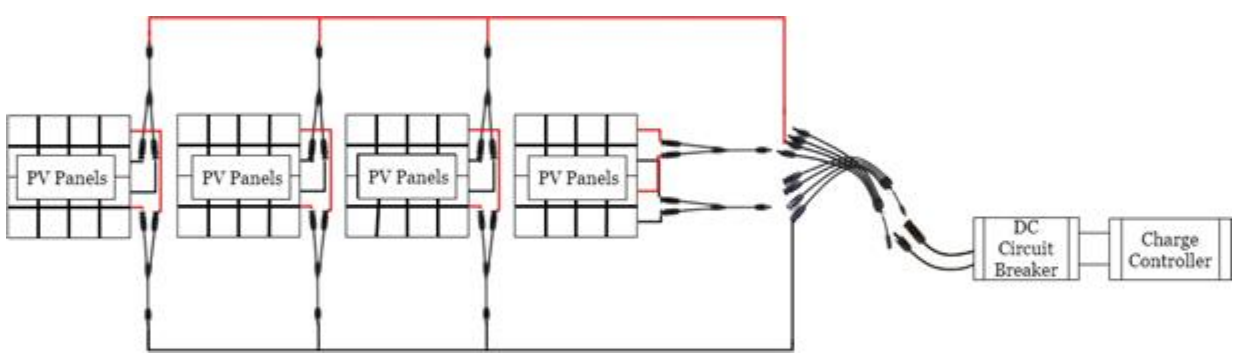


Figure K12. Wiring diagram of the solar panels to the charge controller

The wiring will be done in reverse, such that the open wires will first be attached to the charge controller (at the far right of the diagram above) and then through the DC Circuit Breaker, before other power-supplying wires are connected. Since all the panels and connecting wires have MC4 connectors, no live wires will be in use once the panels are connected.

6. Loads to Inverter

All the loads have simple AC plugs common to home appliances that will plug easily onto the side of the inverter (image on the bottom right).

Figure K13. Image of the power inverter with its on and off switch and AC outlets

Since these plugs still generate 110 V AC power, it is important to be careful when plugging in the different pumps.

Final Steps

Before turning on the system (uncovering the solar panels) and turning on the switch in the inverter, the certified electrician will walk through the system to make sure all connections are wired properly. Additional attention will be placed on open wires, potential trip hazards, and following of building codes specified in Appendix D.

Appendix L: Hand Calculations

The following Figures are from the hand calculation on the solar panel chassis.

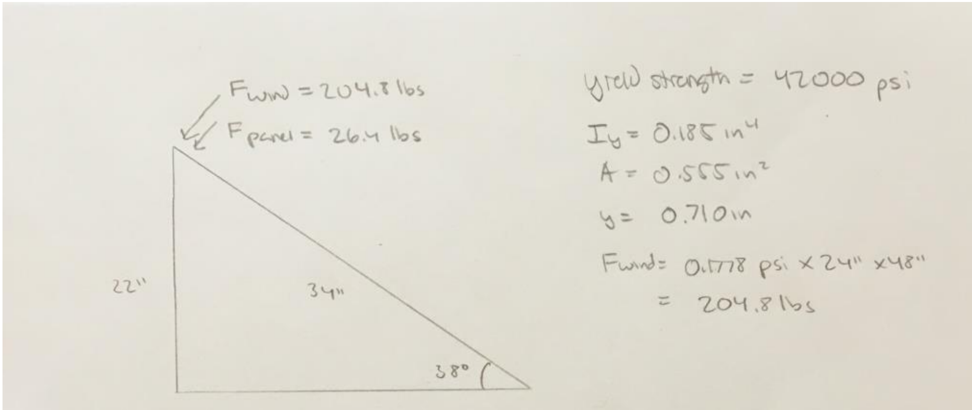


Figure L1. Free body diagram of side support

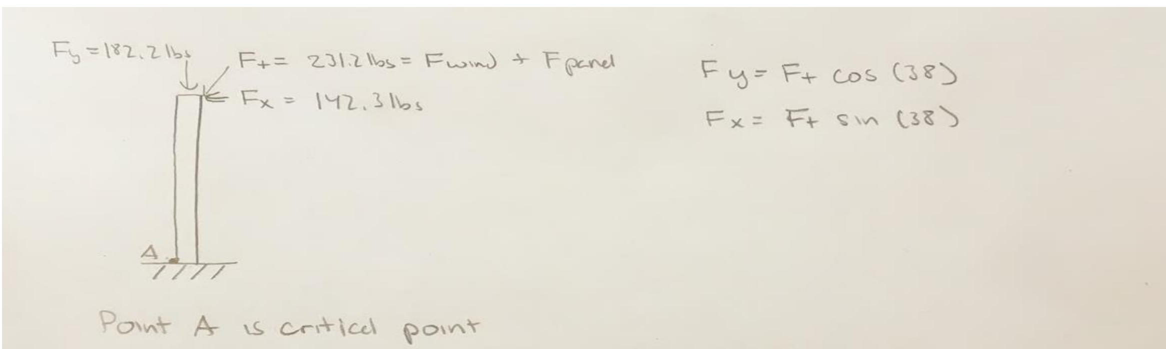


Figure L2. Free body diagram of vertical support

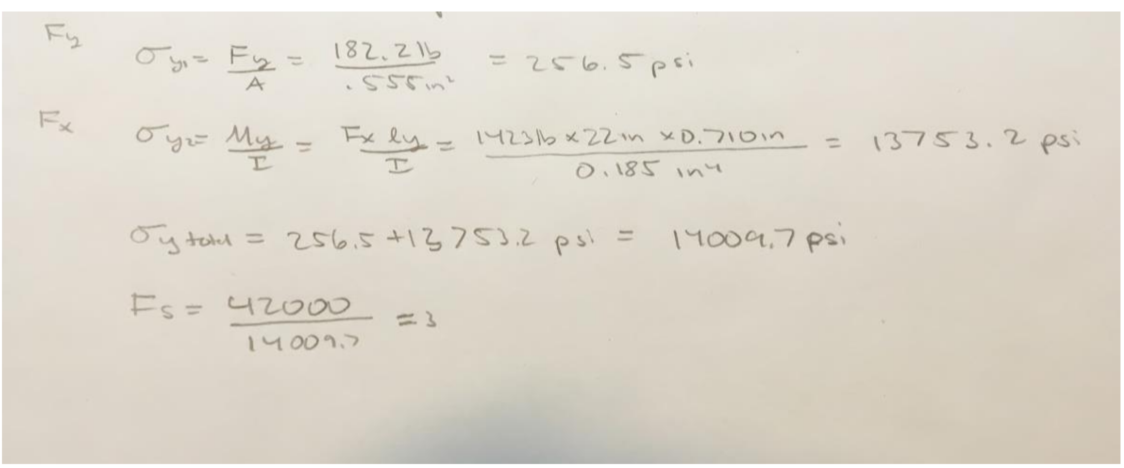


Figure L3. Hand calculation for combined loading of vertical support

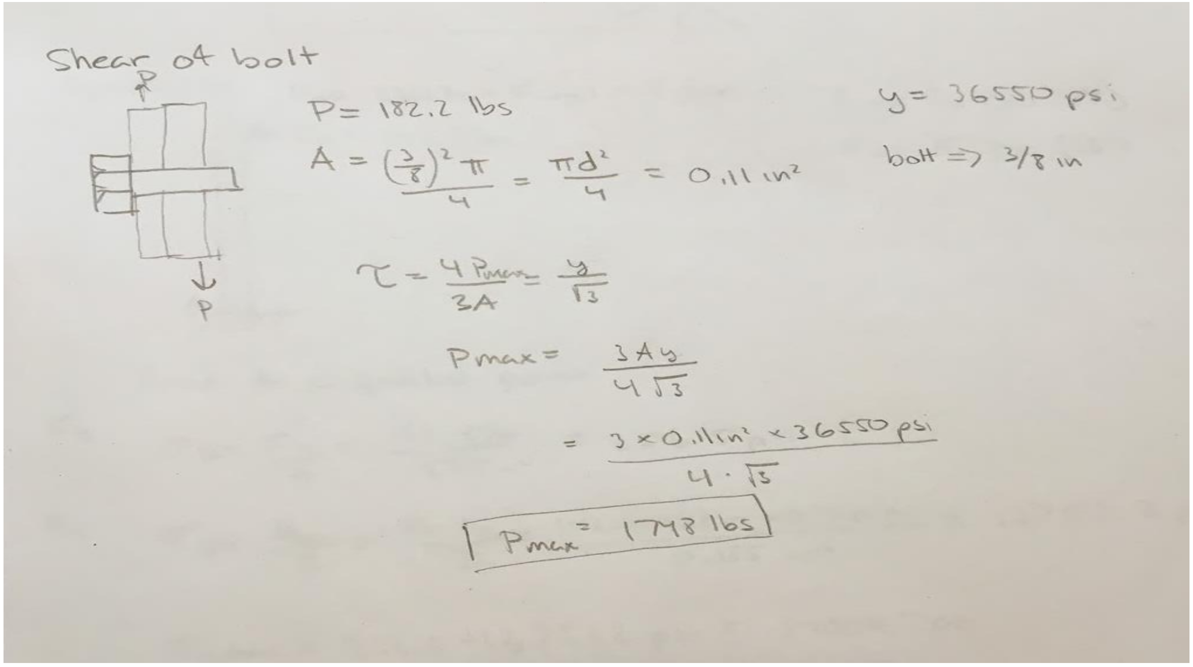


Figure L4. Hand calculation of shear of bolt

Appendix M: Guide to Connecting to ThingSpeak using Dragino LoRa

1. Create ThingSpeak account and create a Channel. Once the channel is created, create the number of fields needed and record the following data:
    a. Channel ID
    b. Write API Key
2. Configure the LG01 LoRa gateway to work with the WiFi network
    a. If connecting for the first time
        i. Connect to the Wifi network created by the gateway with the UN: root and PW: dragino ; then head to the IP set to 10.130.1.1 in a browser
        ii. Under Network → Internet Access, add in WiFi information for the Static IP and record the board IP number (aka)
        iii. If the LG01 is connected, the status screen should have information regarding an "Active Connection"
    b. If already connected to Wifi
        i. Connect it to the unique IP code that was set previously for the gateway
3. Configure Arduino IDE for Lora
    a. Under "Arduino → Preferences → Additional Boards Manager URLS" add this link to install the LG01 board definitions: http://www.dragino.com/downloads/downloads/YunShield/package_dragino_yun_test_index.json
    b. Under "Sketch → Include Library → Manage Library" install the following two libraries
        i. https://github.com/mathworks/thingspeak-arduino (Thingspeak)
        ii. http://github.com/dragino/RadioHead/archive/master.zip (RadioHead)
    c. Choose "Arduino Uno - Dragino Yun" board. Select board IP under port for whichever one corresponds to the one that was recorded when configuring the LG01 gateway for the communication port.
    d. Compile and upload this sample code to the LoRa Gateway to test https://github.com/dragino/Arduino-Profile-Examples/blob/master/libraries/Dragino/examples/LoRa/LoRa_Simple_Server_Yun/LoRa_Simple_Server_Yun.ino replacing Channel ID and API Key respectively
    e. OR select example from "File → Examples → Dragino → Basic → Blink". Click "Upload" and as long as the LG01 Gateway is connected to the same Wifi as the computer, then it should automatically upload without having an Arduino plugged in.
        i. If a password is needed, use "dragino" as default
        ii. If this works, this sketch will connect to the HEART LED on the LG01 and it will turn on/off periodically
4. Test the Arduino-Gateway Connection

a. Upload Sketch to Arduino
    i. Choose “Dragino Yun + UNO” for Board under “Tools”
    ii. Under “File → Examples → Dragino → LoRa”, choose LoRa_Simple_Client_Arduino
    iii. Choose board: “Arduino Uno” and unload the example sketch through the USB com port.
    iv. Open the serial monitor to visualize the output
b. Upload Sketch to LoRa Gateway
    i. Open arduino.exe in the Arduino folder
    ii. Select LG01 for the Board
    iii. Choose example LoRa_Simple_Server_Yun (same process as above)
    iv. Upload this sketch to LG01 through the Wifi
    v. Open serial monitor to visualize what is occurring in the LG01

5. Integrate with Thingspeak
    a. Use Source Code for
        i. LoRa Shield + Arduino: https://github.com/dragino/Arduino-Profile-Examples/blob/master/libraries/Dragino/examples/IoTServer/ThingSpeak/dht11_client/dht11_client.ino
        ii. LG01 Gateway: https://github.com/dragino/Arduino-Profile-Examples/blob/master/libraries/Dragino/examples/IoTServer/ThingSpeak/LG01_ThingSpeak_RESTful_Single_Data/LG01_ThingSpeak_RESTful_Single_Data.ino

Appendix N: Software Code

```
/*
 * This code is upload data from the sensors to the LoRa Gateway.
 * Many parts were slightly shifted from GitHub code posted in regards to uploading information
 * onto LoRa or from sample code provided by the different manufacturers of the sensors
 * For more details, please see information provided in the short guide followed to connect to
 * ThingSpeak in Appendix O.
 * Modified 06/03/2019
*/

// Include the following libraries:
// For LoRa
#include <Console.h>
#include <SPI.h>
#include <RH_RF95.h>

// For temperature sensor and EC
#include <DallasTemperature.h>
#include <OneWire.h>
#include <Wire.h>

// For pH sensor
#include "DFRobot_PH.h"
#include <EEPROM.h>

// For DO sensor
#include <SoftwareSerial.h>

// Preparing temperature sensor
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

// Defining the radio driver
RH_RF95 rf95;

// Defining PIN A2 to store data from DS18B20 water temperature sensors
#define ONE_WIRE_BUS 2
// Set Device Address for each water temperature sensor
DeviceAddress Probe01 = { 0x28, 0xA7, 0xAE, 0x99, 0x1B, 0x13, 0x01, 0x48};
DeviceAddress Probe02 = { 0x28, 0xAA, 0x13, 0xA3, 0x16, 0x13, 0x02, 0x00};

// Preparing EC Sensor
#define StartConvert 0
```

```
#define ReadTemperature 1

// Preparing pH Sensor
#define PH_PIN A3 // Assigning PIN A3 for pH data

// Preparing DO Sensor
#define rx 2  // Defining locations of pins
#define tx 3
SoftwareSerial myserial(rx, tx); // Defining functionality of soft serial port

// Variables for LoRa
char store_data[5]; // Store sensor data
char *node_id = "<2873>"; // creates ID to write the message to
// Ends all the function calls
char temp_end[8] = {"\0"};
char ec_end[8] = {"\0"};
char pH_end[8] = {"\0"};
char do_end[8] = {"\0"};
// Creates bits for data to be sent
uint8_t datasend[144]; // 4 variables with 36 bits each
float frequency = 915.0; // Defines frequency to be 915 MHz
unsigned int count = 1;

// Variables for EC sensor
const byte numReadings = 20; // Sets number of sample times for EC
// Defining PIN A1 to store data from EC Sensor
byte ECSensorPin = A1;
unsigned int AnalogSampleInterval = 5000; // Sample interval: 5s
unsigned int printInterval = 60000; // Serial print interval: 1 min.
unsigned int readings[numReadings]; // Readings from anlog input
byte index = 0; // Index of current reading
unsigned long AnalogValueTotal = 0; // Total throughout the readings
unsigned int AnalogAverage = 0; averageVoltage = 0; // Set parameters for calibration
// Defining variables to use in the future
unsigned long AnalogSampleTime;
float ECcurrent;

// Variables for pH sensor
float voltage, phValue // Use in the future
DFRobot_PH ph; // Defines value for pH sensor

// Variables for DO Sensor
// String inputstring = ""; // Holds incoming data, not needed for this code
String sensorstring = ""; // Holds data recorded from the sensor
```

```
// boolean input_string_complete = false;
boolean sensor_string_complete = false; // Ensures all data from sensor is received
float DO; // Hold floating point number

void setup()
{
  // Initialize temp sensors
  sensors.begin();
  //  sensors.setResolution(Probe01, 10);
  //  sensors.setResolution(Probe02, 10);

  Serial.begin(9600); // set up baud rate for hardware

  // Initialize all the readings to 0 in EC
  for (byte thisReading = 0; thisReading < numReadings; thisReading++)
    readings[thisReading] = 0;
  AnalogSampleTime=millis();
  printTime=millis();

  // Initialize pH sensor
  ph.begin();

  // Initialize DO sensor
  myserial.begin(9600); // set up baud rate for the software
  sensorstring.reserve(30); // set bytes for receiving data from DO Sensor

  // Initialize radio driver
  if (!rf95.init())
      Serial.println("Intialization Failed");
  rf95.setFrequency(frequency); // Set up frequency
  rf95.setTxPower(13);          // Set up power
  rf95.setSyncWord(0x34);       // Set up dBm

  // Ensure it Starts
  Serial.println("LoRa Begin");
  Serial.println("    Sensors Recording\n");
  Serial.print("LoRa Stop ID: ");
}

// Function for temperature data
float readTemp()
{
  float temp1 = sensors.getTempC(Probe01); // Gathers data from the first probe
   if (temp1 == -127.00) // -127.00 is if out of bounds
```

```
  {
   Serial.print("Temperature Error");
  }
  else
  {
   // Prints out data regarding the temperature onto a serial monitor if applicable
   Serial.print("C=");
   Serial.print(temp1);
   Serial.print(" F=");
   Serial.println(DallasTemperature::toFahrenheit(temp1));
  }

  // repeats the above process but for the second probe
  float temp2 = sensors.getTempC(Probe02);
  if (temp2 == -127.00)
  {
   Serial.print("Temperature Error");
  }
  else
  {
   Serial.print("C=");
   Serial.print(temp2);
   Serial.print(" F=");
   Serial.println(DallasTemperature::toFahrenheit(temp2));
  }

 float temp = (temp1 + temp2)/2; // Averages the two temperature values to be sent online
 return temp; // Temp in Celsius for other calculations

float readTempF()
{
  float temp = readTemp()
  return DallasTemperature::toFahrenheit(temp) // Ensures temperature is in Fahrenheit for end-user
}
// Function for EC Data
float readEC()
{
  // Gathers analog data
  if(millis()-AnalogSampleTime>=AnalogSampleInterval)
  {
    AnalogSampleTime=millis();
    AnalogValueTotal = AnalogValueTotal - readings[index]; // Subtract former reading
    readings[index] = analogRead(ECsensorPin); // Read from the sensor
    AnalogValueTotal = AnalogValueTotal + readings[index]; // Add reading to running total
```

```
    index = index + 1; // Go to next part of the array
    if (index >= numReadings) // Check if at end
        index = 0;
    AnalogAverage = AnalogValueTotal / numReadings; // Calculate average for the specified number of
Readings
  }
  // Calculates EC based on voltage from analog average and temp
  float temperature = readTemp();
  averageVoltage=AnalogAverage*(float)5000/1024;
  float tempCoeff = 1.0 + 0.0185*(temperature-25.0);    // Specified temperature compensation formula
  float coeffVoltage=(float)averageVoltage/tempCoeff;
  if(coeffVoltage < 150)
      return 0; // out of range
  else if(coeffVoltage > 3300)
      return 0; // out of the range
  else
  {
    ECcurrent = 7.6*CoefficientVoltage - 289;
//  Other cases that may work for specific values
//      if(CoefficientVoltage<=448)ECcurrent=6.84*CoefficientVoltage-64.32;   //1ms/cm<EC<=3ms/cm
//      else if(CoefficientVoltage<=1457)ECcurrent=6.98*CoefficientVoltage-127;
//3ms/cm<EC<=10ms/cm
//      else ECcurrent=5.3*CoefficientVoltage+2278;                          //10ms/cm<EC<20ms/cm
    ECcurrent/=1000;    //convert us/cm to ms/cm
    return ECcurrent,2;
  }
}

// Function for pH Data
float readpH()
{
    static unsigned long timepoint = millis();
    if(millis()-timepoint>60000U){ // Specify time interval of 1 minute
        timepoint = millis();
        float temperature = readTemp(); // Read the temperature data
        voltage = analogRead(PH_PIN)/1024.0*5000;  // Reads voltage to determine pH
        phValue = ph.readPH(voltage,temperature);  // Converts pH based on temeprature
        return readpH
    }
    ph.calibration(voltage,temperature);          // Calibration process if needed
}

// Function for reading in dissolved oxygen measurements
char readDO()
```

```
{
  if (myserial.available() > 0) // If sensor value is greater than 0
  {
    char inchar = (char)myserial.read() // Input the data
    sensorstring += inchar // Add new data to the string
    if (inchar == '\r') // If reach the end of the string
    {
      sensor_string_complete = true; // Setting flag to read data
    }
    if (sensor_string_complete = true) {
      return sensorstring
      sensorstring = "";  // Clear string for future measurement
      sensor_string_complete = false; // Reset flag
    }
  }
}

// Prepares the data in a packet to be sent
void writeData()
{
  char data[144] = "\0"; // Prepares data by setting all bits to NULL/0
  // Sets the node ID
  for(int i = 0; i < 144; i++)
  {
    data[i] = node_id[i];
  }

  // Calls in the data
  float temp = readTempF();
  float ec = readEC();
  float pH = readpH();
  char DO = readDO();

  // Stores the data by adding it onto a string
  dtostrf(temp, 0, 1, temp_end);
  dtostrf(ec, 0, 1, ec_end);
  dtostrf(pH, 0, 1, pH_end);
  dtostrf(DO, 0, 1, do_end);

  // Adds data until it hits the specified end and allocating specific fields
  strcat(data,"field1=");
  strcat(data,temp_end);
  strcat(data,"field2=");
  strcat(data, ec_end);
```

```
  strcat(data, "field3=");
  strcat(data, pH_end);
  strcat(data, "field4=");
  strcat(data, do_end);
  strcpy((char *)datasend, data);
}

void sendData()
{
  // Creates packet in order to send data
  LoRa.beginPacket();
  LoRa.print((char *)datasend);
  LoRa.endPacket();
  Serial.println("The packet is sent successfully");
  delay(360000); //delays six minutes before next sending
}

void loop()
{
  // For anyone to track on serial monitor the status
  Serial.print("########     ");
  Serial.print("COUNT=");
  Serial.print(count);
  Serial.println("     ###########");
    count++;
    readTempF();
    readEC();
    readpH();
    readDO();
    writeData();
    sendData();
}
```

Appendix O: Experimental Protocol and Results

Volume Flow Rate of Pump at Desired Jead

Location: Loaves and Fishes' Garden

When: After solar installation is completed, which is necessary to power the pump

Equipment needed:

- 5-gallon bucket or graduated cylinders
- Timer/stopwatch
- Submersible pump
- 1-in tubing

Accuracy needed: We will determine the water level when the five gallon bucket is filled with exactly five gallons of water to help improve accuracy or we will use graduated cylinders. This test does not need a high level of accuracy, plus or minus 50 gph will be suitable.

Number of trials necessary: 5

Target outcome: 600 gph

Assumptions:

- Assuming that the water is being pumped at a constant rate

Equations:

$$Q = \frac{V}{t}$$

In this equation, Q is the flow rate in gallons per hour, V is the volume of water, and t is the time in hours to pump the given volume of water.

Hours: 2

Protocol:

- Set up pump with hose, so that the water is being pumped up to the desired head of 8-ft
- Start pump and record time to fill up 5-gallon bucket or graduated cylinder
- Stop pump once container is full, empty container and repeat
- Complete for each grow bed

Table O1. Time to fill five-gallon bucket using pump at desired flow rate

Trial	Time-right (min)	Time-left (min)
1	3.72	3.25
2	4.08	3.08
3	3.55	2.95
4	3.72	2.97
5	3.52	3.17
Average time (min)	**3.72**	**3.08**

With the average time to fill up a five-gallon bucket, the volume flow rate in gph can be calculated.

Table O2. Results of volume flow rate from pump test

	Left	**Right**
Time (min)	3.72	3.08
Flow rate (gph)	80.72	97.30
Total flow rate (gph)	**178.01**	

Velocity of Water Draining from Bell Siphon

Location: Loaves and Fishes' Garden

When: After solar installation is completed, which is necessary to power the pump

Equipment needed:

- 5 gallon bucket or graduated cylinders
- Timer/stopwatch
- Submersible pump

Accuracy needed: We will determine the water level when the five gallon bucket is filled with exactly five gallons of water to help improve accuracy or we will use graduated cylinders. This test does not need a high level of accuracy, plus or minus 0.1 m/s will be suitable.

Number of trials necessary: 5

Target outcome: 0.7 m/s

Assumptions:

- Assuming that the water drains out of the bell siphons at a constant rate, once the bell siphon is initiated

Equations:

$$v = \frac{V}{A * t}$$

In this equation, v is the velocity of the flow in m/s, V is the volume of water, A is the cross-sectional area of the 1-in PVC pipe, and t is the time in seconds to fill the given container.

Hours: 2

Protocol:

- Set up pump with hose, so that the water is being pumped into the media bed and start pump
- Record time to fill up 5-gallon bucket or graduated cylinder once the bell siphon is initiated
- Stop the bell siphon once container is full, empty container and repeat

Table O3. Time to fill five-gallon bucket from bell siphon

Trial	Time-right (sec)	Time-left (sec)
1	23.28	22.31
2	24.56	21.33
3	22.33	21.01
4	23.50	21.24
5	24.68	20.39
Average time (sec)	**23.67**	**21.26**

Table O4. Results of bell siphon velocity test

	Left	Right
Time (sec)	23.67	21.26
Velocity	1.58	1.76
Average velocity (m/s)	**1.67**	

Timing of Flood and Drain Cycle

Location: Loaves and Fishes' Garden

When: After solar installation is completed, which is necessary to power the pump

Equipment needed:

- Timer/stopwatch
- Submersible pump

Accuracy needed: This test does not need a high level of accuracy, plus or minus 2 minutes will be suitable.

Number of trials necessary: 5

Target outcome: 15 minutes

Assumptions:

- Assuming that the water is pumped at a constant rate from the submersible pump

Equations: none

Hours: 2

Protocol:

- Set up pump with hose, so that the water is being pumped into the media bed and start pump
- Record time to fill up the media beds

- Once the media bed is full and the bell siphon is initiated, record the time to drain the grow beds until the bell siphon stops. The time to fill and then drain is one full cycle and would ideally take 15 minutes
- Complete this process five more times

Table O5. Results of timing of flood and drain cycle

Trial	Time-right (min)	Time-left (min)
1	20.66	21.32
2	21.00	20.39
3	19.89	21.39
4	19.25	21.80
5	21.77	20.69
Average time (min)	**20.82**	

Water Temperature
Location: Loaves and Fishes' Garden
When: Week of April 15
Equipment needed:

- 3 thermometers
- 3 temperature sensors

Accuracy needed: plus or minus 1 degree F
Number of trials necessary: 5
Target outcome: N/A
Assumptions: Assume that the water temperature in the fish pond is the same as the water temperature in each raft grow bed
Equations: none
Hours: 1
Protocol:

- Place three temperature sensors in the fish pond and place one sensor in each raft grow bed
- Place one thermometer in each raft grow bed and the pond
- Measure the water temperature using the sensors and thermometers and compare results within each raft grow bed and pond

pH of Water
Location: Loaves and Fishes' Garden
When: Once the pond is complete and we can run a full cycle of water through the system

Equipment needed:

- pH strips

Accuracy needed: This test does not need a high level of accuracy, plus or minus 0.5 pH would be suitable. It is ideal however, to have the pH on the high (acidic) side.

Number of trials necessary: 5/bed

Target outcome: 7.5

Assumptions:

- The media is pH neutral and did not affect the pH of the raft grow bed and pond water

Equations: none

Hours: 3

Protocol for pond:

- Dip the pH strip in the water and compare to the sensor

Protocol for the raft grow bed:

- Dip the pH strip in the water

Protocol for the media grow bed:

- Dip the pH strip in the water in the media guard, and do not contact the strip with the rocks

Dissolved Oxygen of Water

Location: Loaves and Fishes' Garden

When: Once the pond is complete and we can run a full cycle of water through the system

Equipment needed:

- Indigo carmine strips and comparator

Accuracy needed: This test does not need a high level of accuracy, plus or minus 0.5 mg/L would be suitable.

Number of trials necessary: 5

Target outcome: 7 mg/L

Assumptions:

- The dissolved oxygen content in the sample is the same and consistent to the dissolved oxygen in the rest of the pond.

Equations: none

Hours: 2

Protocol for pond:

- Dip the indigo carmine strip in the pond water and compare to the comparator strip and the sensor

Protocol for the Raft grow bed:

- Dip the indigo carmine strip into the raft grow bed water at the inlet and near the end and compare the two samples to the comparator strip and the sensor data

Electrical Conductivity of Water

Location: Loaves and Fishes' Garden
When: Once the pond is complete and we can run a full cycle of water through the system
Equipment needed:

- EC sensor

Accuracy needed: This test does not need a high level of accuracy, plus or minus 1 dS/m would be suitable.
Number of trials necessary: 5
Target outcome: 2 dS/m
Assumptions:

- The electrical conductivity of the water is related to the amount of salts dissolved in the water (TDS)

Equations: TDS (ppm) = 0.64 X EC (μS/cm) = 640 X EC (dS/m)
Hours: 2
Protocol for pond:

- Put the sensor in the pond and wait for the measurement to stabilize

Plant Growth per Month
Location: Loaves and Fishes' Garden
When: Once the pond is complete and we can run a full cycle of water through the system
Equipment needed:

- Ruler

Accuracy needed: This test does not need a high level of accuracy, plus or minus 1 kg of plants would be suitable.
Number of trials necessary: every 3 days for a month
Target outcome: 15 kg of plants in 1 month
Assumptions:

- The plants will not be impacted or eaten by pests

Equations:
Hours: 5
Protocol

- Count the number of leaves on the same plant every 3 days
- Use the ruler to measure the width and the length of the leaves every 3 days

Fish Life Span
Location: Loaves and Fishes' Garden
When: Once the pond is complete and we can run a full cycle of water through the system
Equipment needed:

- Clipboard

Accuracy needed: This test does not need a high level of accuracy, plus or minus 1 fish is suitable.

Number of trials necessary: once every week for a year
Target outcome: 90% fish alive by 2020
Assumptions:

- Most of the fish will survive the shipment and initial entry to the pond.

Equations: None
Hours: 5
Protocol

- Record how many fish have died every week

Summary

The experiments detailed and described above have been summarized in Table N1 below in order to give a more cohesive picture of the various experiments and the equipment and time required to perform them. Each experiment is designed to test a single product design specification that was developed through research and a literature review. The hope is that by following these experiments, the team can trace the success of the project and attain the project health and longevity that they are aiming for.

Table O6. Summary of the requirements and equipment for potential experiments

Test	Where/ When	Equipment	Target Value	Accuracy Needed	# of Trials	Eq's	Hrs
Volume flow rate of pump	Garden	5-gallon bucket or graduated cylinders timer/stopwatch submersible pump 1-in tubing	600	- or + 50gph	5	Q=Vt	2
Flow rate of bell siphon	Garden	5-gallon bucket or graduated cylinders timer/stopwatch submersible pump	0.7	- or + 0.1m/sec	5	v=VA*t	2
Flow rate of drain	Garden	5-gallon bucket or graduated cylinders timer/stopwatch submersible pump	0.4	- or + 0.1m/sec	5	v=VA*t	2
Flood and drain cycle	Garden	1 timer/stopwatch 1 submersible pump	15	- or + 2 minutes	5	N/A	2

Test	Where	Equipment	Target Value	Accuracy Needed	# of Trials	Eq's	Hrs
Flow rate through raft grow bed	Garden	1 food dye and dropper 1 timer/stopwatch 1 ping pong ball	0.4	- or + 0.1 m/sec	5	N/A	1
Water temperature	Garden	3 thermometers, 4 temperature sensors	60	- or + 1 Degree (F)	5	N/A	1
pH	Garden	pH strips	7.5	- or + 0.5 pH	5/bed	N/A	3
Dissolved oxygen	Garden	indigo carmine strips	7	- or + 0.5 mg/L	5/bed	N/A	2
Electrical conductivity	Garden	1 EC sensor	2	- or + 0.5 dS/m	5	TDS (ppm) = 640 X EC (dS/m)	2
Kilograms of fresh produce	Garden	1 ruler	15	- or + kg/month	every 3 days for a month	N/A	5
Lifespan of the fish	Garden	clipboard	225	- or + 10 fish	1/week	N/A	3

Appendix P: Team Management

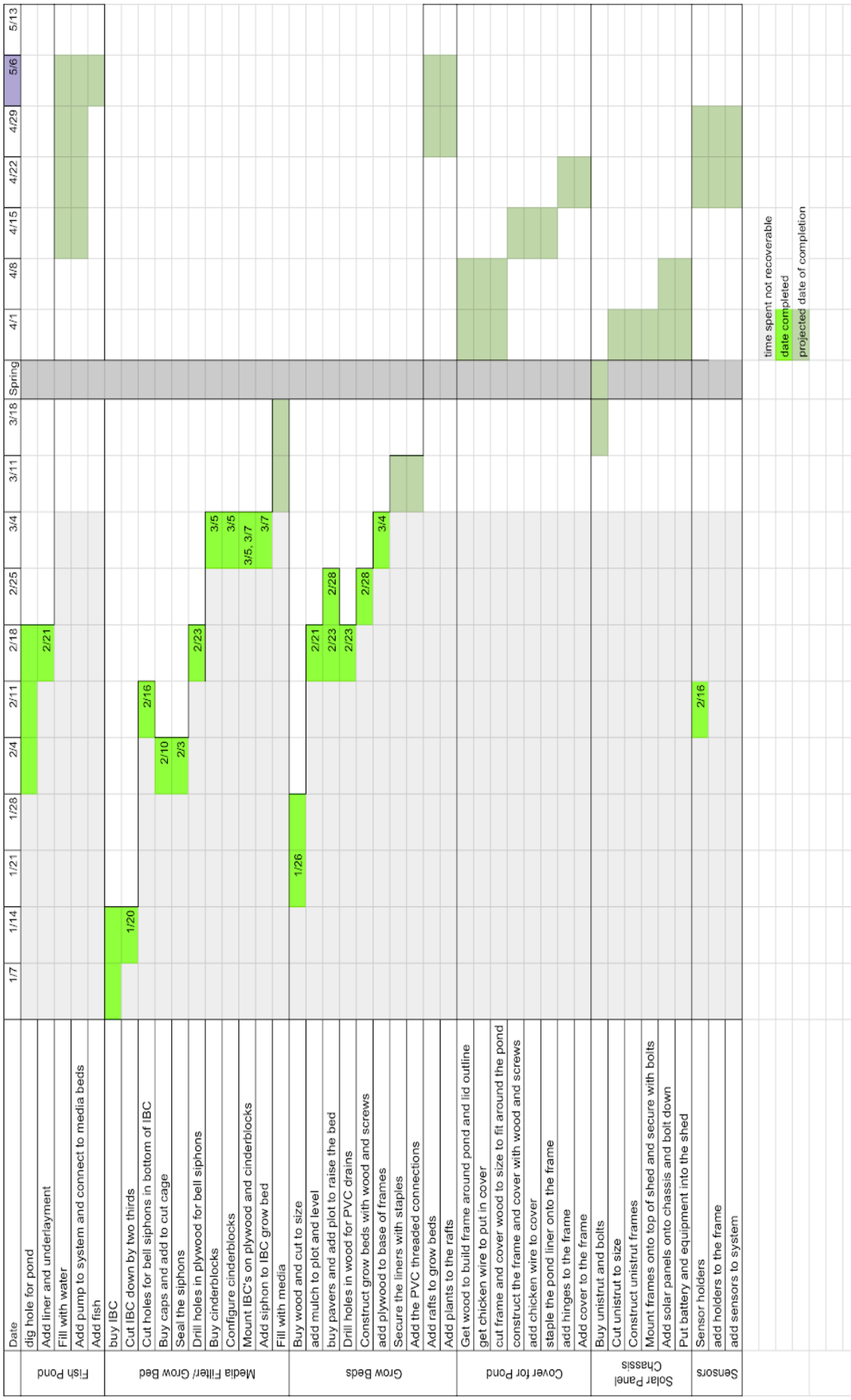


Figure P1. Gantt chart

Appendix Q: Senior Design Conference Slides


SANTA CLARA UNIVERSITY
Design of an Urban Garden Aquaponics System
Riley Albright-Borden (ME), Sydney Thompson (ME) & James Wang (EE)
Advisors: Dr. Laura Doyle (CE), Dr. Hohyun Lee (ME), Dr. Sarah Kate Wilson (EE)
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Project Background
LOAVES & FISHES
FAMILY KITCHEN
goodwill
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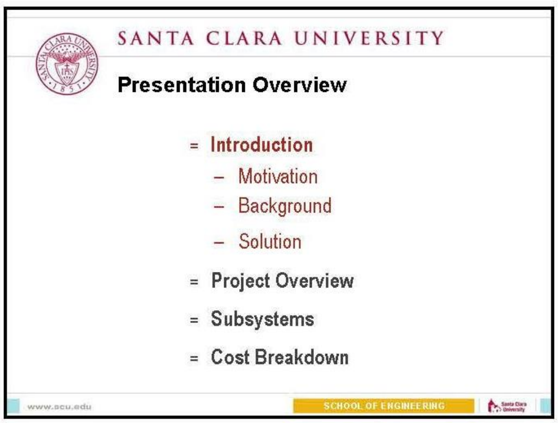
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Presentation Overview
Introduction
– Motivation
– Background
– Solution
Project Overview
Subsystems
Cost Breakdown
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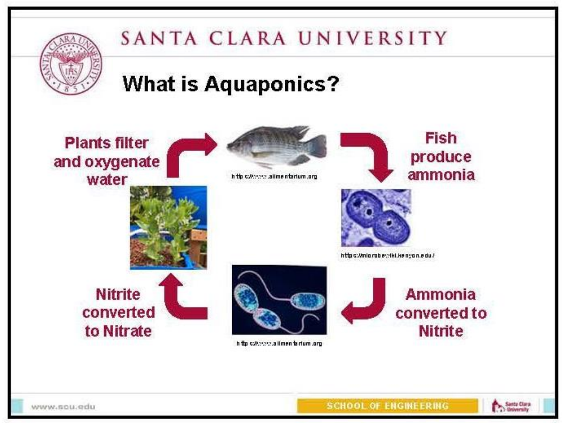
SANTA CLARA UNIVERSITY
What is Aquaponics?
Plants filter and oxygenate water
Fish produce ammonia
Ammonia converted to Nitrite
Nitrite converted to Nitrate
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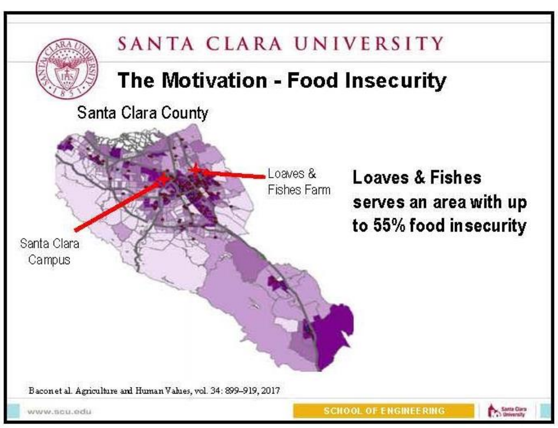
SANTA CLARA UNIVERSITY
The Motivation - Food Insecurity
Santa Clara County
Loaves & Fishes Farm
Santa Clara Campus
Loaves & Fishes serves an area with up to 55% food insecurity
Bacon et al. Agriculture and Human Values, vol. 34: 899–919, 2017
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The Problem: Conventional Aquaponics
High cost due to small size
Relies on connection to the electrical grid
Lack of water quality data
https://www.endlessfoodsystems.com/shop/aquaponics-systems/genesis-24-kit/#configuration
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SANTA CLARA UNIVERSITY
The Project: An Urban Garden Aquaponics System
1. Reduced cost per square foot
2. Water quality data
3. Off-the-grid through solar power
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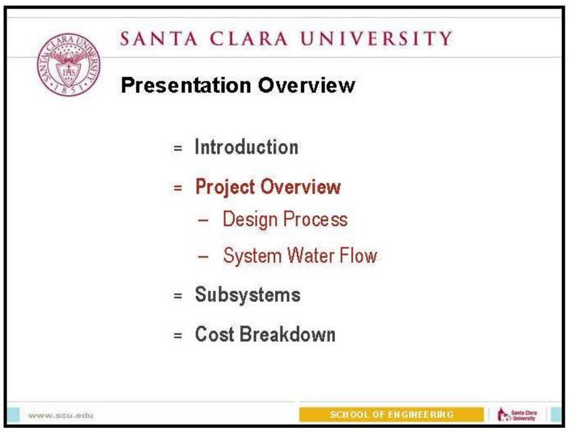
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Introduction
Project Overview
– Design Process
– System Water Flow
Subsystems
Cost Breakdown
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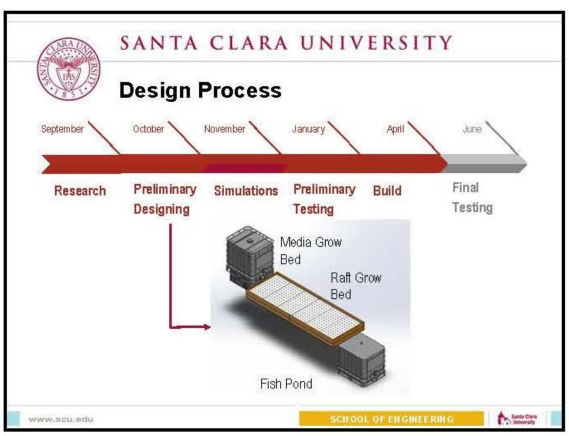
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Design Process
September
October
November
January
April
June
Research
Preliminary Designing
Simulations
Preliminary Testing
Build
Final Testing
Media Grow Bed
Raft Grow Bed
Fish Pond
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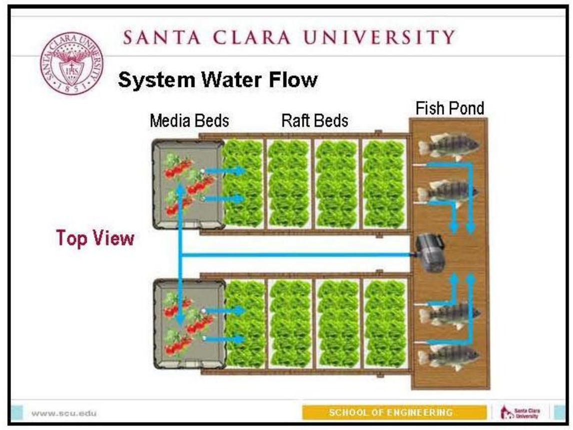
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System Water Flow
Media Beds
Raft Beds
Fish Pond
Top View
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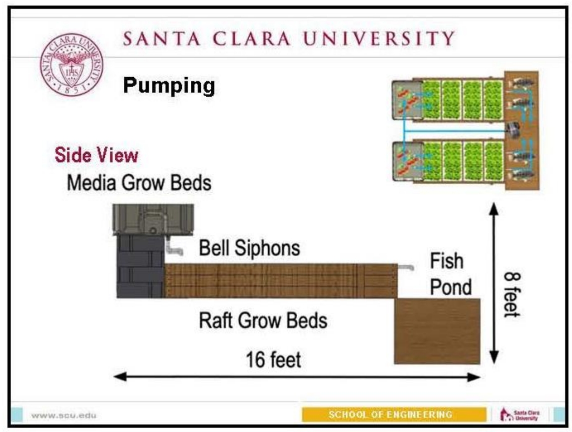
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Pumping
Side View
Media Grow Beds
Bell Siphons
Fish Pond
8 feet
Raft Grow Beds
16 feet
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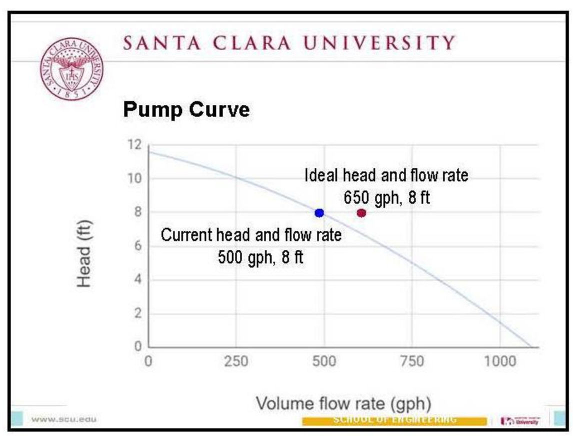
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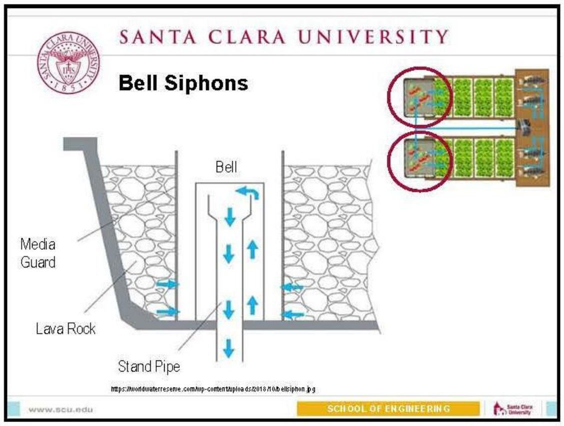
Pump Curve
Ideal head and flow rate
650 gph, 8 ft
Current head and flow rate
500 gph, 8 ft
Head (ft)
12
10
8
6
4
2
0
0
250
500
750
1000
Volume flow rate (gph)
www.scu.edu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Bell Siphons
Bell
Media Guard
Lava Rock
Stand Pipe
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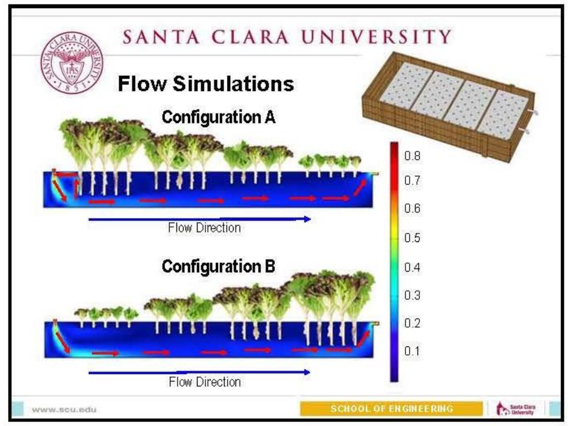
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Flow Simulations
Configuration A
Flow Direction
Configuration B
Flow Direction
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
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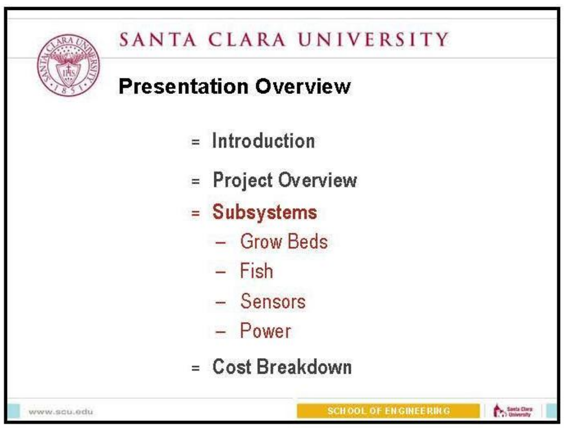
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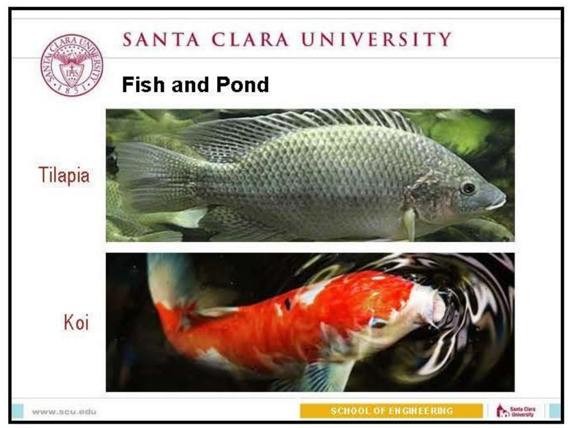
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Tilapia
Koi
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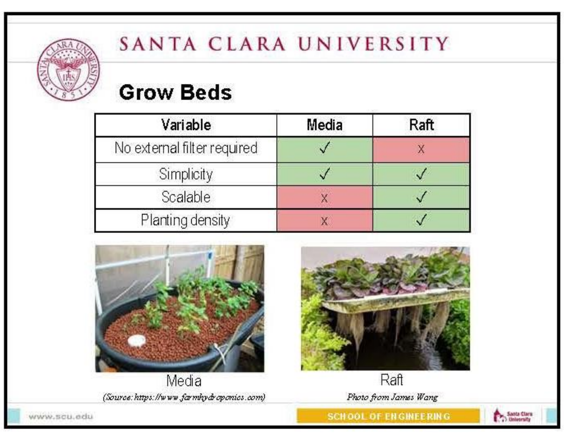
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Grow Beds
Variable | Media | Raft
No external filter required | ✓ | x
Simplicity | ✓ | ✓
Scalable | x | ✓
Planting density | x | ✓
Media
(Source: https://www.farmhydroponics.com)
Raft
Photo from James Wang
www.scu.edu
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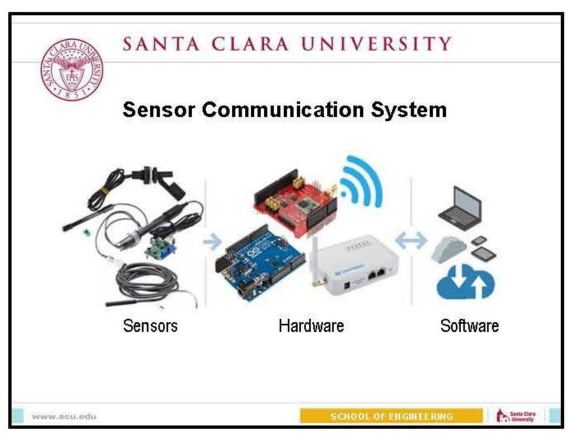
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Sensor Communication System
Sensors
Hardware
Software
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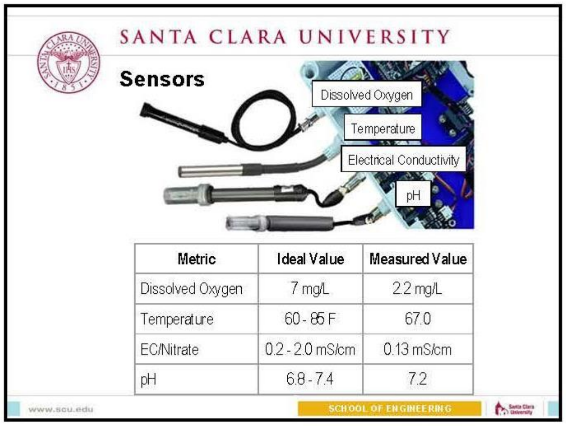
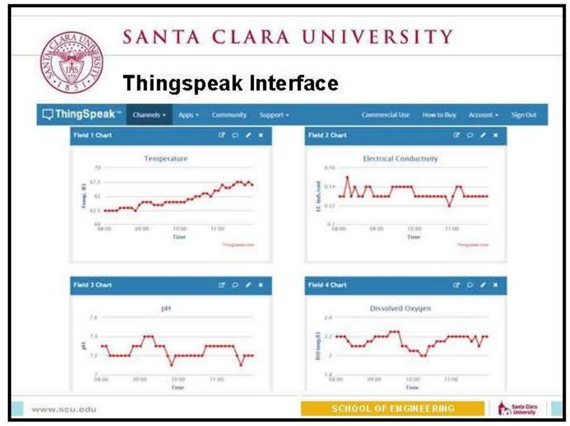
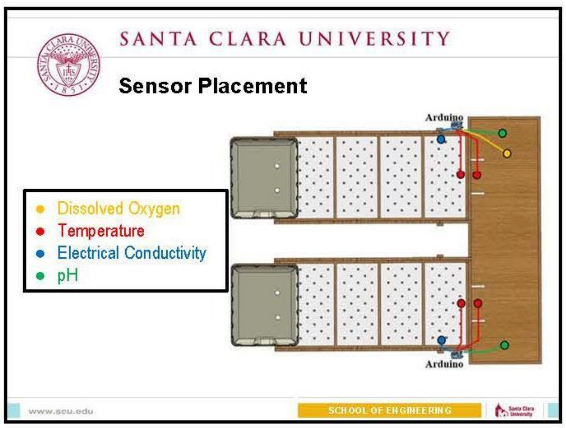
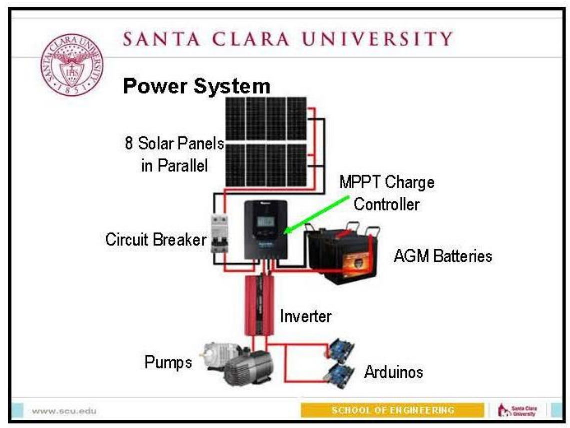
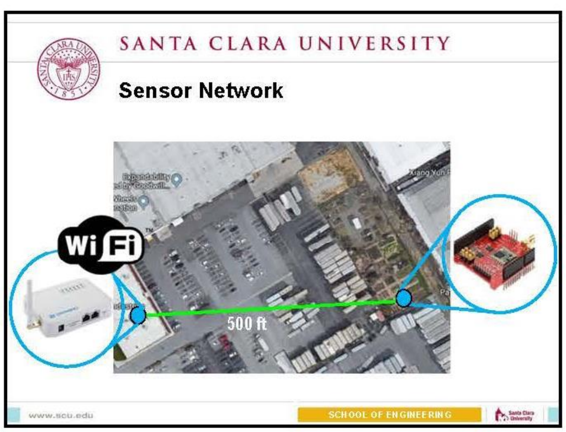


Metric	Ideal Value	Measured Value
Dissolved Oxygen	7 mg/L	2.2 mg/L
Temperature	60 - 85 F	67.0
EC/Nitrate	0.2 - 2.0 mS/cm	0.13 mS/cm
pH	6.8 - 7.4	7.2







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Load Considerations
Monthly Energy Generation and Load
Daily Solar
Daily Load
6000
5000
4000
3000
5360 Wh
5380 Wh
3612 Wh
3416 Wh
Load: 3314 Wh
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Month
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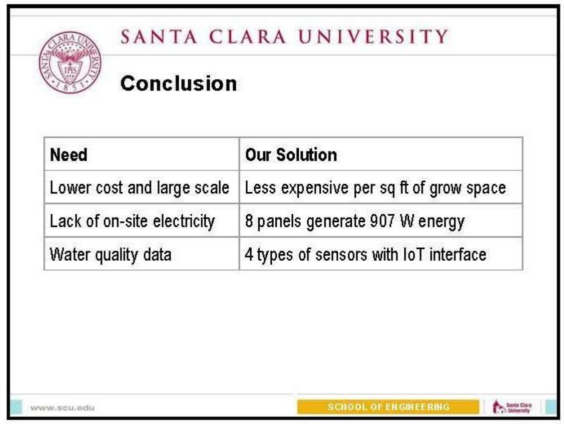
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Conclusion
Need
Our Solution
Lower cost and large scale
Less expensive per sq ft of grow space
Lack of on-site electricity
8 panels generate 907 W energy
Water quality data
4 types of sensors with IoT interface
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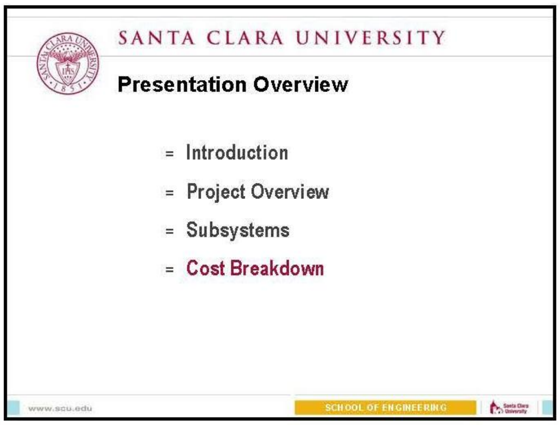
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Santa Clara University
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Frugal Innovation Hub
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Cost Breakdown
Inputs
11.3%
Sensors
17.0%
Tools
1.9%
Power System
22.6%
$600
$ 900
$ 1,200
$ 2,500
Total: $5,300
Building Materials
47.2%
Total Grow Space
Cost of system
Cost/sq foot
Genesis 24
24 ft²
$2000
83.33 $/ft²
Our System
90 ft²
$2500
27.78 $/ft²
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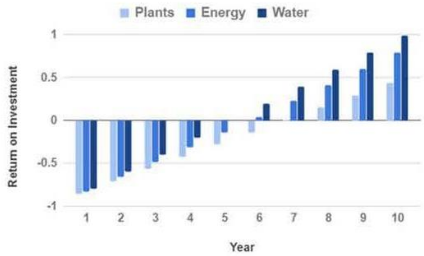
Return on Investment



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Physical Control Feedback

Variable	Method
Too Hot	Shade pond, increase aeration
Too Cold	Decrease pump flow rate; pond heater
pH Too High (Basic)	Add phosphoric acid
pH Too Low (Acidic)	Add calcium carbonate/potassium carbonate
Electrical Conductivity	Feed fish less, add nitrifying bacteria
Dissolved Oxygen	Manually turn on/off additional air pump

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Cost Analysis Breakdown

Subsystem	Total Grow Space (ft^2)	Cost of system ($)
Genesis 24	24	2000
Our System	90	2500

Subsystem	Cost of subsystem ($)
Fish Pond	355
Media grow bed	808
Raft grow bed	1331
Total cost	2494

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Initial Research

- Equations for Subsystem Area Calculation

156=Ap+Am+Ar

Vp=4Ap=4Am

Vp=4Ap=0.93(Am+Ar)

Subsystem	Calculated Area (ft^2)	System Area (ft^2)
Fish pond	30	36
Media grow bed	30	27
Raft grow bed	97	86

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Future Work

- Extension of sensor network
- Automated control system
- User-alert system
- Expand system size
- Increased energy system
- Modular system kit

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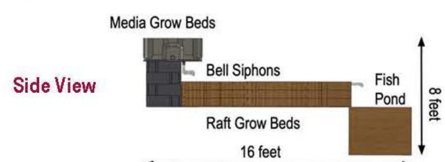
Pumping



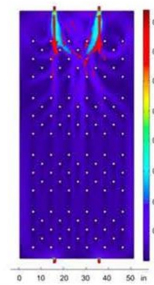
Water Pump Requirements	Head (ft)	Flow Rate (gpm)
Value Required by System	8	650
Value Provided by Pump	12	1110

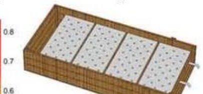
Flow Rate Tests

Requirements	Units	Ideal	Target Range
Flood and drain cycle	minutes	15	10-20
Volume flow rate of pump	gph	600	500-700
Flow rate of bell siphon	m/sec	0.7	0.4-0.9

Computational Fluid Dynamics: Top View

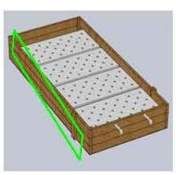
- CFD on Raft Grow Bed
- Max velocity of flow occurs at the inlets with 0.8 m/s
- Test hole arrangement

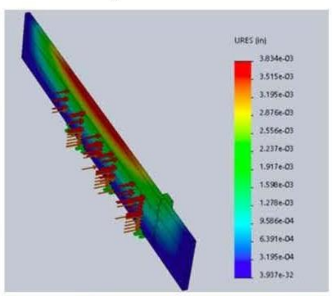




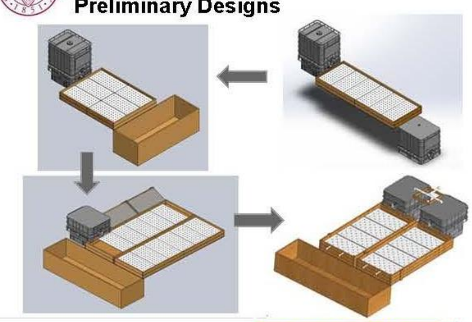
Finite Element Analysis: Deflection

- Displacement:



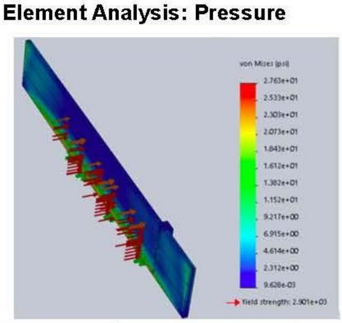


Preliminary Designs



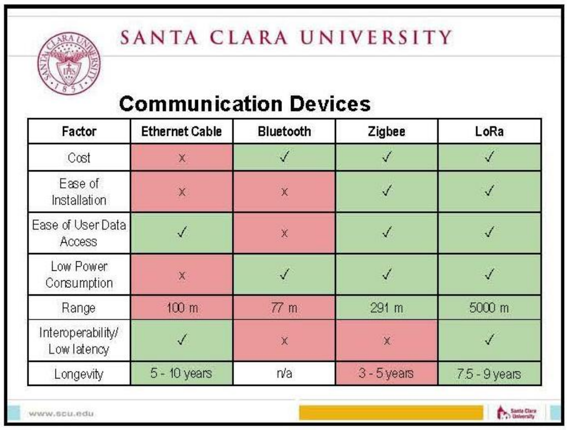
Finite Element Analysis: Pressure

- Von Mises: 27.63 psi compared to maximum yield strength of 2901 psi

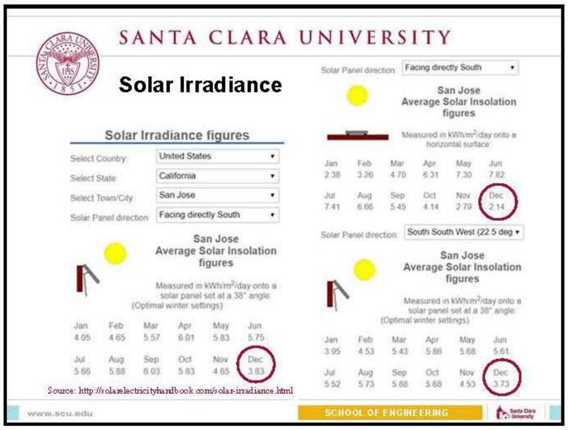


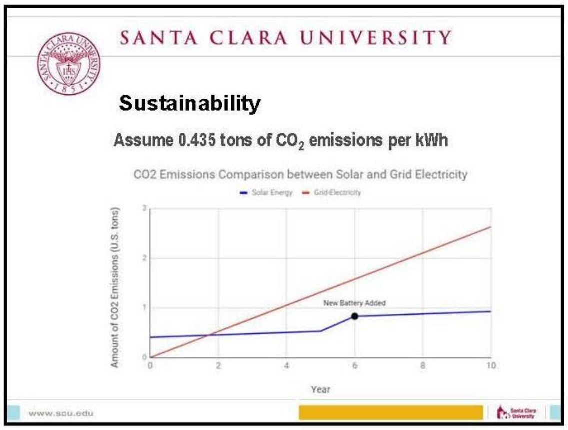
Tilapia in California

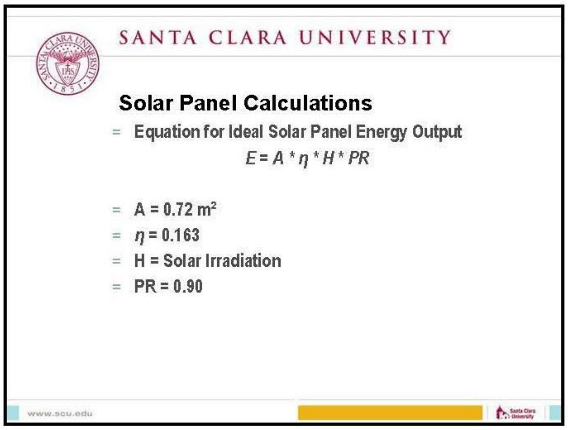
- California Department of Fish and Wildlife
  - Restricted Species Law and Regulations
  - 671.9.O. Importation, Transportation, and Possession of Live Restricted Animals
- "In California, Mossambicus Tilapia can be raised because they can't survive in natural waterways during winter temperatures"
  - aquaponicsusa.com

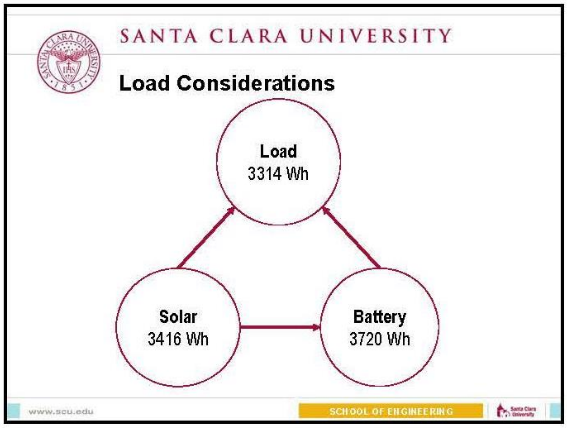


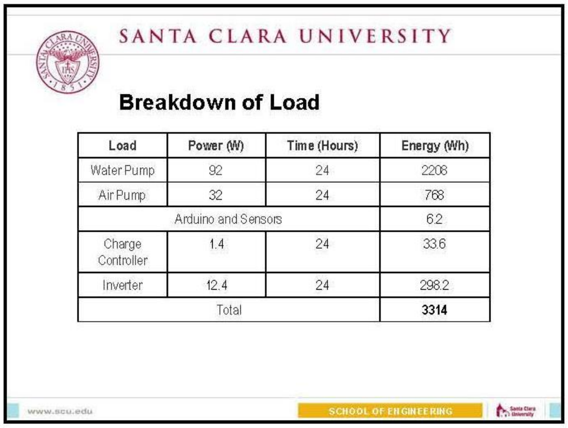
Factor	Ethernet Cable	Bluetooth	Zigbee	LoRa
Cost	x	✓	✓	✓
Ease of Installation	x	x	✓	✓
Ease of User Data Access	✓	x	✓	✓
Low Power Consumption	x	✓	✓	✓
Range	100 m	77 m	291 m	5000 m
Interoperability/ Low latency	✓	x	x	✓
Longevity	5 - 10 years	n/a	3 - 5 years	7.5 - 9 years











Load	Power (W)	Time (Hours)	Energy (Wh)
Water Pump	92	24	2208
Air Pump	32	24	768
Arduino and Sensors			6.2
Charge Controller	1.4	24	33.6
Inverter	12.4	24	298.2
Total			**3314**