Faculty of Agricultural and Environmental Sciences

McGill University

Department of Bioresource Engineering

BREE 495 Engineering Design 3 Final Report

Dr. Madramootoo

Modular Greenwall - Educational Growth System

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April 15th, 2021

Abstract

The purpose of this Capstone Project was to use the knowledge acquired from the classroom to design and construct an aesthetic greenwall for the client, Beaconsfield High School. Building off of the work done in BREE 490, a more detailed project risk assessment was performed and concluded the scope of the project was too large given our restricted access to McGill facilities due to COVID-19 governmental regulation. It was at this time we parted from the client and changed the scope of our project. Our new scope aimed to design, model and explain the assembly and installation process of the original greenwall system, while constructing a scale model, focusing on the aspects of our project that are unique, the growth cell, the educational stand, and the irrigation.

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1.0 Introduction

Over the past 15-20 years, greenwalls have become increasingly popular features of urban architecture. They can be found in corporate office atriums, to the facades of public buildings, and even inside homes. While most greenwalls are installed for aesthetic purposes, (Sutton, 2014) there are numerous benefits to their integration in any interior or exterior building space, including increased thermal and acoustic insulation, improved air quality (Manso et al, 2015) as well as physiological benefits (Wood et al., 2014).

Our goal is to design a greenwall system that brings a new dimension to what has previously been accomplished. We approached the staff at a local high school who were very interested in installing a greenwall system in their school's atrium. This opportunity, combined with the client’s other goals, led to this project’s aim of designing a greenwall system that could be permanently installed and could be used as an educational tool within the classroom. As well, our design must be an automated system with modular and removable growth cells that give an aesthetically pleasing installation in a school's atrium. This system will allow for the plant cells to be removed from the wall easily and often, brought into the classroom and used as a hands-on educational aid in science classes to teach about earth sciences, plant biology and urban agriculture.

1.1 Change of Scope

The initial goal of the project was to design, build and install a full scale greenwall system in the atrium of the high school. Unfortunately, due to the COVID-19 pandemic, the restrictions put in place by McGill prevented our full team from accessing the technical services building (TSB) at any given time. Additionally, there was limited access to technical support from staff at the TSB that we had previously relied on in order to execute certain aspects of the construction and fabrication of our greenwalls frame. Issues brought up by the first review of our BREE 490 design report forced us to re-evaluate certain aspects of the design and introduce additional safety and failure prevention protocols. Solving these issues would have increased the scope of the project substantially, increasing the cost of the project well above the initial budget. Due to this, our team reached the conclusion that the scale of the project was too big to be completed within the time constraints of the semester given government restrictions, and that the scale would need to be significantly reduced. These issues were discussed with both the client and Dr. Madramootoo, at which point it was agreed upon that the initial project would not go forth. Rather, the team would shift focus to the construction of a scale model in order to demonstrate the viability of a greenwall with removable growth cells intended for in-class exercises. As such, this report aims to outline literature surrounding greenwall design and uses, our original design process, and the results from having constructed a working model of the removable growth cell system. As well, we have included the aspects of the project that were not carried out because of the change in scope but that would be integral to a working greenwall system such as the automation architecture, and specifications for the automated control system.

2.0 Project Background

2.1 Types of Greenwalls

A greenwall is a general term that can be used to describe any number of different designs that enable plants to be grown on a vertical plane. As such, greenwalls can be employed in many different spaces, their design changing depending on the intended application (Manso et al, 2015). Greenwalls can be designed for interior and exterior spaces for food production (functional greenwalls), or to add greenery and decoration to a space (decorative greenwalls). Greenwalls can be classified into two main classes, being either green facades, or living walls (Manso et al, 2015). With green facades, plants grow up a wall directly, or indirectly on a frame or other supports. This application is more natural or passive and selects for plants that will naturally climb a wall or vertical surface. Living walls differ by utilizing current technology to allow individual plants, that may not grow as large, to cover an entire vertical surface. These systems can travel higher than green facades because they do not rely on a single root source. These types of walls are more versatile and can be employed in a variety of spaces and uses. Figure 1 outlines the high-level types of greenwalls that are currently employed.

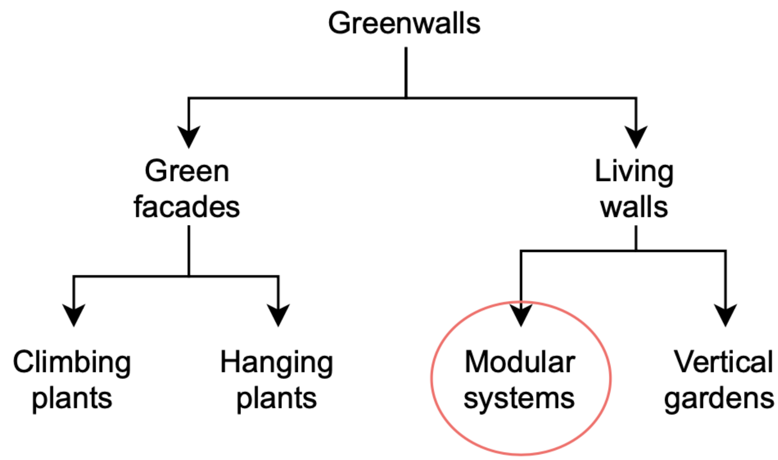


Figure 1: Types of greenwalls, red circle indicates the type explored in this design

Living wall greenwalls can be split into two subcategories: modular systems and vertical gardens (Virtudes et al, 2016). Vertical gardens are similar to green facades and can depend on a plants natural ability to climb a hanging structure but differ in that they consist of continuous sections of a wall covered by plants and may have multiple zones for plants to take root. Modular systems are the most diverse type of greenwall and can be found both indoors and outdoors on building facades or as free-standing structures. Modular greenwall systems rely on specialized engineered solutions that allow for the accommodation of a growth medium and allow the plant to be supported vertically while providing water and nutrients (Manso et al, 2015). These systems can additionally house plants that do not climb or hang, i.e. plants whose foliage does not spread far from the root zone. Thus, they are constructed on the basis of providing a growth medium for the plants along the entire growing surface area. As such, they rely on the use of trays, vessels, planter tiles or flexible bags to hold the growth medium, which is then supported by a frame (Manso et al, 2015). Modular systems differ greatly from one to another, but the majority must provide some framework to account for a substrate, plant and substrate container, space between the wall and system, water and nutrient delivery and vegetation management (Jim, 2015).

2.2 Initial Client Needs & Risk Assessment

As determined in BREE 490, the client wanted a large, aesthetic greenwall installed in the front atrium of the school. In order to determine their other technical requirements, a client needs weight assessment was performed (see table 3). To achieve this objective, a ranking system was developed based on levels of complexity and criticality associated with each technical requirement. They are as follows:

Complexity	**Weighting Score**	**Description**
High	3	Highest risk. Very complex requiring particular design focus.
Medium	2	Moderate risk. Moderate complexity requires some design focus.
Low	1	Low risk. Requiring minor design focus.

Table 1: Complexity Ratings and Weighting Scores

Criticality	**Weighting Score**	**Description**
Must	3	Must be met entirely or not permitted on school property.
Desirable	2	Majority of requirement may be met depending on cost and available resources

Optional	1	Some elements of the requirement may be met depending on cost and available resources

Table 2: Criticality Ratings and Weighting Scores

The weighting assessment is focused on aspects of the project that were ranked highest in terms of potential risk. The assessment indicated that the main focus needed to be on the greenwalls structure, specifically regarding its strength, durability and ensuring that it abides by all relevant building codes required for a school setting. Additional considerations included ensuring the greenwalls modularity to allow select growth cells to be removed and brought into the classroom as an educational tool. The unit itself must be non-obtrusive, low maintenance, and capable of sustaining a variety of plants for 10-14 days with little to no user intervention. All maintenance of the greenwall would be conducted by the client's maintenance staff and a few student volunteers, who would receive a brief training session from the design team. The client's finalized budget for the project was $5,000 excluding the personnel costs of the maintenance staff and cost of repairs and maintenance going forward.

	Complexity	Criticality	Weighting Complexity * Criticality	Project Risk
Low maintenance	2	3	6	Medium
Autonomous	3	2	6	Medium
Robust structure	2	3	6	Medium
Modular	2	3	6	Medium

Meets codes & standards	3	3	9	High
Client staff to operate & maintain	2	2	4	Medium-Low

Table 3: Weighting Assessments – Complexity * Criticality – Project Risk Ranking

2.3 Secondary Client Needs & Risk Assessment

We received important feedback from our BREE 490 final design report regarding safety and failure protocols that required us to re-evaluate certain aspects of our design. In order to determine which aspects needed to change, a larger, more in-depth project risk rating assessment needed to be performed based on complexity and criticality of each requirement. The weighting system is scored on a scale of 0-25, where criticality and complexity were given a rank of 1-5. Additional color coding was included to emphasize rank of importance (Blue = 0-5 Green = 6-10, Yellow = 11-15, Orange= 16-20, Red = 21-25).

	Comments and Considerations	**Process to Ensure Safety**	**Criticality (1-5)**	**Complexity (1-5)**	**Weight = critical * complexity (1-25)**
Frame Stability	• How will the structure be installed? • Who will do the inspection?	• Hiring contractors to properly secure structure to the wall • Inspection by a structural engineer	5	• Scheduling: 4.5 • Design: 4	Scheduling: 22.5 Design: 20

Potential Frame redesign	• Redesign required if deemed unsafe • What is the timeline for redesign and re-inspection? • No qualified TBS technician to provide professional assistance	• Get assistance from TSB shop technician (Scott) during design and assembly	5	•Scheduling: 5 • Design: 5	Schedule: 25 Design: 25
Frame Safety (Grounding/Rust Proofing/Fire)	• In the presence of metal and water, the frame must be electrically grounded • Rust flakes pose a health hazard	• Coating metal with insulating / rust proof paint • Ensuring all electronics are sealed away from water source • Install plastic panels to limit spread of rust •Install fire extinguisher within 6ft of the greenwall	5	2	10
Drainage	• Where would the water go in the event of a leak? • No drain in the atrium	• Need to install a floor drain. This would require a contractor and renovations. High cost.	5	5	25

Water Leakage	• Irrigation system • Reservoir	• Make seals watertight. • Train maintenance staff what to do in a leak scenario	5	4.5	22.5
Water Source and Resupply	• Who will be in charge of water replenishment? • How often will it need to be done?	• Maintenance • Students	5	3	15
Plant Maintenance	• Need to train the maintenance staff and students • Which parts of the irrigation are most likely to need replacing? • What is the life expectancy? • Trimming and replacing plants • What is the procurement process to get new plants • Ensure all plants are given adequate amounts of nutrients	• Provide a service manual and maintenance schedule • Produce a parts manual with the procurement and replacement process	5	5	25

Table 4: Reevaluation of Project Design Risk Assessments

As shown above, there were several severe safety concerns that needed to be addressed in order to ensure the proper function of the greenwall, mainly in terms of structural durability, irrigation and drainage, and maintenance protocols.

We are confident that the strength of the designed structure would not be an issue, as finite element analysis (FEA) simulations revealed the point of structural failure vastly exceeding our realistic maximum weight while including a safety factor of 7x. However, simulations are a tool and are not perfectly realistic. To ensure structural strength and stability of the greenwall's frame we would require the expertise of Scott Manktelow (TBS technician), and other necessary contractors and inspectors. However, due to the COVID-19 pandemic, Scott Manktelow is absent from the shop, and is thus unable to render assistance or provide guidance as to the necessary safety considerations and most importantly in its construction (welding). Additionally, due to the pandemic, procurement timelines are drastically delayed as supply chains struggle to keep up with demand. Thus, it is probable that the timeline to schedule the necessary contractors and inspectors would be longer than our available time frame. To reflect this, frame stability is considered in two parts: scheduling and design, with risk weightings of 22.5 and 20 respectively. Potential frame redesign was also split into scheduling and design categories, both achieving the maximum score of 25.

As safety standards and regulations have not been updated with the growing popularity of greenwalls, it is difficult to reference specific design codes. In hopes of obtaining useful information about the required safety standards, we attempted to contact several greenwall design and installation companies to no avail. As well, not having the expertise of Scott Manktelow adds to the risk of not building a structurally secure frame, potentially requiring a redesign if the hired contractor or inspector deems it unsafe. The time and cost of changing the design last minute is a huge risk that must be greatly considered and communicated to the client. To avoid any issues with electrical shock, all electronic components will be electrically insulated and kept away from the reservoir. A circuit breaker will also be implemented as part of our electronics to add another layer of protection against electric shock. The circuit breaker must be specialized to be used around water, similar to how the National Electrical Code (NEC) requires ground-fault circuit interrupters (GFCI) on all electrical outlets in bathrooms, kitchens and utility rooms. A GFCI is a fast-acting circuit breaker designed to shut off electric power in the event of a ground-fault within as little as 1/40 of a second (United States Department of Labor, 2021). Rust proofing of the frame will be accomplished by constructing the frame from galvanized steel. Installing paneling on the exterior of the frame will also mitigate any spreading of the rust or other contaminants outside of the system, while adding to the aesthetic the client requires.

Implementing watertight seals into our irrigation system and reservoir are essential in order to mitigate leakage. The issue of leakage of the irrigation system raised very important questions regarding the type of drainage available in the atrium and safety hazards of the greenwall. In the event of a leak, the water would pool in the atrium with no drainage system in place. This poses a slipping hazard and is unacceptable in a location with a high volume of foot traffic. In order to resolve these issues, routine maintenance of the system must be done to check for cracks and any other potential signs of failure. In an ideal situation, a floor drain would be installed in the atrium, however that is not feasible within our timeline and would be vastly over the client's budget. Water level sensors would be placed in the reservoir that alert the staff of a potential leak and stop all pumping activity. However, in the summer months when scheduled maintenance activities are spaced out, there is a larger chance of potential leakage issues. Therefore, we gave drainage and water leakage scores of 25 and 22.5 respectfully. A greenwall of this size requires a large reservoir, and as such requires water resupply due to evaporation of the water from the reservoir, and the cell as well as evapotranspiration from the plants. For 84 plants, the reservoir needs to be 150 litres (1sq. ft. = 1L per day), this would warrant a re-supply every 14 days; these values are based on known industry standards (Patil, 2020). The side panel of the greenwall has an access panel to the reservoir. By removing a plug from the lid of the reservoir and turning it over to reveal the funnel, water can be poured right into the reservoir. The custodian's closet located nearby can connect a hose to the sink faucet and is long enough to reach the reservoir. Therefore, water source and supply were given a weight of 15.

Plant maintenance is a major issue that will require significant time from the staff. Maintenance is required roughly every 10-14 days, taking approximately 2 hours to complete. The tasks required to ensure the health, and thereby aesthetic, of the greenwall are pruning, removal and replacement of any dead plants, checking for signs of nutrition and or light excess or deficiency, providing the required nutrients and keeping record of the work performed. Keeping maintenance records would allow for tracking of nutrient and water consumption to allow for system optimization. In order for the maintenance staff to complete these duties effectively, we must provide a service manual and maintenance schedule as well as train the staff how to perform these tasks. The manual will include information and pictures on how to identify and test for signs of nutrient excess or deficiency in the plants; how to obtain the correct nutrient balance; which components are most critical; how these components can be properly maintained and replaced; how to prune each species of plant; how to procure more in the event a plant dies; how to identify common species of mold and mildew that may grow; how to remove and mitigate it; how to remove and mitigate unwanted pests. To ensure the health and longevity of the plants in the greenwall, plant maintenance was weighted 25/25. Although the training and the manual would not be difficult to make, organizing time with the maintenance staff to train them and read through the service manual will take considerable time as regular access to the school is prohibited due to governmental restrictions.

The three major constraints of project management are scope, time and budget. So far, the risks identified have been focused on the original scope of the project and the restricted timeline, and not the project’s budget. In a typical year, meeting with the client to communicate expectations and budget, performing site visits and procuring material would be relatively simple, but due to the pandemic these tasks have become much harder and longer to do. Public high schools do not have very large budgets so there would not be much, if any, wiggle room for any excess fees. Therefore, spending must be done very carefully to limit time and material waste. However, stress on the supply chain and changing government regulations may shut school facilities leaving us unable to complete the project in the given amount of time, wasting the client's money. We consider these time and budget constraints the biggest risks to the project as they are out of our control.

After completing these risk assessments and considerations of failure we voiced our concerns to the client as soon as possible, detailing the above-mentioned risks, as it would be ethically wrong for us to move forward in the project. We focused on the current restrictions to the TSB and the highschool, and how we were reluctant to move forward with the high possibility of stricter government regulation. We offered to build a smaller model of the greenwall, roughly 7' x 4' x 1', however, the client did not want to renegotiate on the size of the greenwall. We agreed to terminate this project as it was the best case for the school since they have a limited window to spend the money.

3.0 Final Design

3.1 Full Assembly

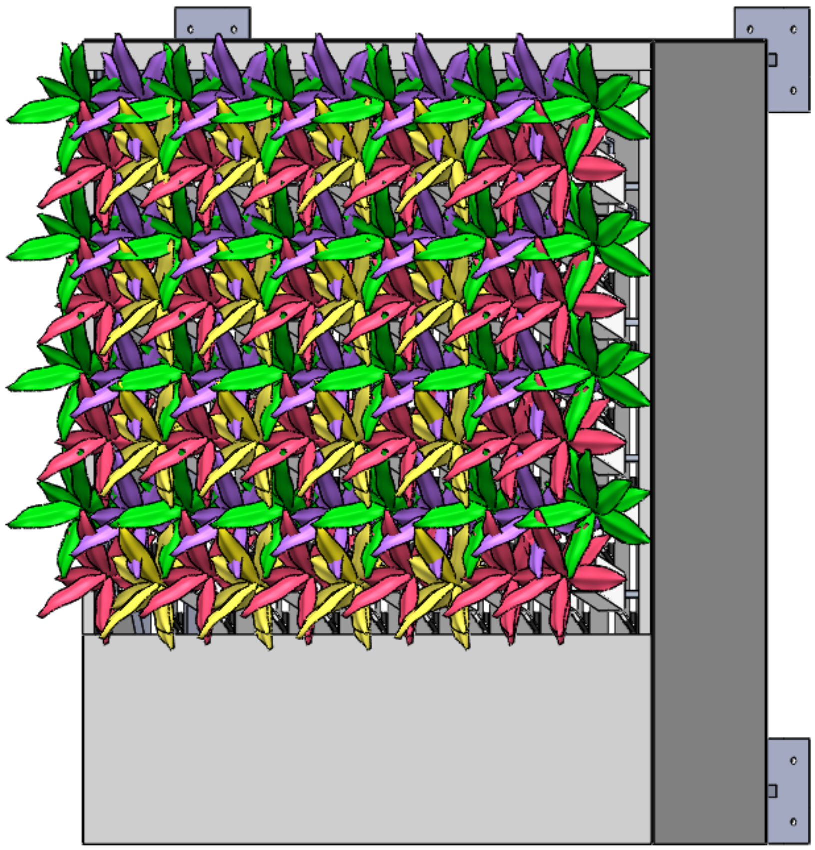


Figure 2A: Full assembly of the greenwall with plants installed.

The full assembly of the original greenwall design was created in order to provide visuals to our explanations of the intended design for Beaconsfield High School. The greenwall was designed to have 8 rows of staggered growth cells, with odd numbered rows having 11 cells and even rows having 10 to make room for the irrigation outlets. Plastic panels are installed on the front, top and sides of the greenwall to hide the internal components. A lower front panel covers the bottom 24 inches of the greenwall making the plant growth area a total of $63ft^2$. Although not included in the figure, doors in the side panels will provide easy access to the electronics and the reservoir.

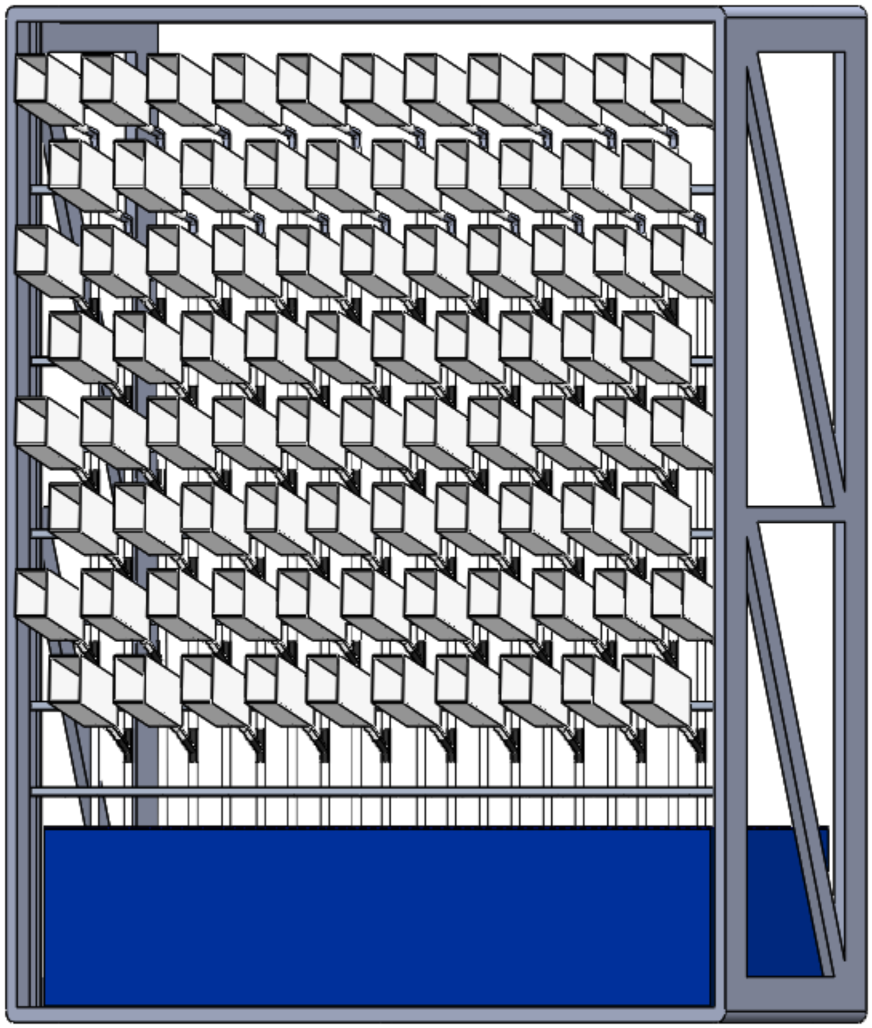


Figure 2B: Full assembly of the greenwall without plants.

3.1.1 Frame

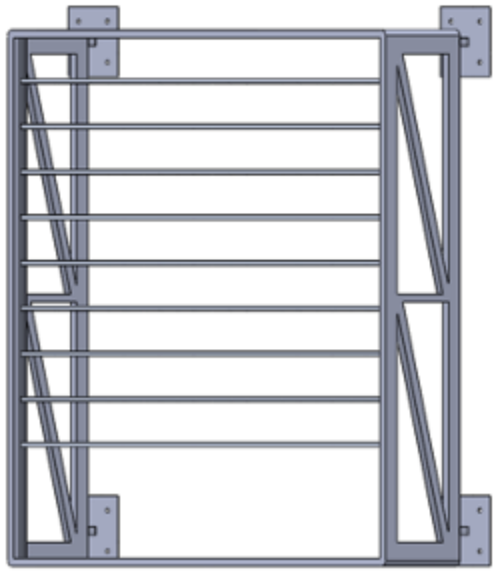


Figure 3: Frame with horizontal u channels.

Purpose: In order to hold 84 growth cells of varying weights upright on the wall, the structural integrity of the frame and how it will be secured to the wall is critical. Assuming a weight of 3kg per growth cell (cell + plant + substrate + water + safety factor), the total weight of the 84 growth cells on the wall is 252kg. This means that the strength of the frame and the anchors must be adequate and that the wall is properly installed.

Description: The frame was designed to be 9’x9’x1.5’ made out of one-inch hot-rolled structural steel tubing welded together in four separate sections. The left and right side are identical as well as the top and bottom. The sides of the frame are designed with diagonal tubing running top to bottom from the front to the back of the frame in order to provide strength against the bending moment caused by the plants on the front face of the greenwall. The steel U-channels are welded onto a flanged piece of steel against the inside of the frame which will provide the required support for the growth cells on each row. The top and bottom sections of the frame are similar to the sides with the exception of the diagonal cross piece. The entire frame assembly will be welded together. The frame will be anchored to the wall by four anchor plates, each with four concrete screw anchors.

Design and Construction:

Square Structural Tubing: structural tubing per ASTM A500 is tubing produced and used for structural applications. A500 structural carbon square tubes range in sizes and wall thicknesses and are used in construction of buildings, industrial shelving units, sign support applications and other general structural fabrications. Square structural members are commonly used in welded steel frames due to their uniform geometry and resistance to torsion and multi-axial loading. Hollow square tubing can be readily bent, formed, punched and easily drilled during the fabrication process of the frame. Additionally, these steel members are fire resistant, do not warp, swell or shrink (Industrial Tube and Steel Corporation, n.d)

Wall Anchorage: In order to anchor the greenwall structure to the concrete wall in the atrium, we referenced Appendix D of the American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-2002) to determine the criteria for anchoring into concrete (Carrato, 2008). For the purpose of this design, we are assuming that the concrete strength in the school atrium is adequate. In an ideal situation we would have full access to the school and work alongside the maintenance staff to determine the strength of the concrete and the required number of anchoring bolts. However, as that is not possible due to the pandemic, we consider this assumption fair. Post-installed anchors achieve resistance against shear and tension by expanding against the concrete or sleeves by bonding with adhesives (National Concrete Masonry Association, 2013). A 12"x 12"x 1/8" base plate welded to a 2" piece of structural steel tubing with four ¾" anchor bolt points make up each of the four anchors. Each anchor bolt has an effective embedment depth of 5", minimum edge and spacing distance of 2.5", and ultimate yield strength of 75,000 psi (Carrato, 2008). Building Code Requirements for Masonry Structures requires that the minimum effective embedment length for anchor bolts is 2" and the distance between parallel anchors be at least equal to the diameter of the anchor to help ensure adequate anchor performance and grout consolidation around the anchor

(National Concrete Masonry Association, 2013). The anchor is a hex head threaded bolt which is welded to the steel plate. The anchor bolts must meet the requirements of ASTM 307, Grade A, the Standard Specification for Carbon Bolts and Studs with 60,000 psi yield strength. These standards are typically used to anchor large industrial scale shelving into concrete floors, and adjacent walls, so considering the size of our structure this design is more than satisfactory to properly secure the frame to the wall.

Greenwall Weight: Using the Solidworks mass evaluation feature we were able to determine the total dead load of our structure. The dead load of the frame is made up of the nine U-channels, the four anchors, and the structure itself. The U-channels are made of 6061 alloy aluminum (Industrial Metal Supply Co.) each weighing 1.23 lbs, totaling 11.07 lbs. By setting the material to A500 steel we were able to determine the weight of the anchor as 5.49 lbs, totalling 21.96 lbs, and the structure as 631.45 lbs. The total of all these frame components equals 665 lbs, which we consider as a reasonable weight given the size of the frame.

The approximate total weight of the full greenwall assembly is approximately 1000lbs. This includes the weight of the frame at 665 lbs, the total wet weight of the growth cells calculated at 168 lbs, all plastic side paneling approximately 135.75 lbs, and irrigation inlet and outlet tubing (with no running water) at roughly 35 lbs. The weight of the reservoir was not included in the weight calculation as it will be resting on the floor.

Rust proofing: The A500 structural steel tubing selected for the frame is galvanized, further rust proofing of the frame is not required. Paint could be applied for aesthetic purposes to match the interior of the school's atrium.

Strength Design of Anchoring Bolts: Calculations provided by the National Concrete Masonry Association (National Concrete Masonry Association, 2013) allowed us to determine the allowable tension and shear of our concrete anchors.

Ba = allowable axial force on anchor bolt

Ab = cross-sectional area of anchor bolt, in2

fy = specified yield strength of steel for anchors, psi

f'm= specified compressive strength of masonry

Φ1= strength reduction factor, tension

Φ2= strength reduction factor, shear

ba= unfactored axial force on anchor bolt, lb

bv = unfactored shear force on anchor bolt, lb

Allowable Tension Load

$$Ba=0.6Ab\,f y$$
$$= 0.6(\pi D2/4)(75{,}000)$$
$$= 19{,}888.4 \text{ lb per bolt}$$

Allowable Shear Load

Note: Assuming a specified compressive strength of masonry as 4,000 psi (National Ready Mixed Concrete Association, n.d)

$$Bv=350\sqrt[4]{(f'm\ Ab)}$$

$$= 2{,}268.25 \text{ lb per bolt}$$

Combined Shear and Tension

Anchor bolts subjected to combined axial tension and shear must also satisfy the following unity equation.

Note: Unfactored axial force was calculated as 960 lbs and unfactored shear force as 800 lbs. These values far exceed our expected axial and shear forces on the greenwall and the anchors with an additional safety factor.

$ba/(Ba \cdot \Phi 1) + bv/(Bv \cdot \Phi 2) \leq 1.0$

$= 960/19888.4(0.9) + 800/2268.25(0.5) = 0.392 \leq 1.0$

∴ Satisfactory

According to these preliminary shear and tension load calculations our design is satisfactory. The calculations were based on one anchor bolt, and our anchor plate is designed with four anchor bolts each (16 bolts total).

Stress Simulation Model:

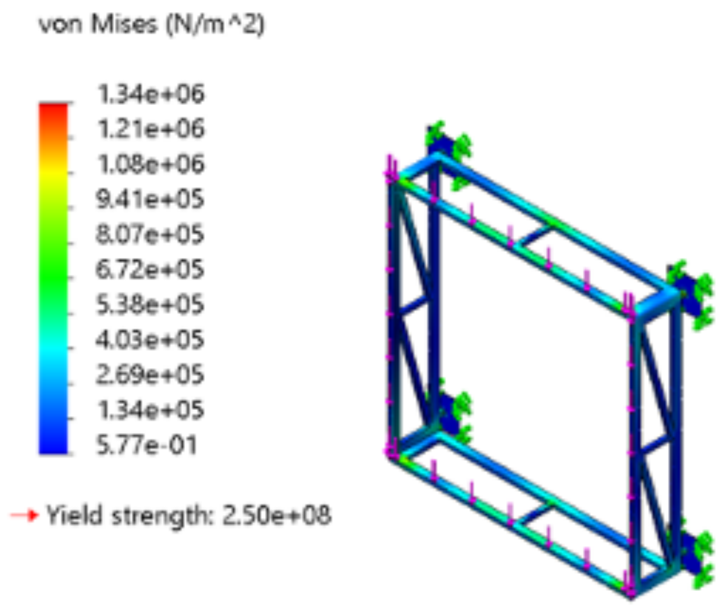


Figure 4: Stress Model of greenwall frame under applied load.

Figure 4 is a representation of the frame design under a static load of 500N applied downward on the front face of the frame, representing the downward force of the growth cells with an additional safety factor. The fixed attachment points are against each of the four anchor plates in multi-axial directions, and the material was selected as A-36 steel, which has a nearly identical composition of A500 steel. Results from the simulation demonstrate the applied load causing a pressure of approximately 0.807 MPa, with a max yield strength of 250 MPa. The frame was intentionally over designed in order to ensure that it will never pose as a hazard to the school.

3.1.2 Growth Cell

Figure 5: Growth cell with plant

Purpose: All greenwalls must have some form of container in which the plant and its growth medium are contained. This container must have the ability to integrate with the wall's irrigation and drainage system and must be strong enough to support the weight of a fully grown plant, with a fully saturated growth medium. Specific to this greenwall, the end design must be aesthetically pleasing, and allow for the plants to be easily removed from the wall in order to be used in an educational setting. As such, the container, or growth cell, must satisfy these given requirements.

The plant's growth cell plays a significant role in the overall aesthetics of the greenwall. As the plants in a modular greenwall are not normally climbing or hanging, they must be supported by a growth cell for their roots to sit in. In order to maximize the aesthetic function of the wall, the surface area covered by the plants must be maximized and internal components of the wall minimized. That is to say, that the growth cells must not be visible when looking at the wall. If standard planters are used with the opening on the top of the box, the planters would need to be staggered, and the wall would not be a flat surface, requiring more depth at its base. Alternatively, the planters could be angled. However, this would present issues with the growth medium, causing the plant to not be properly supported, risking the plants spilling out as they grow. As such, the design of the plant's growth cells must satisfy the following criteria listed below.

Major Considerations:

- Irrigation and drainage integration: Takes into consideration water delivery and drainage
- Strength and support: must hold full weight of plant, soil and water and support the plant
- Aesthetics: Cell design must maximize visible plant and minimize visible structure of wall or cell itself.
- Removable and modular: Cells must be easily removable and easy to handle

Design and Construction: In order to satisfy the above-mentioned design considerations and constraints, we first looked at the types of plant cells and growth containers that have previously been used in similar industrial setups. We found that most large scale greenwalls either use some type of wire or support to prevent the plants from falling off the wall. In the case of perfectly horizontal planters and perfectly vertical planters as used in conventional designs, the designers either employ the use of hanging plants, or the wall itself is sloped to allow the plants below to hide the body of the planter above. The greenwall was to be installed in the school's atrium, as such, the base could not extend very far into the room. Therefore, a sloped wall was not possible. Our goal was to have the plant cells have a perfectly vertical front face, so as to give a pleasing aesthetic when all cells were installed on the wall. In order to achieve this goal, and maintain adequate connection support, we chose to model the plant cell from a parallelogram (see figure 6). This shape of planter allows the cell to support and contain the growth medium in the base of the cell, while allowing for a wide vertical opening. This design promotes the flow of water to the back of the cell for it to be drained away. The shape of the cell in relation to the prototype frame built can also be seen in figure 7

Figure 6 & 7: Plant cell profile (parallelogram)

The interior of the growth cell was designed to promote water to drain to a single point as can be seen in figure 8 allowing all water to drain to the back of the cell, where it is fitted with a wide outlet to prevent clogging. Additionally, the curvature creates a smaller volume for the plant to sit in, supporting the growth medium and roots of the plant. The growth cells were designed using CAD software such as AutoCAD in conjunction with SOLIDWORKS in order to model the cell in 3d. The growth cells were manufactured from PLA plastic filament using a 3d printer.

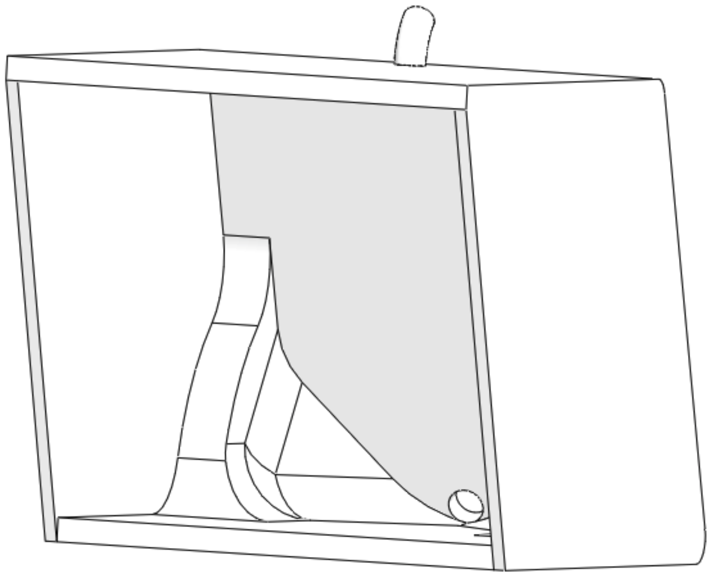


Figure 8: Interior view of growth cell showing interior curvature

Testing: The plant cells were first tested virtually using COMSOL as the simulation software. By modeling the cell in the COMSOL 3d space we applied a 5kg load to the interior of the plant cell where the weight would be located in a real-life situation. Running this COMSOL model yielded minimal deflection of about .5cm in the material and indicated that the forces would be concentrated around the edge of the clip where it joins the backplate of the cell. The results can be observed visually in figure 9.

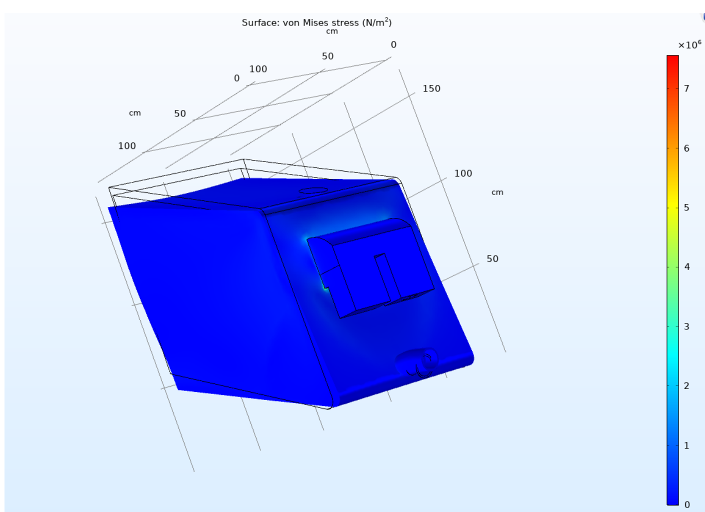


Figure 9: COMSOL model results of plant cell testing.

3.1.3 Cell Clip and Attachment Components

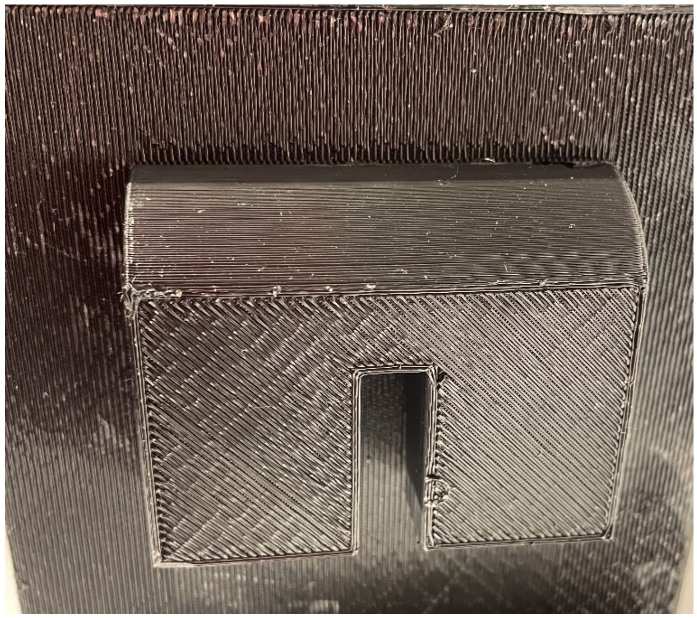


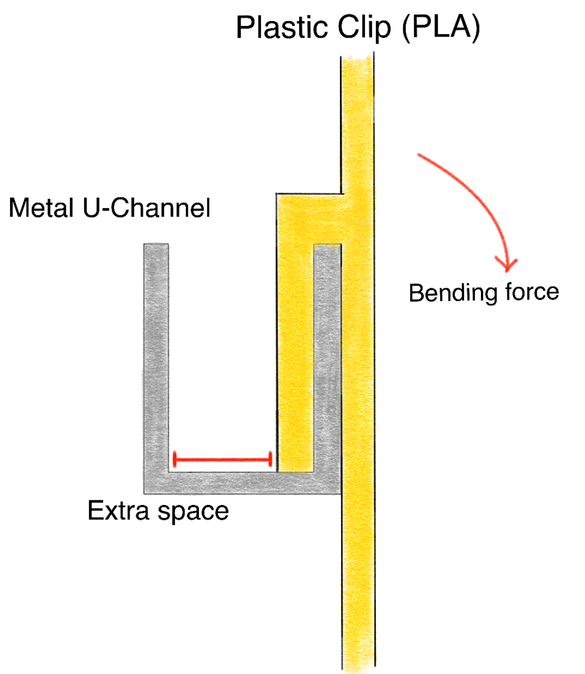
Figure 10: Clip on back plate of growth cell

Purpose: In order for the growth cells to be effectively used in a classroom setting, attaching and removing the cells from the wall has to be easy for the user, and the process must not cause damage to the cells or the wall. The mechanism chosen to attach the cell to the wall must be robust, easy to use and stable when attached. Furthermore, when attaching a single cell to a wall populated with all other growth cells, it must be able to be attached without disturbing the other cells. That is to say, the cell must not require a high tolerance of vertical movement to attach, requiring greater spacing between each cell, potentially disrupting the overall aesthetics of the system. The major considerations for the attachment components that were identified are listed below.

Major Considerations:

- Robustness: ability to withstand thousands of cycles of removal and reattachment to the wall
- Usability: Simple to understand for any user and require little time and minimal steps for removal and attachment
- Stability: The plant is stable in the wall and will not be disturbed when other units are attached.
- Strength: The mechanism must not fail under the weight of a fully irrigated plant cell with a fully grown plant.

Design and Construction: In order to satisfy the constraints identified above, we determined that a slide on clip system that hangs the growth cell on the wall would require minimal vertical tolerance between each bucket and would be able to securely hold the buckets on the wall. The first iteration of the clip was designed to slide over a thin flat metal bar. In this set up (figure 11 and 12) the weight of the growth cell would force the clip onto the bar, preventing it from coming off. Due to the horizontal distance between the clip and the inside of the U-channel, a bending force caused pressure to build on the clip. Under physical testing this caused the clip to fail with the application of minimal weight.



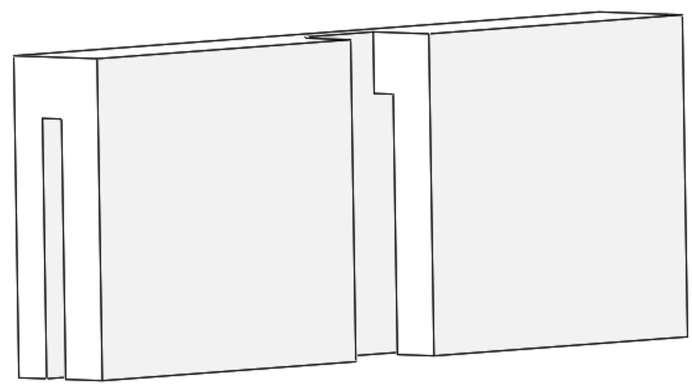


Figure 11: Original clip design and U-channel **Figure 12:** Original clip design render

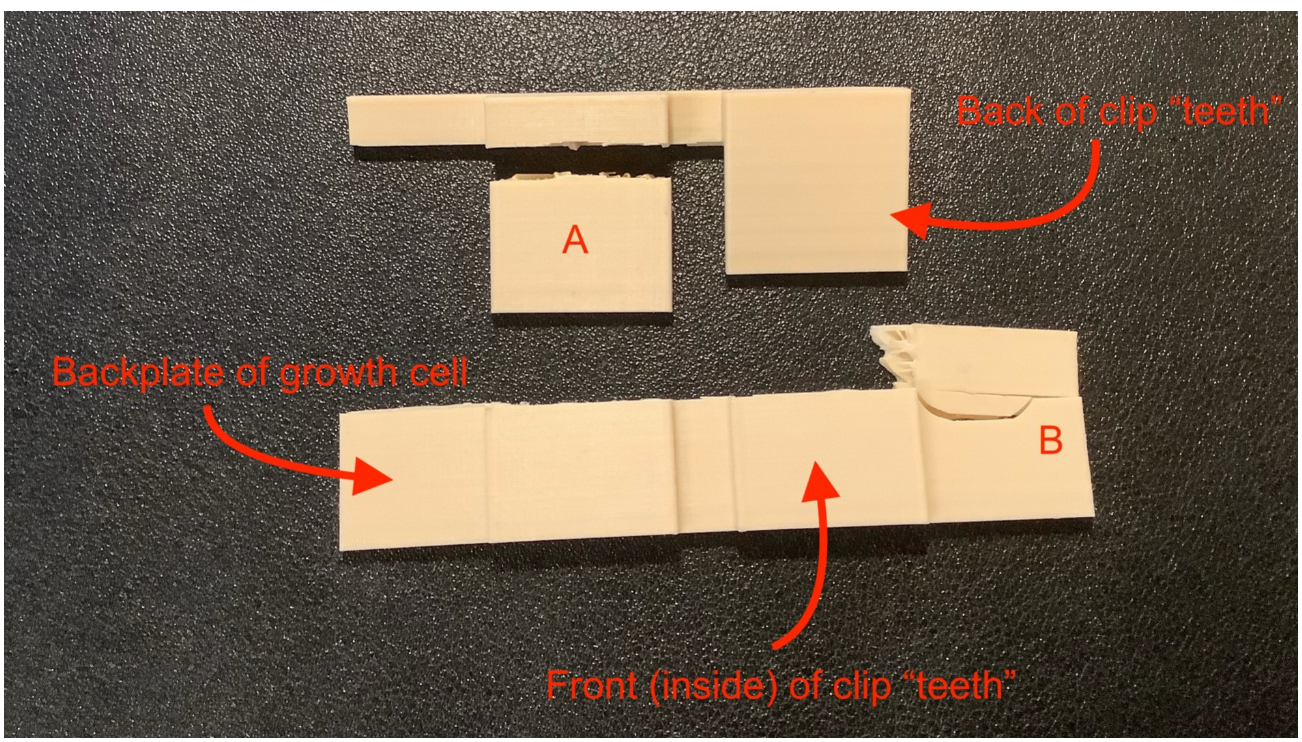
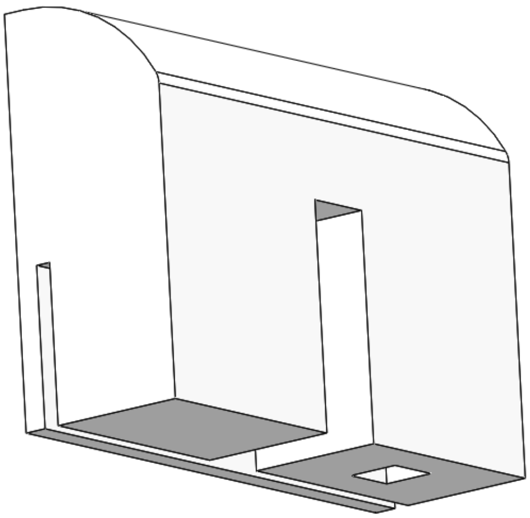


Figure 13: Failure of thin clip design.

Under physical testing there were two main points of failure (Point A and B of figure 13). This test was carried out by placing the test clip on an aluminum U-channel (See figure 11) and applying a bending force, using pliers to grip the top of the clip in between the two “teeth”. Under these conditions, the mechanism first broke at point “A”, where the back of the clip bent past its tolerance point. Past this point, the clip broke away from the back plate at point “B”. What was realized from this test was there was a great deal of space behind the clip in the U-channel (See figure 11). This allowed the back of the clip to bend freely as a moment force was applied to the entire mechanism. As well, because the clip attached to the back plate of the growth cell with such a small surface area, the forces were concentrated to the back plate causing separation. In order to counteract these failure points, the clip was redesigned (see figure 14 of redesigned clip).

To account for the bending of the back end of the clip, the new clip's thickness was extended to fit the entire width of the U-channel. This can be observed on figure 15 at point D. This has two effects for the overall function of the hanging mechanism. Primarily, as the weight of the growth cell pulls the cell forwards, a bending moment is created. Not only is the front facing flange of the U-channel acting as an anchor point, but the back of the clip is also extending pressure to the back facing flange of the U-channel, further securing the clip and translating the force into the metal bar. Secondly, as the clip is now in contact with both inside faces of the U-channel, there is a greater friction force helping stabilize the entire growth cell, preventing it from slipping on or off too easily. Furthermore, by extending the surface area that the clip attaches to the back plate of the growth cell (See figure 15 point C), the forces exerted during bending are distributed and do not concentrate at a single point.



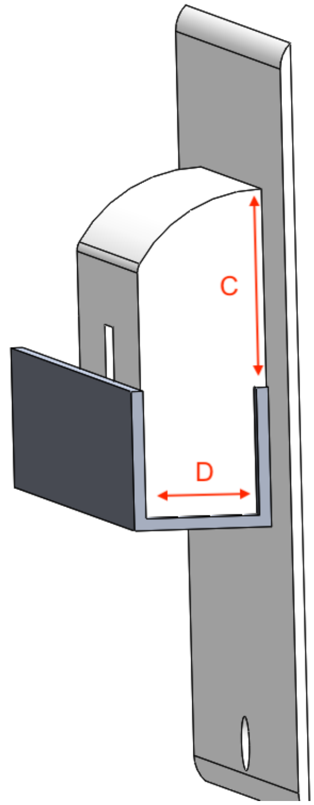


Figure 14: new clip design

Figure 15: New clip, on U-Channel

During physical tests, the clip endured up to 30 pounds of hanging force and did not break away from the back plate under bending. When 35 pounds was supported from the cell, the clip tore away from the back plate of the cell and as such was determined as the failure point (see figure 18). It should be noted that simulated testing previously revealed that the points of failure should be concentrated at the corners where the clip joins the backplate of the cell. The set up used for physical testing can be seen below in figure 16. Under this set up weights were attached to the base of the plant cell and incrementally increased until failure. Figure 17 shows the cell and clip supporting 30 pounds of weight. Under these conditions there was no failure although in figure 17 the resulting bending of the U-Channel bar can be observed. When the weight was released, the bar returned to its original shape with no permanent deformation.

Figure 16: Weight attached to cell

Figure 17: Visible bending of U-Channel

Figure 18: Damage to clip after testing with 35 pounds of weight

3.1.4 Stand for Growth Cells

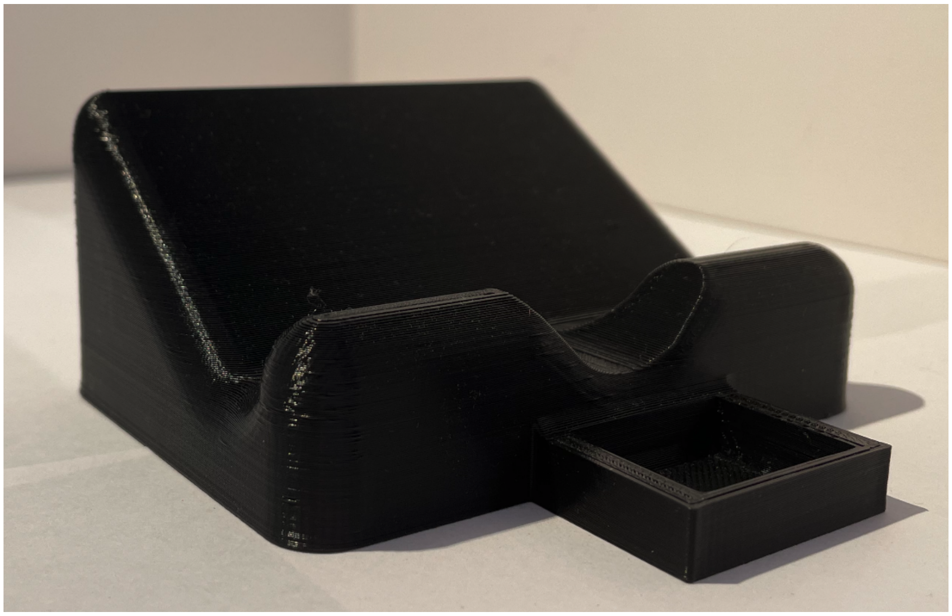


Figure 19: Stand for growth Cell

Purpose: When the growth cells are removed from the wall and brought into a classroom, they will not be able to sit on a desk or surface on their own because of the shape of the container. If the cells were placed on a desk as is, it would risk disrupting the plant and potentially causing it to fall out of the growth medium. As discussed in previous sections, the shape of the growth cell allows for a continuous vertical plane of greenery while keeping the soil from falling out, as well as promoting water flow through the substrate and into a single outlet point. By designing an independent stand for off-wall use (see figure 19), the original design did not require changing and the cell could be effectively set up for short periods of time in a new location.

Description: The stand measures 3 inches wide with 4 inches of depth and 2 inches of height at the tallest point. Full dimensions and detailed plans can be found in appendix B. The stand is designed as a stand alone unit that allows the growth cell to sit upright off the wall. To prevent the growth cell from sliding off either side of the stand, the edges indicated by point A in figure 20 are rounded, creating a lip that keeps the cell centered in the stand. In order to accommodate the outlet valve there is a gap in the back wall indicated by point C, and at point B a drip tray is integrated with the stand to collect any excess water that may leak out.

When there are plants in the growth cells, there is extra weight at the front of the cell. When attached to the wall this does not prove an issue as they are supported from the top of the cell. In order to prevent the cell from tipping forwards while in the stand, the angle of the stand is made so the growth cell is angled towards the back, shifting the center of gravity so that it is lined up with the stand. The result is that the growth cell is stable in the stand even when weighted with a plant.

Design and Construction: The growth cell was initially designed using Solidworks. By importing the 3D model of the growth cell, the stand was designed around it in a virtual space. For the purpose of our project the stand was then constructed from PLA filament using a 3D printer. The first iteration of the stand when printed did not have a steep enough angle as previously discussed and easily allowed the growth cell to tip over, the wedge in the stand was made steeper so as to hold the stand at a greater angle. The renders and images presented below (figure 22 and 23) are those of the final design.

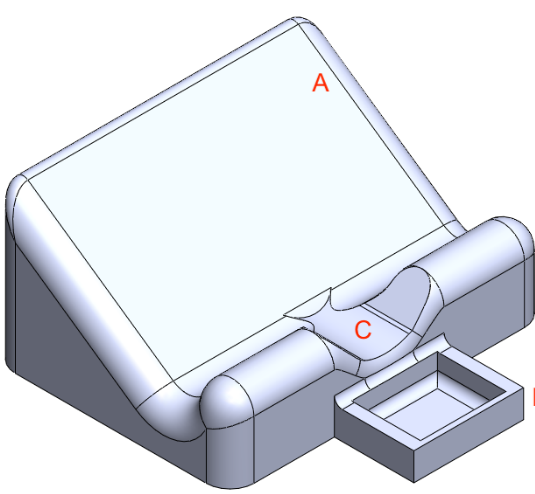


Figure 20: Render of growth cell stand

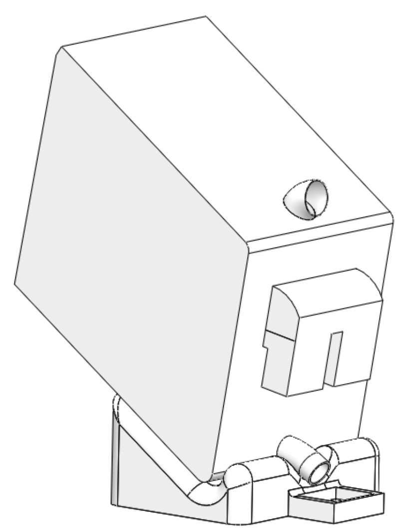


Figure 21: Render of plant cell in stand

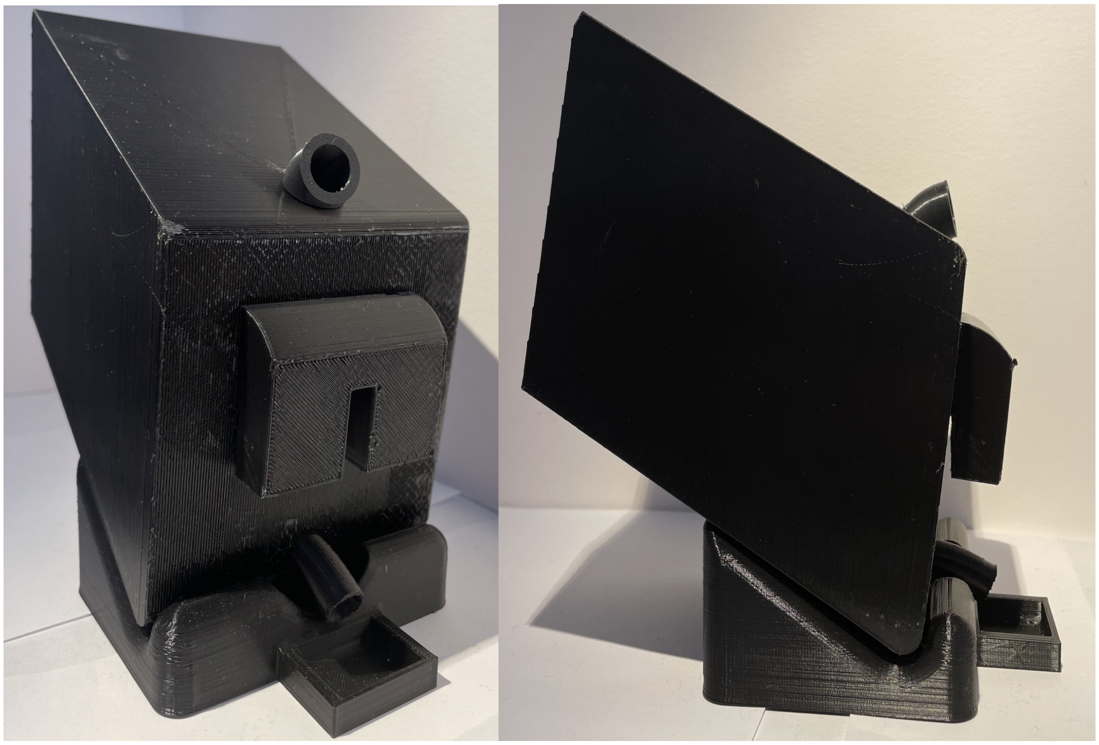


Figure 22 and 23: Final growth cell in stand

3.1.5 Irrigation & Substrate

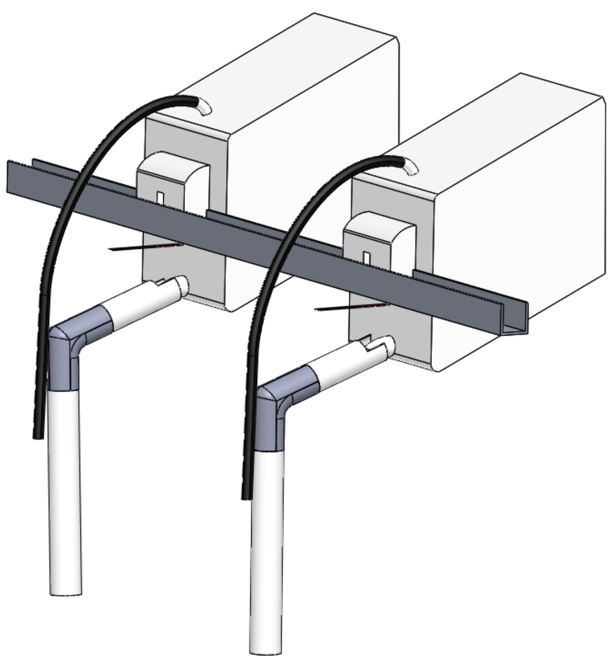


Figure 24: View of irrigation inlet and outlet with plant cells

Purpose: Delivering water to the plants and maintaining an optimal moisture level for the root ball area requires a multi-tier approach to ensure maximum efficiency and optimal plant health. First, the irrigation system is intended to serve as the sole conduit through which water is provided to the hosted plants on the unit. The distribution network should be capable of self-pressurizing and providing necessary resources to all plant growth nodes at predetermined intervals, while subsequently allowing for the drainage of excess water. Finally, when not in use, the irrigation system should store this water in a permanent basin equipped with aeration hardware used to supplement dissolved oxygen levels when not actively providing resources to the plants.

The substrate is intended to serve two distinct uses. First, it should provide a medium through which water can conduct through capillary action to the active root ball area of the host plants. Additionally, said substrate should be capable of maintaining a notable moisture level at all times, while still allowing for passive oxygen diffusion into said root ball area. Second, the substrate should act as a primary source of macro and micronutrients for the host plants through bio-available compounds readily found throughout its volume.

Description: Due to the need for a high level of autonomy within the hardware systems, the irrigation system must be extremely robust and incorporated with a number of optimizations to minimize user intervention. The distribution network comprising the irrigation system is separated into two distinct branches, namely the inlet and outlet networks respectively. The inlet network consists of flexible quarter-inch vinyl tubing terminating at the attachment node of each plant growth cell, as seen above in Figure 24. The end of the inlet attaches to a solenoid valve modulated by the status of its corresponding node on the wall. That is to say the valve is open and active when a growth cell is mounted at a given node, but inactive when no cell is present. The presence of this growth cell as detected by a switch mounted on the U-channel activated by the clip when inserted into position.

The drainage system consists of rigid three-quarter inch PVC tubing organized into columns, with branching elbow nodes for each row, terminating in an open-face tip for connecting with the drainage outlet of the growth cell, as seen below in Figure 26 and above in figure 24. The resulting geometry is a branching vertical tree with a branch node for each growth cell.

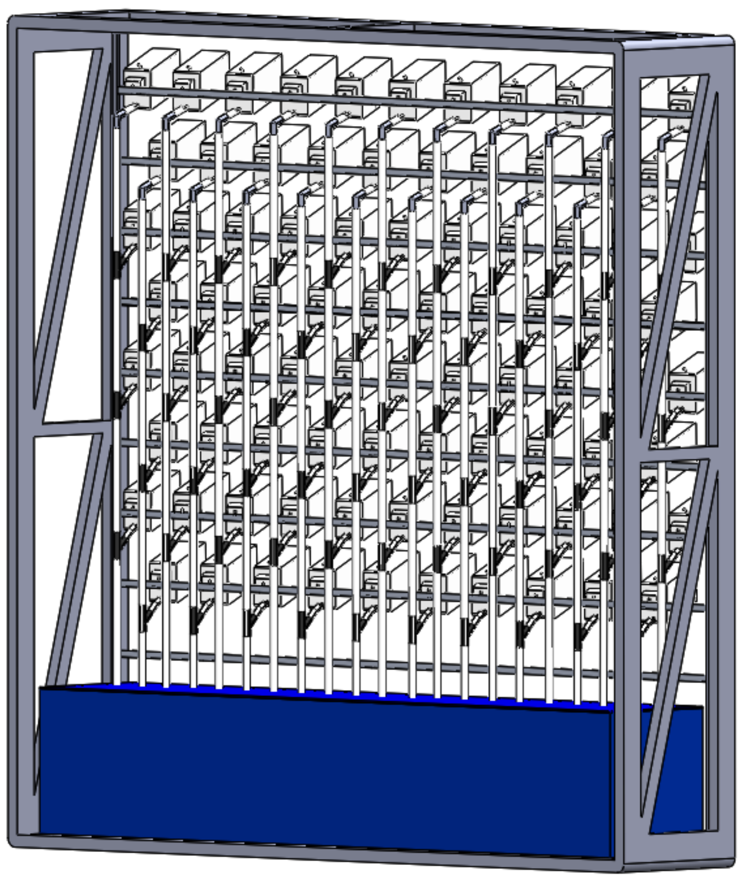


Figure 25: Back side view of frame with exposed irrigation Network

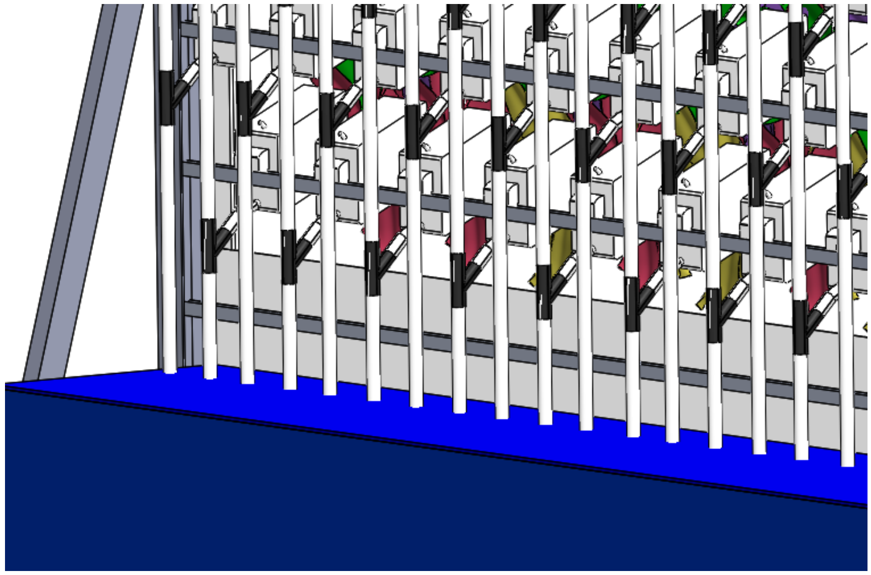


Figure 26: Close up of irrigation branching

In regard to the selection of an acceptable substrate, many greenwall systems employ a sterile substrate with little to no nutrient availability, and thus must artificially supply plants hosted in the environment with nutrients via dissolved compounds in the irrigation solution (Patil et al., 2020). Although effective, these systems require a very high level of user interaction as well as user knowledge in order to maintain these nutrient levels at adequate values. The user would need to monitor said levels and supplement, accordingly, likely requiring the synthesis of concentrated stock solutions, typically requiring knowledge of chemical handling procedures. As our client's maintenance crew is limited to inexperienced staff and students, this substrate type would not be ideal. Thus, our selection of substrate must be capable of providing nutrients to the hosted plants natively without the intervention of a nutrient-bearing irrigation solution. The most natural selection for this would be natural potting soil, as this substrate readily has sufficient concentrations of bioavailable nutrients within its volume. Unfortunately, this variety of substrate is not without drawbacks: due to the tendency for soil particles to migrate and clog essential systems, a filtration media must be implemented within the drainage conduits of the irrigation system. Without this filter, the pump used to circulate the irrigation solution would quickly become clogged and in turn damage the internal assembly. Luckily, with this simple addition, a soil-based substrate becomes quite appealing and fulfills our needs within the context of a functioning low-maintenance greenwall system.

Design and Construction: The inlet subsystem of the irrigation network was a relatively straightforward exercise in design and construction. As previously mentioned, the entirety of the inlet network consists of flexible vinyl tubing mounted to the vertical columns of the rigid drainage system. For installation, the inlet tubing was measured to the height of each column and cut accordingly. Subsequently, the spacing of each row was marked on the tubing, with cuts then placed on these zones. At this cut, a “T” splitter was installed to split the line in order to provide a branch to the growth cell located at the height of the cut. This line was then fed into a solenoid valve used to modulate flow to a given node, and a subsequent final length of tubing attached to the outlet of the valve was used to interface with the growth cell.

The drainage system was assembled in a similar fashion, albeit using a rigid structure. A length of PVC tubing was cut to the height of the tallest row in the greenwall assembly, and subsequently marked with the heights of each row. These markings were then used to place cuts, where 45 degree joints were subsequently placed. These joints interfaced with the drainage outlet of the growth cell, allowing water to drain from the cell when required.

3.1.6 Automation and Control Hardware

Purpose: As mentioned throughout, one of the most crucial requirements of this system is that it be nearly completely autonomous. This is largely due to our inexperienced user base, whose limited knowledge in the topics related to greenwall maintenance necessitates a system that operates with a high level of autonomy. In the rare instances where user intervention is necessary, the system must explicitly and clearly state the issue at hand. Thus, the automation system on this unit must cover all necessary components essential for plant growth; these include:

1. Irrigation
2. Lighting

3. Nutrient/ Resource Levels

The automation system should be able to regulate all of these variables, perform a range of on-the-fly compensation operations, be equipped with redundancies to limit issues, and clearly alert the user when intervention is finally necessary.

Description: The automation and hardware system comprises an array of subsystems, including specialized software and a network of hardware used to monitor and control physical aspects of the greenwall. The software is derived from an Arduino control routine, and thus it is written in C++. The program readily monitors aspects of the greenwall including:

1. Substrate Moisture
2. Reservoir Water Level
3. Dissolved Oxygen

Originally, the system was intended to monitor macronutrient levels present in the irrigation solution via ion-selective electrodes. Nutrients selected to be monitored included Potassium, Calcium, Magnesium and Phosphorus, that is to say most major nutrients required for healthy plant cultivation. Unfortunately, due to the project's change of scope and associated budget constraints, these hardware components were no longer able to be considered, as they are typically high cost. Specifically, the Vernier brand electrodes cost ~$330 (Vernier, n.d.), while more robust sensors cost several thousand (Fisher Scientific, n.d.). Due to this exorbitant cost, the nutrient monitoring sub-system was removed from the automation routine, and a dissolved oxygen monitoring sub-routine was used in its place. Oxygen sensors are significantly cheaper, costing less than $200 for a reliable unit (Atlas Scientific, n.d.). The remaining sub-routines, namely irrigation control and lighting control, were maintained due to their relatively low cost of associated components.

The irrigation’s automation system operates by monitoring data flows provided by an array of moisture sensors present in a small number of growth cells of the greenwall to act as a sampling array. When the monitored value drops below a threshold of ~15% (Cornell, 2010), the monitoring software will initiate a watering cycle. There are several safety checks in place to ensure that this cycle executes effectively, including verifying the water reservoir has sufficient remaining supply so as not to dry-run the water pump, as well as verifying that all moisture sensors are still operational throughout the course of the irrigation loop. This latter verification is essential, as the system is designed to continue executing the watering cycle as long as moisture values are below the accepted threshold. If the moisture sensors are not outputting data, the software could potentially interpret this as “dry”, and continue watering indefinitely, causing a flood. In order to eliminate this risk, the software is designed to enter a passive “safe mode” watering state if the sensors return NULL values, at which point the user will be instructed to check the state of the moisture sensors. If all is well however, the irrigation system will complete its water cycle, and return to a passive monitoring state once the average moisture reading from the sensor array is above the accepted threshold.

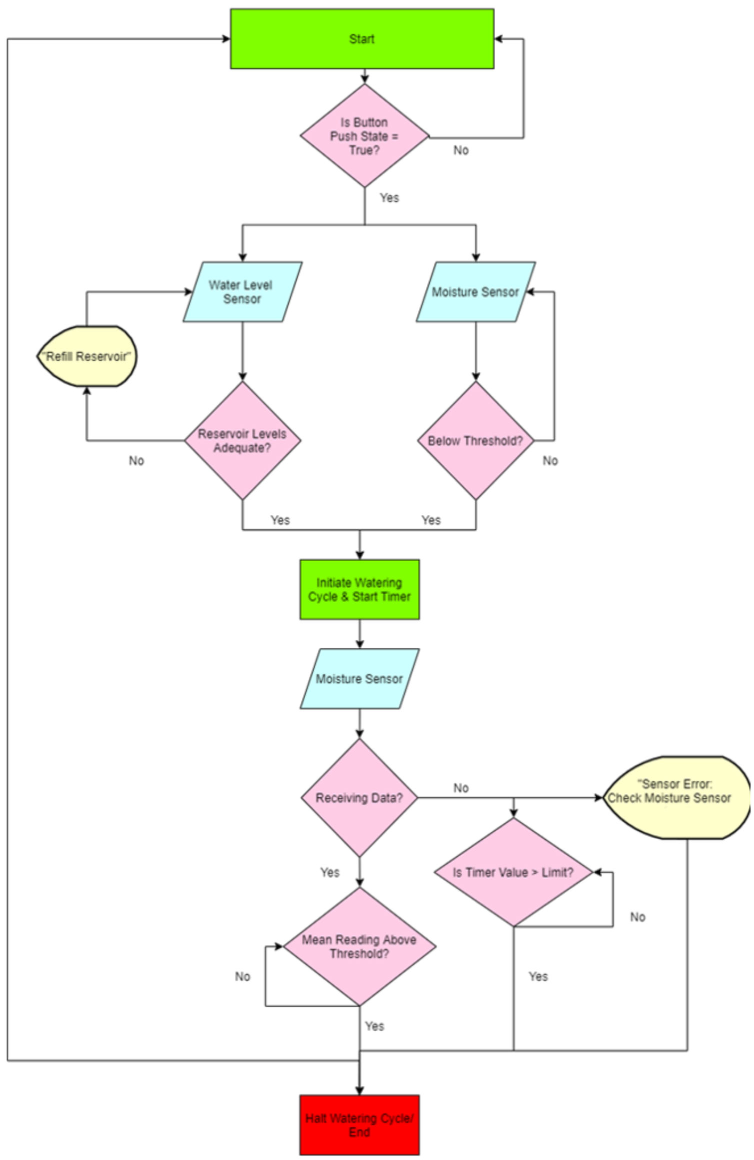


Figure 27: Logic flowchart for Irrigation Automation

The lighting system is reasonably simple, relying only on a clock used for time management. The photoperiod is set to the standard for most plant cultivation experiments; that is to say a 16/8h on/off cycle (Jackson, 2009). The lights are set to initiate at 6am and terminate at 10pm, as modulated by a 5V relay. This monitoring was proven to be rather challenging, as the Arduino board used for the control of these systems does not have a built-in clock. It is however capable of counting, and thus the option was explored of using a “counter” based timing setup. That is to say the system would count the seconds corresponding to a 16hr elapsed period, without knowing the actual time. This is problematic, as the Arduino would need to be initiated at exactly 6am to reliably execute the system, and would terminate its count and reset the counter in the event of a power failure. It was therefore decided that in the interest of failure-prevention, an independent clock module would be attached to the Arduino in order to relay the actual time to the system, as well as protect against power failure, as the clock module is capable of operating on battery power if needed.

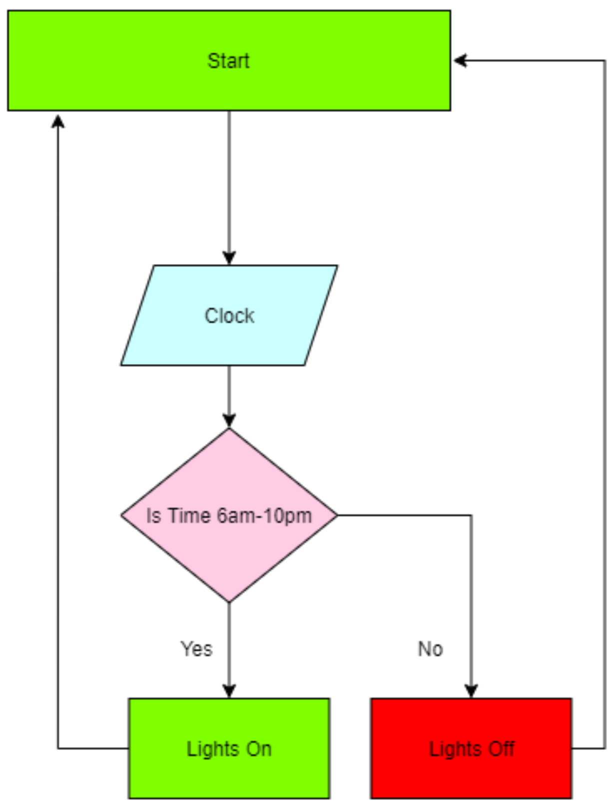


Figure 28: Logic Flowchart for Lighting System

The final automation system component is the monitoring of oxygen levels within the reservoir. A dissolved oxygen sensor is present within the reservoir at all times, monitoring oxygen levels and relaying this information to the automation CPU. If levels drop below the acceptable 8mg/L threshold (Grower Talks, n.d.), the system initiates an air pump supplying a stream of air to an airstone placed within the reservoir. Once activated, the airstone will dispel large amounts of small bubbles, oxygenating the water in the reservoir and maintaining acceptable levels. Once levels return to above the threshold, the air pump is terminated, and the system returns to its default passive monitoring state.

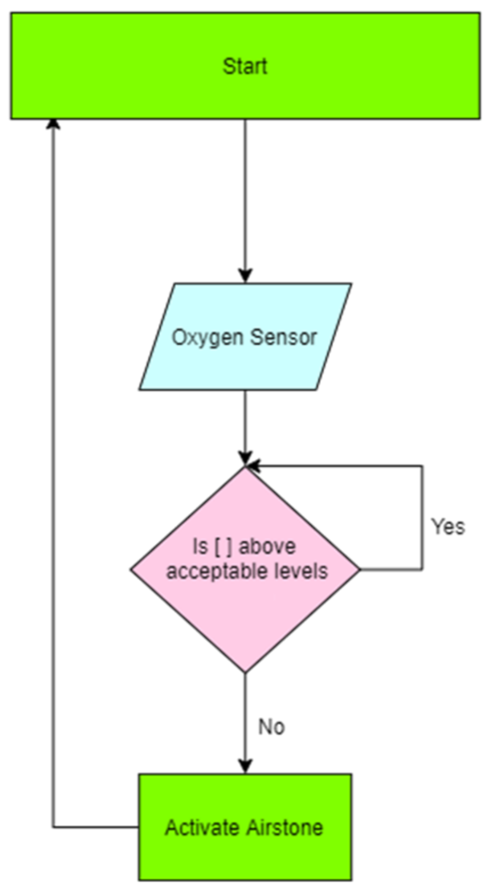


Figure 29: Logic Flowchart for Aeration System

Design and Construction: After short deliberation regarding which CPU was best suited for the housing of the software, an Arduino Uno was selected based on a variety of criteria. These included:

1) Low cost of acquirement
2) Ease of direct communication with hardware
3) Inclusion of native Analog data ports
4) User-friendly nature of proprietary software used for coding

Once selected, the team proceeded to employ Arduino's IDE for the construction of the code, based on the flowcharts as seen above.

Syntax & Support Hardware Initiation:

```
void setup() {
  Serial.begin(9600);
  Wire.begin();
  DS3231_init(DS3231_CONTROL_INTCN);
  //Clock is initiated on May 1st, 2021
  t.hour=0;
  t.min=0;
  t.sec=0;
  t.mday=1;
  t.mon=10;
  t.year=2021;
  DS3231_set(t);
  pinMode(11,OUTPUT);
  pinMode(12,OUTPUT);
  pinMode(switch1,INPUT);
  pinMode(switch2,INPUT);
  pinMode(switch3,INPUT);
  pinMode(valve1,OUTPUT);
  pinMode(valve2,OUTPUT);
  pinMode(valve3,OUTPUT);
  pinMode(LEDrelay,OUTPUT);
  pinMode(airpump,OUTPUT);
}
```

Figure 30: Snapshot of Code block 1: Initiation

Due to the nature of the Arduino ecosystem, preliminary initiation logic must be used to prime the CPU for use. These routines include establishing the groundtruth initiation time, instructing the Arduino to begin communicating with the clock module that has been mounted to its I/O array using a particular baud rate (not pictured: instructing Arduino to include the built-in library for communicating with this module), as well as declaring the state of each of the populated I/O pins on the Arduino.

Lighting:

```
void loop() {

//Lighting Control Block (6am to 10pm Photoperiod)
  DS3231_get(&t);

  if t.hour = 6 {
    digitalWrite(LEDrelay,LOW);
  }
  if t.hour = 22 {
    digitalWrite(LEDrelay,HIGH);
  }
```

Figure 31: Snapshot of Code block 2: Lighting Control

The next sub-loop is dedicated to the handling of the lighting system. As seen in the flowchart included in figure 28, the lighting system dictates the photoperiod of the hosted plants, selected to a standard 16/8hr on/off cycle. The LED array is modulated via a 5V relay switch, which allows a low-voltage board to control the flow of power to higher voltage components. The loop polls the current time as monitored by the attached DS3231 clock module. If the hour reads 6am, the system will trigger the relay switch, allowing power to flow through the circuit and thus powering the LED array. Conversely, if the time read from the DS3231 is 22:00 (i.e. 10pm), the system will shut off power to the lighting system.

```
//Moiture, Water Level and Oxygen Check Block
int moisture1 = analogRead(A1);
Serial.println(moisture1);

int moisture2 = analogRead(A2);
Serial.println(moisture2);

int oxygen = analogRead(A3);
Serial.println(moisture3);

int waterLevel=analogRead(A0);
Serial.println(waterLevel);
```

Figure 32: Snapshot of Code block 3: Sensor Input Handling

This code block's purpose is to simply poll the data arriving from the analog inputs of the Arduino. Similar to the *Syntax & Support Hardware Initiation* block, this section is largely necessary due to the syntax of the IDE and associated computer language. In brief, the data streams originating from the analog ports are classified into their respective variables for later use in the logic sub-systems. Additionally, the system is instructed here to explicitly state the values of each stream on the monitoring console via the **Serial.print** command, which the user would be able to view.

Modularity Monitoring:

```
//Growth Cell Mounted Check Block
  int switchstate1 = digitalRead(switch1);
  int switchstate2 = digitalRead(switch2);
  int switchstate3 = digitalRead(switch3);
```

Figure 33: Snapshot of Code block 4: Modulation Sensor Input

This code block is intended to poll the state of the installed switches responsible for monitoring the presence of a growth cell at a particular node. The block assigns the binary output value (0 empty node, 1 occupied node) for a given switch, and assigns it to a dedicated variable.

Moisture Calculation:

```
//Average Moisture Calculation
  int total_moisture = moisture1 + moisture2
  int moisture = total_moisture / 2;
```

Figure 34: Snapshot of Code block 5: Moisture Array Calculation

This block's purpose is to receive the input of the moisture sensor monitoring array, and generate an average moisture reading from this data stream for future evaluation.

Modulation Control:

```
//Modulating Irrigation Inlet to Node
  if switchstate1 = 0 {
    digitalWrite(valve1,HIGH);
  }
  if switchstate1 = 1 {
    digitalWrite(valve1,LOW);
  }


  if switchstate2 = 0 {
    digitalWrite(valve2,HIGH);
  }
  if switchstate2 = 1 {
    digitalWrite(valve2,LOW);
  }
```

Figure 35: Snapshot of Code block 6: Modulation Control

This block receives the binary state variables assigned in the previous *Modulation Monitoring* section and employs it in order to control the modular aspects of the greenwall. Namely, the block controls the state of the solenoid valves feeding to the inlet of each growth node, dependent on the signal broadcast by the switches. The *if* statements seen here will set the valve to **open** if the binary signal reads 1, indicating a growth cell is present at a given node and thus that irrigation is required. If the signal reads 0, indicating the absence of a cell at a given node, the valve will be set to **closed**, as that location does not require irrigation.

Irrigation Control:

```
//Irrigation Control Block
while (moisture < moistureThreshold){
   if (waterLevel > 500){
    digitalWrite(waterpump,LOW);
    delay(10000);
    digitalWrite(waterpump,HIGH);
   if (waterLevel < 500){
    Serial.println("Resevoir Low");
   if (moisture1 = null, moisture2 = null, moisture3 = null) {
    digitalWrite(waterpump,LOW);
    delay(10000);
    digitalWrite(waterpump,HIGH);
    Serial.println("Sensor Error, Please Check");
   }
   else if {
    digitalWrite(pump,HIGH);
   }
   }
   }
   }
```

Figure 36: Snapshot of Code block 7: Irrigation Control

This largest code block is the main control logic for the operation of the irrigation system. As mentioned, and as seen in the software flowchart, the irrigation system is reinforced with failsafes that minimize the risk of failures, such as flooding or dry-running the water pump. The block initiates by verifying the average moisture value generated by the *average moisture* subsystem is below the threshold value of 30 based on tests previously conducted. If the average value indeed falls below this threshold, the system will move to check the water level in the reservoir to ensure that there is adequate water remaining to execute a watering cycle without running the water pump dry (i.e. above a value of 500). If this is not the case, the system will not initiate a watering cycle, and will display a warning to the user to fill the reservoir. If the reservoir water level is determined to be adequate however, the system will proceed with the watering cycle. Intervals of 10 seconds will be executed until moisture values return to nominal levels, at which point the system will return to passive monitoring. Finally, in order to ensure that the system does not enter an infinite loop due to a sensor failure during watering, the block contains a specialized routine reserved for sensors in an error state. If any of the sensors are detected outputting a **null** signal, the software will run the greenwall on a “standby” mode, where it will periodically initiate a shortened watering cycle to keep the plants alive without flooding the area, while simultaneously displaying a message to check the moisture sensors. Once the issue is resolved by the user, the system will resume normal functions.

Air Pump Control:

```
  //Air Pump Control (Activate if levels below 8mg/l)
  if oxygen < 8 {
    digitalWrite(airpump,LOW);
  }
  if oxygen > 8 {
    digitalWrite(airpump,HIGH);
  }
}

}
```

Figure 37: Snapshot of Code block 8: Aeration Control

The final code block controls the operation of an air pump feeding an air stone in the reservoir. It is simply controlled via monitoring of the dissolved oxygen values in the reservoir, in order to keep them above an 8mg/L threshold. If levels drop below this value, the air pump is initiated in an identical manner to the LED array, that is to say by modulating the state of a 5V relay. Conversely, when values return to the acceptable range, the system will terminate the air pump by switching off said relay.

Hardware Selection:

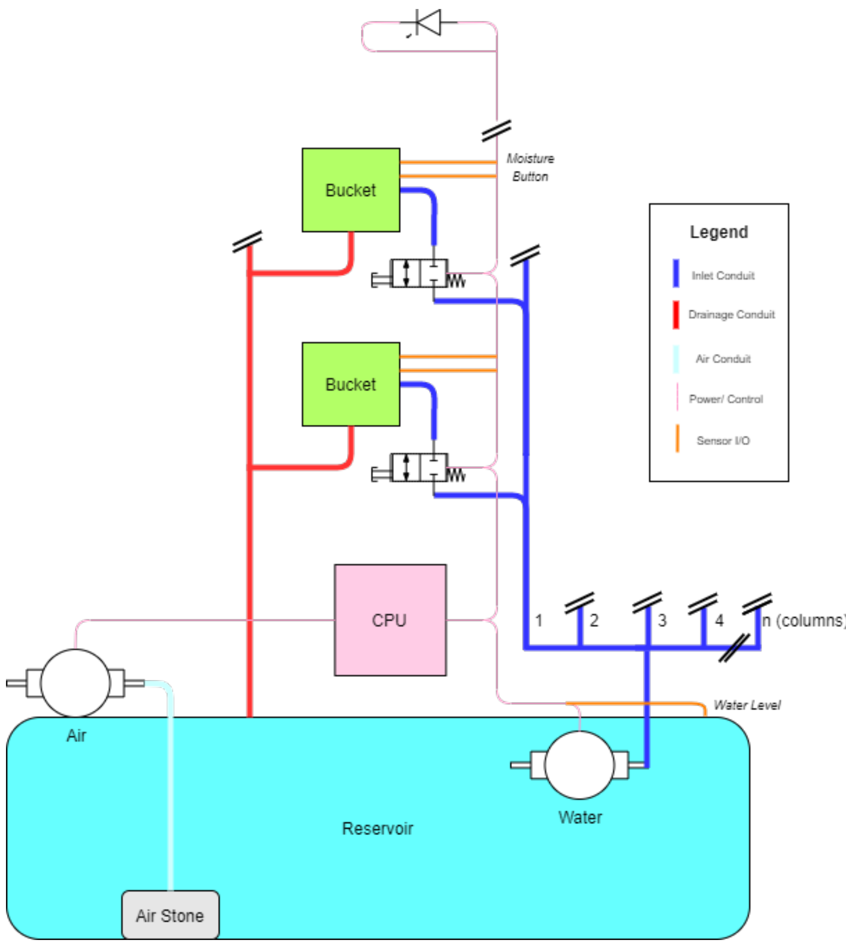


Figure 38: Hardware Conceptual Schematic

Complimentary to the software sub-system, a parallel hardware sub-system was designed to directly control necessary aspects of the greenwall system, as well as execute commands as dictated by the CPU. This array of hardware is comprised of numerous components, including:

I. Pumps (Air and Water)
II. Sensors
    A. Moisture

    B. Oxygen
    C. Water level
    D. Switches
III. Control Valves
IV. Relays
V. CPU
    A. Clock module

All of these components, working in parallel with each other and the software, serve to render the greenwall into an autonomous and intelligent system, suitable for users with limited experience.

Pumps:

Two varieties of pumps were required for this system: water and air. Air pumps are quite simple to select, as most are capable of supplying adequate aeration to a reservoir, particularly a medium-sized unit such as ours. As such, a Pawfly aquarium pump capable of providing aeration to a tank up to 80 gallons (~300L) was chosen due to its low cost of $29.99 (Amazon, n.d.) and small form factor.

Figure 39: Pawfly Air Pump

Selecting a water pump for the system is a similarly trivial exercise, as commercial units are readily available for the aquarium hobby and fountain industry. Due to the large head height required (~30ft), a large pump was necessary in order to reliably provide water to all growth cells on the greenwall. To this end, an AC centripetal pump was selected due to its high power and relative ease of use; the specific unit in question is the *Iwaki MD-70RLT*, capable of 492GPH flow and ~32ft head height and costing $658.68 (Aquabiotech, n.d.).

Figure 40: Iwaki MD-70RLT Centripetal Pump

Sensors:

In order to provide data to the software subsystem, an array of sensors must be employed to measure:

I. Soil Moisture
II. Dissolved oxygen
III. Water level
IV. Switches

These environmental readings are achieved via the following sensor modules:

FC-28 Soil Moisture Sensor:

The FC-28 is a soil conductivity probe designed for use with Arduino boards, and is an extremely common unit for this use case. The sensor passes a mild electric current between its probes in order to correlate relative moisture content with soil conductivity. This value is relayed to the Arduino as an analog signal, that is to say an unprocessed electrical reading as observed by the sensor's potentiometer. The sensor is available at a cost of $6.91 (Abra Electronics, n.d.

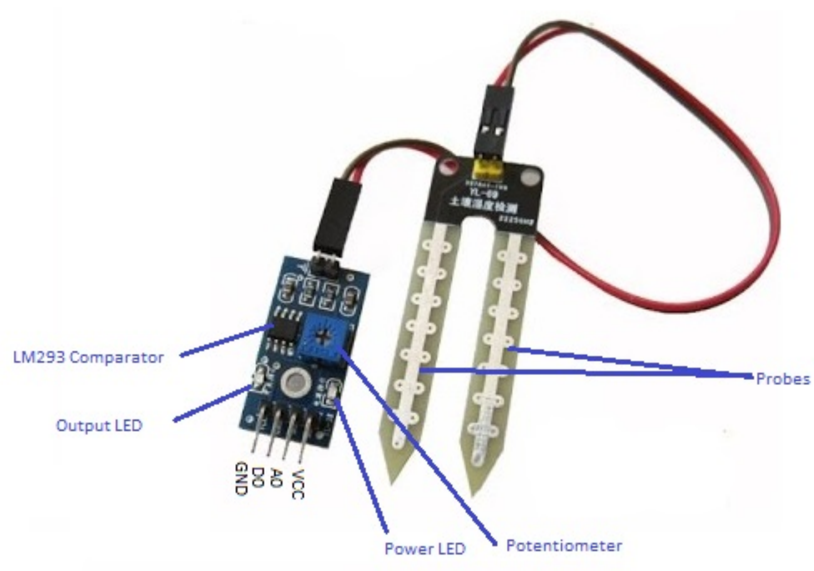


Figure 41: FC-28 Moisture Sensor

Dissolved Oxygen

The *Gravity Dissolved Oxygen Sensor* manufactured by Atlas Scientific is a high fidelity laboratory grade dissolved oxygen sensor, used at McGill's Biomass Production Laboratory among many others. The sensor outputs an analog data signal to an attached Arduino board, which can be used to estimate relative oxygen levels. Although the unit is measurably more expensive than the other sensors used, costing $282.99 (Atlas Scientific, n.d.), the greenwall only requires a single sensor for this purpose, and thus the cost can be argued as justifiable.

Figure 42: Gravity™ Oxygen Sensor

Water Level:

The SL067 was the water sensor selected for use on this greenwall, predominantly due to its low cost of $1.84 (Abra Electronics, n.d.) and ease of use. The sensor is a simple array of metallic plates that measure conductivity in a similar manner to the moisture sensor, determining water level based on this value. As with many other sensors used in this system, the sensor outputs an analog signal which can be directly interpreted by the Arduino microcontroller.

Figure 43: SL067 Water Level Sensor

Switch:

The switch used in the greenwall to monitor the presence of growth cells was selected to be a GAMES-SW-01 lever-action unit. This switch outputs a binary signal of 0 or 1 depending on the state of the unit; as mentioned, this signal is used to modulate the numerous solenoid valves present throughout the irrigation system. The unit is low-cost, being $3.07 per switch (Abra Electronics, n.d.), and is very simple to implement.

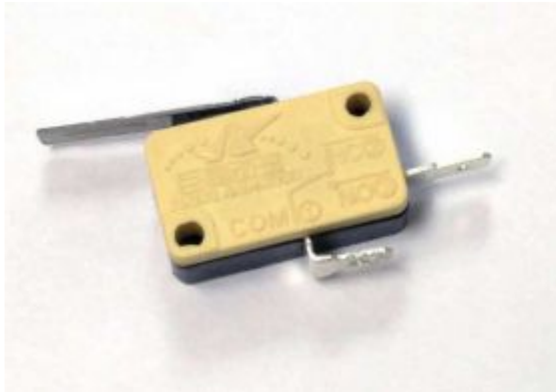


Figure 44: GAMES-SW-01 Switch

Control Valves*:*

Complementing the action of the switch array, the greenwall employs solenoid control valves in order to modulate the flow of water in the irrigation system's inlet network. The valve chosen for this purpose is the AQT15SP, which employs an electrical signal to modulate the state of a magnetic valve, thus controlling the flow of water through the pipe. The unit is relatively low cost at $15.31 (Abra Electronics, n.d.), and is available at local Montreal retailers for easy replacement if necessary.

Figure 45: AQT15SP Solenoid Valve

Relay:

Magnetic control relays are used in order to allow the low-voltage Arduino board to control high-voltage (120V) components, such as lighting and pumps. The relay operates by receiving a digital control signal from the Arduino, and modulating the state of a magnetic switch, which depending on the wiring configuration is normally open (i.e. off). When power is required to be delivered through the unit, the 5V end supplied by the Arduino triggers the magnetic switch, which in turn allows the 120V current to flow through the metallic switch located inside the relay's housing. This action isolates the Arduino from the high voltage, ensuring safe and reliable operation. The relay selected is the RM-1 unit, although it should be noted that this is a single relay node, and there are boards with multiple relays working in parallel which are equally suited for use in this system. This particular unit is available for a low cost of $4.49 (Abra Electronics, n.d.)

Figure 46: RM-1 5V Relay

CPU:

In order to house the software as well as control all the aforementioned hardware components, a centralized computer was required. As mentioned previously, the Arduino Uno was the board chosen for this purpose, mainly due to its low cost, abundance of I/O and native support for analog signal I/O. Although more complex microcontrollers such as Raspberry Pi provided attractive features such as built-in clock support and wifi/bluetooth connection, these features were ultimately less attractive than the Arduino's low cost and analog signal support. Arduino Uno boards are sold at a cost typically similar to $23.00 (Arduino, n.d.)

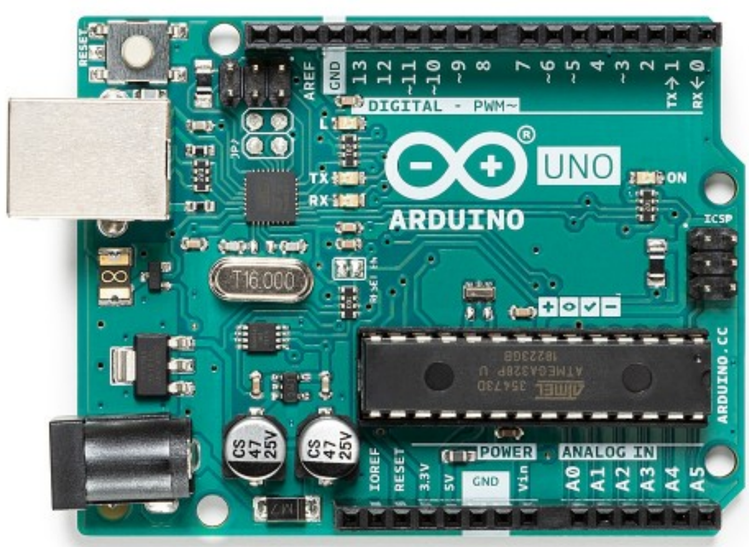


Figure 47: Arduino Uno Microcontroller

Clock Module:

As mentioned, Arduino boards are not capable of natively maintaining a 24hr clock, rather they are simply able to count how much time has elapsed since boot. As mentioned, this behavior is not ideal, as this counter will be reset in the event of a power failure. To avoid this issue and simplify the timing process, our team opted to employ a DS3231 clock module, which is capable of supplying a time data stream to the Arduino, as well as operate independent of power due to its included battery. The unit is very low cost, typically costing no more than $4.99 (Abra Electronics, n.d.)

Figure 48: DS3231 Clock Module

3.1.7 Plant Selection

In order for the greenwall to be versatile the plant cells were designed to be big enough to accommodate almost any type of plant. The plant selection would be limited by how much or how little water they would require in relation to other plants on the wall, as the irrigation is not variable for different sections of the wall. As such, all plants on the wall would need to be selected so as to have similar water requirements. That being said, this type of greenwall would work best with broad leafed indoor houseplants so as to cover aspects of the wall that might be visible with smaller plants. These would include but are not limited to spider plants, Chinese blackfern, aglaonema (which we used in our model), Bird of Paradise, Variegated Ficus Triangularis, Basket Grass and Alternanthera dentata. We would want to avoid the use of any plants that flower or could release pollen. As well we want to avoid delicate plants, or those that are not tolerant to water stress.

Additionally plants whose leaves become very large should be avoided to prevent the substrate from falling out of the cells.

3.2 Assembly and Installation

Assembly of the greenwall begins with constructing the steel frame. A500 steel can be cut using a chop saw equipped with a metal cutting blade (Industrial Tube and Steel Corporation, n.d). This equipment is provided at the shop. The cut pieces of metal tubing will be welded together to assemble each section (top, bottom, sides), but will not be welded together to form the frame until installation. Holes in the aluminum U-channels will be drilled in order to bolt them to the metal flange along the inside of the frame, as well as the switch that indicates if the cell is connected or disconnected from the wall. The irrigation system will be assembled by cutting and connecting the ¾” PVC outlet pipes to their branching components, as well as cutting and fitting the ¼” inlet tube pieces together. The separate components of the greenwall will then be transported to the highschool for installation.

Assuming all of the concerns addressed in table 4 have been resolved (no installation of floor drain, but assumed site has adequate drainage), the installation of the greenwall will require hiring a licensed tradesman in order to perform the higher risk, technical tasks. These tasks include, drilling holes into the wall to secure the anchor plates and welding the sections of the frame together on site. When the frame has been secured to the wall by the tradesman, the reservoir will be installed, and installation of the irrigation system can begin. This is done by simply fitting the bottom of the irrigation pipes into their designated sections of the reservoir. To fully secure the inlet tubing and the outlet irrigation pipes in place, they will be strapped to the crossing U-channels while they are being assembled. Next, the pump and electronics can be installed, followed by bolting on the exterior plastic paneling. Fabrication of the growth cells will have been done continuously over the course of the assembly and installation period on our personal 3D printers. If required, we would hire a 3D printing company to speed up the process. Installation of the growth cells starts by first installing the guides designed to guarantee a successful connection to the wall. All the growth cells are then placed on the wall and the irrigation system is tested to make sure all systems are functioning properly. After a successful test, the plants can be installed in the growth cells and a final test of all systems can be performed.

3.3 Operations and Maintenance

In order to properly take care of the greenwall after installation, the maintenance staff (chosen by the school) needs to be trained. The main sections of the Operations and Maintenance Manual have been specified below, however for the purposes of the report they will not be explained in detail as to keep within the page limitations. Training would be done in three sections with their different sub-sections:

1) Electronics
   a) Pump
      i) General Maintenance and Schedule
      ii) Identifying Issues and Solutions
      iii) Critical Components
      iv) Procurement Procedure
      v) Replacement Procedure
   b) Arduino and Sensors
      i) General Maintenance and Schedule
      ii) Identifying Issues and Solutions
      iii) Critical Components
      iv) Procurement Procedure
      v) Replacement Procedure
   c) Wiring
      i) General Maintenance and Schedule
      ii) Identifying Issues and Solutions
      iii) Critical Components
      iv) Procurement Procedure
      v) Replacement Procedure
2) Plants

a) Pruning
    i) General Maintenance and Schedule
b) Removal and Replacement Procedures
c) Identifying Health Issues and Solutions
    i) Identifying Nutrient Excess or Deficiency and Solutions
    ii) Identifying Mold, Mildew and Pests and Solutions
d) Growth Cell Replacement
    i) STL File and Printing Procedure (school has one available)

3) Irrigation
    a) Leakage
        i) General Maintenance and Schedule
        ii) Identifying Location and Solutions
        iii) Critical Components
        iv) Procurement Procedure
        v) Replacement Procedure
    b) Water Resupply
        i) Procedure and Schedule

3.4 Social, Environmental and Occupational Aspects

Due to the fact that the greenwall would have been installed in a school's atrium that is a high traffic zone, we had to take into account that the overall design must not take up too much room so that it alters the use of the space. As well the overall design must be robust enough to prevent damage caused by misuse or tampering as the audience is young high school students. To account for this the total depth of the wall was limited to 1.5 ft and does not slope. As well the first 24in of height do not contain any plants. As people will be walking by it often this will prevent any plants from being accidentally kicked. All ports for accessing the internal components of the wall would need to be locked so as only accessible by maintenance staff and administrators.

In addition to these social considerations, the system must be simple enough for relatively untrained individuals to operate. That is to say the procedure involving refilling the water talk, removing the plant cells, replanting and monitoring other data must be simple and straightforward. These aspects have been discussed in their respective sections of this report.

3.4.1 Life Cycle Considerations

The steel construction of this greenwall allows for the construction to be extremely durable and unlikely to require any type of repair due to damage. As such we estimate that the structural aspects of the greenwall will last until the greenwall is removed from the space. This is further possible by the fact that in selecting galvanized steel, they will not rust due to any water that may leak from the system. As these parts will not require replacement at any point in the future their impact environmentally is minimal. As well at the end of life the metal could easily be recycled or repurposed as the major parts of the construction are made of standard sized members. The plant cells would be constructed out of plastic and may break over time especially due to misuse. As such these would need to be replaced as needed and depending on the level of use and care could have a significant impact on the overall sustainability. In order to minimize their impact a thermoplastic such as ABS could be used for a working version of the greenwalls growth cells as it is easily recyclable.

4.0 Design of Scale Model

As previously discussed after parting ways with the client, and discussing our options with Dr. Madramootoo, we came to an agreement that we would build a model of the original greenwall (figure 2). We shifted our focus to the aspects that make our greenwall unique, such as the removable growth cells, the in-class stand and the automation of the irrigation system. Our team was able to secure new funding from BESS in the amount of $285.00 (~5% of original budget). This small budget allowed us to carry out the construction of the new scope of the project.


Figure 49 & 50: Constructed scale model

The new frame which can be seen in figure 49 and 50, has been scaled down from the original design to be 24”x 40”x 7.5” and is constructed out of 2”x2” dimensional lumber. Since the frame was not considered a novel part of our design and required less focus, it was determined that wood construction was the best option as it is cheap, and easy to work with. Four ¾” horizontal aluminum U-channels have been chosen as a substitute for the vertical steel hat channels (similar to those used for sign posts) used in the original design. This is due to the fact that the vertical channels were much larger, more expensive and harder to work with. The change to the horizontal channel meant that the growth cell clip needed to be redesigned. Each U-channel was spaced 8” apart and measured to hold three growth cells each. In figure 49 and 50 only the top row has the full three cells. This was done in order to save on filament cost and waste. The growth cells fit easily into place with the help of guides installed on the U-channel allowing the cell to trigger a switch installed on the U-Channel which initiates irrigation. Connection between the growth cell and the irrigation system has changed as well. The ½” outlet tube of the cell fits easily into its designated ¾” main outlet pipe. The main irrigation outlets were only assembled for the first row as that was the only row that would have three cells. The irrigation outlets fit inside the 11.3L reservoir at the bottom of the frame. Water is pumped via a 12V, 3A Bayite model BYT-&A102 irrigation pump with an 80 psi cutoff pressure and 4 LPM flow rate (through ¼” vinyl tubing spanning up the wall and into each growth cell on the top row. The automation software responsible for maintaining most essential aspects of the system was designed with this new scale in mind. Notably, aspects such as the number of growth cell monitoring switches, number of moisture sensors, and the number of solenoid valves were scaled to reflect the novel form factor. It should be noted, however, that scaling up the software to be functional with the original full scale greenwall would be quite simple, as the sole changes required would be the addition of variables to control the added hardware.

5.0 Cost Breakdown

This cost breakdown represents the actual costs of constructing the scale model of the greenwall.

No.	Part	Qty	Description	Cost
1	Framing Wood	4	2”x 2”x 8’ lumber	$3.02 each Total: $12.08
2	Wood Screws	1	Bucket of 50 screws	$9.98
3	Irrigation Outlet Tubes	1	¾” x 8’ PVC pipe	$11.60
4	⅝ Vinyl Tubing	1	40’ of clear vinyl tubing. Not used	$16.20
5	Aluminum U-Channel	1	¾” x 7’ U channel	$20.43
6	Reservoir	1	11.3L container	$8.02
7	Angled Irrigation fittings	3	¾”, 45˚ PVC fittings	$1.24 each Total: $3.72
8	Tapped Metal Screws	1	Bucket of 24 ½” screws	$7.00
9	Irrigation outlet tube	1	½ x 24” PVC irrigation tube. Not used	$3.84
10	T Split	1	Pack of 6 ¼” T split	$4.87
11	90˚ Elbow fitting	1	Pack of 6 ¼” elbow	$4.87

12	¼” Vinyl Tubing	1	¼” x 100’ tubing	$18.20
13	Zip Ties	1	8” zip ties	$5.68
14	Plant	1	Plant for growth cell demo	$19.53
15	3D printing filament	3	Combination of filament used for prototyping and final demo prints	$34.99 each Total: $104.97
16	Pump	1	BYT-&A102 12V, 3A pump, 80PSI, 4 LPM	$33.50

Table 5: Bill of Materials

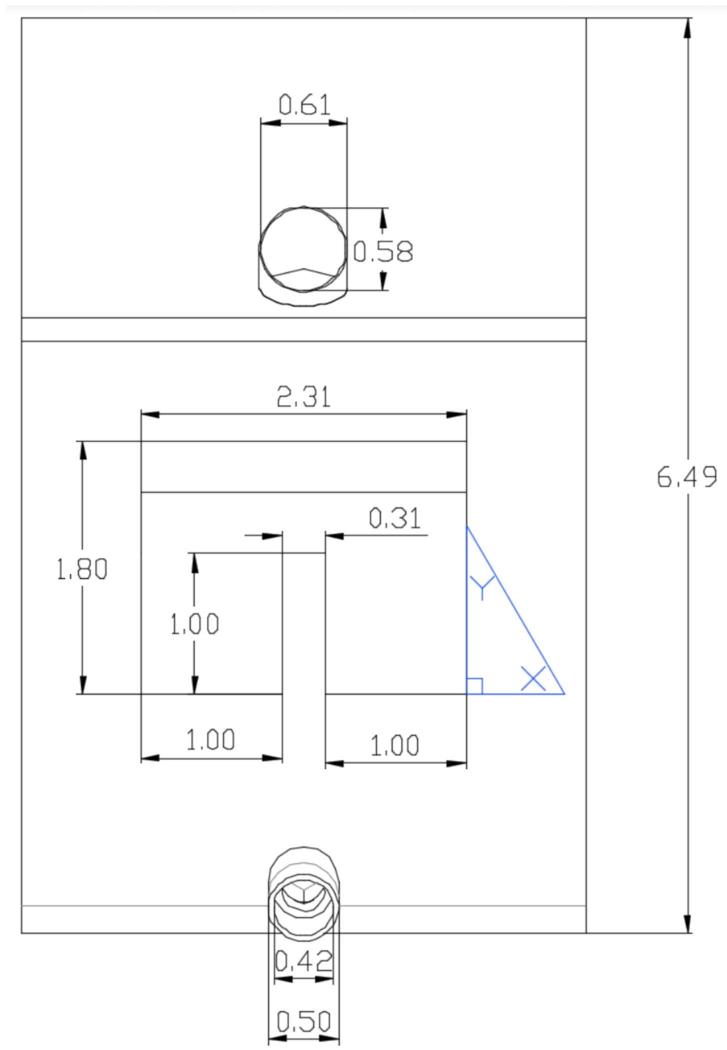
Total material cost = $284.49

6.0 Conclusion

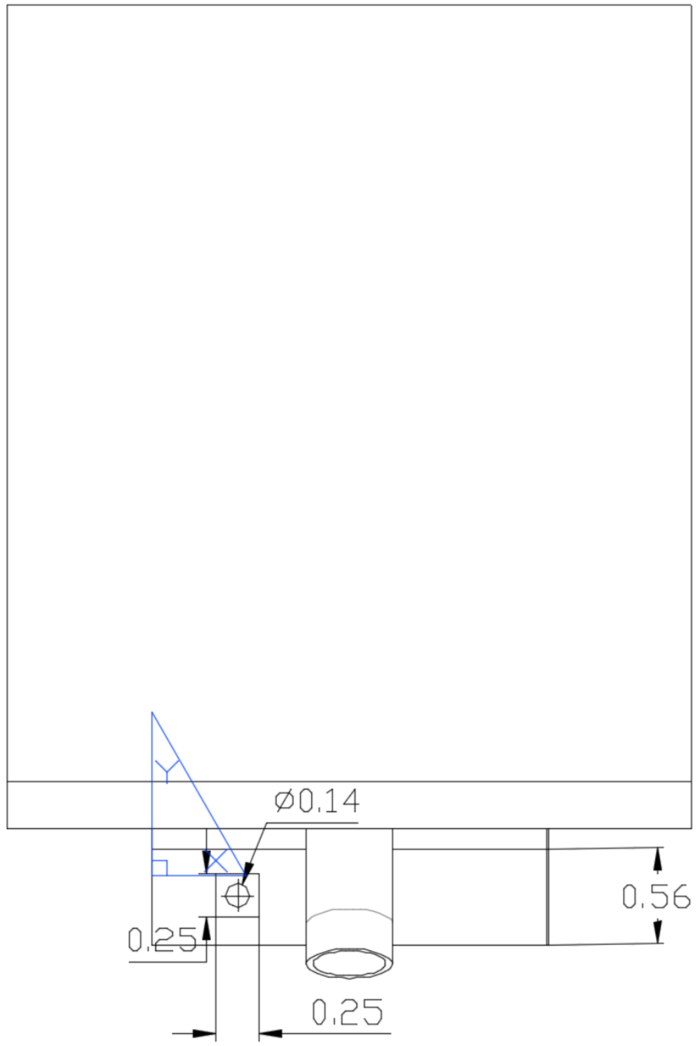
In conclusion, the greenwall model constructed has met the requirements we set out to fulfill. Namely the growth cells are easily removed and replaced onto the greenwall and can easily be transported into a classroom setting through use of the stand. As well, the greenwall allows for the irrigation and drainage system to be easily integrated with the cells, all while providing an aesthetically pleasing design. Under both physical and simulated testing the design was validated as being viable for use as it met the physical requirements defined (strength and support, aesthetics, modular and removable). Even though we were met with significant challenges due to the COVID-19 pandemic preventing us from completing the original scope of the project, we have learned a great deal from this project and will carry this experience and skills learned with us going forward in our careers.

Appendices

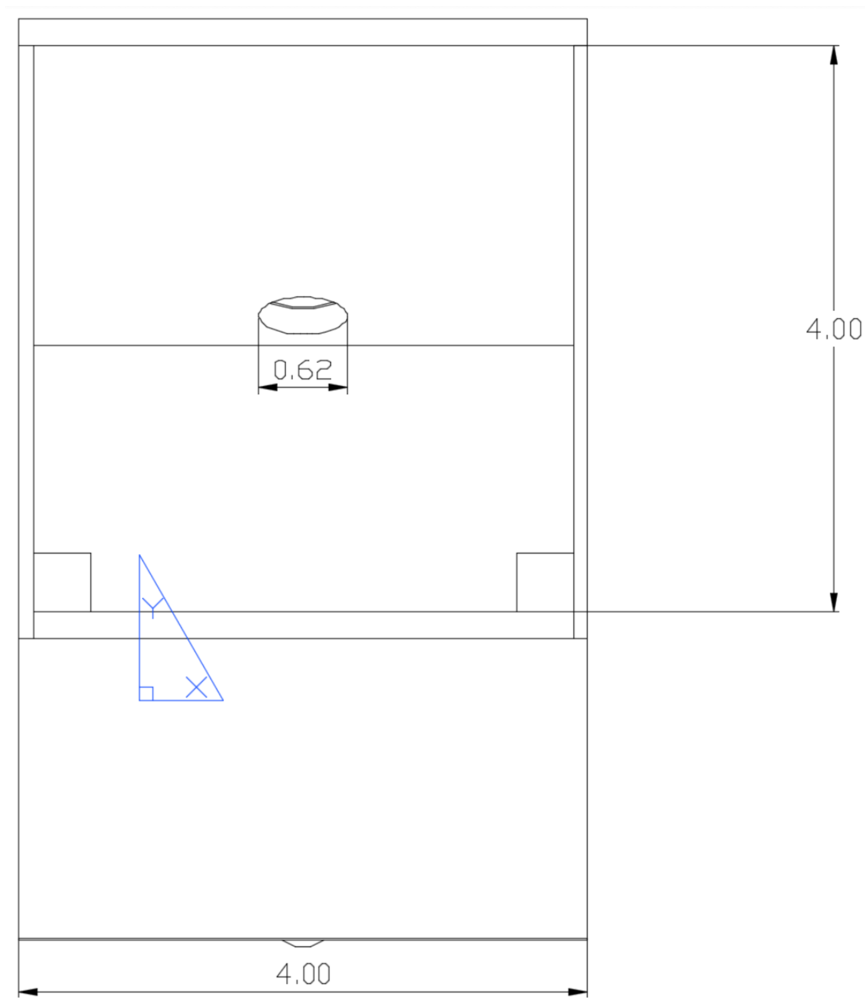
A) Technical drawings and details: Growth Cell (all units in inches)



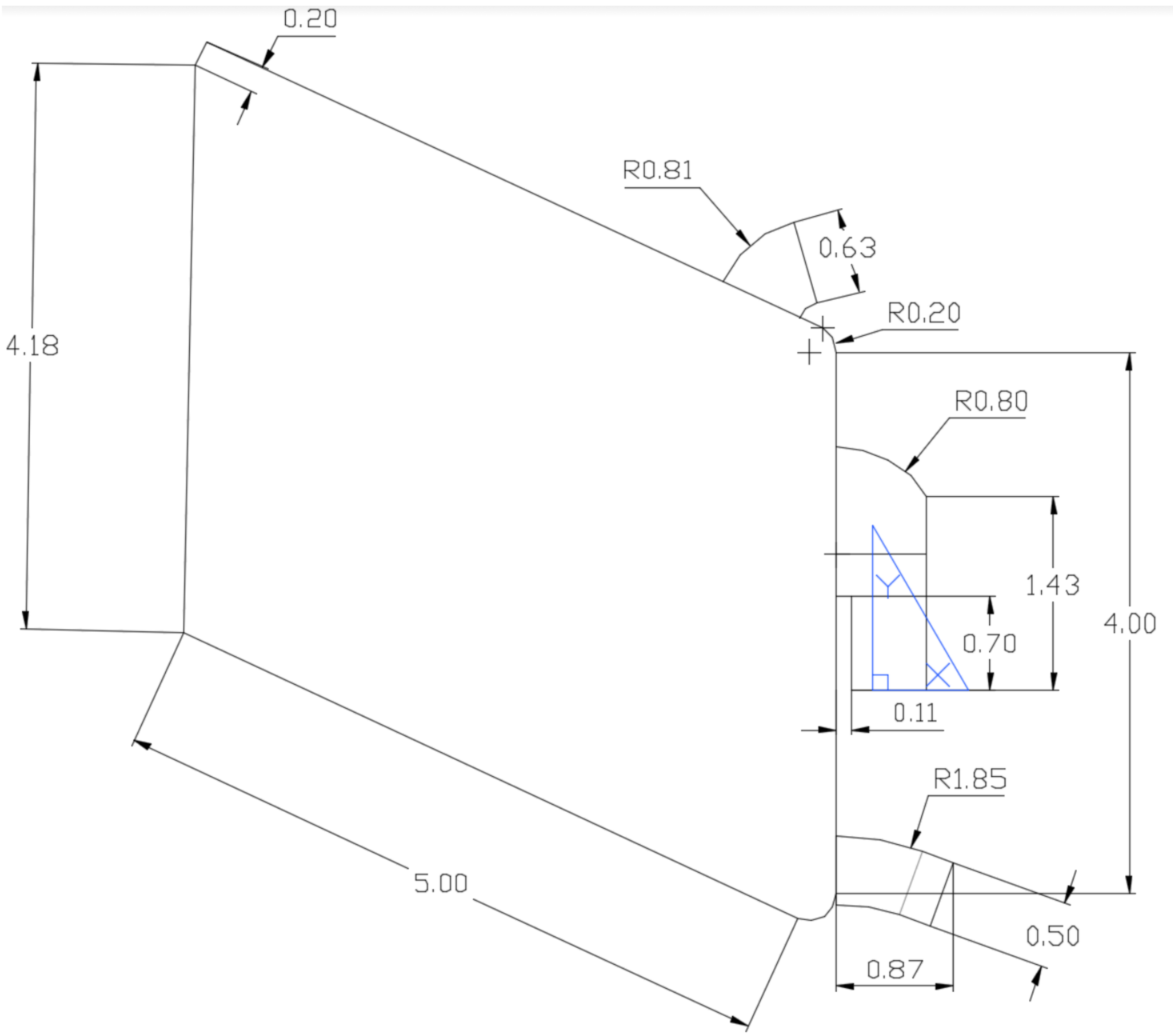
Drawing 1: Back view of growth cell



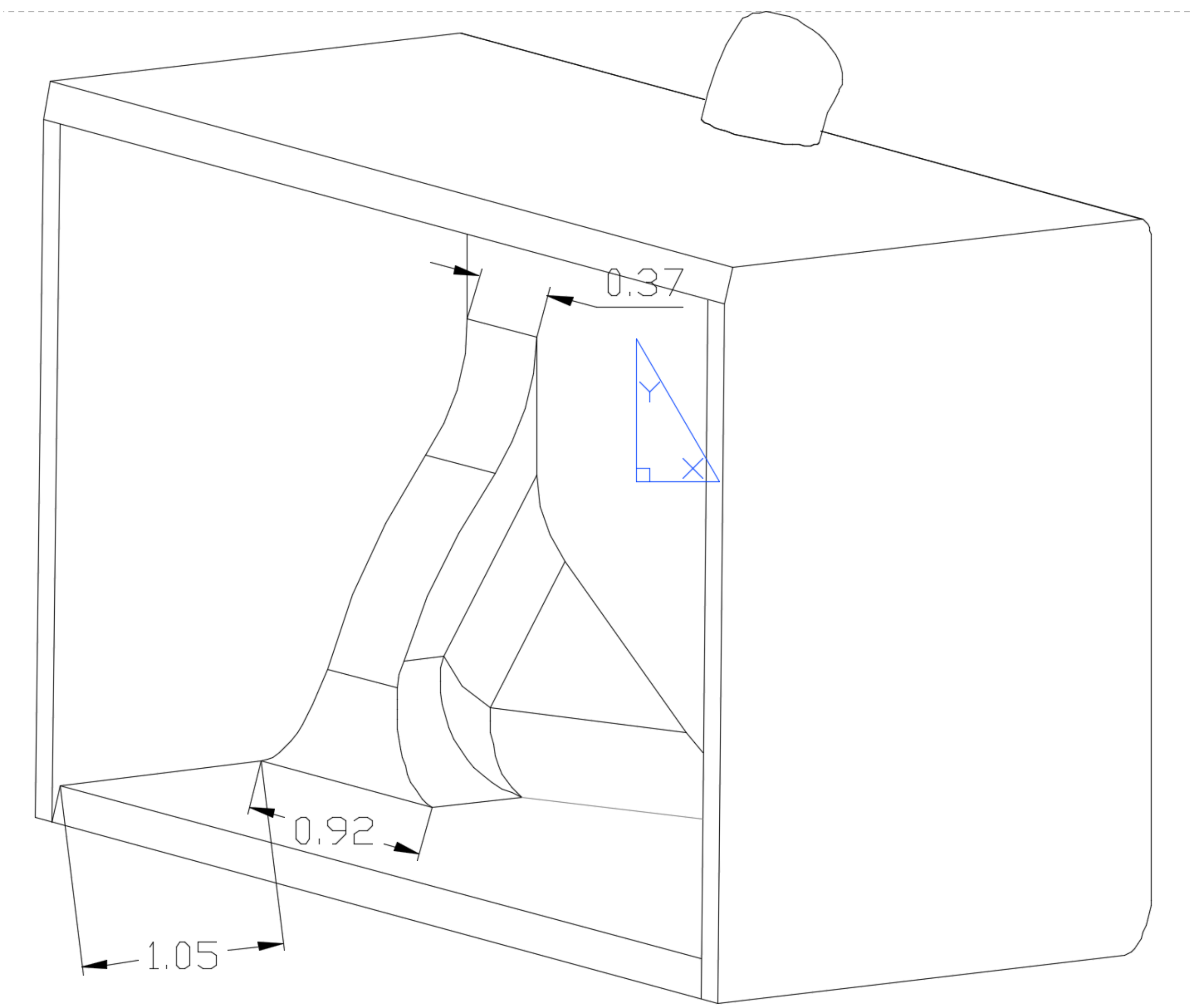
Drawing 2: Top view of growth cell



Drawing 3: Front view of the cell

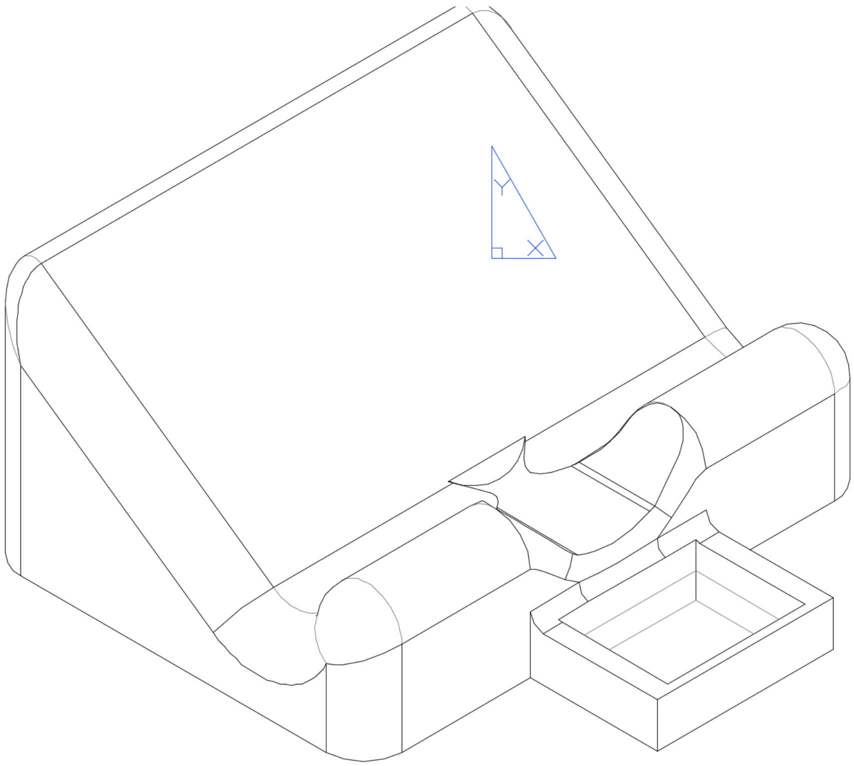


Drawing 4: Side view of the growth cell

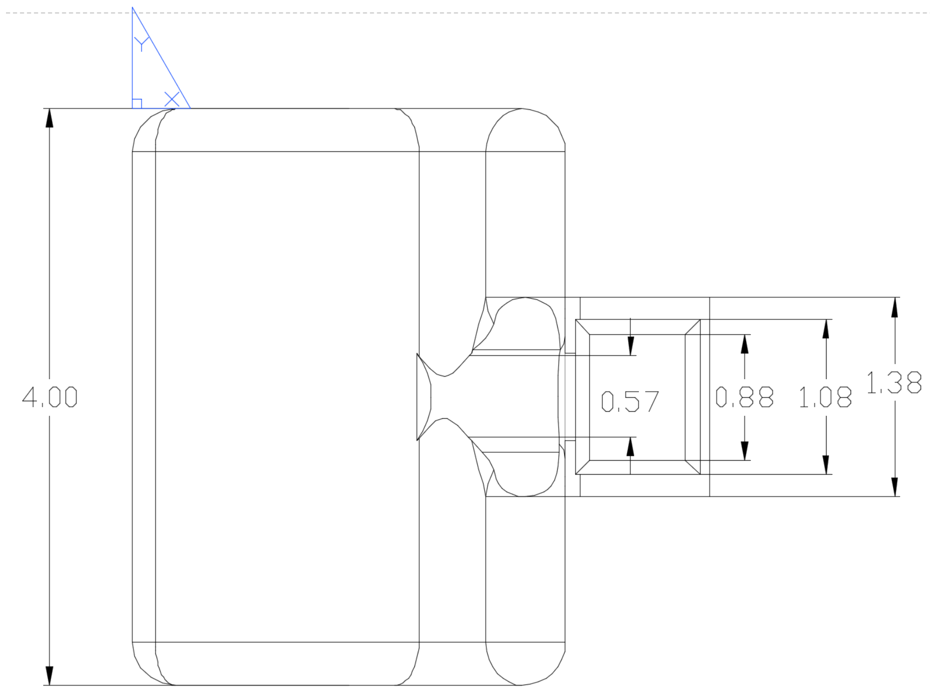


Drawing 5: Isometric view of the growth cell

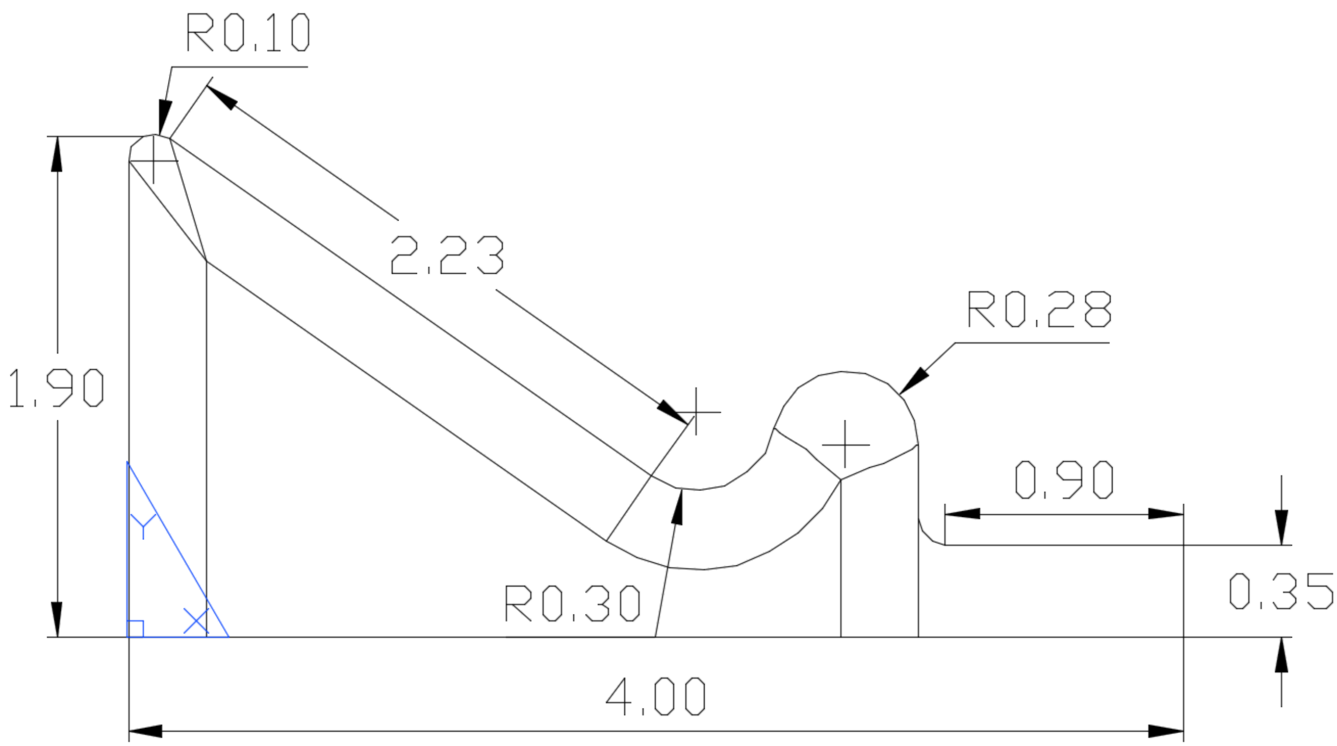
B) Technical drawings and details: Growth Cell Stand (all units in inches)



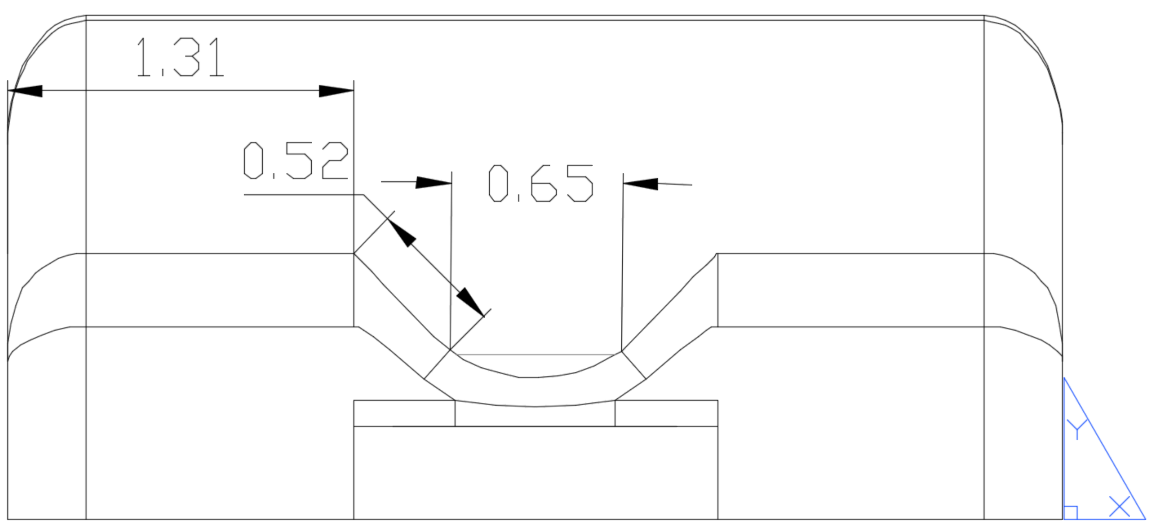
Drawing 6: Isometric view



Drawing 7: Top view

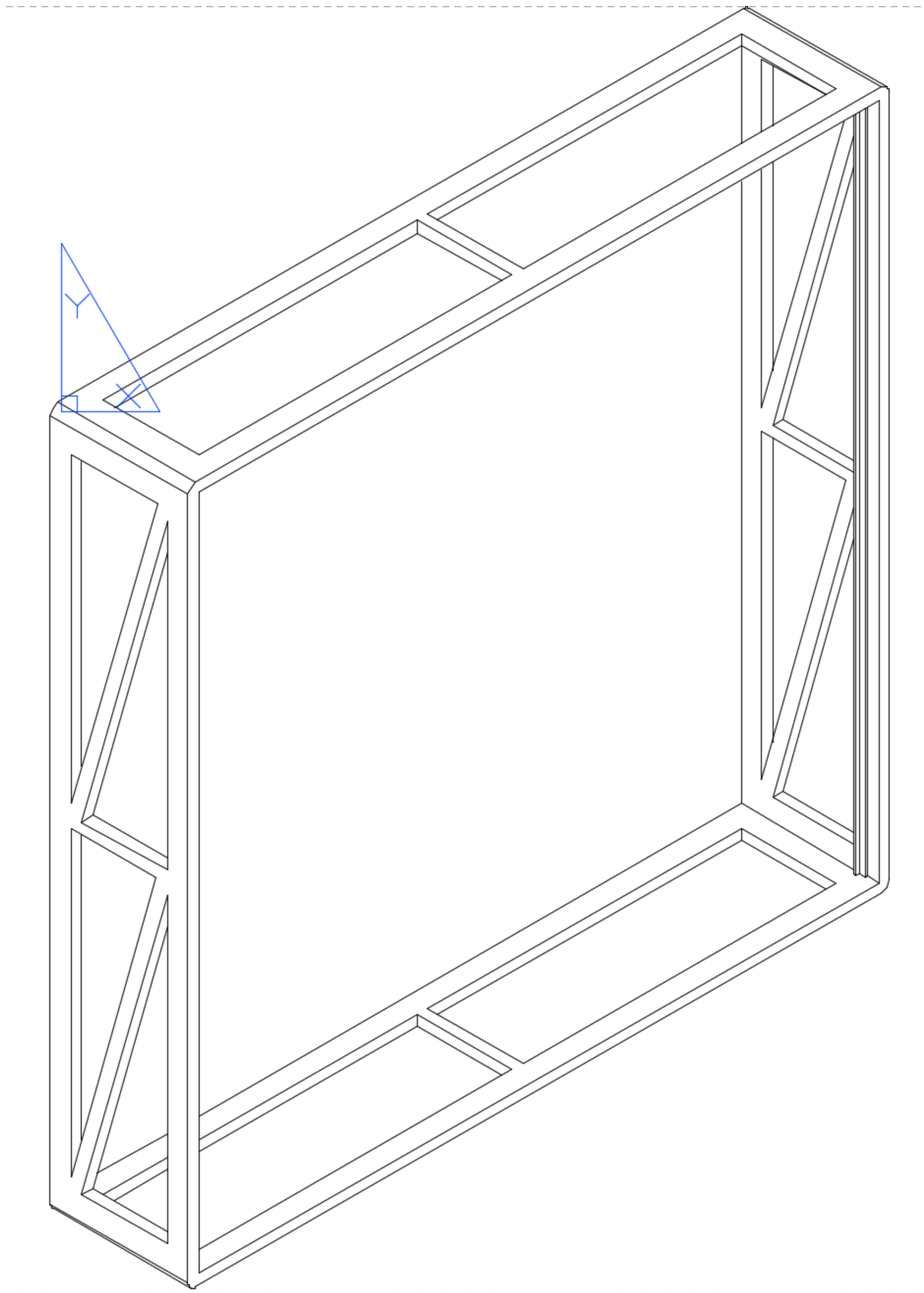


Drawing 8: Side View

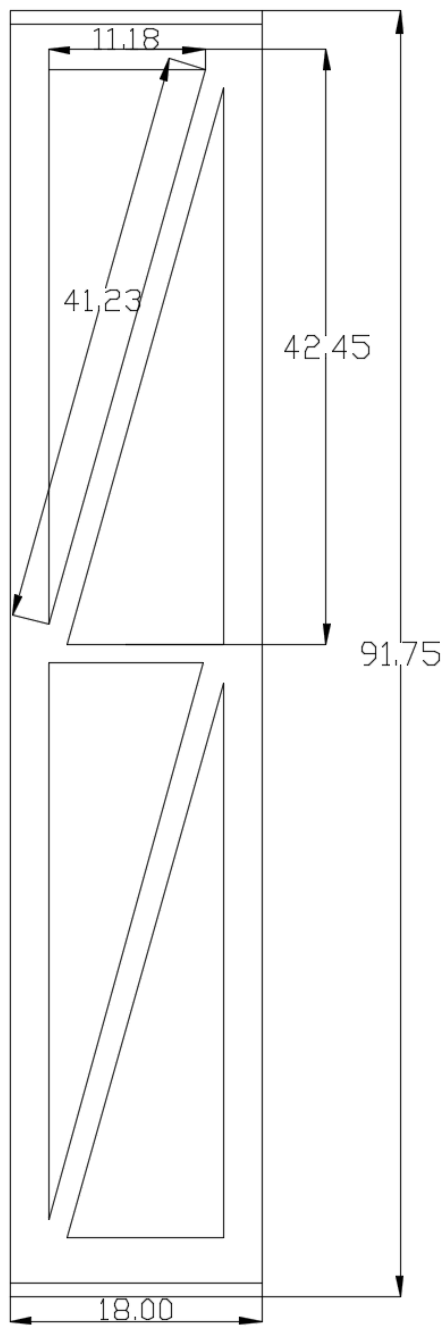


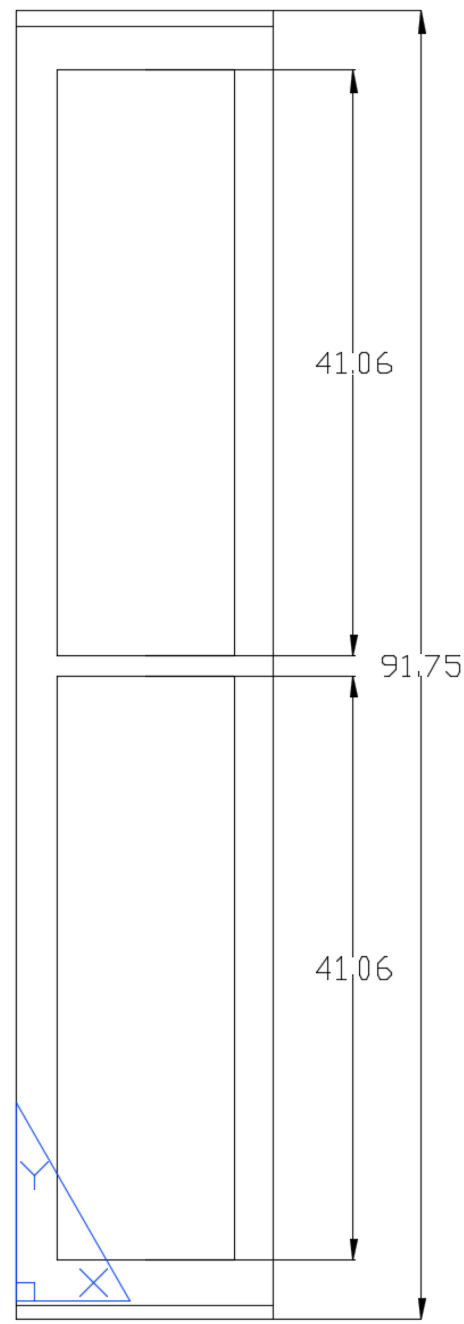
Drawing 9: Back view

C) Technical drawings and details: Wall / Frame Structure (all units in inches)



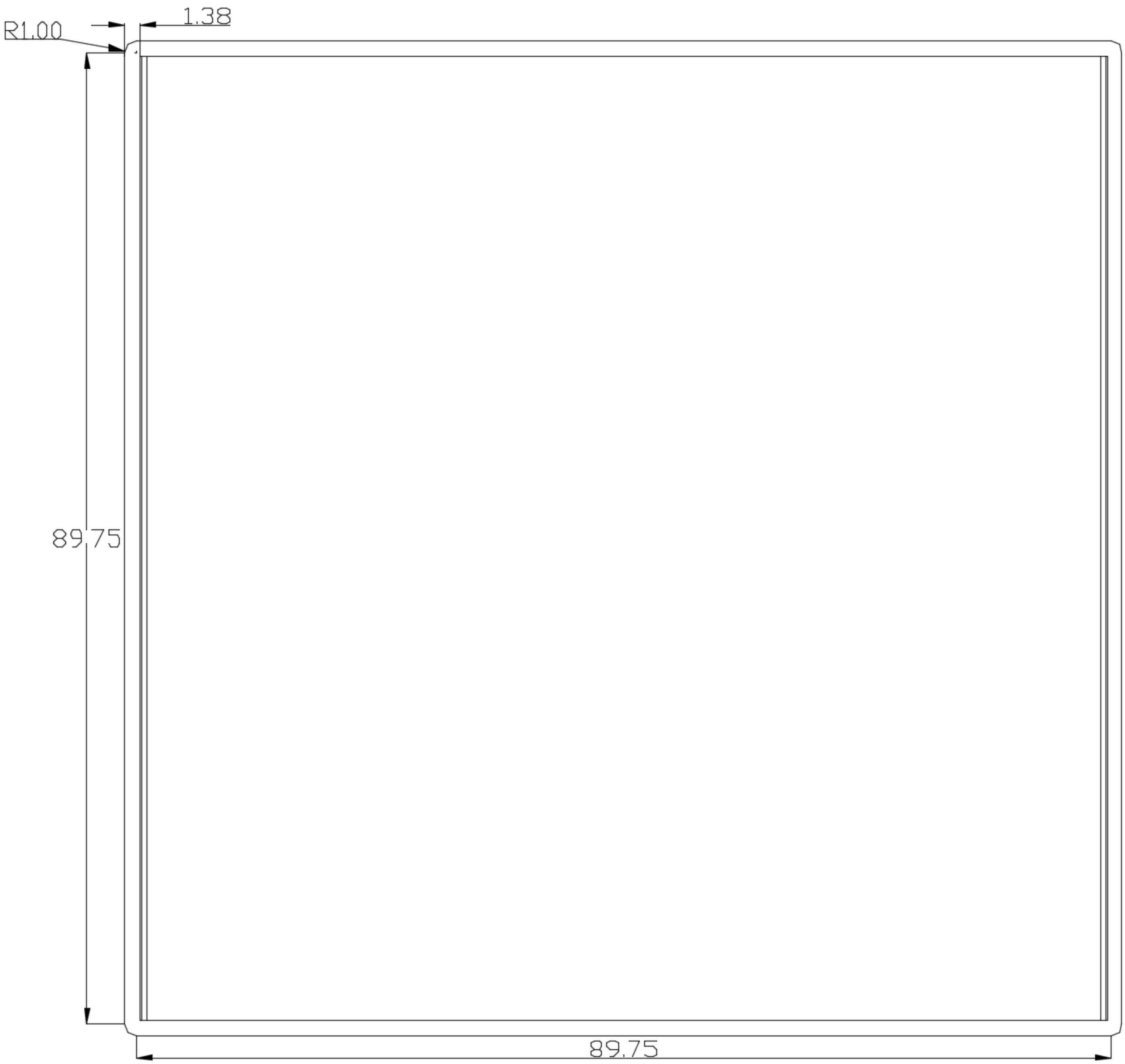
Drawing 10: Isometric view of frame structure without growth cell support structure.





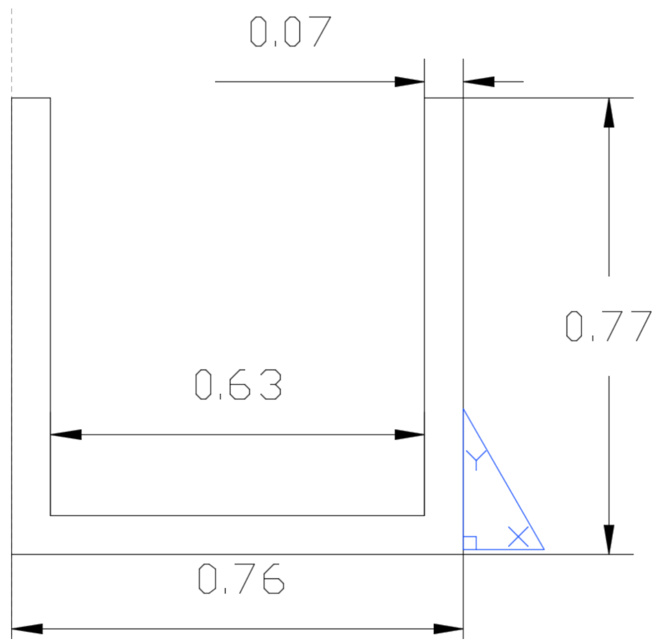
Drawing 11: Right & left structure structure

Drawing 12: Top & bottom

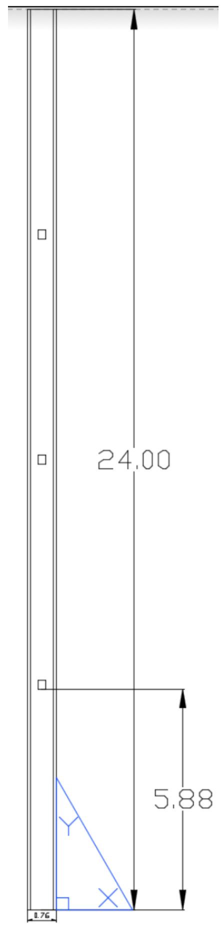


Drawing 13: Front & back view of frame structure

D) Technical drawings and details: U-Channel support bar for growth cells (all units in inches)

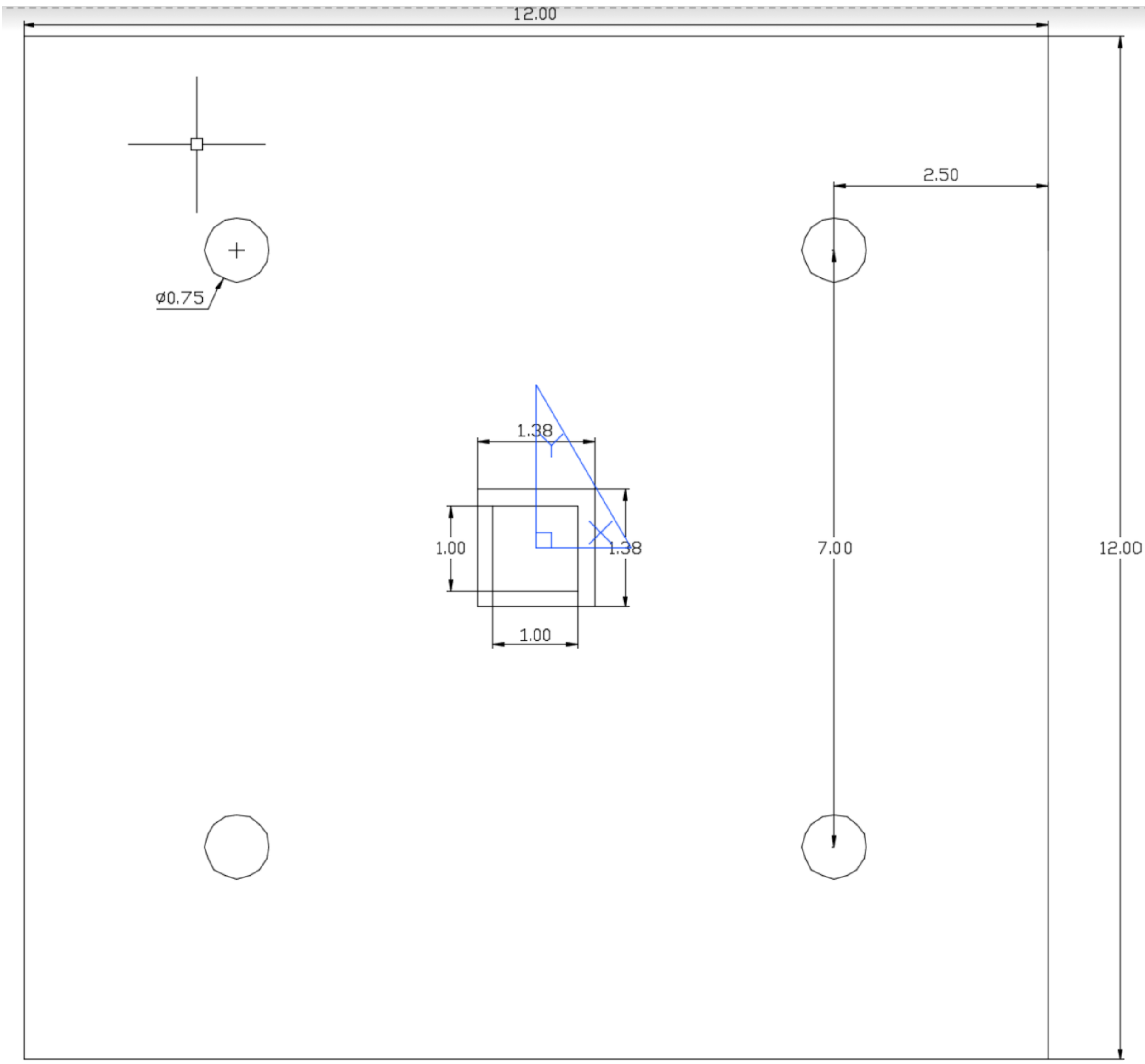


Drawing 14: Cross-sectional view

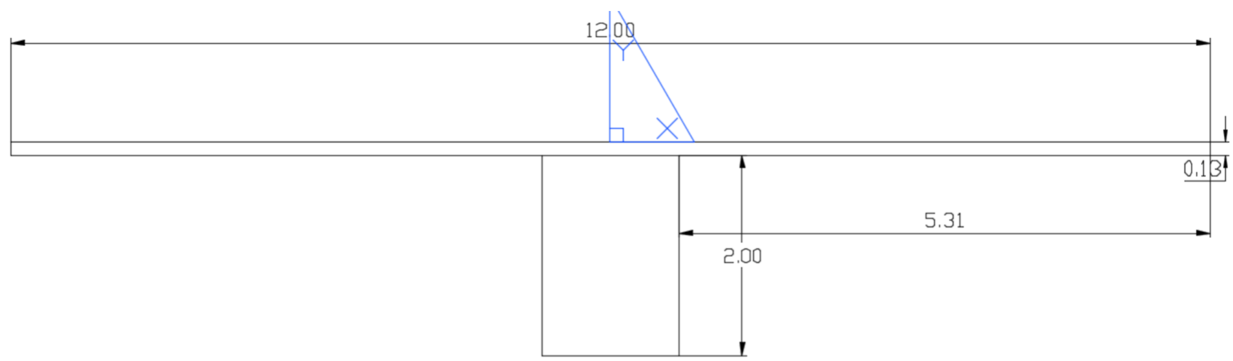


Drawing 15: Top View

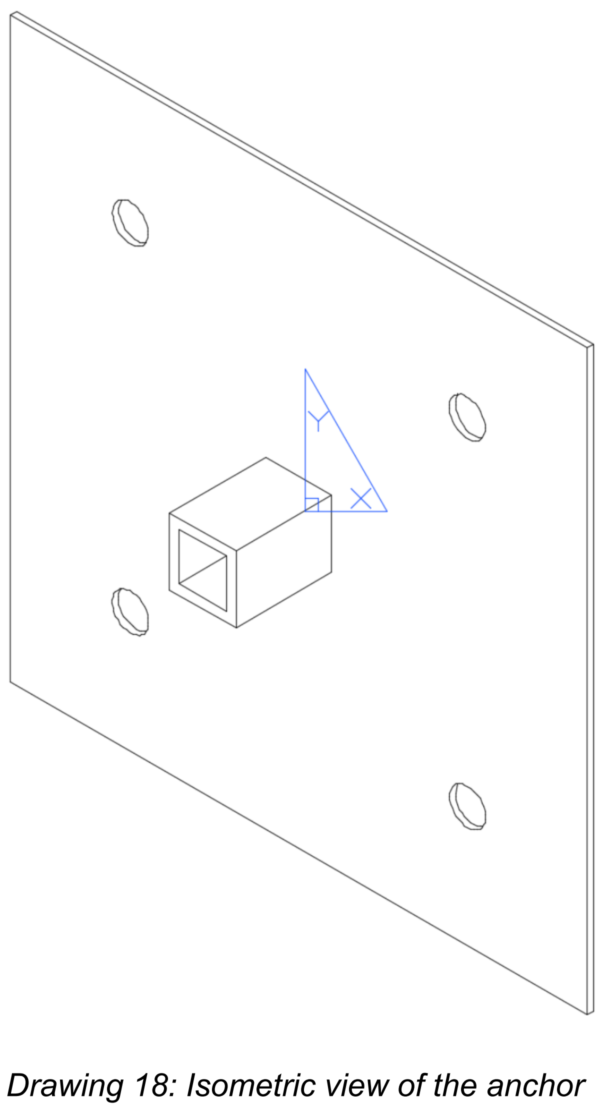
E) Technical drawings and details: Anchor Plates (all units in inches)



Drawing 16: Front view of the anchor



Drawing 17: Top view of the anchor



Drawing 18: Isometric view of the anchor

F) Details of Automation Code

```
#include <Wire.h>
#include <ds3231.h>


struct ts t;

int waterpump = 11;
int valve1 = 12;
int valve2 = 10;
int valve3 = 9;
int moistureThreshold = 30;
int delay1;
int switch1 = 2;
int switch2 = 3;
int switch3 = 4;
int oxygen;
int airpump = 5;
int LEDrelay = 8;

void setup() {
  Serial.begin(9600);
  Wire.begin();
  DS3231_init(DS3231_CONTROL_INTCN);
  //Clock is initiated on May 1st, 2021
  t.hour=0;
  t.min=0;
  t.sec=0;
  t.mday=1;
  t.mon=10;
  t.year=2021;
  DS3231_set(t);
  pinMode(11,OUTPUT);
  pinMode(12,OUTPUT);
  pinMode(switch1,INPUT);
  pinMode(switch2,INPUT);
  pinMode(switch3,INPUT);
  pinMode(valve1,OUTPUT);
  pinMode(valve2,OUTPUT);
  pinMode(valve3,OUTPUT);
  pinMode(LEDrelay,OUTPUT);
  pinMode(airpump,OUTPUT);
}
```

```
void loop() {

//Lighting Control Block (6am to 10pm Photoperiod)
  DS3231_get(&t);

  if t.hour = 6 {
    digitalWrite(LEDrelay,LOW);
  }
  if t.hour = 22 {
    digitalWrite(LEDrelay,HIGH);
  }

  //Moiture, Water Level and Oxygen Check Block
  int moisture1 = analogRead(A1);
  Serial.println(moisture1);

  int moisture2 = analogRead(A2);
  Serial.println(moisture2);

  int oxygen = analogRead(A3);
  Serial.println(moisture3);

  int waterLevel=analogRead(A0);
  Serial.println(waterLevel);


//Growth Cell Mounted Check Block
  int switchstate1 = digitalRead(switch1);
  int switchstate2 = digitalRead(switch2);
  int switchstate3 = digitalRead(switch3);

//Average Moisture Calculation
  int total_moisture = moisture1 + moisture2
  int moisture = total_moisture / 2;

//Modulating Irrigation Inlet to Node
  if switchstate1 = 0 {
    digitalWrite(valve1,HIGH);
  }
  if switchstate1 = 1 {
    digitalWrite(valve1,LOW);
  }


  if switchstate2 = 0 {
    digitalWrite(valve2,HIGH);
  }
  if switchstate2 = 1 {
    digitalWrite(valve2,LOW);
  }


  if switchstate3 = 0 {
    digitalWrite(valve3,HIGH);
  }
```

Arduino Code Inside IDE Environment

```
  //Irrigation Control Block
  while (moisture < moistureThreshold){
     if (waterLevel > 500){
      digitalWrite(waterpump,LOW);
      delay(10000);
      digitalWrite(waterpump,HIGH);
     if (waterLevel < 500){
      Serial.println("Resevoir Low");
     if (moisture1 = null, moisture2 = null, moisture3 = null) {
      digitalWrite(waterpump,LOW);
      delay(10000);
      digitalWrite(waterpump,HIGH);
      Serial.println("Sensor Error, Please Check");
     }
     else if {
      digitalWrite(pump,HIGH);
     }
     }
     }
     }

  //Air Pump Control (Activate if levels below 8mg/l)
  if oxygen < 8 {
    digitalWrite(airpump,LOW);
  }
  if oxygen > 8 {
    digitalWrite(airpump,HIGH);
  }
}

}
```

References

Arduino Uno REV3. (n.d.). Retrieved April 15, 2021, from https://store.arduino.cc/usa/arduino-uno-rev3

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Acknowledgements

Our team wants to sincerely thank Dr. Lefsrud and Dr. Madramootoo for their continued support, and guidance during the entirety of our design process.