Greenhouse Redesign for Elementary Educational Needs (G.R.E.E.N)

Greenhouse Redesign for Elementary Educational Needs (G.R.E.E.N)

An Interactive Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
degree of Bachelor of Science

Dan Barra
Katie Nugent
Daniel Ottey
Adam Peternell
Jonathan Toomey
Sean Traynor

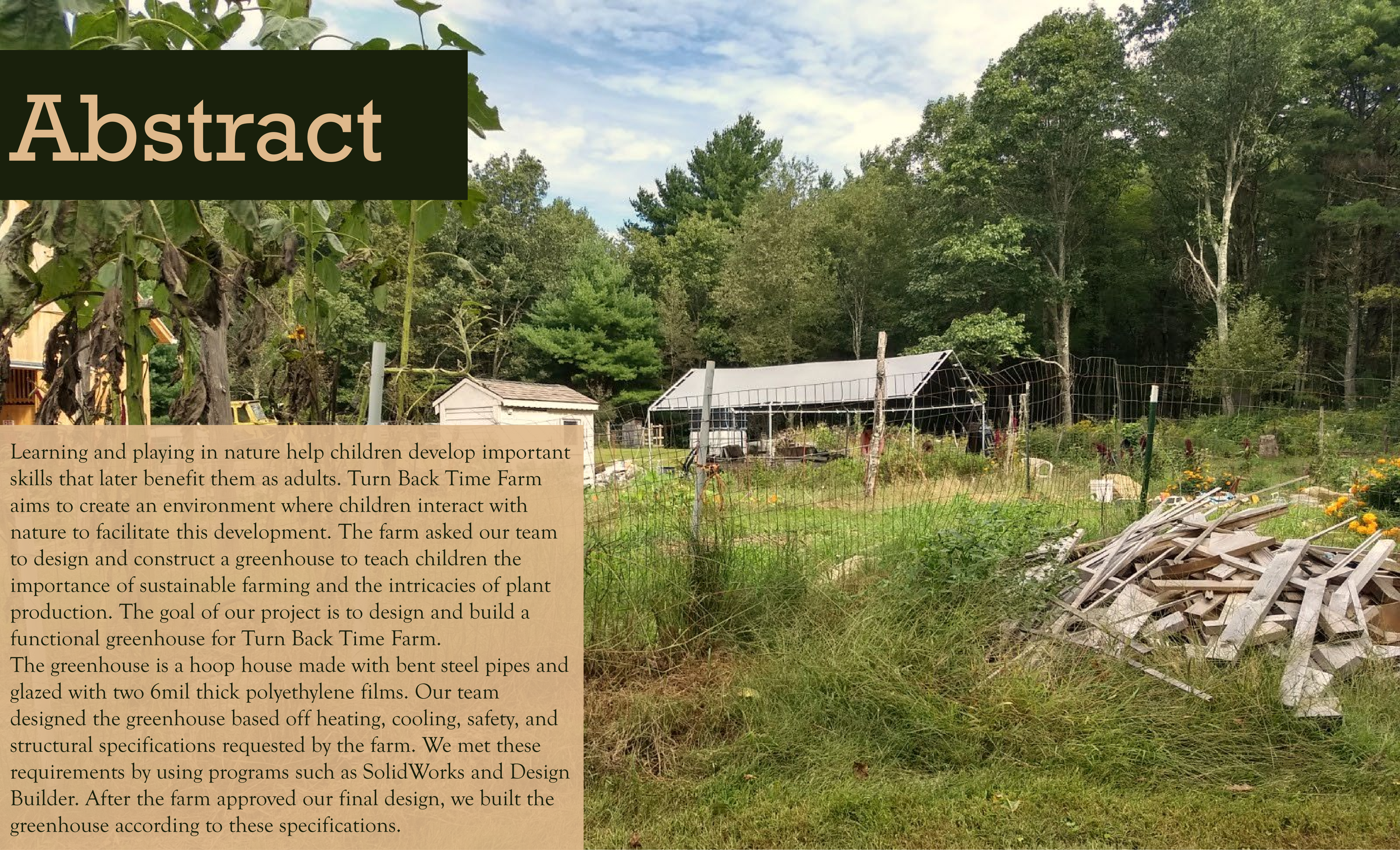
25 April, 2019

Project Advised by:
Professor Ahmet Can Sabuncu

Project Sponsored by:
Turn Back Time Farm

Abstract

Learning and playing in nature help children develop important skills that later benefit them as adults. Turn Back Time Farm aims to create an environment where children interact with nature to facilitate this development. The farm asked our team to design and construct a greenhouse to teach children the importance of sustainable farming and the intricacies of plant production. The goal of our project is to design and build a functional greenhouse for Turn Back Time Farm.
The greenhouse is a hoop house made with bent steel pipes and glazed with two 6mil thick polyethylene films. Our team designed the greenhouse based off heating, cooling, safety, and structural specifications requested by the farm. We met these requirements by using programs such as SolidWorks and Design Builder. After the farm approved our final design, we built the greenhouse according to these specifications.



A Little Help From Our Friends

We would like to thank Professor Ahmet Can Sabuncu for advising us and this project. We would also like to thank Lisa Burris and the Turn Back Time Farm team for their assistance, patience, and utmost generosity. We would like to thank Professor Lisa Stoddard, Professor Tahar El-Korchi, and Professor Nima Rahbar for their assistance in our design. We would like to thank Professor Leslie Dodson for her assistance and guidance in our visual report. We would like to thank Home Depot of Worcester, American Earth Anchors, and Agricultural Solutions for their generous donations to our project.

Lisa Burris (Far Left) and the Turn Back Time Farm Family

Jim, Lisa, and Lola

EXIT

Meet the Team!

My name is Adam. I took charge of the metal design and building phase. I also ensured we stayed on budget, while searching for donations and discounts on supplies.

My name is Katie and I was apart of the metal design team. I was also the safety manager, ensuring all jobs done onsite were up to safety regulation.

Ayo, my name is Dan, and I was the construction logistics guy! I laugh at large cows then cry, eat moron seeds, am a half decent cook, and a certified farm fresh idiot.

Meet the Team!

Daniel Ottey(ME), primarily worked on the wooden greenhouse design and the heating and cooling of both the metal and wooden greenhouse.

Hi, I'm Sean. I modeled and helped design the wooden greenhouse, and helped construct the final greenhouse. I enjoy reading, video games and hiking.

Jonathan Toomey (ME) helped design the wooden greenhouse, manage scheduling, and construct the final greenhouse. He enjoys reading, cooking, and hiking

Our Story

Introduction

The Birth of Turn Back Time Farm

Turn Back Time Farm is Lisa Burris's vision becoming a reality. In 2010 their family was raising two children with special needs. Lisa was also working at a medical device company, and soon resolved she could not raise both children and work a demanding job. After much reading and research, Lisa determined that not only would her children benefit from more time with her, but they needed exposure to nature. Both children are considered at-risk, Damion due to his autism, and her other daughter was struggling to regulate her emotions due to an early emotional tragedy. Lisa convinced her husband Jim that a change needed to be made, so they sold their house in search of their outdoor white whale. After 2 months Lisa and her family found themselves on the 58 acre homestead, which would soon become the home for Turn Back Time Farm (Burris, 2011).

Lisa and Jim are no strangers to helping others. They have expanded their family through an adoption/foster care program in 2002 and have had custody of their granddaughter Izabella since 2015 due to a personal tragedy (Burris, 2011). When the land for the farm was purchased, Lisa wanted to share the nature experience Damion and his sister as well as the rest of the world. Thus, Lisa created a non-profit program dedicated to helping children experience the outdoors in a way she used to be able to as a child, and Turn Back Time Farm was born. Today, Turn Back Time Farm continues to help all children with a mission of having 30% of their attendance come from at risk youth. They currently have approximately 500 children per year attend a variety of programs with a goal to reach even more (Burris, 2019).

The goal of the farm is simple…

"The goals of the farm is to provide education to children by using the farm as a medium"

"Provide better problem solving skills, interest in science related topics, and health benefits"

"We want children to run and play, fall down and get dirty, and splash in rain puddles"

"We want to help give every child the opportunity to have the childhood we had"

"We want to raise interest in farming"

"We help at risk children for job training, summer camps, and farm programs for families"

Get children outside

All quotes are taken from interactions or interviews with Lisa Burris (Burris, 2019)

The Need for Nature

In his most popular novel, *Last Child in the Woods*, Richard Louv describes the phenomenon that affects today's generation of children, "nature deficit disorder". This is not a medical or clinical term, but nevertheless, it describes the situation perfectly. Children today do not have access to unregimented outdoor play. Louv states that the problem is not with the children, but how we raise them. He does not put himself on a pedestal when he describes how today's parents are failing their children, as he sees these faults in his own style, and in his own children.

> "I believe that, as a parent, it's my job to protect my sons from the brutality of the world for as long as I can" ~Louv

Children are raised in fear. Fear of strangers, fear of the outdoors, fear of wild animals. Parents today have more oversight of their children's lives. Between practices, homework, and "forced" hobbies, children do not have time to themselves. During whatever free time is leftover, parents find their children are bored. Louv states this is because children have never had to make their own fun.

He also references studies about the healing properties nature has on children with mental disorders. A 20 minute walk in nature helped improve reading skills and positive emotions when compared to an urban walk or listening to music for the same duration. Children in nature based daycares have better motor skills and have an easier time concentrating (Louv, 2008).

The Green Need

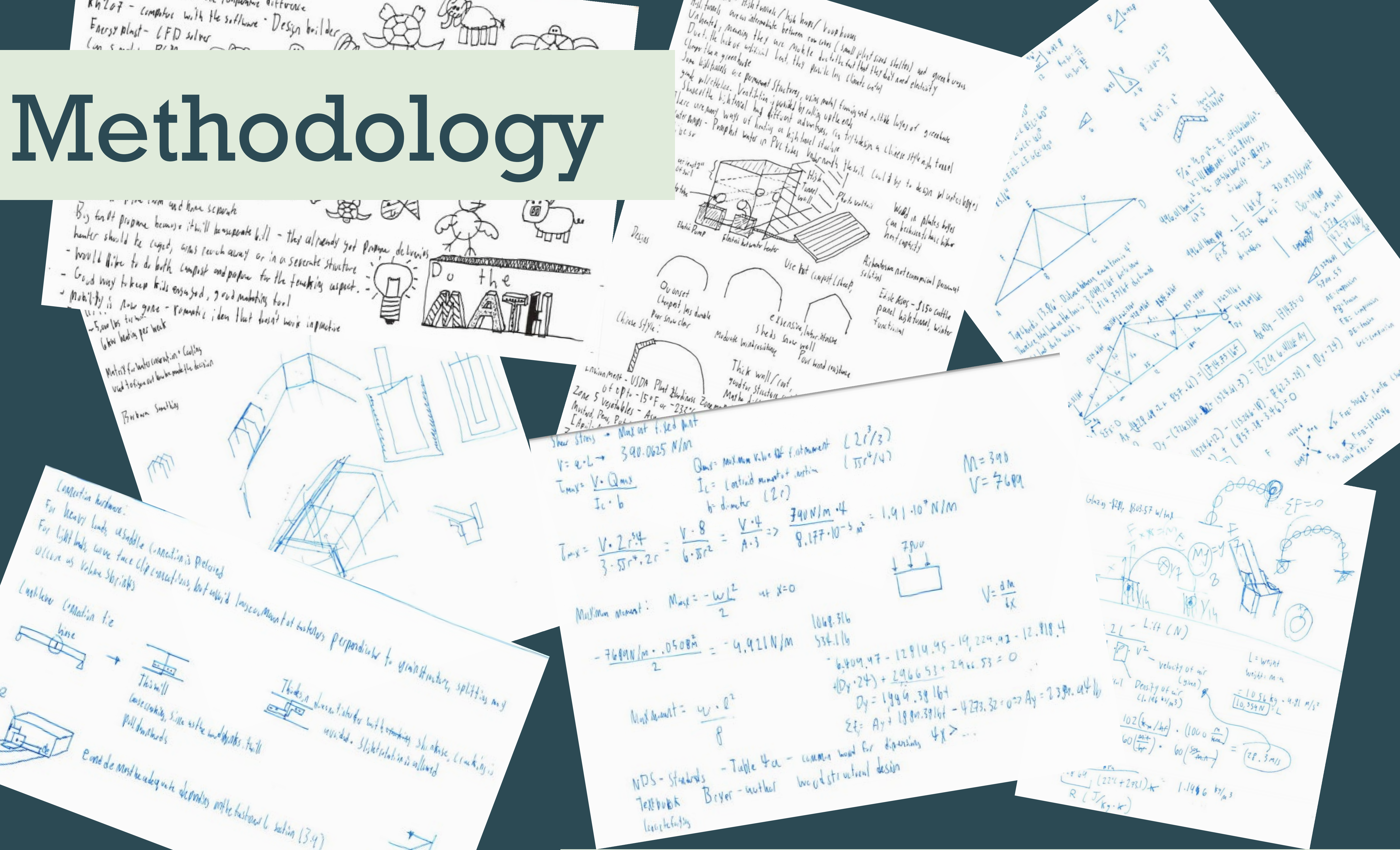
One of the programs at Turn Back Time is “Time in the Garden”. This program is a “cooperative age appropriate effort in raising vegetables and fruits”. This program coincides with “Cook What You Grow”, which is used to help children make the connection between what they eat and their physical and emotional health. Both programs are vital to a child’s developmental success. However, they are difficult to run during the winter months. A greenhouse would lengthen the growing and learning season at Turn Back Time (Burris, 2011).

Our goal is to design and build a greenhouse to serve as a teaching tool for children enrolled in Turn Back Time Farm’s programs. The greenhouse is designed to increase the interaction children have with the growing process, including planting, watering, and harvesting of food.

Design Constraints

The greenhouse should increase the interaction children will have with nature and each other. The children will work with their hands, so there will be no automation regarding watering or harvesting. The greenhouse should be able to fit 15 children inside, with 35 ft^2 per kid, meaning the total surface area should be at least 525 ft^2 (Burris, 2019). The greenhouse will be used to grow “kitchen garden vegetables”, such as tomatoes, zucchini, peppers, and squash. These foods are suitable for Paxton, MA, labeled as zone 5 and 6 where the average minimum temperatures reach -15 °F (-26 °C) (USDA, n.d.). The greenhouse should be able to provide temperatures above the freezing point of 32 °F (0 °C) during early spring and late autumn. We designed the greenhouse so artificial heat could later be added, for example a compost system. The structure is also safe in all seasons. In Paxton, Massachusetts, structures must be able to withstand snow loads of 55 psf and three second sustained 111 mph winds (ICC, 2015).

Methodology



KN207 - computer with the software - Design builder

Energy plust - CFD solver

Buy for it propane because it'll be a separate bill - they already got propane deliveries

heater should be caged, gas reach away or in a seperate structure

- would like to do both compost and propane for the teaching aspect.
- Good way to keep kids engaged, good marketing tool
- Mobility is now gone - romantic idea that doesn't work in practice

~5,000 lbs for ...

Grow heating per week

Matrix for water conservation + cooling

used to figure out how he made the decision

Do the MATH

High tunnels / high hoops / hoop houses

High tunnels are an intermediate between row covers (small plant sized shelters) and greenhouses

Unheated, meaning they are mobile due to the fact that they don't need electricity

Due to the lack of artificial heat, they provide less climate control

Cheaper than a greenhouse

Some high tunnels are permanent structures, using metal framing and multiple layers of greenhouse grade polyethelene. Ventilation is provided by rolling up the ends

Shape of the high tunnel has different advantages, can try to design a Chinese style high tunnel

There are many ways of heating a high tunnel structure

Water pumps - Pump hot water in PVC tubes underneath the soil. Could try to design pl... boxes

at least 2" of soil

High tunnel wall

Photovoltaic

Electric Pump

Electric hot water heater

Water in plates boxes can be used to have higher heat capacity

Air heaters are not economical permanent solutions

Use hot compost (sheep)

Edible Acres - $150 cattle panel high tunnel, winter functional

Designs

Quonset

Cheapest, less durable

Poor snow clear

Moderate wind resistance

Sheds snow well

expensive, labor intensive

Poor wind resistance

Chinese Style:

Thick wall / roof, good for structure ...

Environment - USDA Plant Hardiness Zone ... of up to -15°F or -23.3°C

Zone 5 vegetables - ...

Mustard, Peas, Pot...

Connection hardware:

For heavy loads, a saddle connection is preferred

For light loads, use face clip connections, but avoid ... perpendicular to grain structure, splitting may occur as volume shrinks

Cantilever Connection tie

This will ...

This design ... avoided. Slight rotation is allowed

... depending on the fastener ... section (3.4)

Shear stress = Max at fixed point

$V = q \cdot L \rightarrow$ 390.0625 N/m

$\tau_{max} = \frac{V \cdot Q_{max}}{I_c \cdot b}$

Q_{max} = maximum value of first moment $(2r^3/3)$

I_c = centroid moment of inertia $(\pi r^4/4)$

b = diameter (2r)

$\tau_{max} = \frac{V \cdot 2r^3 \cdot 4}{3 \cdot \pi r^4 \cdot 2r} = \frac{V \cdot 8}{6 \cdot \pi r^2} = \frac{V \cdot 4}{A \cdot 3} \Rightarrow \frac{390 N/m \cdot 4}{8.177 \cdot 10^{-5} m^2} = 1.91 \cdot 10^7 N/m$

M = 390

V = 7609

Maximum moment: $M_{max} = \frac{-wL^2}{2}$ at x = 0

$V = \frac{dM}{dx}$

$-\frac{7609 N/m \cdot .0508 m^2}{2} = -4.921 N/m$

Max moment $= \frac{w \cdot \ell^2}{8}$

NDS - Standards - Table 4a - common wood for dimensions

Textbook Breyer - author wood structural design

Top Chords 13.86'. Distance between each truss is 4'

Therefore, total load on the truss is 3,049.2 lbf due to snow

1,714.75 lbf due to wind

$\Sigma F_x = 0$

AE = compression

AB = tension

FB = compression

DE = tension

GC = compression

Glazing - $281, $303.57 w/ tax

$\Sigma F = 0$

L - Lift (N)

Velocity of air (given)

Density of air (1.146 kg/m³)

L = weight

Weight = m·g

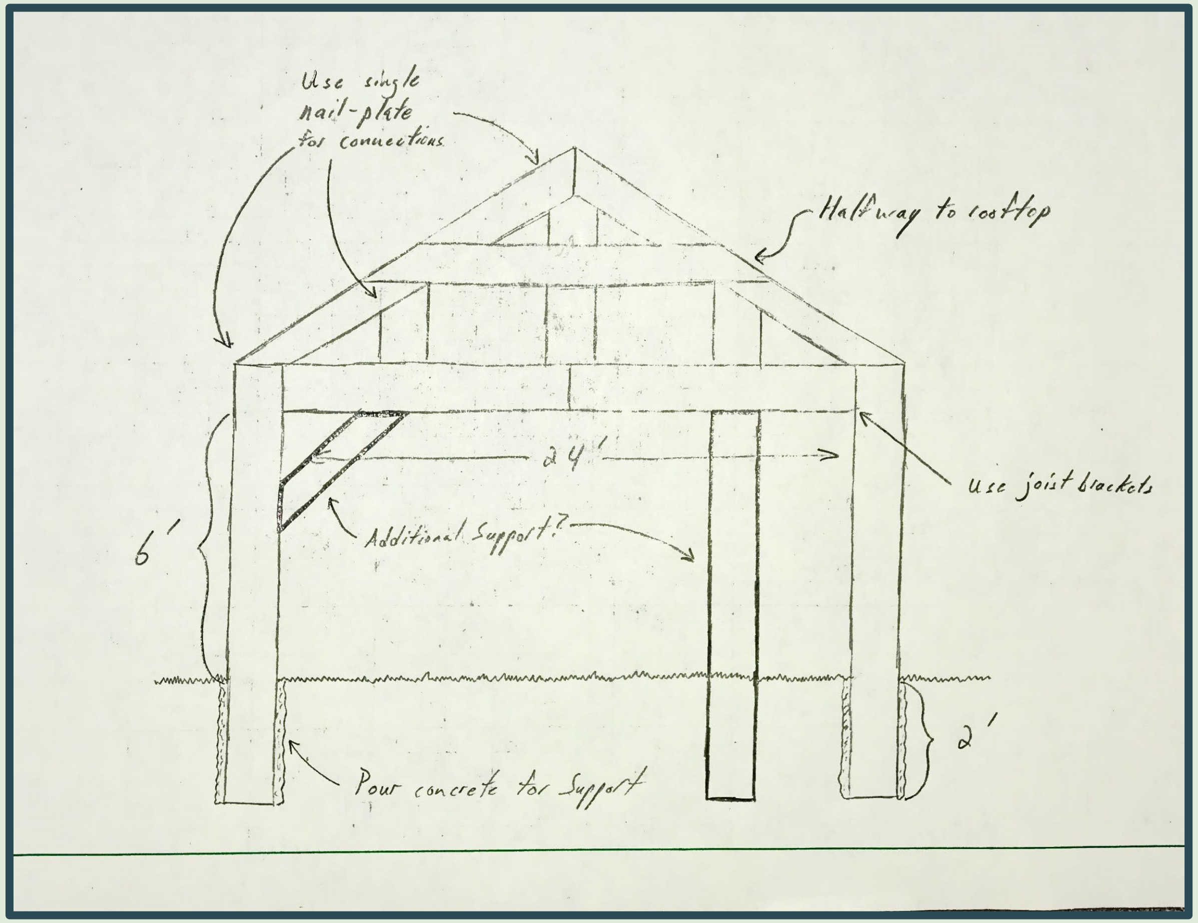
1056 kg · 9.81 m/s²

$\boxed{10,354 N} = L$

$\frac{102 (km/hr) \cdot (1000 \frac{m}{km})}{60 (\frac{min}{hr}) \cdot 60 (\frac{sec}{min})} = \boxed{28.3 m/s}$

1.1466 kg/m³

Our Design Journey Begins



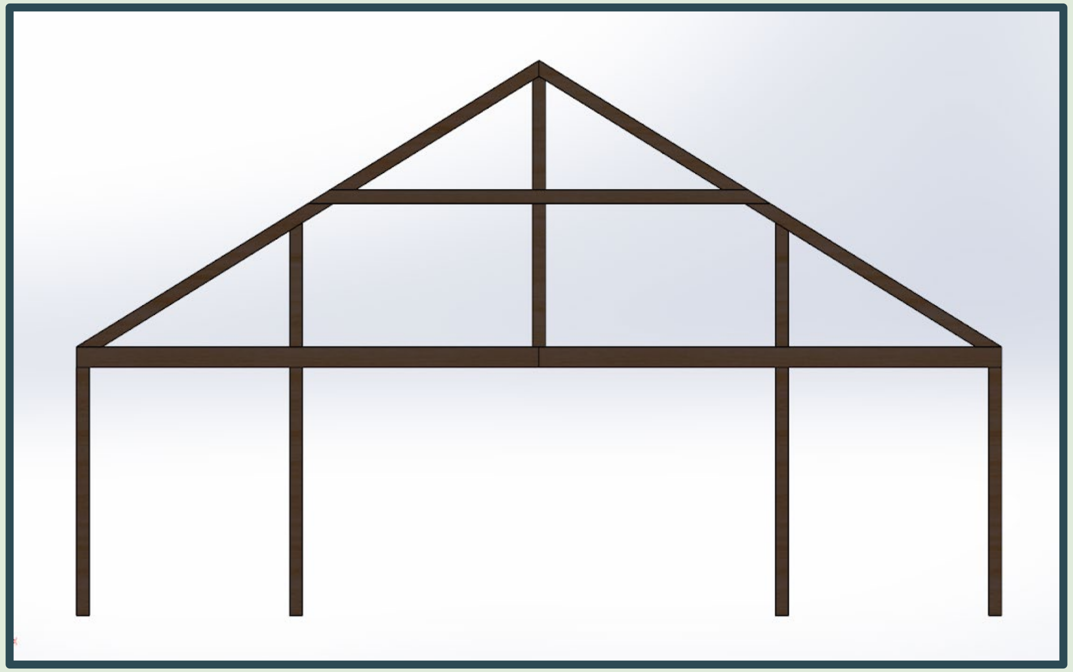
First Greenhouse Sketch

After preliminary research and group discussion, we sketched our first greenhouse design. We envisioned our structure to be made out of four wooden A-frames that would span 24 feet. Each frame would be six feet apart to meet the area design constraint.

Protect the Plants!

There are three plastic options to use to cover a greenhouse: polycarbonate panels, polyethylene film, and polycarbonate walls. Our team decided to use polyethylene film because it was the only option that fit our budget constraints. Although the film has the lowest insulation value, using a film does have benefits. It is the simplest option to install, and is adaptable to any size or shape. To make up for the lack of heat retention in a single 6mil film, we used a double layer with no gap. In the future, Turn Back Time Farm can install a small air blower to create a gap between the two layers (Rasheed, 2018).

For Nature, by Nature

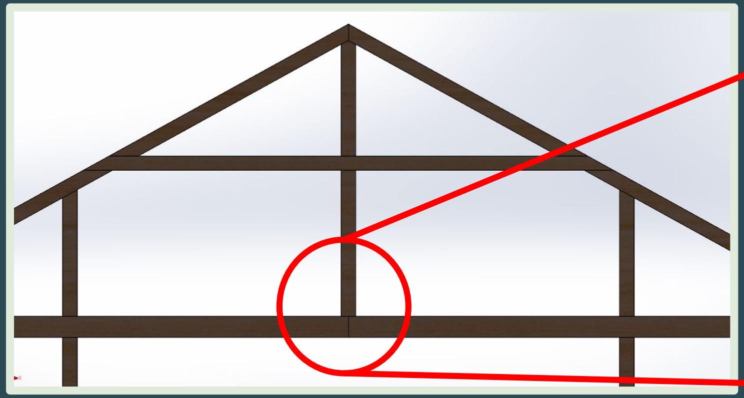


Early Greenhouse Frame Design With Vertical Supports Shown

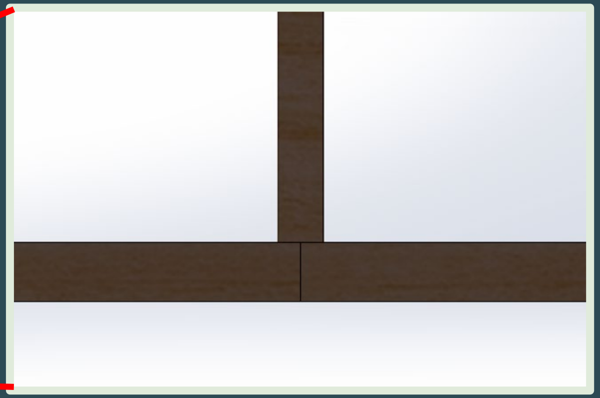
The initial design for the greenhouse was inspired by the farm’s existing barn and pavilion. The original design featured pressure treated lumber with polyethylene glazing stretched over it. We designed the front and back walls out of studs and plywood to mimic the barn’s forward façade and to better handle shear forces from the wind. Both walls would have a door and vent (See Appendices C and D). The roof was comprised of four, triangular trusses, spanning the 24’ gap. Eight 4”x4” vertical columns would support the roof trusses, with two columns working in tandem to carry a single truss. The columns would be 8’ long, with 2’ sunk into the ground and 6’ above ground. A series of perpendicular joists sat on top of the array of columns to provide a connection point for each truss. We chose to use fewer columns and trusses to provide adequate sunlight penetration into the greenhouse. The original idea to construct this design was to assemble individual frames and then raise them barn-style into place.

Evolved Wood Design

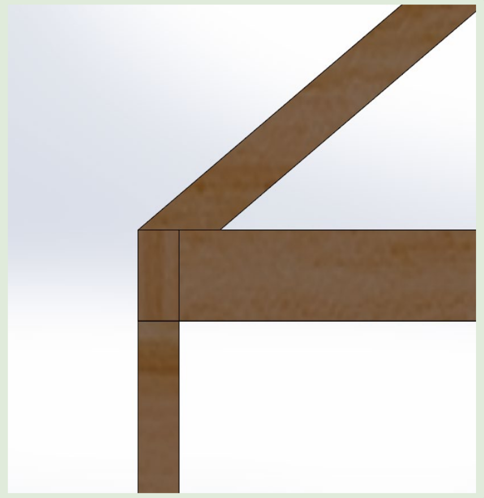
We faced when designing the wooden greenhouse. The original truss's rectangular webbing is inefficient at distributing loads to the bottom chord. The bottom chord is comprised of two, 12' beams with no vertical support from below at the meeting point. This creates a major stress point in the truss design. The original design featured roof angles which ended on the vertical posts. This was then changed to an overhang design to better distribute the applied load.



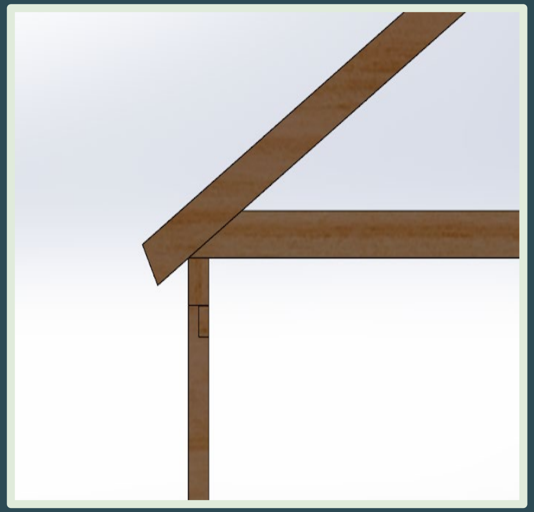
Early Truss Design With Rectangular Webbing



Split Bottom Chord With No Vertical Support

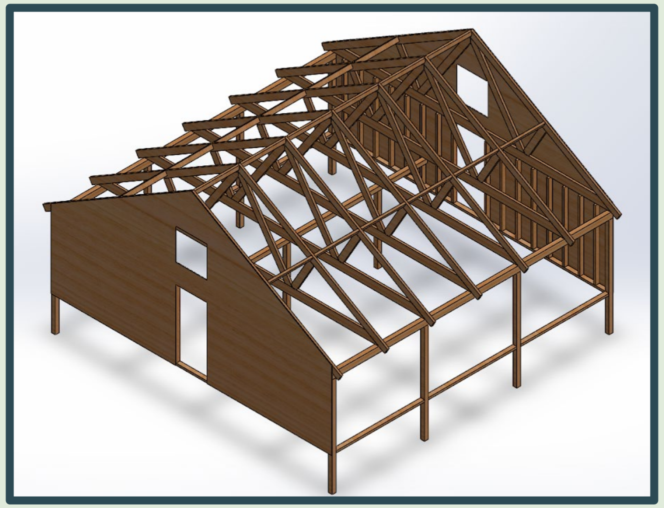


Original Roof Connection

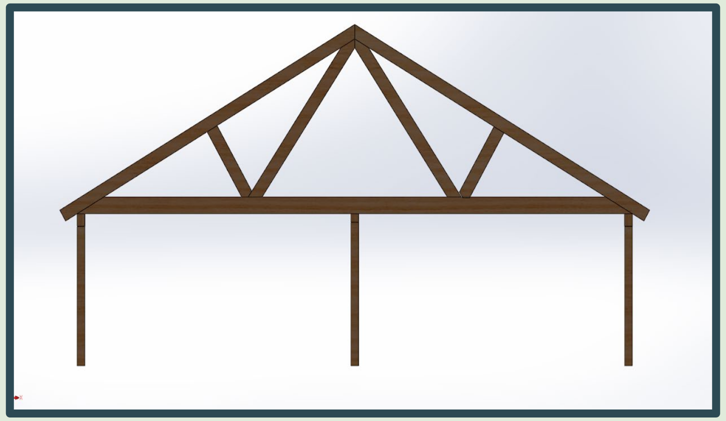


Modified Truss Overhand to Provide Robust Fixturing

Finalized Wood Design



Final Wooden Greenhouse Design With Trusses and Columns for Improved Weight Distribution



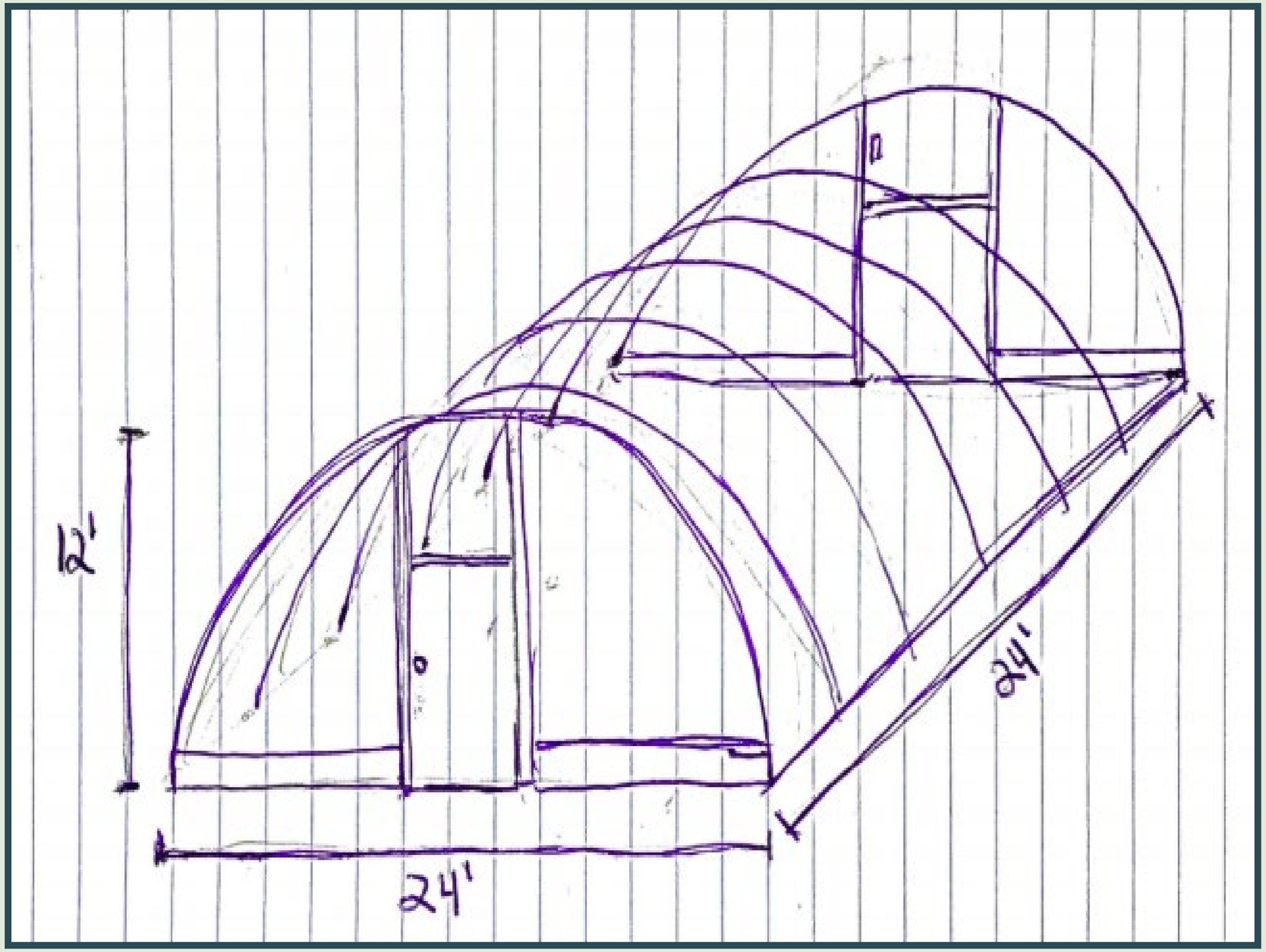
Final Truss Design With Central Column for Improved Resistance to Bending Stresses

The roof was the primary focus for changing the wood design. The finalized design for the wooden greenhouse utilized seven trusses supported by a total of ten vertical columns. The original eight columns would remain, but an additional two columns were added in the center to help support the trusses from moment stresses (See Appendices B, E, F, and G). The eight original columns were supported by concrete footings with cast in place metal anchors. This allows moisture to drain from the columns. Furthermore, two, 4”x6”x24’ beams rest upon the outer eight columns, linking four of them in a row and serving as the rest for the roof trusses. Each truss utilizes the Fink Truss design and has support at the ends and center (See Appendices E and F). While the front and back trusses would have the shear walls to support the load, the middle five trusses are linked in the center by a horizontal beam beneath the midpoint of each bottom chord. Two columns support this internal beam. One vertical column is halfway between the second and third trusses while the other is placed between the fifth and sixth trusses.

Choices, Choices, Choices

During the design phase of the wooden greenhouse, the farm expressed concern about the longevity of the wood in the humid environment. We felt this issue could be solved with more research, but did not want to go too far down a possible dead end without any other options. We decided to split the team into two groups, one researching solutions for the wood and the other making a new design out of metal.

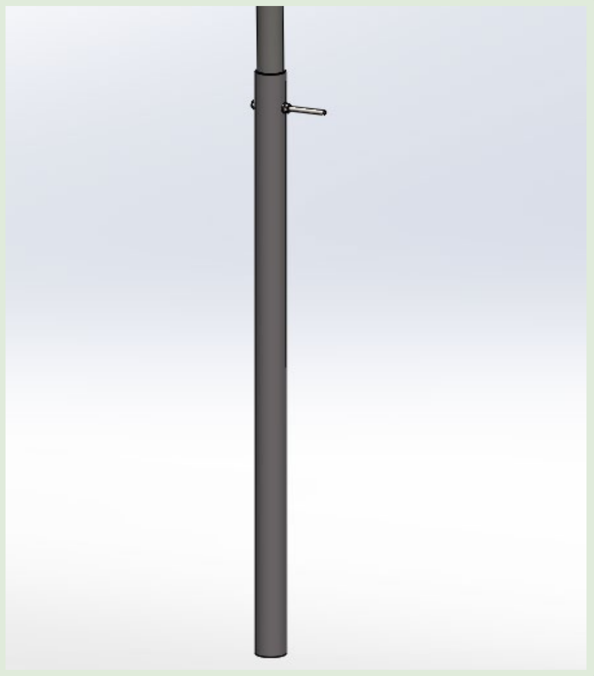
Harder than Stone



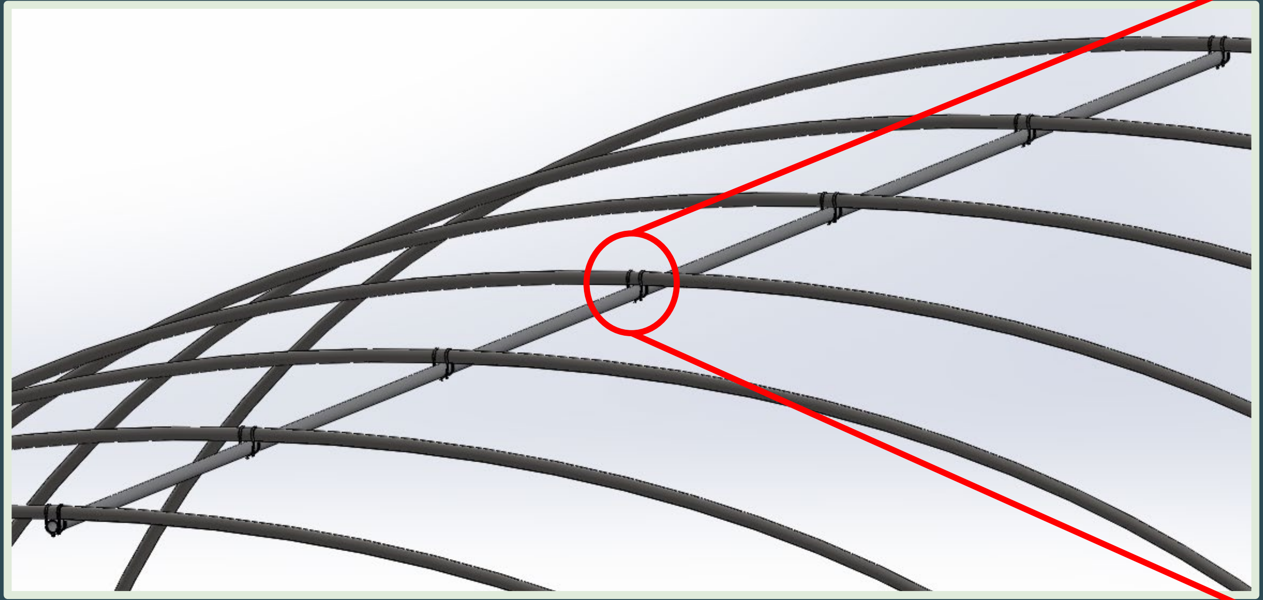
First Metal Greenhouse Design

For our metal design we went with a traditional hoop house high tunnel. We looked at many different types of metal designs and decided that using pipes (top rail) would be the easiest and cheapest metal material to work with for the building phase. Originally, we had shied away from using metal as we assumed cutting, bending, and fixing metal pieces together would be a hard process that requires a lot of outside help. Relying on others was not ideal due to time constraints on the building phase. Fortunately, with more research, we found that using top rail would allow for simple press fit connections, along with easy bending and shaping. Finally, we decided on a hoop house structure as it would be easy and cheap to buy straight top rail and bend it to the desired curvature. Additionally, a hoop house design is beneficial because wind force on two of the four sides can be neglected as most of the wind flows over the curved face.

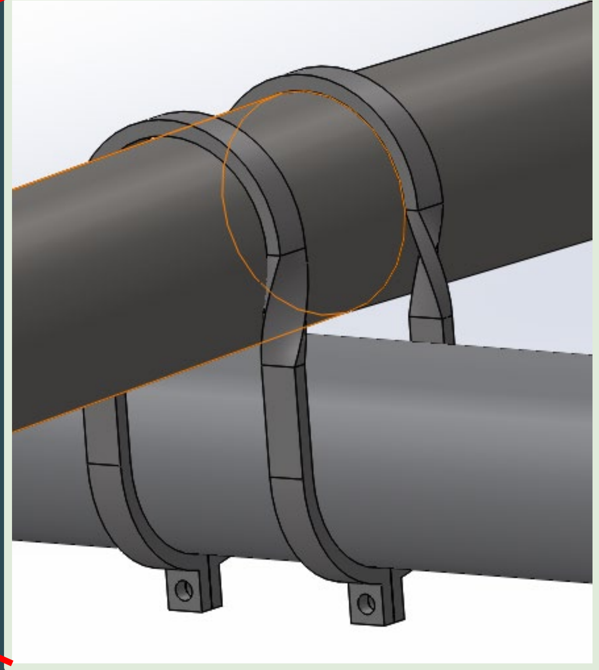
How it's Made



Pipe Anchor for Hoop Attachment



Ridge Pipe for Top of Hoop Connections

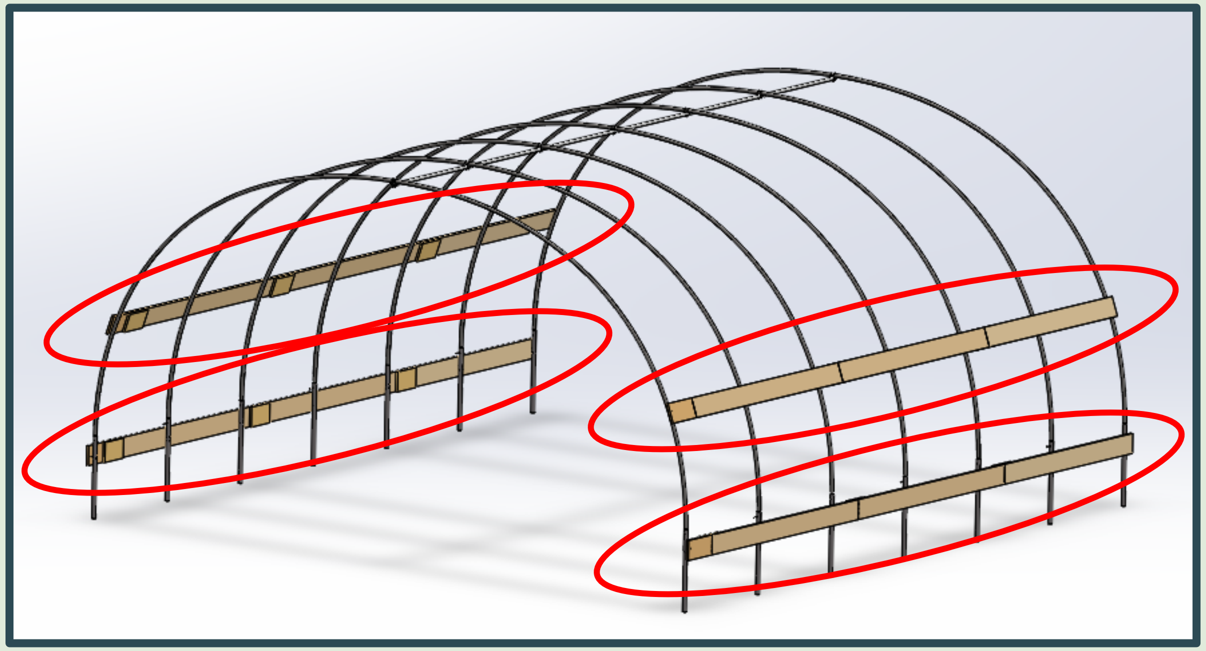


Cross Connector for Hoop and Ridge Pipe

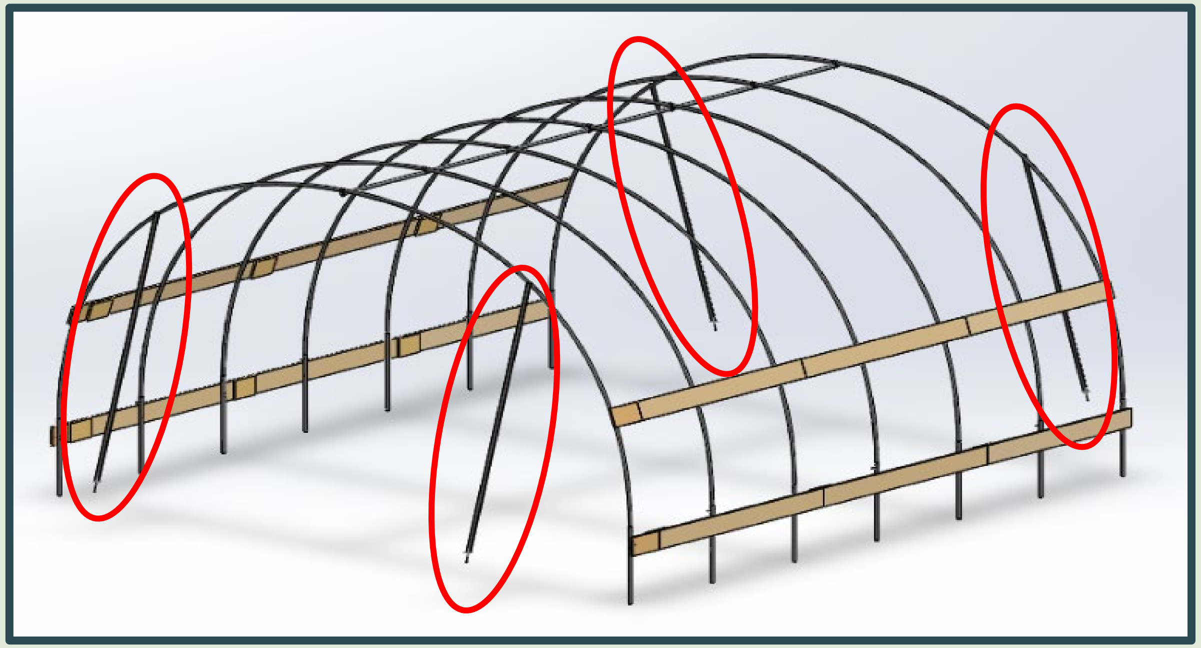
Each end of the seven hoops is inserted into "pipe anchors" and bolted together. "Pipe anchors" are pipes that are sunk 2' into the ground (below the frost line). The anchors help provide a reaction moment necessary for holding the hoops up in cases of strong wind gusts.

The ridge pipe as well as the cross connectors hold the hoops together and ensure that each hoop is four feet from the adjacent hoops. They also provide structural stability as they transfer any force on the front or back hoops to the rest of the hoops.

How it's Made Pt. 2



Hip Boards for Hoop and Polyethylene Connection

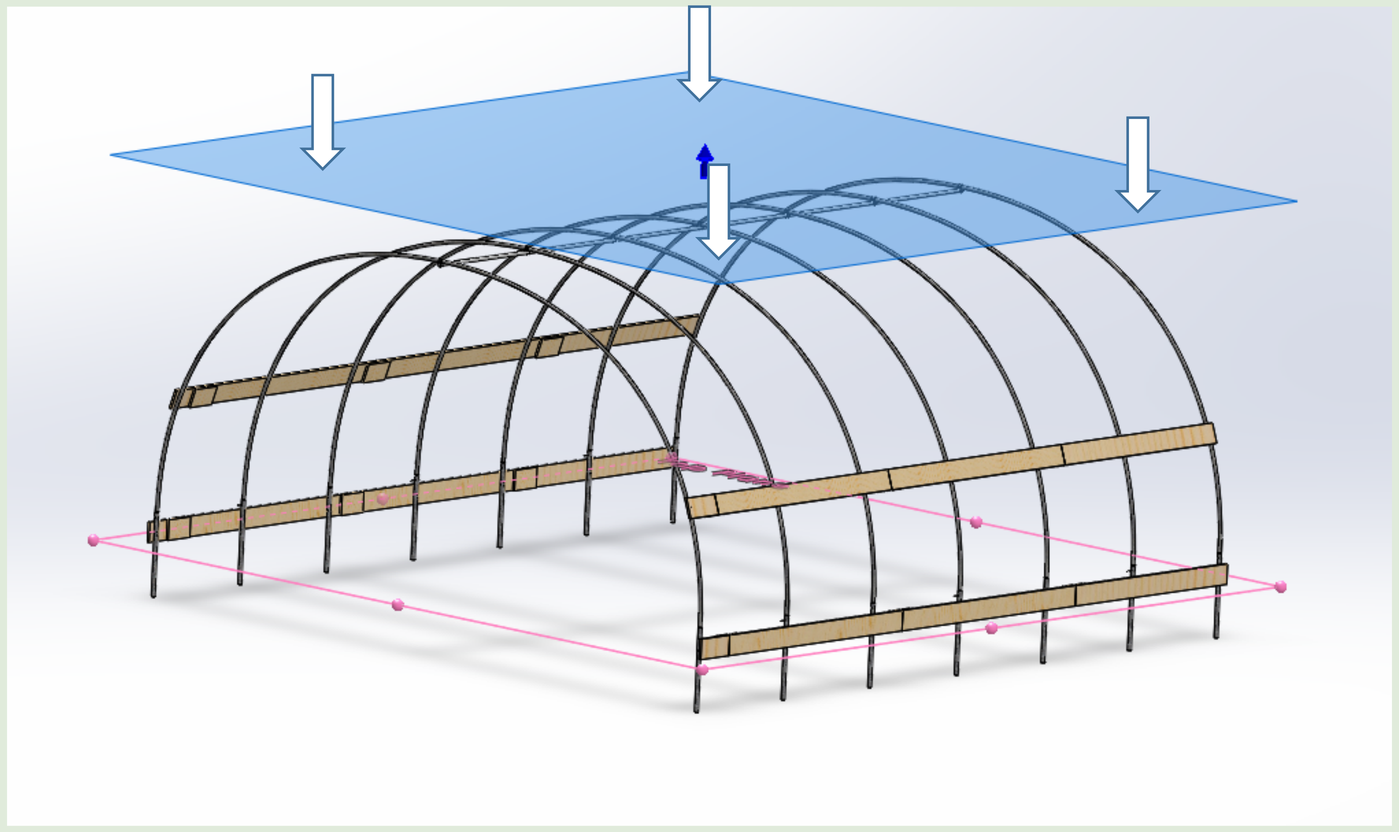


Earth Anchors to Prevent Pipe Bending

The hip boards were another important addition to the structural design of the hoop house. Similar to the ridge pipe, the hip boards are used to lock the hoops together and help with wind force on the front and back ends of the structure. Additionally, the hip boards have channels running along them that allow for the polyethylene plastic to be secured over the hoops.

We chose seventeen gauge pipe for our hoops based on manufacturability and cost. Unfortunately, we determined that the bending stress caused by the wind would bend the hoops. For this reason we looked into using lower gauge pipe in order to increase the maximum yield strength of the pipe. However this would increase cost and difficulty in the build phase. Instead earth anchors were added to the design to help counteract the wind force. Earth anchors are driven into the ground and can each withstand 600 pounds of force in tension before being pulled out (AEA, 2017) For more information on wind load analysis, go to Appendix J.

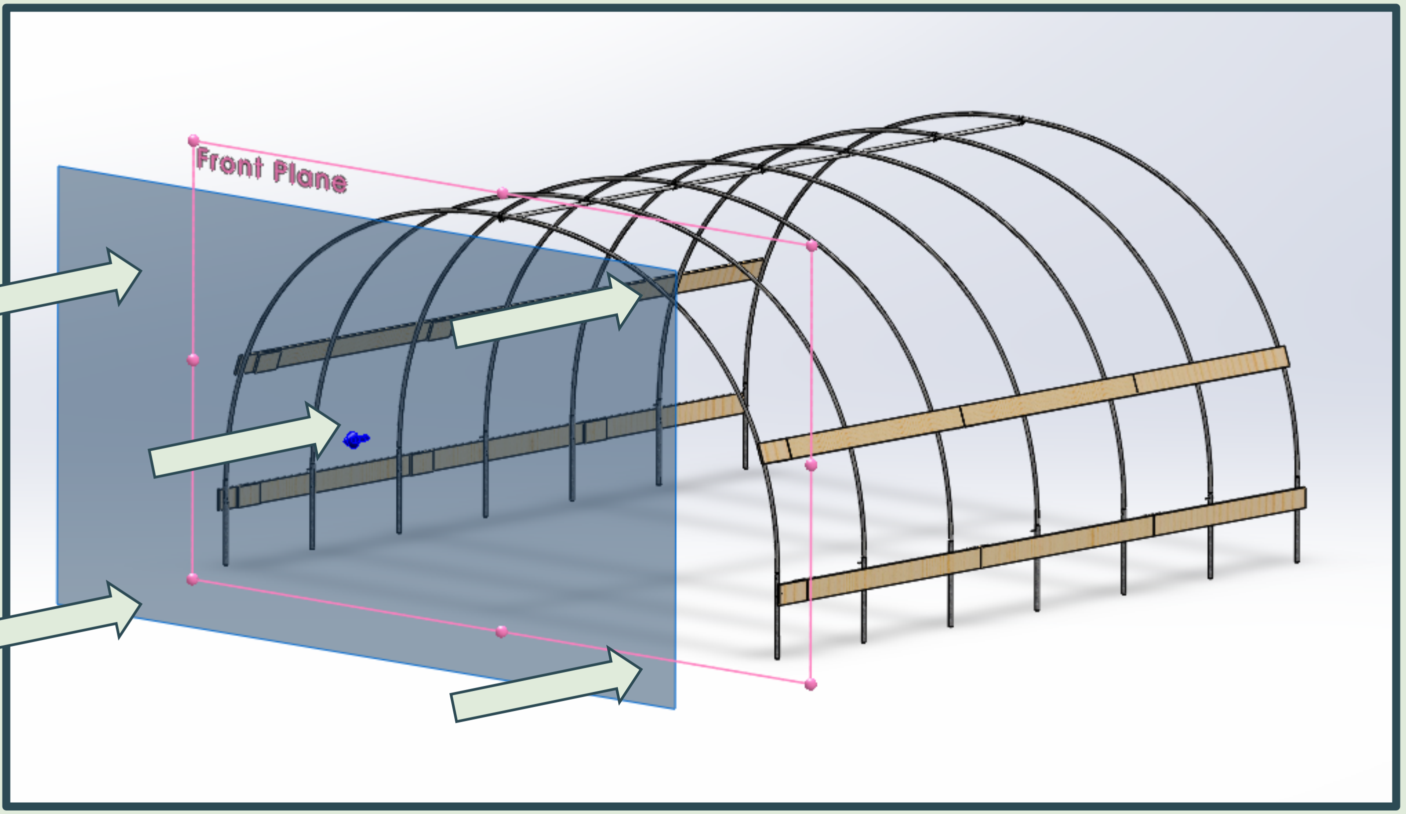
Let it Snow



22,198 lb Distributed Snow Load on Greenhouse

Given the size, location (Paxton, MA), and building codes for the greenhouse, the snow load on the greenhouse can be up to 22,198 pounds of distributed downward force. In order for our structure to be considered safe, it must be able to withstand this force. We analyzed the bolts connecting the hoops to the pipe anchors to ensure they could hold up the hoops. The bolts would have to be able to withstand a 1,850 pound force on each side. We concluded that they would be strong enough for the snow load. The details of the snow load is given in Appendix H.

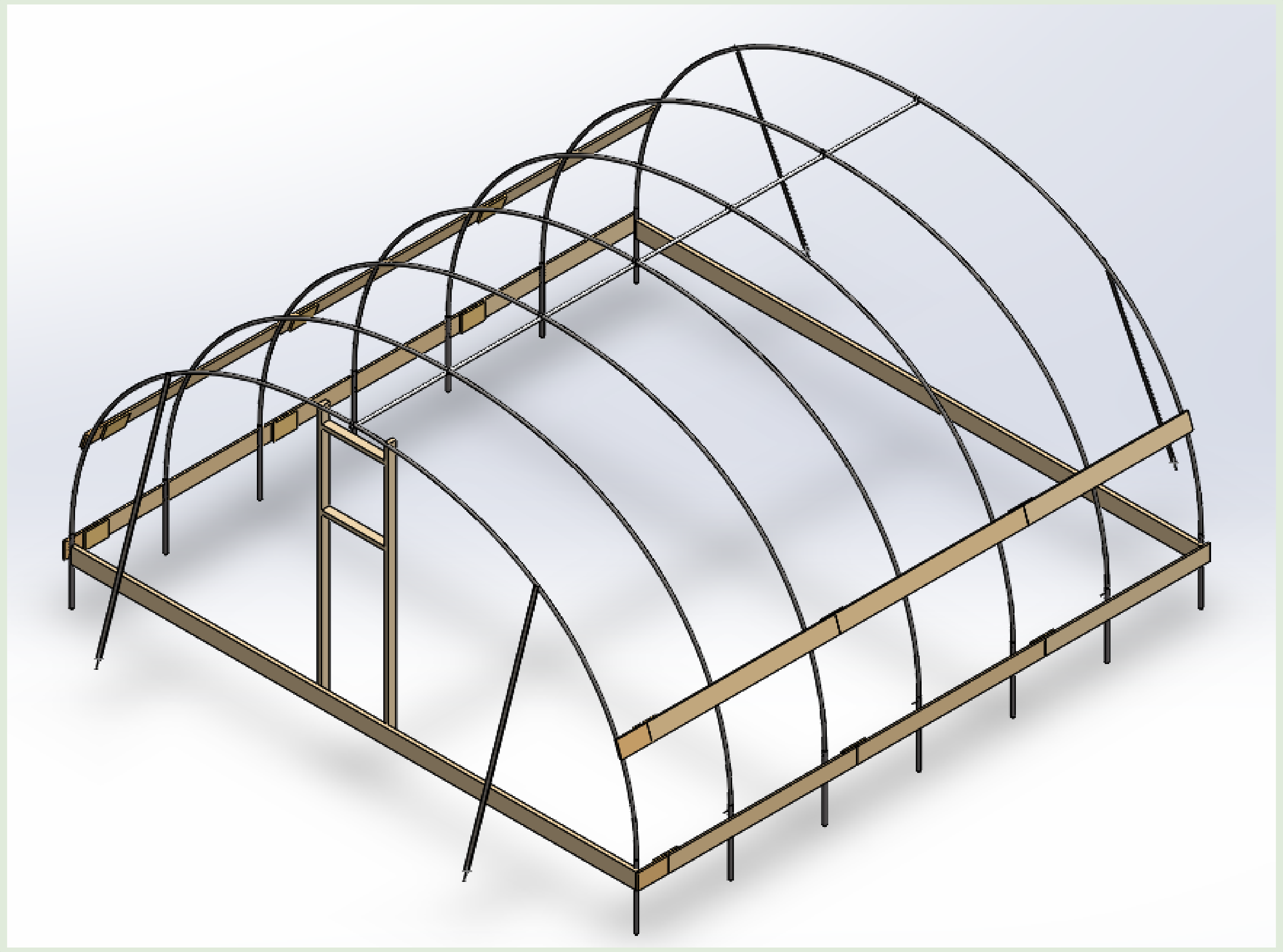
Wind Load



Distributed Wind Load on Front Face of Greenhouse

Based off the building codes for wind speeds, the greenhouse must endure 111 mph, and the wind pressure in Paxton is 14.7 lb/ft^2. Given the area of the hoop face, we calculated that the force on each hoop due to the wind is 457.4 lbs. Furthermore, the moment created from this force was calculated to be 2,424.54 lbf*ft. This moment created a bending stress of 414,549 psi. The galvanized steel piping can only withstand 50,800 psi. This meant the pipes would either bend or completely break from the wind. To solve this problem, earth anchors were incorporated into the design. The details of the wind load is given in Appendix I & J.

Final SolidWorks Design



Heating and Cooling

From December to March, special considerations are needed to keep the greenhouse warm for the plants as well as its occupants. We used a program called Design Builder to calculate the heat loss of the greenhouse provided that the glazing is double layered 6mm polyethylene film, for a typical winter week. We then looked at conventional and innovative methods of heating the greenhouse.

In the summer, we looked into cooling the greenhouse. To avoid additional cost and energy usage of using a fan, air conditioner or heat pump, we designed the greenhouse to maximize natural ventilation.

Heat- Wood vs Metal

Key Results- Metal	
Indoor Temperature	5°C
Outdoor Temperature	-16.7°C
Heat Loss	4.6kW

Key Results- Wood	
Indoor Temperature	5°C
Outdoor Temperature	-16.7°C
Heat Loss	5.4kW

We used the software, Design Builder, to calculate the necessary heating for the greenhouse in winter.

The software works by modeling the building based on location, geometry and material used for the greenhouse. In both simulations for wood and metal, we set the glazing to be a double layer of 6mm polyethylene film. We also used data obtained by the Worcester Regional Airport, the closest airport to the worksite.

Design Builder, then finds the insulation value of the polyethylene as well as the temperature and convection coefficient of the area. After setting a minimum indoor temperature of 5°C, the software calculated the heat loss for a typical winter in the Worcester area.

Conventional Heating

In order to heat the greenhouse during colder months, we investigated using a propane heaters. They work by combusting propane gas with a pilot flame in a controlled manner. A 20lb propane tank costs approximately $30. There are three main concerns which include incomplete combustion potentially leading to the formation of carbon monoxide, gas leakages, and lack of oxygen if heaters ran for an extended period of time.

Another method researched was an electric heater. An electric heater works by passing a current through a resistor to produce heat. Ultimately, this eliminates the need for gas and its potential hazards. In order to power the heater, the greenhouse needs access to electricity, which could pose a challenge. To produce substantial heat, a significant amount of electrical energy is needed over time.

An advantage to both of these modern heating systems is that they have built in thermometers and an automatic shut off devices. This is built into the system so that the heater can shut off once it is at the desired temperature and turn on if the temperature gets too low. It is also a safety measure if the heater overheats.

Innovative Heating

Another feasible heating option for our greenhouse is composting. Composting is the process of organisms breaking down dead organic matter. Conventionally, compost is used to turn organic waste into a nutrient rich fertilizer that can be used to improve the health of soil and as a result of the plants growing in the soil. One side effect of composting is the production of heat from the process of bacteria breaking down the organic matter. Ultimately, compost is a very inexpensive option of heating as the operation costs are close to nothing. The challenge of compost is the variability that comes with the many factors that affect how well the bacteria can break down the organic matter.

The last option researched was thermal storage. Thermal storage is a method of storing heat in a material that will later be released to its surroundings. One effective material commonly used is water. Water has a high heat capacity value, which indicates that it is excellent at storing heat. The benefits of this thermal storage system is that it only requires a barrel and water. The issue faced with this method is that the barrels could block sunlight needed for the plants and limit the space in the greenhouse.


Compost Pile At Turn Back Time Farm

Cool for the Summer

Roll Up Sides for Cooling

In addition to considering the cold month, high temperatures exceeding 30 degrees Celsius during the summer were also examined. At these temperatures, there will not be significant heat loss to the outdoors but the sun would be adding heat to the greenhouse. The insulation of the greenhouse would trap the heat inside and raise interior temperature to uncomfortable levels. To tackle this we added a vent above the door and a system to roll up the glazing on the sides.

Decisions, Decisions

Criteria (1-2)	Wt. (1-2)	Wood	Metal	Considerations
Serviceability	1.0	2	2	If the structure breaks, how easy is it to fix?
Cost	1.0	1	2	Cost of materials involved. Which structure is more expensive?
Ease of Construction	2.0	1	2	How long will it take to build? How easy will it be to build?
Heating	1.0	1	1	What is the heat loss for each structure? Which structure requires more energy to heat?
Strength	2.0	2	1.5	How strong is the structure? Which structure can handle a stronger wind load?
Safety	2.0	2	2	How safe is the overall structure? Is it structurally sound? Safe for the children?
Weighted Scores		15.0	17.5	

After finalizing the metal and wood greenhouse designs, we created a decision matrix comparing both structures. This was a tool used to measure different qualities for each design. We presented this matrix to the shareholders of the farm so they could have a quantifiable value for both designs. Qualities used for comparison were determined based on aspects that were important to our sponsor as well as our team. Specifically, the overall cost and safety were important to Turn Back Time, whereas ease of construction, strength, heating, and serviceability were more crucial aspects to our team.

The Final Decision

The farm chose the metal design because of the low cost and ease of construction. The farm also decided to heat the greenhouse with propane because they already use this method on the farm.

Final Cost

Item	Used For	Total Cost ($)	Donated?
24’ pipe bender	Bending Pipe	107.73	No
Top Rail	Pipe Anchors, Hoops, Ridge Pole	266.42	Partially
PT Lumber	Hip Boards, Base Boards, Door Frame, Door, Vent	140.72	Partially
Earth Anchors & straps	Anchoring Hoops	60	Yes
Polyethylene & Wiggle Wire	Glazing	652.39	30% off
Fasteners	Connections	125.48	No
	Overall Cost	1,352.74	

Construction

Greenhouse in 11 Easy Steps

Step 1: Level and excavate
Step 2: Lay foundation
Step 3: Cut and install anchors
Step 4: Bend and fasten hoops
Step 5: Attach hoops in anchors
Step 6: Raise the ridge beam
Step 7: Install base and hip boards
Step 8: Fasten wiggle wire to frame
Step 9: Drive Earth anchors
Step 10: Build door and vent frame
Step 11: Secure polyethylene

Level and Excavate

The first step of construction was to clear and level the area so our team would have a flat surface to work on. Before we started, there were remnants of raised beds from previous gardening endeavors. The logs holding up the soil had to be removed, and the soil required flattening. The overgrown grass was torn out using rakes, leaving exposed mud and dirt for the upcoming winter elements.

New England was carved by enormous, changing glaciers and ice sheets, leaving behind a plethora of large rocks buried just feet below the surface. We encountered many rocks that could not removed by hand. They had to either be dug up with the backhoe or chipped away by hand; a long and painstaking process.

Lay Foundation

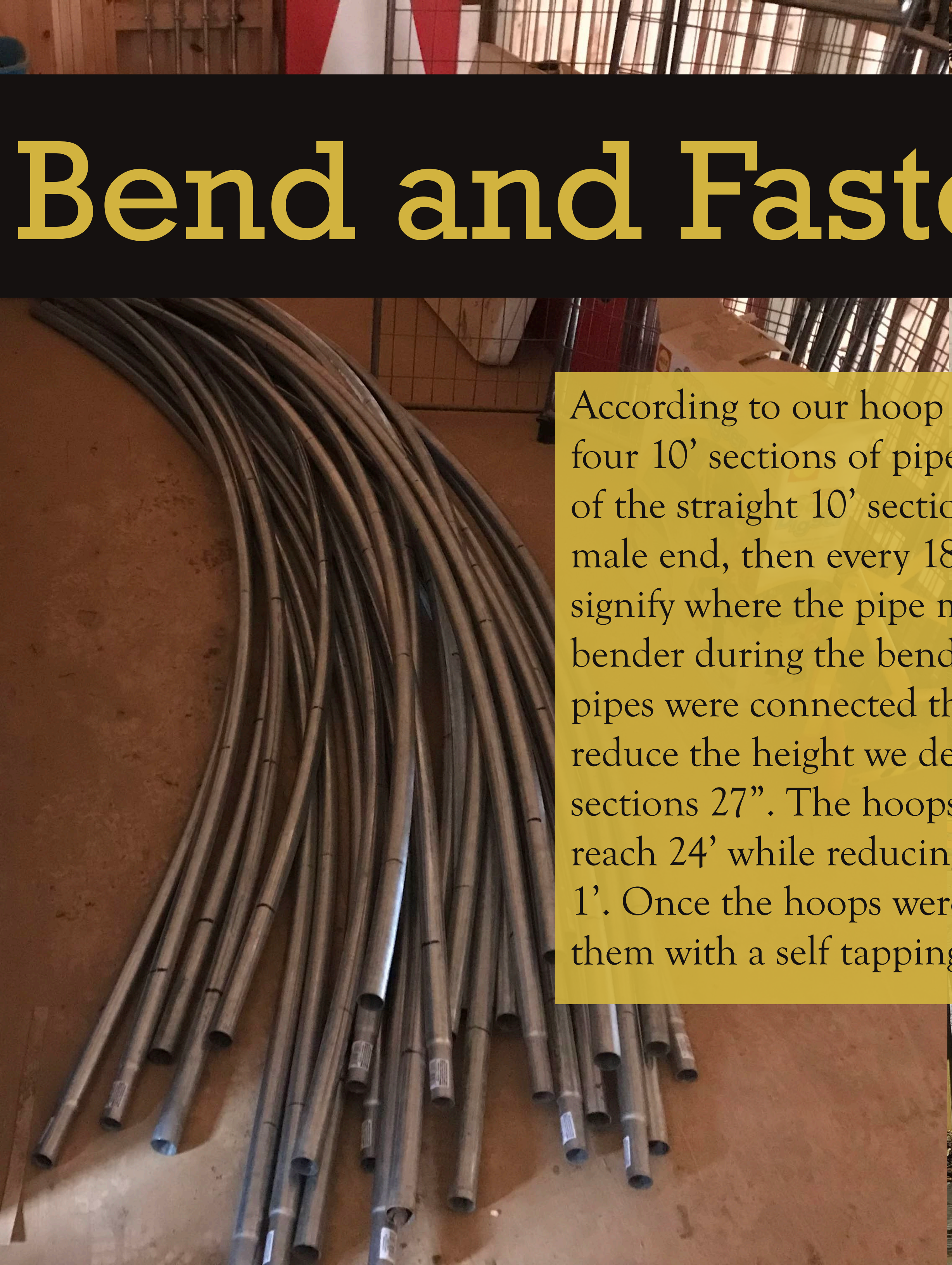
Once we had a relatively level surface, we could lay the measurements for where the greenhouse would go. To do this, we used a combination of rebar stakes, string, and tape. In order to make sure the foundation lines were square, we used common industry methods to ensure we had right angles in the corners. Once the lines were set, we could mark where we needed to drive in the hoop anchors.

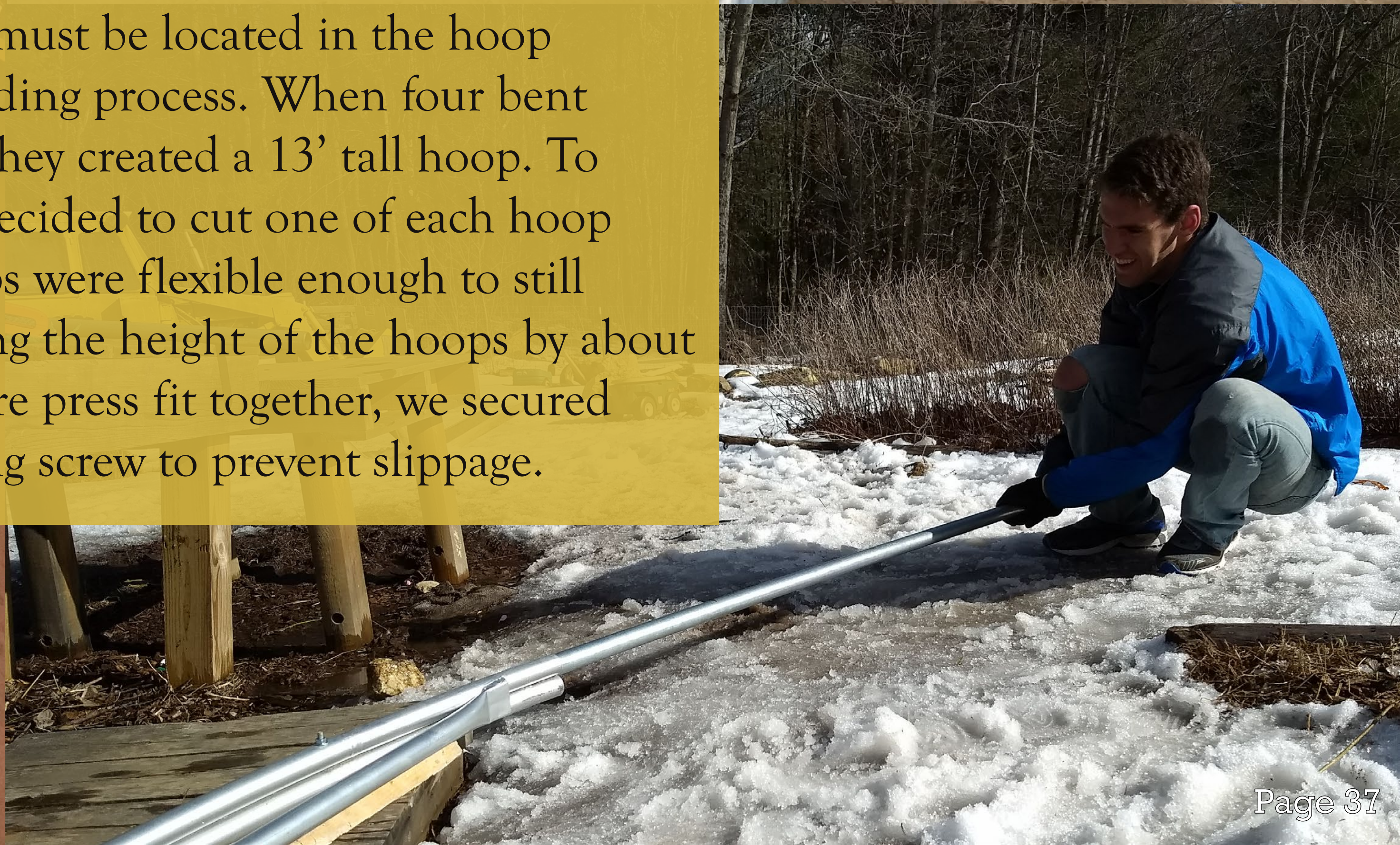
Cut and Install Anchors

The hoop anchors are cut from 16 gauge 1-5/8” galvanized steel pipe. It was cut into 4’ sections such that 2’ were sunk into the ground. They were sunk by hand with a post driver. To harden the soil, we mixed the dirt with concrete powder to ensure the posts would not liquify the soil when fatigued. The ground was not completely level after the winter, so we leveled off each pipe 15” up from the shortest pipe. This way, we knew that all the pipes were level across the foundation. The level anchors will mean that the hoops, when attached, will sit at the same height.

Bend and Fasten Hoops

According to our hoop bender specifications, we needed four 10’ sections of pipe to make a 24’ wide hoop. Each of the straight 10’ sections were marked at 9” from the male end, then every 18” afterwards. These markings signify where the pipe must be located in the hoop bender during the bending process. When four bent pipes were connected they created a 13’ tall hoop. To reduce the height we decided to cut one of each hoop sections 27”. The hoops were flexible enough to still reach 24’ while reducing the height of the hoops by about 1’. Once the hoops were press fit together, we secured them with a self tapping screw to prevent slippage.





Attach Hoops in Anchors

After assembling the hoops, our team secured them inside the anchors. Each hoop is fed 9” into the anchors, and secured with two ¼” carriage bolts to prevent rotation of the hoop inside the anchors.

Raise the Ridge Beam

In order to attach all the hoops together, our team installed a ridge beam at the highest point of all of the hoops. In order to attach the hoops to the ridge beam, our team used a multi-axis clamp, which is held together with carriage bolts. In order to center the ridge beam, we marked the center between the anchors and used a make-shift plumb bob to mark the center on the hoops.

Install Base and Hip Boards

In addition to the ridge beam, the hoop anchors and hoops were connected with hip and base boards. These boards provide lateral stability to the greenhouse and provide an attachment point for the aluminum wiggle wire channels. These channels are secured with ¾” self tapping screws in 6.5’ sections. We used at least one screw per linear foot of wiggle wire channel to prevent screws from snapping. This is important during ventilation of the greenhouse when the sides are rolled up. During a gust of wind, air can be forced against the plastic from the inside, pulling on the wiggle wire channel screws.

Fasten Wiggle Wire to Frame

The wiggle wire channels were installed into the top face of the end hoops with self tapping screws. We used at least one screw per linear foot. In order to reach the top of the hoops, we used ladders and the back-hoe. The wiggle wire channels were flexible enough to be contoured to the hoop by hand. These channels allow the plastic to form a weatherproof "bubble" around the frame.

Drive Earth Anchors

The bullet shaped Earth anchors are secured using a 3 ft driving rod, which is inserted into the bored out bullet. We took turns swinging the hammer, and 3 feet later, we could remove the driving rod from the anchor. In order to secure the anchor, we pulled on the exiting cable. This spins the anchor in the ground so the fins are perpendicular to the entrance hole. Based on a soil study done by the National Resources Conservation Service, most of the soil around Turn Back Time Farm is a fine loamy sand with a large amount of stones. The manufacturers of the Earth anchors state that this type of soil quality means that the anchors can withstand 600 lbs before they are pulled out of the ground. In order to attach the anchors to the greenhouse, we used 700 lb rated tow cables which is hooked onto a bolted on loop.

Build Door and Vent Frame

The first step in building the door was to build the vertical frame. These pillars are bolted into the hoop and buried in the ground to provide lateral stability. Since the wood is slightly warped, the headers of for the door and vent required separate measurements. The headers prevent the vertical frame from further bending which would affect how the door sits inside the frame. The door and vent were built in a similar fashion, two vertical posts, horizontal bracing, and a diagonal brace to prevent rotation of the door.

Secure Polyethylene

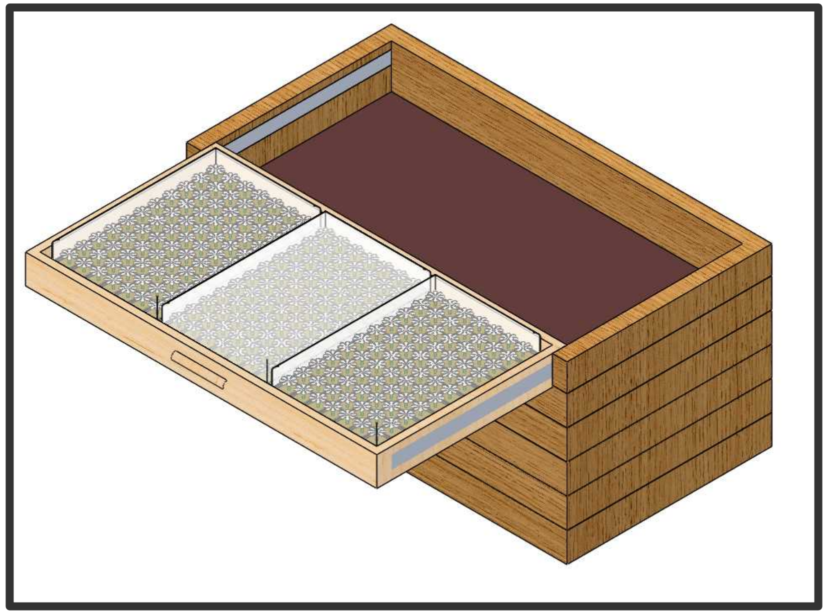
Due to time and building constraints, our team was not able to install the polyethylene film before the due date for this report. However, we do have the film at the farm. It is folded in quarters, and is rolled up in a 140 linear feet roll. In order to attach the film to the greenhouse, we will divide it into three sections, the front face, back face, and the sides. For the front, we can cut out two rectangles of plastic that will go from the baseboards to the top facing wiggle wire channel. We can cut the plastic to shape to fit the curve of the hoop after it is attached. For the sides, we can use a flexible tape measure to find the linear distance across our hoop, and cut out a rectangle of that size. We plan on using many volunteers from the farm to help us unfold this piece and lift it over the hoop. The back face will be installed the same way the front face will, just a larger rectangle will be used.

Lessons Learned

Our team made many mistakes along our greenhouse journey. Our first challenge involved laying out the foundation. For a few days we struggled getting an exact square foundation using a string, but eventually we succeeded. Unfortunately, due to many factors the string stretched and the dimensions changed. If we were to do the process again, we would use paint lines instead of string. Our second mistake was starting the building process to early. Before our design was finalized we poured eight concrete footings in anticipation of a wooden structure. When we switched to metal, we tried to adapt by building makeshift hoop anchors out of wood. The anchors held up, but the cast in place anchors in the concrete snapped, making the footings useless. We were forced to pull them out of the ground, eliminating weeks of work.

Current Progress

Future Improvements



Garcanz Compost Planters Box Design

There were a variety of different systems that we wanted to test if we had the time and budget to implement them. Among these systems included: compost heating and propane heating. Compost heating would provide a sustainable green heat source for the plants as well as an opportunity to teach the children about compost. Emilee Gancarz, a graduate student at WPI, designed a planters box, that can be heated by compost. The box has a shelf on top where the seedlings go, while the box is filled with compost to provide direct heat. Propane heating would be used to heat the entire greenhouse in the colder months. Additionally, a group of WPI student working on their Interactive Disciplinary Project designed a water catchment system to be implemented on the sides of our greenhouse. Unfortunately, due to time constraints the system could not be utilized. These systems could be further explored and ideally implemented in future Major Qualifying Projects.

Bibliography

American Earth Anchors (AEA). (2017) Load Capacity. Retrieved from https://americanearthanchors.com/files/1914/9631/4709/load-capacity-rev7.pdf

ASCE. (2006). Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers/Structural Engineering Institute.

Burris, L (2011). *Turn Back Time.* Retrieved from https://www.tbtinc.org/

Burris, L. (2019). Personal Interview

Gancarz, E. (2019). Personal Interview

International Code Council (ICC) (2015) *Chapter 16 – Structural Design Amendments.* Retrieved from https://www.mass.gov/files/documents/2018/06/08/Chapter%2016%20Structural%20Design%20Amendments_1.pdf

Louv, R. (2008). *Last child in the woods*. Chapel Hill, NC: Algonquin Books

Pasupathy, A., Velraj, R. (2008) Effect of double layer phase change material in building roof for year round thermal management. *Energy and Buildings, 40*. 193-203.

Rasheed, A., Lee, J., & Lee, H. (2018). Development of a model to calculate the overall heat transfer coefficient of greenhouse covers. *Spanish Journal of Agricultural Research, 15*(4), e0208.

Ross, R. (2018). The Science Behind Composting. *LiveScience.* Retrieved from https://www.livescience.com/63559-composting.html

United States Department of Agriculture (USDA). (n.d.) Interactive Map Retrieved from https://planthardiness.ars.usda.gov/PHZMWeb/InteractiveMap.aspx

Youst, B. (2019) How to Build a Greenhouse - Free Greenhouse Plans. *Bootstrap Farmer.* Retrieved from https://www.bootstrapfarmer.com/blogs/building-a-greenhouse/how-to-build-a-greenhouse

Appendix A - Wind and Snow Loads

Qz = .00256 * V^2 * I * kz * kzt * kd
Qz: Adjusted Wind Pressure = 31.09 $\frac{lbf}{ft^2}$
V: Site Specific Wind Velocity = 111MPH = 162.8 FPS
I: Occupancy Importance Factor = 0.77
Kz: Velocity Pressure Exposure Factor = .7
Kzt: Topographic Factor = 1
Kd: Wind Directionality Factor = .85
Ac: Max Cross Sectional Area of Building = 441.23 ft^2
Qz * Ac = 13715.95 lbf

Ps = (.7) * Cs * Ce * Ct * I * pg
Ps: Adjusted Snow Pressure = 38.54 $\frac{lbf}{ft^2}$
Cs: Roof Slope Factor = 1
Ce: Exposure Factor = 1.3
Ct: Thermal Factor = 1.1
I: Occupancy Importance Factor = 0.77
Pg: Site Specific Snow Load = 50 $\frac{lbf}{ft^2}$
Af: Area of Floor = 596 ft^2
Ps*Af = 22198.76 lbf

Final Total Wind Load (lbf)	Final Total Snow Load (lbf)
13715.95	22198.76

(ASCE, 2006) and (ICC, 2015)

Appendix B – Wooden Greenhouse Design

Pressure on Each Column Due to Bending:

Variable Definitions:

$\sigma =$ *maximum stress due to bending*

$c =$ *distance from the base of the beam to the centroid of the beam*

$M =$ *maximum bending moment*

$I =$ *moment of Inertia of beam*

$D =$ *dead load*

$W =$ *wind load*

Moment per Column Row:

$$(.6 * D) + (.6 * W) = Max\ Lateral\ Load$$

$$(.6 * 3000\ lb) + (.6 * 13716\ lb) = 10{,}029.6\ lb$$

$$\frac{10{,}029.6\ lb}{4\ Columns} = 2507.4\ lb$$

$$\frac{2507.4\ lb}{3\ Columns} = 835.8\ lb$$

$$M = W * l, l = 6ft$$

$$M = 835.8\ lb * 6ft = 5014.8\ lb * ft$$

$$\sigma = \frac{c * M}{I}, c = 2\ in, I = \frac{1}{12} * b * h^3$$

$$\sigma = \frac{2\ in * 5014.8\ lb * ft * (12\frac{in}{ft})}{\frac{1}{12} * 4\ in * (4\ in)^3} = 5641.65\ psi\ Bending\ Moment$$

Moment per Column Row:

$$w = \frac{\text{Max Lateral Load}}{\text{Side Wall Area}} * \text{Tributary Length} = \frac{5625.6\ \text{lb}}{6\ \text{ft} * 24\ \text{ft}} * 4\ \text{ft} = \ 156.3\ \text{plf}$$

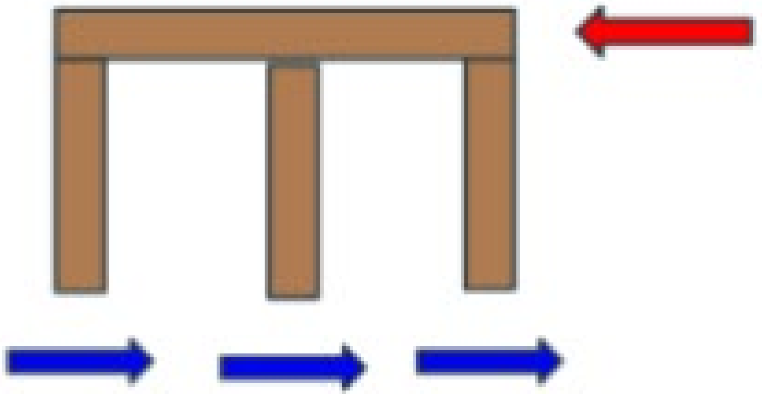
$$\frac{5625.6\ lb}{7\ Joists} * \frac{1\ \text{Joist}}{2\text{in} * 6\text{in}} = \ 67.0\ \text{psi}$$

Moment per Column Row:

$$M = W * l$$

$$\frac{2507.4\ lb}{3\ Column} = 835.8\ lb$$

$$\frac{835.8\ lb}{4in * 4in} = 52.24\ psi$$



Appendix C – Wooden Greenhouse Design

Shear Wall Design:

Variable Definitions:

$F_{s,exterior}$ = *Shear Capacity of Exterior Sheathing*, $F_{s,interior}$ = *Shear Capacity of Interior Sheathing*

C_{NS} = *Coefficient of Nails*, C_{SP} = *Coefficient of Sheathing Material*, SF = *Safety Factor*

F_s' = *Design Shear Capacity*, F_{PSW} = Design Capacity of Perforated Shear Wall

C_{OP} = *Coefficient of Wall Openings*, C_{dl} = *Coefficient of Dead Load*

a = *Ratio of Openings' Area to Total Area*, b = *Ratio of Unperforated Length to Total Length*

r = *Sheathing Area Ratio*

T = *Tensional Force due to Wind*, C = *Compressive Force due to Wind*, d = *Depth of Wall*

Δ = *Creep due to Loads*, G = *Specific Gravity of Sheathing Material*, V_d = *Wind Load*, h = *Height*

Max Shear Capacity for Front/Back Walls:

$F_{s,exterior} = 1{,}356\ plf, F_{s,interior} = 0\ plf$

$SF = 2.0, C_{NS}(8d\ Common\ Nails) = 1.0, C_{SP}(Douglas\ Fir - Larch) = 1.0$

$$F_s' = F_s * C_{SP} * C_{NS} * \frac{1}{SF}, F_s = F_{s,exterior} + F_{s,interior} = 1{,}356\ plf$$

$$F_s' = 1356\ plf * 1.0 * 1.0 * \frac{1}{2.0} = 678\ plf = Design\ Shear\ Capacity$$

$$F_{PSW} = F_s' * C_{OP} * C_{dl} * L, L = 24\ ft$$

$$C_{OP} = \frac{r}{3-2r}, r = \frac{1}{1+\frac{a}{b}}$$

$$a = \frac{Area\ of\ Openings}{Total\ Area} = \frac{Vent + Door}{Front\ Area} = \frac{[(2ft * 2ft) + (3ft * 6ft)]}{228ft^2} = .096$$

$$b = \frac{Length\ of\ Unperforated\ Wall}{Total\ Wall\ Length} = \frac{21ft}{24ft} = .875$$

$$r = \frac{1}{1+\frac{.096}{.875}} = .901, C_{OP} = \frac{.901}{3-(2 * .901)} = .752$$

$$C_{dl} = 1.0\ (Assumed)$$

$$F_{PSW,Wind} = 678\ plf * .752 * 1.0 * 24\ ft = 12{,}236.544\ lb$$

Appendix D – Wooden Greenhouse Design

Shear Wall Design (Continued):

Max Shear Tension/Compression in Shear Walls:

$$T = C = \frac{d}{x} * F_s' * h, d = 24\ ft, h = 6\ ft$$

$$x = d - (width\ of\ end\ stub + offset\ from\ wall\ anchor)$$

$$x = 24\ ft - (4in + 1.5in) * \frac{1ft}{12in} = 23.79\ ft$$

$$T = C = \frac{24\ ft}{23.79\ ft} * 678\ plf * 6\ ft = 4104.62\ lb$$

Max Creep due to Lateral Forces:

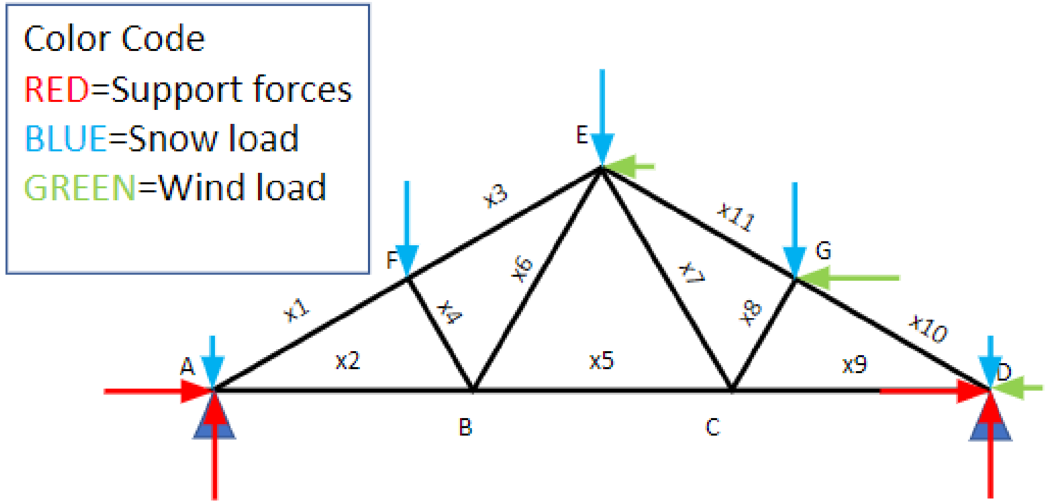
$$\Delta = 1.8 * \frac{.5}{G} * \frac{1}{\sqrt{r}} * \left(\frac{V_d}{F_{PSW,Wind} * SF}\right)^{2.8} * \frac{h}{8}, G(Douglas\ Fir - Larch) = .5, V_d = Wind\ Load$$

$$\Delta = 1.8 * \frac{.5}{.5} * \frac{1}{\sqrt{.901}} * \left(\frac{6400\ lb}{12{,}236.544\ lb * 2}\right)^{2.8} * \frac{6}{8} = 4.6 * 10^{-9}\ in$$

Appendix E – Wooden Greenhouse Design

Fink Truss Calculations:

The calculations were done using Matlab. The tables below shows the load on each member of the fink truss.



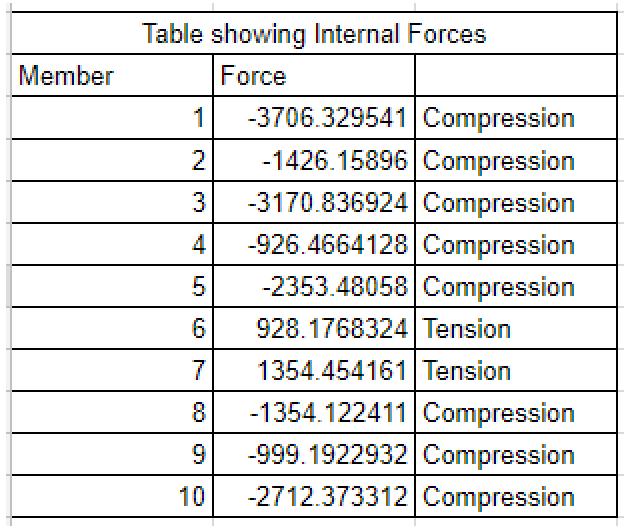
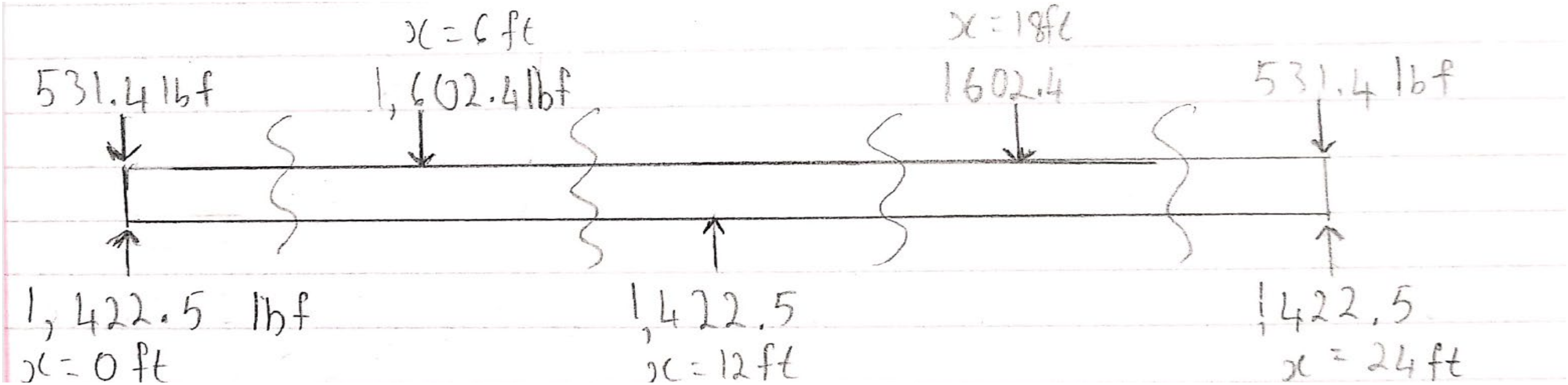


Table showing Internal Forces

Member	Force	
1	-3706.329541	Compression
2	-1426.15896	Compression
3	-3170.836924	Compression
4	-926.4664128	Compression
5	-2353.48058	Compression
6	928.1768324	Tension
7	1354.454161	Tension
8	-1354.122411	Compression
9	-999.1922932	Compression
10	-2712.373312	Compression

Appendix F – Analysis of Chord AD



Note:
Curvy lines represent “cuts” and it goes Cut 1 to Cut 4 from right to left
“X” represents the horizontal distance from the origin on the left.

Appendix G – Analysis of Chord AD

Normal Stress:
= maximum tensile force/cross sectional area
= 8272.68/8= 1034.09 psi

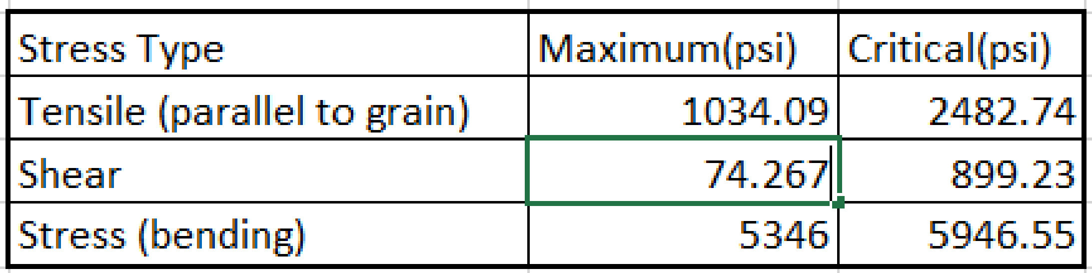
Shear Stress:
Cut 1: V=891.1 lbs
Cut 2: V= -711.3lbs
Cut3: V= 711.2lbs
Cut 4:V= -891.2lbs

τ= Max V/A
T=891.2bs/12 =74.267

Chord AD is the member most likely to fail due to shear stress and bending so a special analysis was done on that chord. The normal stress was calculated by finding the maximum normal force in ay member on the truss and dividing by the area.

Stress due to Bending:
Cut 1: M1=891.1x
Cut 2: M2=-711.3x+9614.4
Cut3: M3=711.2x-7455.6
Cut 4: M4=-891.2x+21388.8

Max M=5346lb*ft
I=(1/12)*b*h3
σ=cM/I
σ=5346psi



Stress Type	Maximum(psi)	Critical(psi)
Tensile (parallel to grain)	1034.09	2482.74
Shear	74.267	899.23
Stress (bending)	5346	5946.55

Appendix H – Snow Load Analysis

$$Snow\ load\ in\ Paxton, Ma = 50\ psf$$

$$Snow\ load\ after\ building\ code\ corrections\ (s)(See\ Appendix\ A) = 38.5\ psf$$

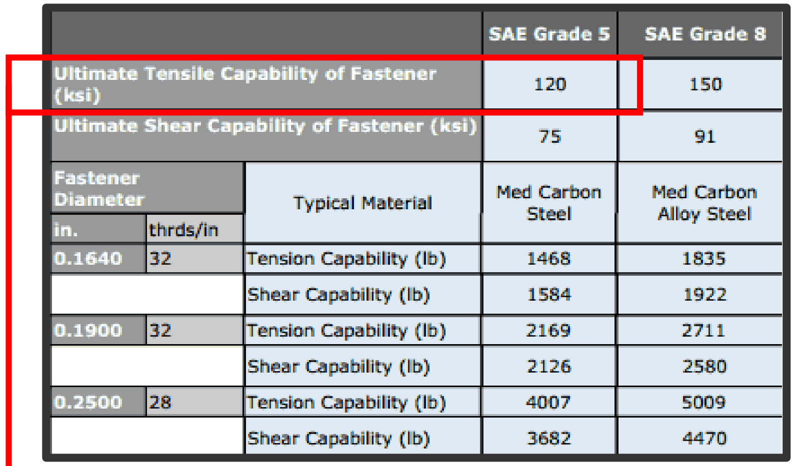
$$Area\ of\ greenhouse\ (A) = 576\ ft^2$$

$$Snow\ load\ over\ area\ of\ greenhouse = s * A = 22{,}198\ lbf$$

$$Load\ per\ middle\ hoop = \frac{22{,}198}{3} = 7{,}400\ lbf$$

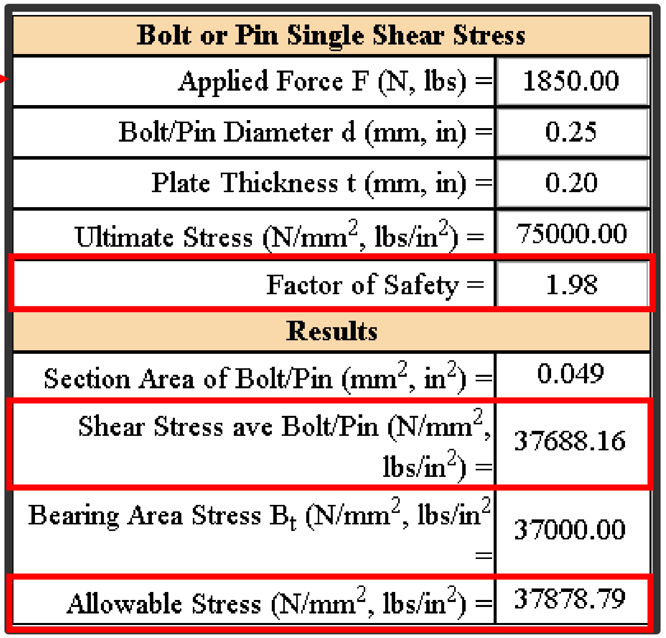
$$Load\ per\ side\ of\ hoop = \frac{7{,}400}{2} = 3{,}700\ lbf$$

$$Shear\ force\ on\ one\ side\ of\ bolt = \frac{3{,}700}{2} = 1{,}850\ lbf$$



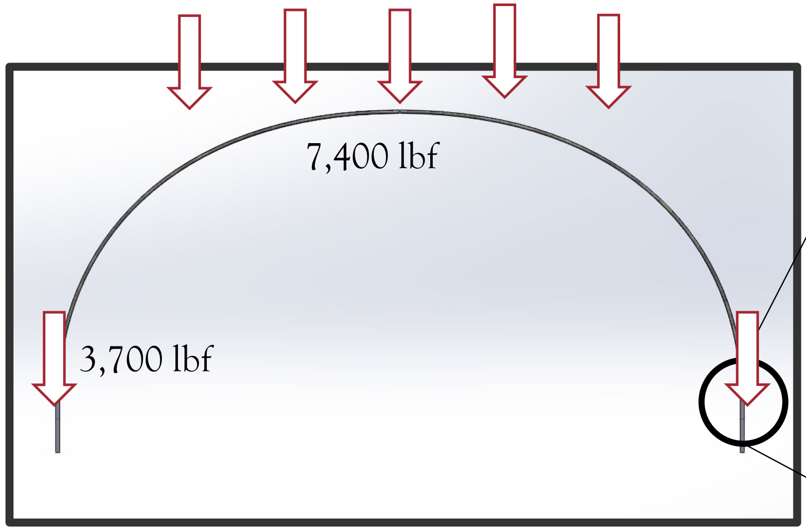
			SAE Grade 5	SAE Grade 8
Ultimate Tensile Capability of Fastener (ksi)			120	150
Ultimate Shear Capability of Fastener (ksi)			75	91
Fastener Diameter		Typical Material	Med Carbon Steel	Med Carbon Alloy Steel
in.	thrds/in			
0.1640	32	Tension Capability (lb)	1468	1835
		Shear Capability (lb)	1584	1922
0.1900	32	Tension Capability (lb)	2169	2711
		Shear Capability (lb)	2126	2580
0.2500	28	Tension Capability (lb)	4007	5009
		Shear Capability (lb)	3682	4470

SAE Grade 5 Bolt Specifications

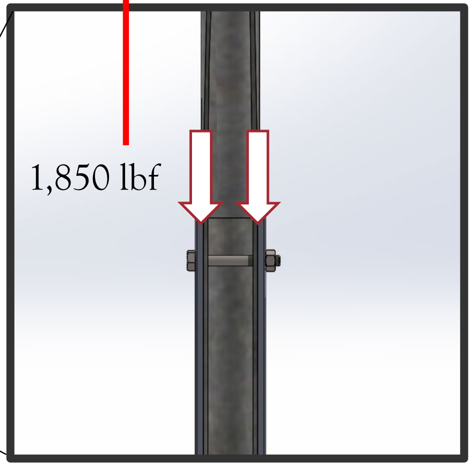


Bolt or Pin Single Shear Stress	
Applied Force F (N, lbs) =	1850.00
Bolt/Pin Diameter d (mm, in) =	0.25
Plate Thickness t (mm, in) =	0.20
Ultimate Stress (N/mm^2, lbs/in^2) =	75000.00
Factor of Safety =	1.98
Results	
Section Area of Bolt/Pin (mm^2, in^2) =	0.049
Shear Stress ave Bolt/Pin (N/mm^2, lbs/in^2) =	37688.16
Bearing Area Stress B_t (N/mm^2, lbs/in^2) =	37000.00
Allowable Stress (N/mm^2, lbs/in^2) =	37878.79

Online Bolt Stress Calculator



Front View of Hoop with Snow Load



Inside of Hoop and Pipe Anchor Connection

Appendix I – Wind Load Analysis

$$Wind\ pressure\ in\ Paxton, MA\ (See\ Appendix\ A) = 14.7\frac{lbf}{ft^2}$$

$$Hoop\ radius\ (R) = 12\ ft$$

$$Hoop\ area = 226.2\ ft^2$$

$$Distance\ to\ point\ load\ (d) = \frac{R*4}{\pi*3} = 5.1\ ft$$

$$Wind\ load = 14.7\ *226.2 = 3327.9\ lbf$$

$$Load\ per\ side\ of\ \ hoop\ (l) = \frac{3327.9}{14} = 237.7\ lbf$$

$$Moment\ on\ each\ pipe\ (M) = d*l = 1210.6\ lbf*ft$$

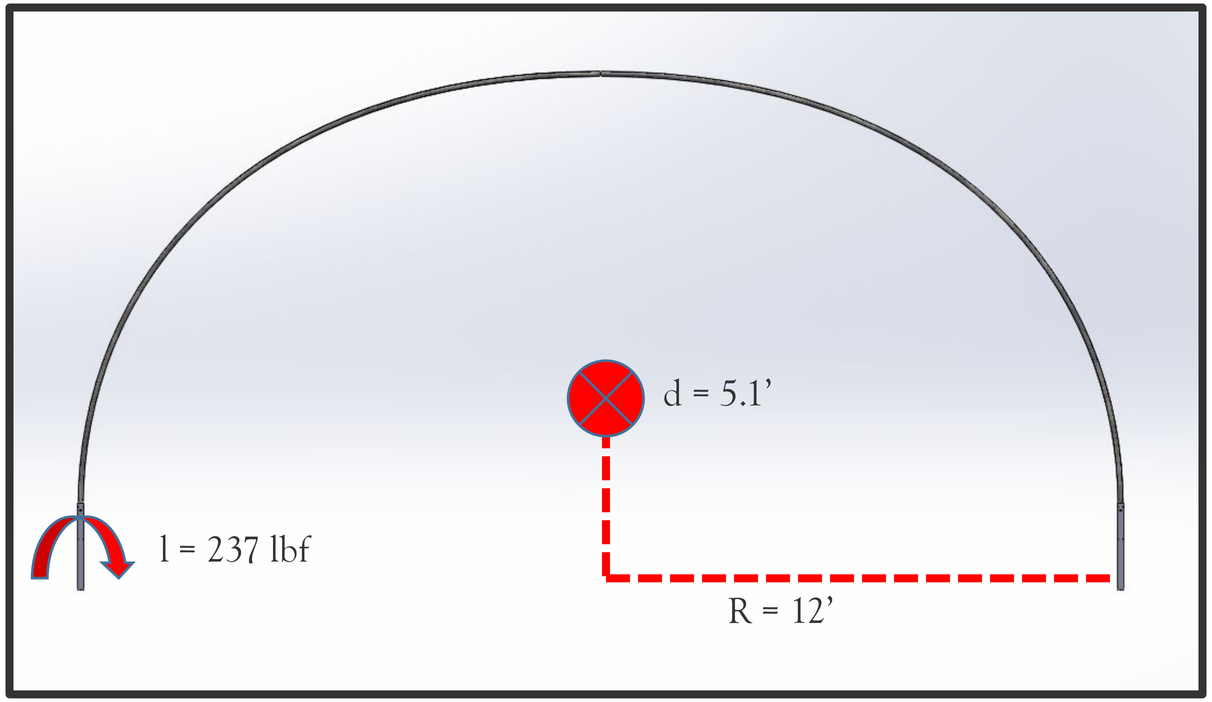
$$Outer\ diameter\ (OD) = 0.11\ ft$$

$$Inner\ diameter\ (ID) = 0.105\ ft$$

$$Moment\ of\ Inertia\ (I) = \frac{\pi(OD^4 - ID^4)}{64} = 1.1*10^6$$

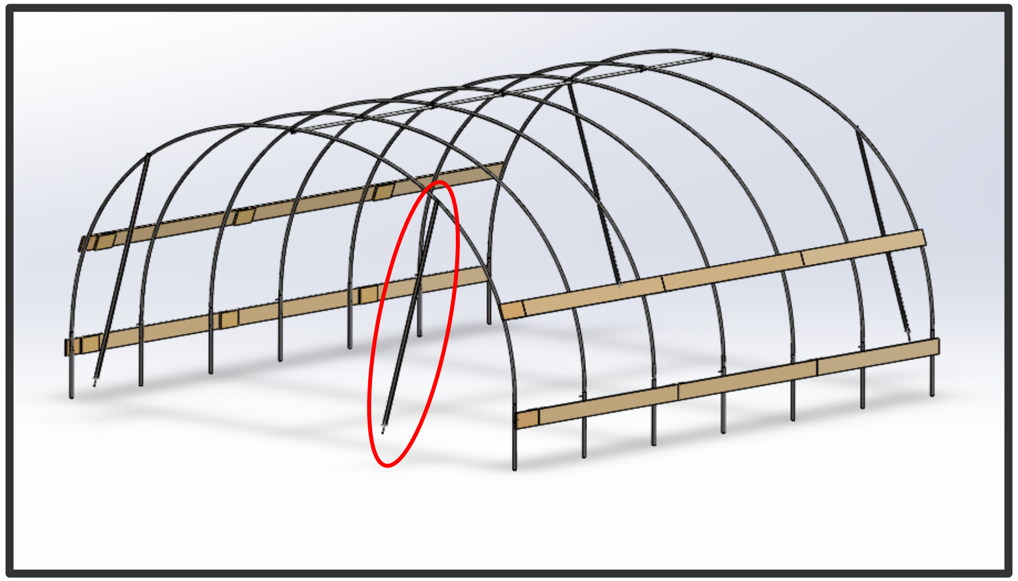
$$Bending\ Stress = \frac{M*OD}{I*288} = 414{,}549\ psi$$

$$Yield\ Strength\ of\ Steel = 50{,}800\ psi$$



The wind load on the face of the front and back of the hoop house was assumed to be the worst load on the 17 gauge pipes. For this reason, the bending stress on the pipe was calculated and analyzed. Unfortunately the bending stress was much higher than the yield strength of the steel we used. To ensure this would not be a problem, earth anchors were added to the design.

Appendix J – Earth Anchor Analysis



Earth Anchors Attached to Hoop

$Pull\ out\ force\ (F) = 600\ lbf$

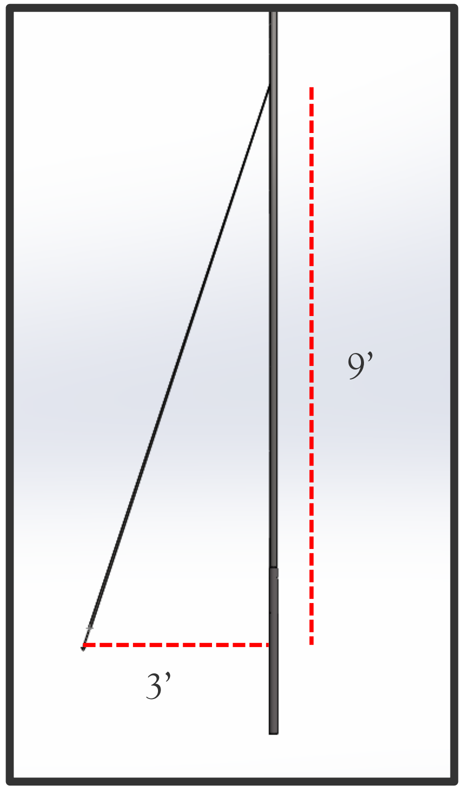
$Vertical\ distance\ (y) = 9\ ft$

$Horizontal\ distance = 3\ ft$

$$Angle\ (a) = \tan^{-1}\frac{9}{3} = 71.5°$$

$$Horizontal\ force\ (x) = f * \cos(a) = 189.7\ lbf$$

$$Reaction\ moment = x * y\ = 1707.6\ lbf * ft$$



Placement of Earth Anchor in Reference to Hoop

With four earth anchors set up in the position shown, the hoops would be able to withstand the worst wind speeds in Paxton, MA. The moment created on each pipe is 1,210.6 lbf*ft and the earth anchors can react up to 1,707.6 lbf*ft.