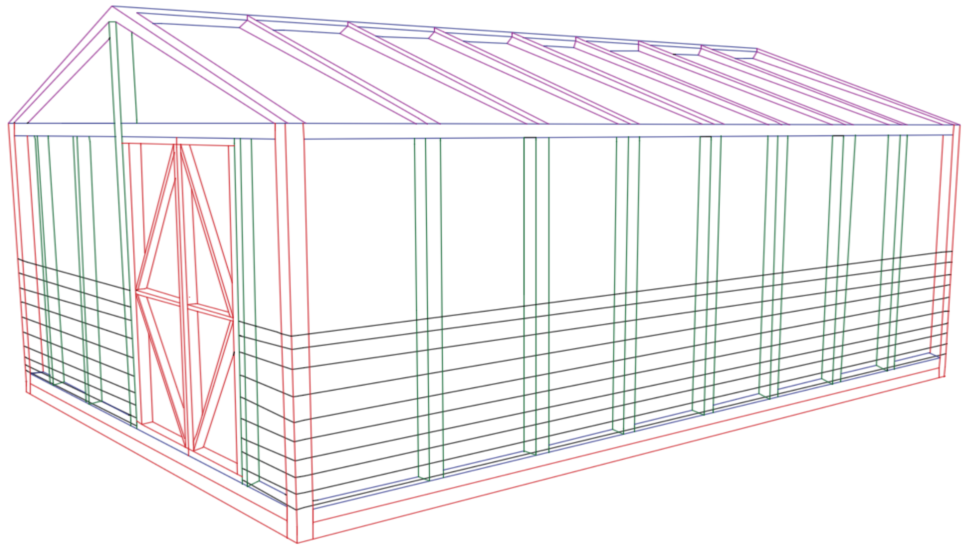
Designing an Aquaponic Greenhouse for an Urban Food Security Initiative



By

Rashid Chatani

Gabriel Demeneghi

Redon Hoxha

Khazhismel Kumykov

Blaine Rieger

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in partial fulfilment of the requirements for the
degree of Bachelor of Science

By
Rashid Chatani
Gabriel Demeneghi
Redon Hoxha
Khazhismel Kumykov
Blaine Rieger

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Report Submitted to:

Matt Feinstein
Worcester Roots Project

Professors Stephen McCauley and Lorraine Higgins
Worcester Polytechnic Institute

Abstract

This project supported the Worcester Roots Project's effort to build an aquaponic greenhouse at Stone Soup Community Center by designing a greenhouse and prototyping a modular aquaponic growing system. The team collaborated with Worcester Roots and Technocopia to develop a vision for the greenhouse project, evaluate options and determine appropriate designs for the system. We proposed a design for a wooden greenhouse with several growing systems using cheap, readily available materials, and successfully built a prototype growing system that to be by a future cooperative incubated by Worcester Roots. This project will enable growing local, fresh food in the City of Worcester and provide a starting point for developing a cooperative food business.

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1 Introduction

Access to fresh, healthy, and affordable food is a fundamental requirement for healthy living. As of 2013 in the United States 38.9% of low-income households and 14.3% of all households were considered "food insecure" – meaning they did not have access to enough food for "active, healthy living" (Alisha Coleman-Jensen C. G., 2014; Alisha Coleman-Jensen C. G., 2014). One of the manifestations of food insecurity are *food deserts* – communities that have limited access to supermarkets or grocery stores that often rely on fast food and convenience stores with a lack of healthy affordable food (USDA AMS, n.d.).

Cities are becoming increasingly concerned with how food relates to the urban environment and are encouraging the development of "sustainable food systems" that contribute to high quality neighborhoods, meet the health and nutrition needs of residents, and promote environmental sustainability (Koc, 1999).Food deserts and food insecurity are all signs of unsustainable food systems. A community that does not have ready access to supermarkets nor is able supply itself with fresh food cannot sustain its inhabitants. According to the data stipulated by the USDA, there are about five of these communities here in Worcester, one of these communities is Main South.

Worcester Roots, the main sponsor of our project, in an effort to address food security as well as to empower the local residents, has decided to build a greenhouse capable of providing fresh and affordable food. Worcester Roots is a non-profit organization seeking "to create opportunities for economic, social and environmental justice" (Worcester Roots, n.d.). In this effort, they lead local projects to help clean their local areas, raise awareness for issues such as toxic soil and a just economy. Worcester Roots supports the worker cooperative style of economy and incubates a number of cooperative businesses (Worcester Roots, n.d.).

The goals of the greenhouse project was to design and construct a greenhouse and aquaponic growing facility and start a pilot cooperative business running out of the greenhouse. With the project they seek to empower local residents, provide a healthy, local food source for Worcester residents, and educate members and local youth about greenhouse growing, aquaponics, and the cooperative businesses. The organization has expressed its wish to have students from schools come in and learn about co-ops as well as how a greenhouse works; these students would then take back that knowledge to their schools and homes, spreading interest and knowledge. If the interest is widespread and the 3 year pilot is successful, the organization has articulated that scaling up the greenhouse will be very high on their priority list (Worcester Roots, n.d.). Possible expansions include expanding up to industrial scale operations in warehouses throughout Worcester, or expanding out to individual residences with many family sized productions.

The goal of our project was to assist Worcester Roots in their development of the pilot greenhouse project and the cooperative greenhouse business by providing: technical support, research assistance and insight into the social context associated with the project. We collaborated with partner organizations, including Worcester Roots, Technocopia, and various other parties interested in the greenhouse project and cooperative pilot to synthesize an open sourced design that will be easily replicated by anyone having an interest in aquaponic systems.

We competed the project by conducting research in the Aquaponic field and comparing various components for the creation of an Aquaponic system. From our research, we then produced complete designs for both a greenhouse that fulfills Worcester Roots' needs and a modular self-contained aquaponic growing system that would be housed in the greenhouse, including the biological and mechanical aspects of the system. We also produced a budget for the complete system build and operating costs, and an operating schedule. We collaborated closely with Worcester Roots, Technocopia and other experts throughout the project in order to ensure that the results and deliverables are appropriate to the stakeholders needs. Finally, we worked out of the Technocopia makerspace with assistance from Technocopia members, to produce a prototype aquaponic growing system that will be used by Worcester Roots.

2 Aquaponic Growing Systems and their Potential to Contribute to Urban Food Security

Aquaponics is a bio-integrated food system which allows for the production of both plants and animals for consumption without requiring arable land. Aquaponics can be defined as the integration of hydroponics – growing without soil – and aquaculture – fish farming. Plants situated on water beds are grown with aquatic life, usually fish. The intricate design allows for the waste products of one biological system to serve as nutrients for another (Wahl, 2010).

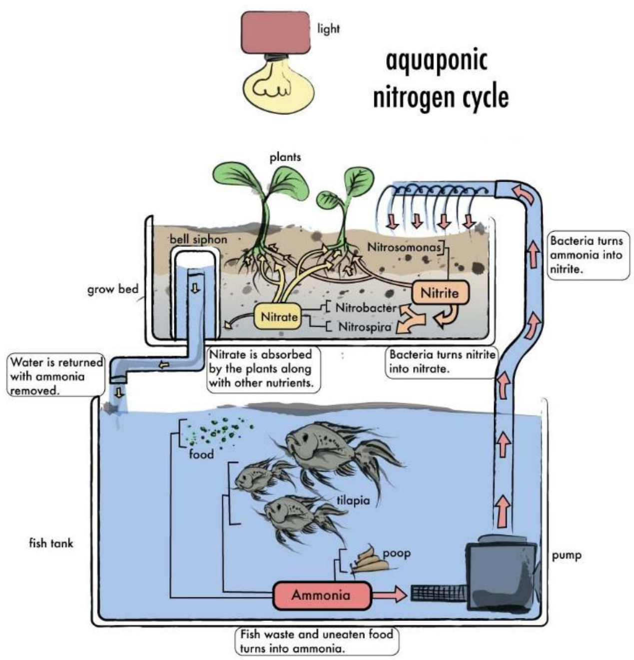

Figure 1. The Aquaponic Cycle (Acquired from Worcester Roots http://www.worcesterroots.org/projects-and-programs/youth-in-charge/)

In aquaponics water is reflowed through the system circulating fish runoff and plant/algae matter, which creates an efficient ecosystem that provides fertilization for the plants and cleans the water for the fish, creating an extremely efficient system for growing.

Aquaponics recycles a lot of the raw materials put into the system and makes the process very efficient. Aquaponics uses 90% less water than traditional farming, while simultaneously producing on average six times more yield per square foot than traditional farming (Marklin, 2013). This is partly due to the interior homeostasis that allows production in any type of climate zone. Plant growth is also drastically increased as the threat of pest is reduced as plants are grown indoors, and the water is naturally fortified by the fish. The lighting also plays a very important role in the growth efficiency as they are hung vertically and used to simultaneously grow two areas of plants as opposed to one are. (Jason, 2012)

In addition to these farming benefits there are also environmental benefits to using aquaponics. Since the process is regulated and the waste material is cycled, there is no harmful fertilizer run off into and water sources such as water sheds and rivers. This greatly reduces the instances of water pollution that arises as a misuse of fertilizers, this causes great damage to the aquatic life in these water bodies. (Jim, 2009).

Using aquaponic systems to enable growing food in urban environments provides the residents with more sustainable, local food sources. Eliminating the waste of needing to transport food from long distances, localized food production is a more sustainable and green way of providing a community with food. As well, coupling the localized food production with a cooperative economy enables the residents to not only have access to fresh food, but also gives them the power over their own food.

3 Methods

The end goal of this project was to help Worcester Roots develop a design for a greenhouse and growing system to be built on at the Stone Soup Community Center, and provide information and a plan for operating it. Our team developed a design for a greenhouse and growing system and worked with Technocopia to build out a prototype growing system.

Our team developed the following objectives to meet our goals:

- Assess the stakeholder’s needs
- Develop an understanding of aquaponics and evaluate design options by investigating existing literature, visiting greenhouses in the region, and consulting with experts.
- Design greenhouse and growing system that fit Worcester Root’s needs (incl. cost estimate)
- Build out prototype system

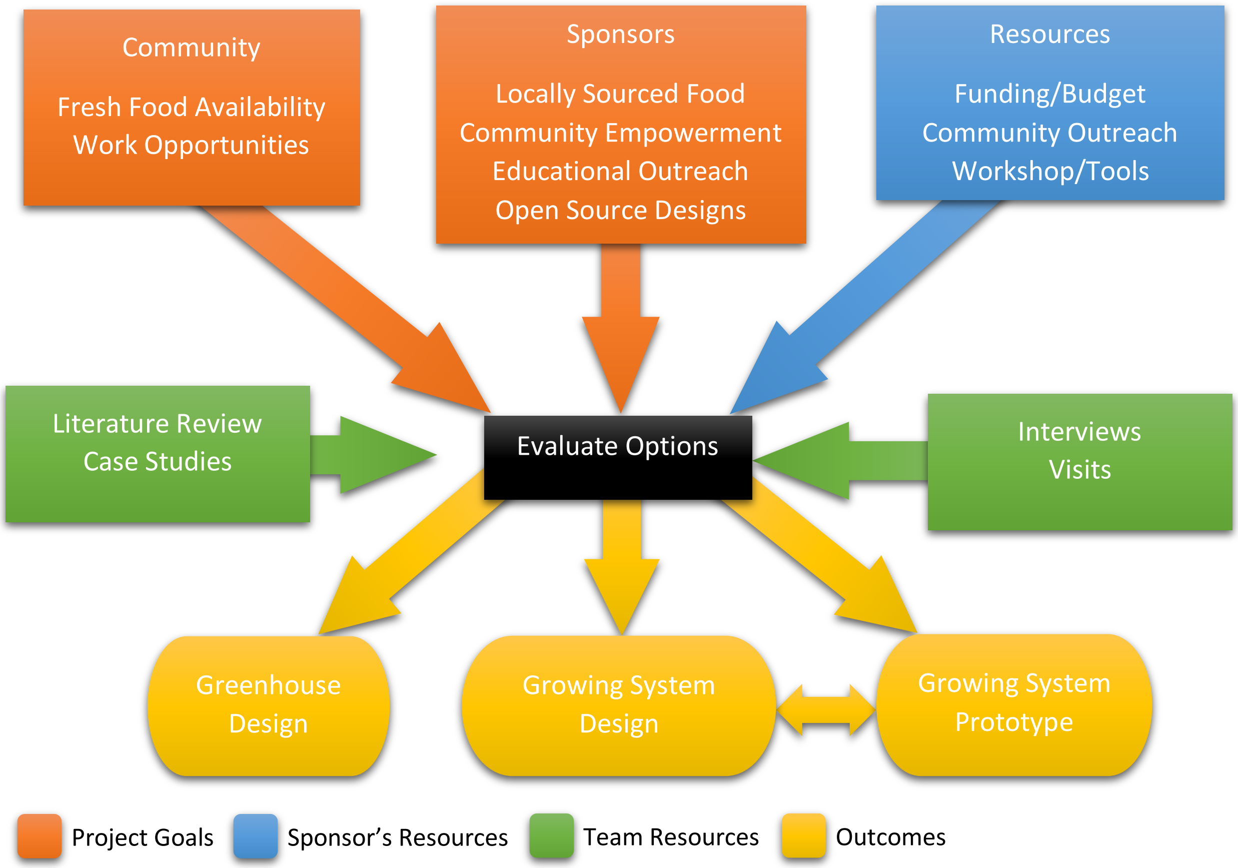

Figure 2. Project Overview

3.1 Assessing the Stakeholder's Needs

In order to fully understand the various stakeholder's needs we participated in regular group meetings at Worcester Roots and Technocopia to provide status updates, discuss design decisions, and steer the course for the project. We met semi-regularly, starting with weekly meetings at the beginning of the project, and later spreading out to weekly or monthly meetings as the project got underway. Early meetings focused on identifying research areas and identifying the role of the IQP group in the greater greenhouse project, while later meetings focused on refining an ongoing design and budget for the greenhouse and growing system, and providing status updates. The project uses an email list for regular communication and update that included all the sponsors and IQP group members and advisors, as well as other interested parties.

3.2 Understanding Aquaponic Greenhouse Systems and Evaluating Design Options

To develop a strong understanding of both aquaponics and greenhouses we consulted the relevant literature, considering both the technical and social aspects related to aquaponics. We investigated the biological characteristics of aquaponics system, and evaluated the benefits and drawbacks that it poses. We identified various components that would have to be used in an aquaponic system as well as in a greenhouse, and researched each of the components individually to best assess the benefits and drawbacks of each one. We also investigated the economic position of aquaponics and similar industries in the United States (specifically hydroponics and aquaculture, the two “parts” of aquaponics). We consulted numerous academic and industrial journals, as well as studies conducted by educational and governmental institutions worldwide.

To further understand aquaponics, we read blogs of other people who built their own aquaponic systems. Many hobbyists and professionals are eager to share their progress and designs in building aquaponic system, and many of the components had do-it-yourself alternatives (such as water tanks) that were documented by enthusiasts online.

We also visited three greenhouses to get a feel for the designs and operations. We first visited a local Worcester greenhouse owned by Amanda Barker, and conducted an interview on how factors such as ventilation and internal layout affects the growth of plants. We also visited WPI’s own greenhouse on top of a campus building, it has automated heating systems and windows, which present some fatal flaws, such as heating the greenhouse up in the winter and opening the windows when the internal temperature heats a point, cooling the greenhouse again. The last visit was an aquaponic greenhouse in Holyoke, Massachusetts, during this visit we discussed insulation, the design, and interior layout of their aquaponic system to compare to ours.

To obtain further information on the design we interviewed Professor Alamo, a structural engineer, who provided the team with valuable information about the design of the roof, walls, and foundation of the building. When finalizing the greenhouse structural design contractors from JEMCO were presented with draft schematics and consulted for revisions and recommendations.

3.3 Designing the Greenhouse System

The design of the greenhouse and aquaponic growing system was the major deliverable for the project. It entailed extensive research and planning. The major tasks we completed as part of the design were:

- Developing a structure and layout for a greenhouse
- Designing a modular aquaponic growing system
- Developing a budget for implementation of the entire system
- Creating an operating schedule

Using knowledge gained from our research and consolation with experts and practitioners, we developed and iterated our designs, going back-and-forth between designing and consulting with the sponsors, experts, and our research. Additional information about the greenhouse structure was found through intensive research on blogs, web stores, scientific journals, and research published by universities and institutions, as well as interviews with pertinent engineers and scientists in the field. To design the system itself we used CAD programs such as SolidWorks to develop schematics. These schematics also proved useful in communicating our designs with the sponsors and consultants.

In order to determine prices of pre-made materials such as pre-made water tanks and piping, local suppliers were surveyed. For pre-owned materials, such as 55-gallon drums and 1000L water tanks Craigslist (craigslist.com) and eBay (ebay.com) were surveyed in the local area. While these listing are temporary, they represent the rough actual price of locally sourced materials. A bill of quantities was made to keep track of all known and unknown quantities and costs. The bill of quantities along with the price quotes for the different materials were compared with the budget to ensure that all expenses were met.

With the complete startup cost and budget a logistical step by step process for operating the greenhouse was necessary for its longevity. The catalogs for currently established greenhouses and aquaponic greenhouses were researched and a preliminary schedule was synthesized. The initial schedule was then updated after a phone interview with Eric Varinje, a representative from Planet Natural. Planet Natural is a company that specializes in indoor organic growth, greenhouses and hydroponics. With the input from the sponsor (Worcester Roots) the specifics of the schedule, such as the timeframe for growing crops and selling fish were then created. The schedule was synthesized in an attempt to maximize productivity and increase the viability of the greenhouse.

3.4 Building Out Prototype Aquaponic Growing System

One of the goals of the project was to build out a prototype aquaponic growing system for the sponsor. Technocopia and Worcester Roots together provided access to Technocopia's tools and workshop which was used as staging for building out the prototype system. The IQP group, with some assistance from Technocopia members, built the prototype system over 6 build days.

4 Findings

In our project we worked closely with the stakeholder to identify key research areas, and then investigated and found various possible solutions in three main areas: designing a greenhouse for the New England climate, designing an aquaponic growing system, and what running such a system would look like.

4.1 Stakeholder's Needs

Early on it was identified that the IQP group would focus on developing a design for a greenhouse structure and a prototype aquaponic growing system. For the system we identified the major criteria and constraints for the project: the design will need to function in cold winters and hot summers, so must be **energy efficient** to reduce costs as well as to encourage a green economy; the design should be **cost effective** so we must weigh the costs versus the benefits of different solutions to best fit our budget and limit waste; the design should be **sustainable**, using locally sourced materials to promote a local and green economy; the design should be **maintainable** and resistant to vandalism, so that ongoing costs are kept to a minimum; the design should **maximize food production**, as the goal of the project is to provide food, rather than other commodity crops; the design should **enable education**, to allow for ease of bringing in local high school students or tour groups to learn; the design should be **fit for local market demand**, similar to being sustainable, so that the system can be self-sustaining and can provide to the local demand; the design should be **scalable** so that our work and research can apply to larger future systems. As well, the design must be finished by the end of the WPI school year; the design must fit into the allotted space – a 20'x33' area behind the Stone Soup Community Center in Worcester; it must fit into the budget Worcester Roots has raised, roughly $5500 for the growing system and roughly $20000 for the greenhouse structure and site work; it must follow all city and state rules and regulations, including zoning, safety, and licenses.

4.2 Design Considerations

4.2.1 The Greenhouse Structure

The first major component was the greenhouse structure that will be housing the aquaponic system. We needed a system that could survive the harsh New England climate, which drops plenty of snow and drops below freezing in winter, and becomes very hot and humid in the summer, and would be easy to maintain.

4.2.1.1 Greenhouse Frame

The frame of the greenhouse is what keeps the building in place. A well thought design is necessary to withstand the lateral forces of the wind and storms as well as the weight of the materials and potentially wet snow. It will also dictate what can or cannot go inside of the greenhouse as for the height and internal space.

The style of the frame considerably increases or decreases the cost of building a greenhouse. Each different shape dictates the materials used to build the frame as well as the paneling that will be used in the greenhouse. For example, if it is a hoop house, it will be hard to install rigid plastic or glass to cover the greenhouse. In New England, where we have harsh winters, the hoop house would need constant maintenance to remove the snow and fix soft coverings. The figure below show a few different shape styles.

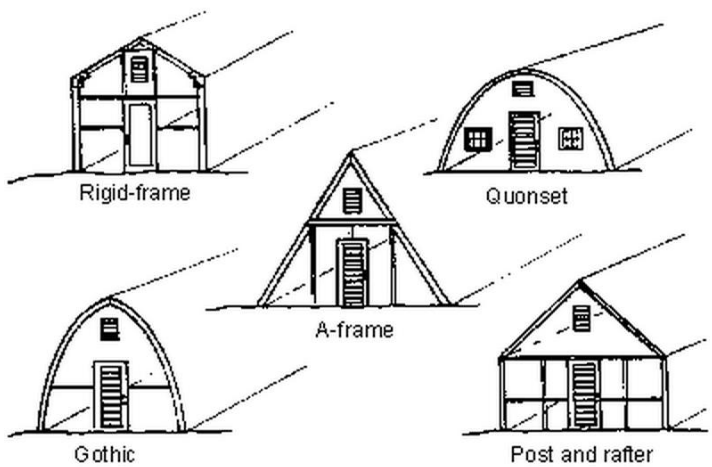

Figure 3. Possible greenhouses structure designs. Our final design uses the post-and-rafter style. (Acquired from http://www.nafis.go.ke/vegetables/tomatoes/shapes-of-frames/)

Due to the snow accumulation it would be necessary to have a steeper slant in the roof, and styles such as Gothic fare much better than Quonset or hoop style roofs which risk collapse. A style such as an A-frame provides excellent structure, but limits usable space. Rounded shapes also suffer from this space limitation, and also prevent usage of solid paneling, requiring a thin film be used instead. ***For this project, we found that the post and rafter style would provide the best stability and space balance.***

After deciding the shape of the greenhouse, the choices for materials used are narrowed down to a hand full of materials. Therefore, we gave special attention to aluminum, steel, and wood. (Ross, n.d.) (Greenhouses, n.d.). The criteria considered were; cost, strength, location, and how much technical support was necessary to put it together.

4.2.1.2 Greenhouse Floor

The floor of greenhouses are normally dirt and fabric, but since this is an aquaponic system we need a strong floor to support tons of pounds of water without giving in. The first option which comes to mind is concrete, but it is actually one of the worst possible floors that there are for greenhouses, because the floor has to be able to absorb water. Preventing the accumulation of water on the floor helps to ensure a clean environment and save time not having the extra work of moping the floor all the time (Little Greenhouse).

4.2.1.3 Greenhouse Insulation

The idea behind insulation is to keep on side warmer than the other. A proper insulated structure can provide a significant save in the energy used for the heating and cooling the greenhouse. If the greenhouse is in a region where temperatures have a big variation during the year, insulation is a key part of the design in order to be able to keep the greenhouse running (John W. Bartok J. , 2007).

Ideally, every inch of the building should be insulated, starting from the ground, going all the way up to the roof. On the ground, the insulation is placed around the foundation of about one foot deep.

After the ground insulation is done we can build the greenhouse. In aquaponic greenhouses the plants grow in vegetable beds, which are a few feet higher that the ground, therefore, we can build the walls below the line of the plants out of a non-transparent materials and insulate as much as possible. There are many different types of insulation materials, like; foam, fiber glass, wool, and many more. When choosing the best material to use in the greenhouse, there are two main things to take in consideration, the R value and the cost. The R value should be the highest possible at a reasonable price.

For the transparent walls and roof, there are limitations on how much it can be insulated, normally the thicker the material the best it insulates, but it also loses light transparency with every inch of thickness. The key to choose the right material here is to scale the pros and cons of each individual material and choose the one that can best fit the greenhouse needs.

Another technic that can be used to conserve heat is the use of thermal blankets at night. Because the greenhouse loses most of its heat during the night, putting thermal blankets against the walls inside of the greenhouse prevents part of this heat from getting away (Roberts, Mears, Simpkins, & Cipolletti, 1981).

4.2.1.4 Greenhouse Ventilation

Ventilating the greenhouse is removing the air from inside of the greenhouse and replacing it with the outside air. The main purposes of ventilation in a greenhouse are: control the high temperature during the summer, to preserve the humidity at adequate levels during the winter, to provide a uniform air circulation in the entire greenhouse. (Dennis E . Buffington, n.d.) (Hopper, 2012).

The ventilation is important thought the year, it helps to regulate de temperature in the summer and to prevent moist, molds, and humidity in general during the winter. It is an indispensable piece of the greenhouse in order to have healthy vegetables and a strong structure.

A simple way to create a natural and cheap ventilation system is the use of doors, and windows on the roof. Following the rules of physics, hot air rises and escapes as new fresh air comes in. However, in general we found that ***fans would be necessary to provide the necessary air flow to regulate temperature effectively.***

4.2.1.5 Greenhouse Heating

We found that to prevent frost during the winter and keep ambient temperature up, especially at night, a space heater would be strongly recommended. Our research show that in Worcester the temperatures have a considerable variation throughout the year, according to NOAA, occurs in January and it is about 17 degrees Fahrenheit, which is well below our ideal temperature of 60 degrees Fahrenheit.

During the meeting with the sponsor we discussed about solar, electrical, gas and also firewood. The factor that played the biggest whole was the cost of each one of them. Besides the expensive heating equipment required to build each system, we also have to consider the month to month cost of each system. A very good practice in designing systems is to take in account and to calculate the worst case scenario in order to promote a more efficient and safe system.

Another option that was considered was to heat the water and to provide the optimal environment for the fishes, since they are the ones that require a warmer environment. If we choose to heat the water we would not need to heat the rest of the greenhouse because the water would serve as thermal masses, which store heat and keep its surroundings warm.

4.2.1.6 Greenhouse Internal Layout

We found that the internal layout may be regulated by OSHA and Worcester building code for wheelchair accessibility. As such, we found that ***walkways would need to be a minimum of 3' wide***. As well, we identified that as the greenhouse would be used for educational purposes, the layout would have to allow bringing in tour groups that can easily traverse the greenhouse and see the grow beds, while also maximizing effective growing area. For this, ***we found having walkways on all sides of the grow systems was effective.*** We also found that for effective use of the greenhouse, the doors would need to be wide enough to bring large objects in and out, so ***double doors were recommended***.

4.2.2 The Aquaponic Growing System

The major components of the aquaponic growing system are the fish tank and the plant growing bed, connected by piping and pumping. We investigated the ideal ratio between plant growing area and fish tank volume, and investigated different solutions for growing beds, fish tanks, and the plumbing to connect them.

4.2.2.1 Plant and Fish Ratio

Through our research we found that the ideal ratio for fish space and water space was 5-10 gallons of water for 1 square foot of growing area. Through our calculations we found that 1 pound of fish will produce enough waste to support roughly 1 square foot of growing area, which matched research conducted by aquaponic specialist Sylvia Bernstein, and Bernstein found in her research that 1 pound of fish generally requires 5-10 gallons of water to grow effectively (Bernstein, 2013). We used these numbers to inform our growing system design later on.

4.2.2.2 Growing Bed

The structure must be carefully designed to ensure that the growing bed will be able to withstand the water that it contains. The structure must be made from materials that are readily available. Using non-standard materials can add complexity to the project. It is best to use materials that are both cost effective and widely available. ***Inspired by existing designs, we found that building a bed out of plywood and lumber, with a pond liner, would be the cheapest and most fitting solution.*** Also investigated were beds built by cutting 55-gallon drums in half, but we found that these were not ideal due to their unusual shape limiting plant growth at the edges and their small size requiring a significant number of barrels to be used in a larger scale system.

4.2.2.3 Fish Tank

To find an ideal fish tank for our aquaponic system we investigated professional solutions advertised for hydroponic and aquaculture setups, looked at do-it-yourself projects for water tanks, and spoke with those that had experience with fish and hydroponics. Many hobbyists write up or record their aquaponics builds and upload them to the internet, which provided inspirations for our designs and initial research. The water tank needed to be easy to procure or create, sturdy enough to handle large volumes of water, and provide easy access to the fish. Ease of cleaning and water flow also impacted the tank design – rounded corners or a cylindrical or conical design would be self-cleaning, versus hard edges.

Figure 4. The IBC Tote was recommended to be used as a fish tank

A 1000 liter intermediate bulk container (IBC) tote—a commonly available and used industrial water tank—was found to be the most effective solution for the primary fish tank for the modular system. It was compared against 55 gallon drums—another common type of industrial storage, a wooden tank design—a cheap design similar to our bed using plywood and reinforcement, and injection molded plastic tanks—large professionally made tanks. The IBC tote proved most cost effective, and was readily available in local sources. A plywood tank could potentially provide additional cost savings, but the additional labor involved was deemed not worth the marginal cost savings over the IBC tote. 55 gallon drums also could cost less than IBC totes for our system, but would require additional piping and pumps, and would increase overall complexity, so was ruled out. The injection molded tanks were the most expensive option, required shipping from out of state, and were unwieldy, so were ruled out.

4.2.2.4 Water Circulation

The aquaponic system requires that the water circulates constantly in the system. According to Dr. Nate of brightagrotech.com, a professional aquaponics website, it is recommended to circulate the water in the system every two hours. There is two ways that the water will flow: into the growing bed and the drainage. Since the growing beds will be higher in elevation than the water level in the tank we will need a mechanical pump to pump it up to the desired level. The return water will flow in the fish tanks by gravity. The factors to take in consideration while choosing a pump are the GPH rating of the pump and the static head. GPH is the amount in gallons that the pump can deliver in an hour and the static head is the maximum height the pump can deliver the water without losing pressure. Also we will need durable and safe pipes to connect the tank to the bed.

The system should have two drainage outlets with drainage pipes wide enough to sustain a large amount of water flow. One is for emergency, in case of overflow and the other will be for the everyday use. The incoming water pipe should flexible in order for the water to flow without obstruction in every angle.

We investigated three different types of pumps, the impeller pump – the most common type of water pump powered by a shaped rotor, the airlift pump – powered by blowing compressed air pushing an air/water mixture into a pipe and out of the system, and a peristaltic pump – a pump that isolates moving parts from the fluid commonly used in medical applications. ***We found that the traditional tried and true impeller pump would be best suited for use in an aquaponic system as they are readily available, recommended, and efficient.***

5 Proposed Aquaponic Greenhouse Design

When designing the greenhouse exterior structure and its various components we took in consideration the necessities of our sponsors as well as the challenges posed by our climate. The design provides the optimal environment for the biological systems and the good health of the structure while it maintains a good internal space to be used to as a working/teaching space. We discuss below the design, organized around the external greenhouse structure and growing system.

5.1 The External Greenhouse Structure

When designing the greenhouse exterior structure and its various components we took in consideration the necessities of our sponsors as well as the challenges posed by our climate. The design provides the optimal environment for the biological systems and the good health of the structure while it maintains a good internal space to be used to as a working/teaching space. We discuss below the design, organized around the external greenhouse structure and growing system.

5.1.1 Greenhouse Frame

Because we wanted to maximize the internal space, especially vertically, we decided to use a post and rafter design, which has vertical walls and a high celling, it is a strong frame and also optimizes the internal space. The figure below is a design drawn by our group for the greenhouse.

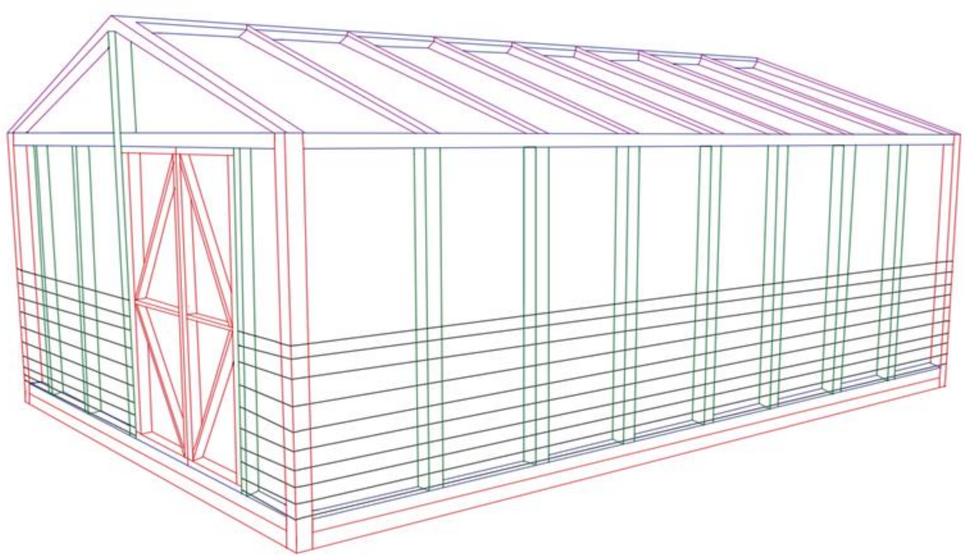

Figure 5. Greenhouse Design - Our design follows a post and rafter style, with insulation on the bottom 4ft. of the walls.

This frame design has the corners and the ground frame made out of pressure treated wood to prevent the wood from rotting. It also has half of all walls made of plywood to conserve heat and save on energy costs.

For the materials, the final decision was wood as the main material to build the frame because it was cheaper than other materials, it is strong, we can get it locally, and it requires minimum technical support to build the entire frame.

5.1.2 Greenhouse Floor

For the floor to be clean and effective we chose to use a combination of materials. First we will open the floor on the total area of the greenhouse when building the foundation of about one foot deep and fill it with crushed stone. The ***crushed stone*** will provide a firm foundation and also absorb all the spilled water, preventing any kind of water accumulations. Next we will install a ***special greenhouse floor*** on top of the crushed stone and under the walls of the building. This special floor and a resistant porous fabrics, which will also absorb the water. The combination of these materials will optimize the hygiene of the greenhouse and prevent weeds from growing inside of the building. They will also provide a firm and stable floor that will be comfortable enough to walk on, or wheel on.

5.1.3 Greenhouse Insulation

For the ground Insulation we will use Extruded Polystyrene Foam, which is a rigid foam board that can resist high humidity. The Extruded Polystyrene Foam not only insulates the greenhouse but it also absorbs heat during the day and transforms the floor into a thermal mass, which provides heat at night, when most of the heat is lost. (Fratzel, n.d.)

The non-transparent walls we did a double skin of plywood filled fiber-glass in the middle. We chose this materials mostly because of the price and effectiveness, the plywood is easy to find, cheap and normally it is already pressure treated. As for the fiber glass, it is one of the cheapest insulating material and we can achieve basically any R value with it.

As for the transparent part of the walls and ceiling we used Solexx, which is a rigid, milky plastic panel with multiple layers. Because this material has multiple layers, it traps air in the middle of each layer, and air is a great insulator (John W. Bartok J. , 2007).

5.1.4 Greenhouse Ventilation

Through calculations on the volume of the greenhouse and the amount of air change that is ideal for the greenhouse we arrived to 1600cfm (cubic feet per min) which is a hard number to achieve with only one fan. After talking to a few greenhouse owners, ***we decided to use two industrial fans of 800cfm*** in the opposite sides of the greenhouse horizontally positioned. This set up creates a circular air movement that provides uniform air through the entire greenhouse.

5.1.5 Greenhouse Heating

To better approach our heating needs, we calculated the exposed surface area, which was 1760 square feet, and combined it with the heat loss coefficient of the materials used. From our calculations we conclude ***that the greenhouse would need a heating power of 12kW***. In order to achieve this amount, we chose to use two heaters about a feet above the ground in the opposite sides of the building in order to distribute a uniform wave of heat throughout the greenhouse.

Also, from the calculations we came up with an approximate temperature that would be good for the fishes and plants at the same time. The temperature is around 60 degrees Fahrenheit, which achieves the maximum efficiency related to the cost of heating, plant growth and fish wellness.

In this project the sponsors required the electricity to be the primary source of energy for the heater, this decision was made because of the convenience of using the already existing grid and also because startup cost is a fraction of the cost of the other heating mechanisms.

5.1.6 Greenhouse Internal Layout

Growing beds were designed using the Solid Works program and the design for the tanks were researched to see what shapes would accommodate the best circulation of water. The length of the walkways and the width of the door were cross referenced with building codes and other designs to see that they had both functionality and comfort for the users of the greenhouse.

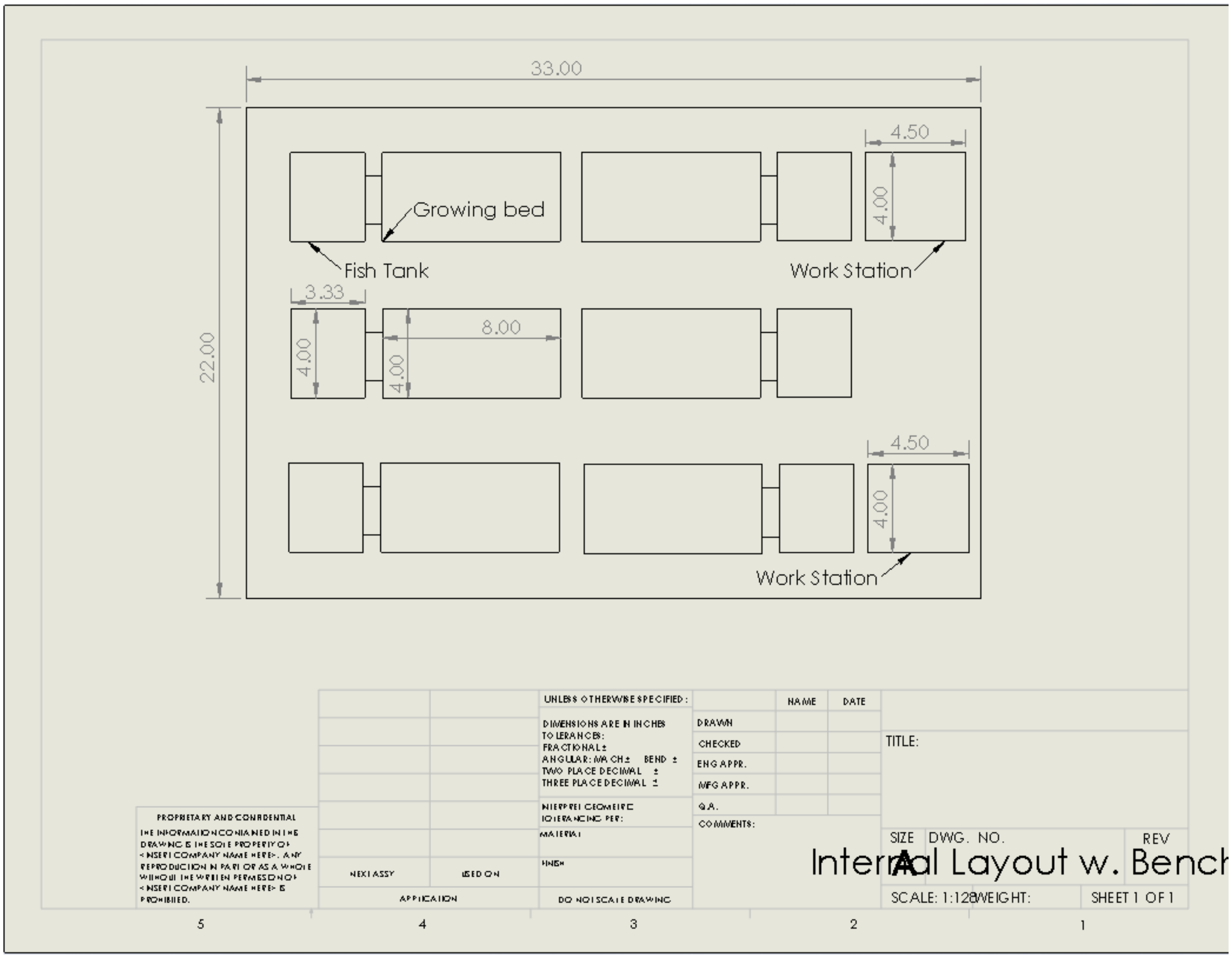

Figure 6. Internal Layout for 22'x33' Greenhouse

5.2 The Aquaponic Growing System

When designing the growing system we set out to create a simple, modular, self-contained growing system. The size of the bed was fit to the amount of growing area a single 275 gallon IBC tote could support. The bed has 32 sq. ft. of growing space, which calls for 160 to 320 gallons of water. The bed and stand are made from locally available materials, and can be assembled easily.

5.2.1 Growing Bed and Stand

The growing bed is comprised out of wood. It serves as the area that the plants grow. The growing bed is going to be completely filled with water, so it needs to be strong enough to withstand the force of the water that is in it. The base is made out of a 4x8 foot piece of plywood. The walls will also be cut out of a similar piece, but it will be 8 ft. x 1 ft. and 4 ft. x 1 ft. These sections need to be reinforced so that it won't break when it is filled with water. It is reinforced with 2x4s along the top of the bed. There are also vertical supports that are connected to the horizontal supports. The bed is lined with a pond liner so that the wood won't be damaged.

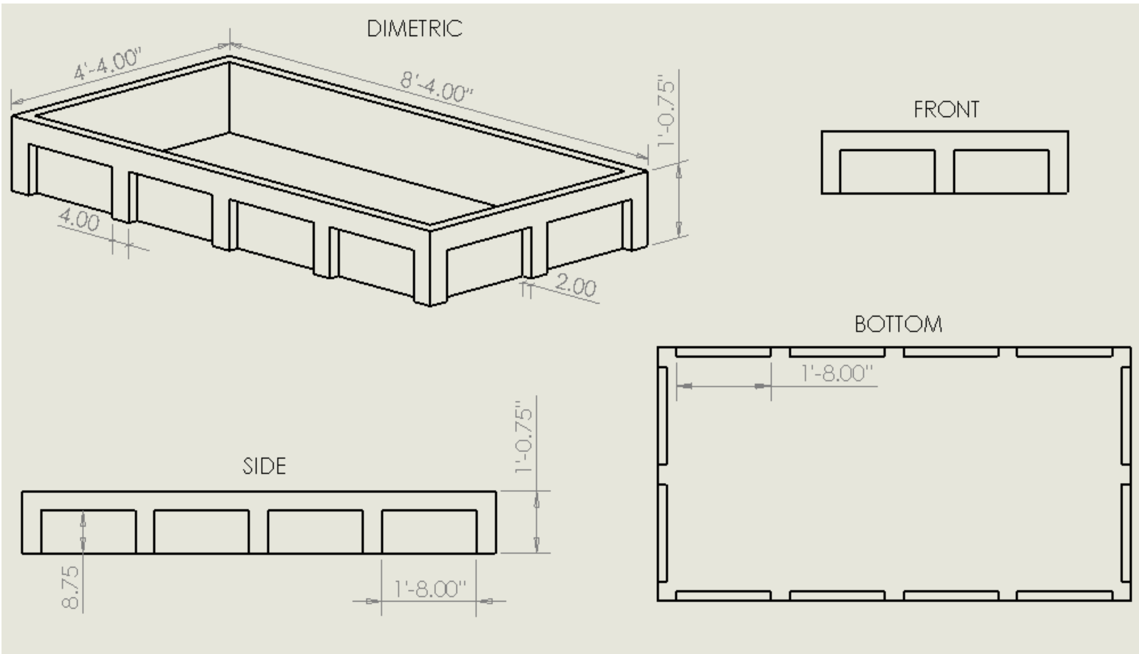

Figure 7. Schematic for Growing Bed. Sized to be general purpose growing bed.

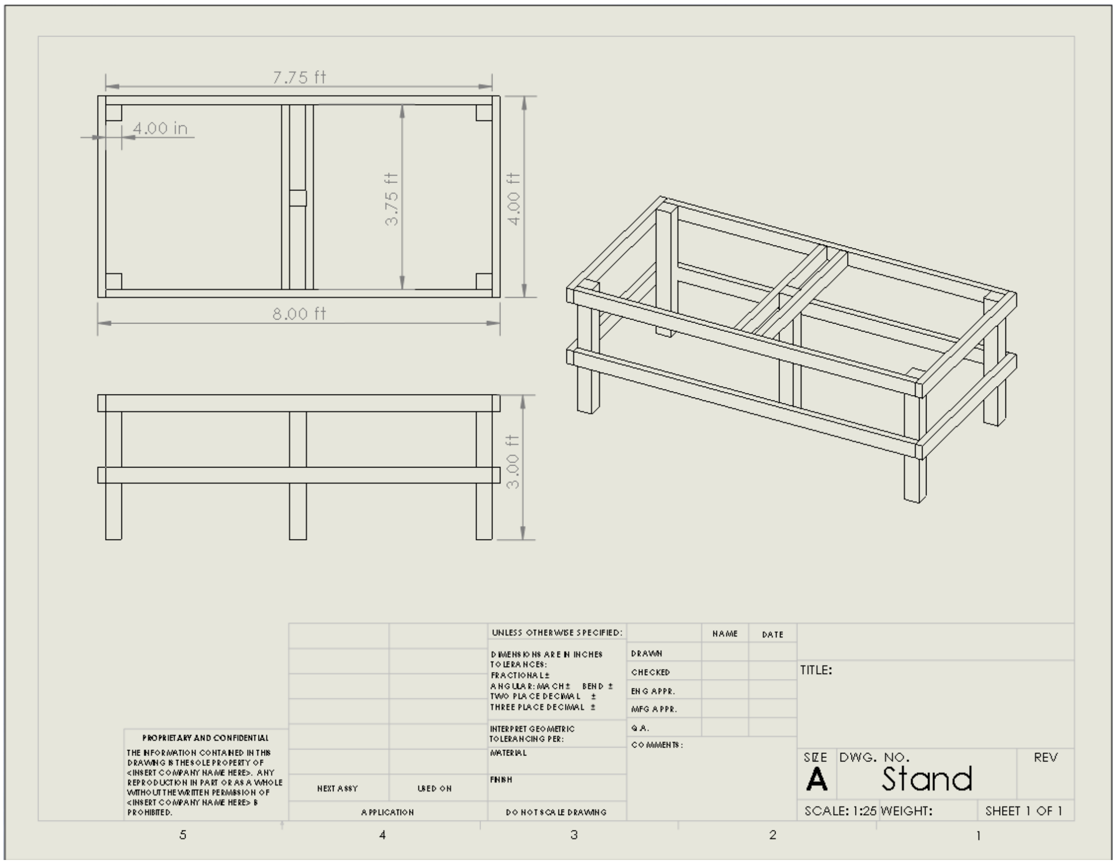

Figure 8. Schematic for bed stand.

The growing bed stand serves to both elevate and support the growing bed that is on top of it. It is made out of lumber because it is strong and inexpensive compared to steel or aluminum. The legs are 3 feet tall. There are five feet. Four of the feet are on the corners of the stand, and the fifth is on the center for added support on the base. The legs are held in place with 2x4s. There are also 2x4 supports for added stability on the bottom half of the outer legs. This design is quite simple, but it is strong enough to support the weight of a growing bed that is completely filled with water.

5.2.2 Fish Tank and Water Circulation

For a fish tank we used a 275 gallon IBC Tote as we recommended previously, and designed a plumbing system to accommodate the tank and the bed. After doing a wide research on the methods for water flowing we concluded that the best material to build the piping system is PVC. We chose a Hydrofarm AAPW1000 submersible pump for our system as it provides the necessary flow rate and water pressure, and can be adjusted easily.

The pump will be connected with a ¾’ PVC pipe that will go directly to the growing bed. For the drainage we choose to use two siphons. The automatic bell siphon as primary and the S-shaped siphon as a secondary. The bed also has a 1-inch diameter pipe siphon from Desert Aquaponics that will keep the water 8 inches height at all times in the growing bed. This type of siphon will drain the whole water of the tank when the level reaches the predefined level. The same principle is used with the S-shaped siphon, but in this case we used a 2-inch in diameter pipe to achieve a larger amount of drainage in case of extreme emergencies, this pipe has a shower drain on it and a mechanical filter to prevent the pipe from clogging. All the connections will be attached and reinforced with PVC cement. It is also recommend that the drainage outlets and incoming water be installed in the opposite sides of the bed to promote better water flowing throughout. The piping concept is shown in Figure 9.

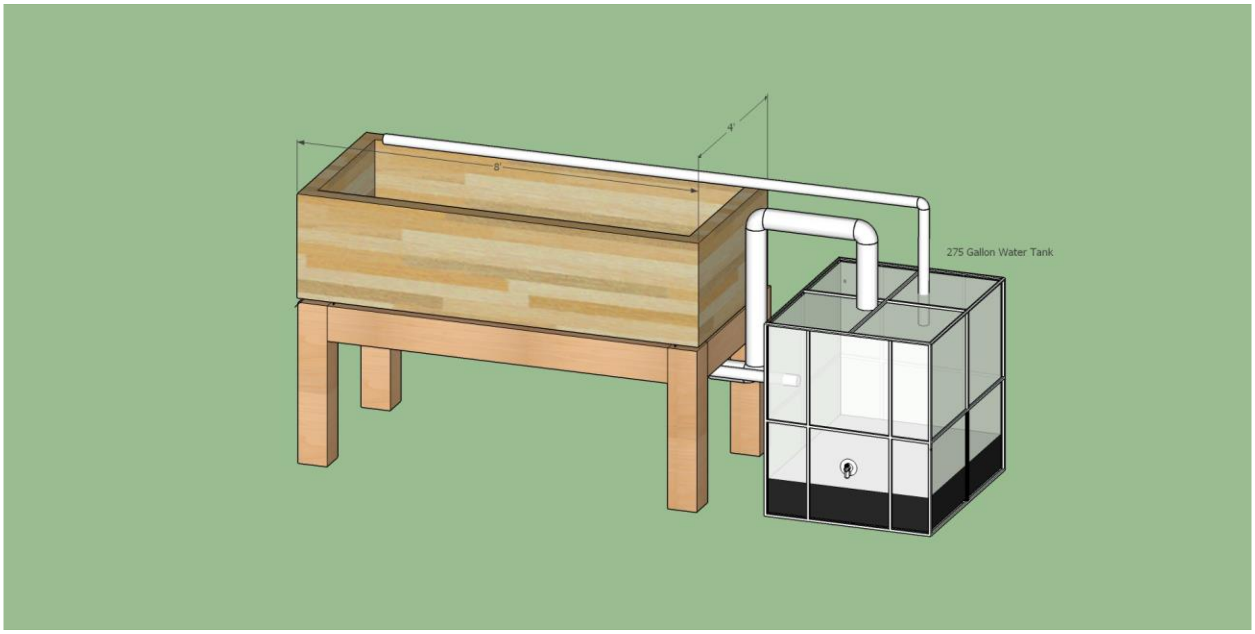

Figure 9. Full System Layout, incl. plumbing. The bed has two drains, a bell siphon and a larger emergency drain to prevent over-filling. One tube extends from the fish tank to provide water into the bed.

5.3 Operating Schedule

Aquaponic Greenhouses require an ambient temperature of approximately 70F to support the ecosystem present. The conditions presented by the weather in New England are very challenging with the average low in the months of January and February being below 20F. The following table is a tentative schedule that attempts to maximize profitability of the green house. An organized schedule of the greenhouse is important for maintenance and will also help to educate others about the difficulties faced in managing an eco-system in this cold climate region.

Month		**Additional Comments**
January	"Sales of Winter Crops"	-High Cost of Heating -Lack of Natural Sunlight -Plants will include lettuce and leafy vegetables
February	Prepare seedling beds	-High Cost of Heating -Lack of Natural Sunlight
March (Assume we start the greenhouse at this month)	Begin Planting Seedlings Stock Fish	-Risk of Frost still Present (Very Dangerous to Seedlings) -Seedlings take 6-8 weeks to mature

		-Fish take approximately three months to mature
April	Preliminary Sales of Seedlings to Local Markets	-Major Source of Income for Greenhouse
May	Preliminary Sales of Mature Plants to Local Markets	
June	Preliminary Sales of Mature Fish Planting of "Warm Climate"	-Sales begin after Fish have had time to replenish These plants do well in Temperatures over 60F
July		
August	Sales of Warm Climate Plants	
September	Planting of "Cool Climate" Plants	These plants do well in temperatures 40-50 F
October		
November		
December	Fully automate the heating for the winter months to come. Planting of "Winter" crop Sales of Cool Climate crops	-Plants are at great risk for frost, adequate heat is needed to preserve fish as well.

Figure 10 : Tentative Operating Schedule of Greenhouse

5.4 The Prototype Aquaponic System

The team designated several build days in order to facilitate the testing of the prototype. The prototype featured a one foot deep growing bed of dimensions 4' by 8', a 3' deep fish tank as well as a 3' stand capable of supporting the weight of the growing bed.

Figure 11. Constructed Prototype. Left: Fish Tank; Right: Bed & Stand. Piping has not been cemented yet.

The purpose of building the prototype provides a testing platform for our system and allowed us to work out the fine details of construction. There are a few additions that still need to be made to the prototype system for completion. The team has yet to implement the plumbing and drainage system, we have made the appropriate cuts for these fixtures but we have not permanently cemented them in place as the aquaponic system will need to be moved off site to the greenhouse's location. The prototype aquaponic system will be moved on site to Worcester Roots after the completion of the project.

6 Conclusion and Recommendations

The team successfully created a greenhouse design to enable efficient year round operation. This design provides a solid starting point for prospective aquaponic greenhouse builders, even if their specific requirements are different from that of Worcester Roots. Although ultimately our design was not constructed due to a generous donation of an existing greenhouse, the design provides a solid foundation for future constructions, and informs any possible modifications Worcester Roots may want to make to the donated greenhouse.

The team also created a design for a modular, easily replicable aquaponic growing system. The design was successfully built as a prototype of the system which includes a growing bed, a stand for the growing bed and a fish tank. We also synthesized a month by month working schedule which highlighted key growing seasons for plants and suggested the optimal year round operation considering the climate.

Below there are a few recommendations the team made for future improvements and alterations in the greenhouse.

For immediate consideration **we recommend investigating installing in extruded polystyrene foam insulation along the perimeter of the donated greenhouse** as it will provide essential insulation for the ground in the winter months. The insulated ground will stay at a higher temperature and buffer out cold from frozen ground around it.

For a more effective insulation **we recommend the installation of thermal blankets**. The thermal blankets are placed against the walls at night helping to conserve heat inside the greenhouse.

We recommend the Stone Soup Community Center investigate installation of a solar electric generation system for providing power to the building and the greenhouse which is planned to be wired in. This would aid to achieving self-sustainability for the building and the greenhouse.

We strongly recommend warehouse style growing designs investigate solar water heaters as they can provide hot water significantly more efficiently than electric heaters (which would be required if using solar PV).

We recommend investigating an automated ventilation system to regulate the temperature and humidity. Extreme temperature and humidity threatens the plant life in the greenhouse as well as the components in the greenhouse, and while manual operation is feasible, automated systems limit human error and provide easier operation.

We recommend investigating an alternative bed design focusing on shallower, stacked vertical beds, as opposite to a single larger bed, this style would enable higher growing density. A potential draw back to this is that it would require artificial lighting and would not be able to utilize the natural lighting of the greenhouse, but it would work well in an indoors environment and particularly could be suited for dense seedling production, as seedlings do not require deep beds.

For artificial lighting **we recommend investigating LED grow lights utilizing optimal wavelengths** as was brought up by Technocopia as it may provide efficient and effective grow lights in a situation without natural light such as a warehouse.

As for the team's expectations, in the short term, we expect to get the community of Main South in Worcester more involved with the greenhouse. This pilot will have the opportunity to educate the youth as well as anyone that is interested on the pathway for urban food production.

By empowering local residents, the project aims to provide a healthy, local food source for Worcester residents, and educate members and local youth about greenhouse growing, aquaponics, and the cooperative businesses.

As for the long term goes we are being more ambitious, we expect to help creating the idea of urban farming, by demonstrating that small systems can provide an entire diet, with fish, fruits, and vegetables. We also hope that this project will have a positive impact on entrepreneurs, to scale up this system, as well as anyone who wants to scale down the project and have a self-sustaining aquaponic greenhouse on their backyard.

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