University of Ottawa
Faculty of Engineering

GNG 5140 Engineering Design

Project Deliverable D: Initial Prototype Analysis and Test Results

Group 4 – Sustainable Food Storage

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Abstract

This report investigates and analyzes an existing prototype for food storage in Eastern Canada: an above-ground vegetable root cellar designed by a local grassroots organization called Deep Roots Food Hub. The report documents the creation of the initial prototype. The team then tests each design to compare the performance against target specifications. Based on these results, the team listed out potential fixes to further improve the prototype. A bill of materials table is also provided.

Table of Contents

List of Figures

List of Tables

List of Acronyms

Acronym	Definition
DRFH	Deep Roots Food Hub
HVAC	Heating, Ventilation, and Air Conditioning

1 Introduction

Higher temperatures, water scarcity, extreme events like droughts and floods, and greater CO_2 concentrations in the atmosphere have already begun to impact staple crops around the world [1]. Maize (corn) and wheat production have declined in recent years due to extreme weather events, plant diseases, and an overall increase in water scarcity [1]. The threat of the varying global climate has greatly driven the attention of scientists, as these variations are imparting negative impact on global crop production and compromising food security worldwide [2].

As discussed, climate change poses an eminent threat to growing our crops and sustaining our population's food consumption. With climate change reducing harvests, this means that the lean period (skipping one or more meals a day to reduce food consumption) may be extended if there are fewer supplies, or if it takes longer to get an adequate harvest. In many food-insecure areas, such as Eastern Canada, agriculture and food production is seasonal (during the Summer and Fall seasons); leaving the population to rely on the harvests for the Winter and Spring seasons. However, the harvests from our local farmers are not enough to sustain the current population of Easter Canada during these seasons. Therefore, a lot of the food we consume has to be imported from warmer climates.

The aforementioned factors are motivators for a working, all-year round crop storage. Providing long-term storage for crops in a well-designed environment will decrease the likelihood of having to extend the lean period, and thus, have enough crops available. This will sustain a controlled population during foreseeably harsher climate conditions and moments of uncertainty, which can include an increase in food prices due to a lower production and higher demand.

The Deep Roots Food Hub (DRFH) is a grassroots, West Carleton-based non-profit organization that aims to create a secure, sustainable food system in West Carleton, Ontario [3]. This system is in the form of a prototype root cellar (see Figure 1).

Figure 1. Root cellar exterior (February 2020).

This above-ground cellar and off-grid storage structure provides small-scale vegetable growers with a post-season sustainable and energy-efficient storage facility, providing longer root crop storage and extended sales and/or distribution possibilities [3]. Prior to bringing this prototype design to life in the West-Carleton area, there wasn't a community-based storage space for local root crops. This innovative Quonset-styled metal building is designed to capture and circulate ground-sourced geothermal heat to maintain a near-constant + 2°C temperature and 90-95% humidity within the structure's root storage chamber [3].

There are other more traditional methods of prolonging root crops such as: freezing, canning, and dehydrating. However, these methods involve having to thaw them in order to be readily edible (in the case of freezing), or are laborious in practice (such as the case of canning, which must be done to some root vegetables because of their low acid content).

The controlled environment in the root cellar is better at providing fresher and readily-available foods (no waiting for food to thaw – which could take hours depending on the environment), and extending the life of root crops.

The main objective of this report is to document the creation of initial prototypes and their test results. This will help us better understand the prototype's performance and flaws and generates the opportunity towards the final prototype. This report will discuss in detail the creation of the prototypes, the testing results against target specifications, and updated project plan for the next deliverable.

2 Global Solution Concept

2.1 Physical prototype

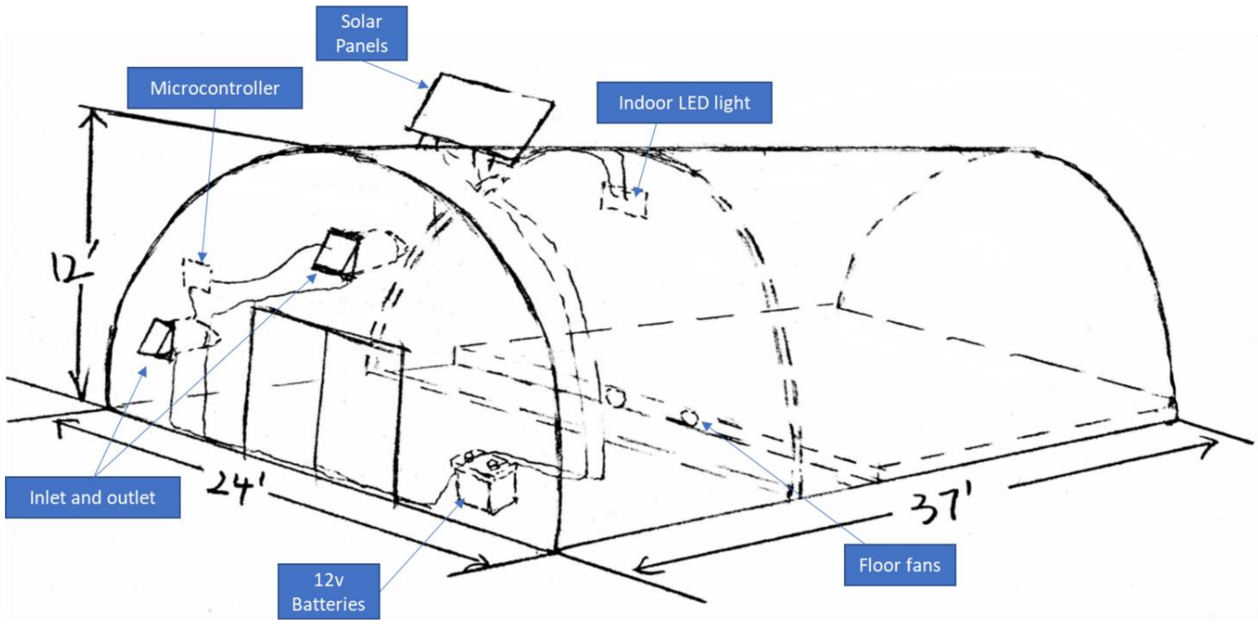


Figure 2. 3D view of the root cellar (detailed visuals of storage shelves, insulations, ice chamber are in section 3)

The above picture shows 3D visual of the overall prototype, due to limited space, the detailed visuals of food storage, wall insulations, and heating/cooling elements are included in the section 3. The prototype uses galvanized steel for the structure, and they are connected by using pins and rivets. A dividing wall separates the inner space into two sections, the front is an antechamber for equipment storage, and the back is the produce chamber. As agreed with the client, the teams focus will be mainly on the storage method improvement, and the control system is neglected because the current one works very well. Therefore, only the description for control system and its connection with power system are given here. Solar panels are set on the top to provide green energy, and they are connected to vehicle batteries inside the antechamber to store power. On the front wall, a microcontroller is mounted on it to control inlet, outlet, fans, and all sensors inside the chamber. All electrical wires are taped on the wall to avoid tangling. The intake air fan from outside will run if the outside air is cooler than the inside air, but only if the inside air is above the target range, and the outlet fan exhausts the warm air from inside. The floor fans are only turned on when indoor temperature is below targeting range and the underfloor temperature is between or above the range. To efficiently use the produce chamber space, several food storage methods are proposed and compared in section 3. In addition, the next section also has a detailed verification of the picked insulation materials, and heating and cooling elements, which are crucial for keeping the indoor temperature in range.

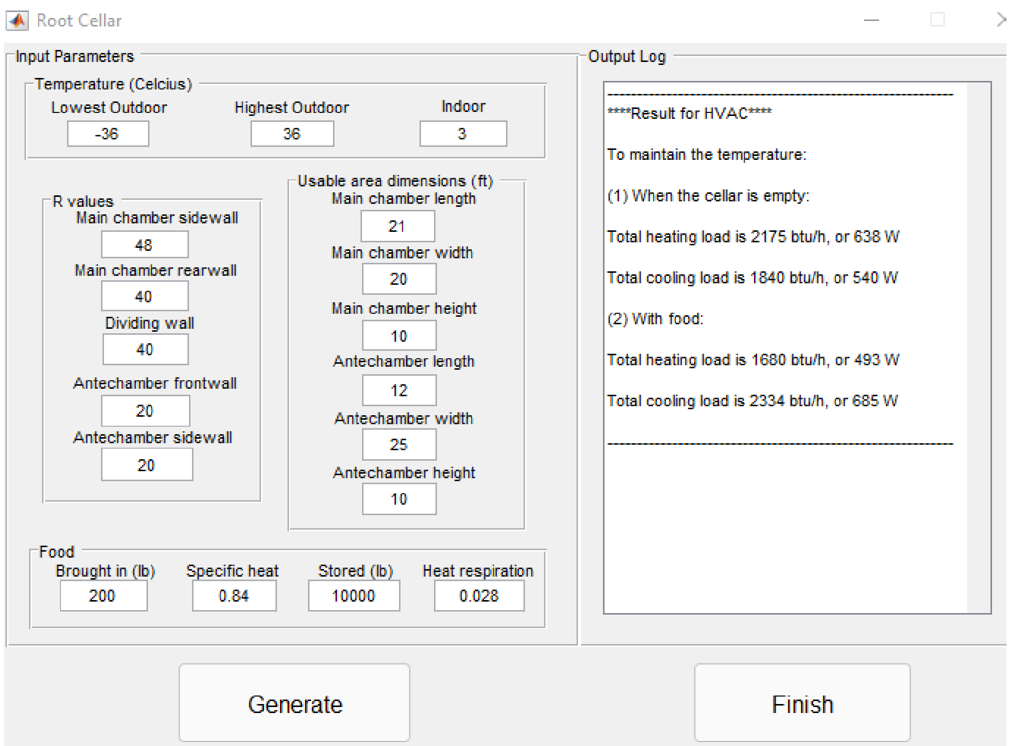


Figure 3. GUI of the food storage design software.

Due to the exclusion of the control system, the project does not involve software prototype development. However, as shown in the above figure, a MATLAB software is developed to simplify the future analysis of the HVAC and power consumption, this is included in this section because the software is made to assist the physical prototype design. This tool can also be utilized to help the client choose materials and heaters for his future food storage projects.

3 Prototype and Test

The dimensions of the root cellar were calculated in Project Deliverable D and are summarized in Table 1. Because these numbers were retrieved from 3 sources, we assumed an average value for all three dimensions (width, length, and height). These values are summarized in Table 2.

Table 1. Dimensions of the root cellar according to three sources. Dimensions are listed in feet units as W, L, and H, which stand for width, length, and height. Some cells are empty because the value was not stated in the source(s).

Source	Main produce chamber (usable food storage area)				Entrance/Antechamber (utilities, air inlet and outlets, and storage batteries housed here)				Entire root cellar (main produce chamber + antechamber)			
	W	L	H	Total (sqft)	W	L	H	Total (sqft)	W	L	H	Total (sqft)
DRFH website [3]	21	20		400	25	12		300				
Informative video speech [5]		24				12			37	24	12	10,656
Slides from informative video [6]						10			40	24	10	9,600

Table 2. Average dimension values for the main produce chamber, entrance/antechamber, and entire root cellar. Dimensions are listed in feet units as W, L, and H, which stand for width, length, and height.

Main produce chamber (usable food storage area)				Entrance/Antechamber (utilities, air inlet and outlets, and storage batteries housed here)				Entire root cellar (main produce chamber + antechamber)			
W	L	H	Total (sqft)	W	L	H	Total (sqft)	W	L	H	Total (sqft)
21	22	11	**5,082**	25	11.4	11	**3,135**	38.5	24	11	**10,164**

From the dimensions in Table 2, we had estimated that in the main produce chamber (the only place in the root cellar where the produce will be stored), there is enough space for 24 plywood boxes (see Figures 4-6). Since each plywood box can hold 16 coroplast boxes, that brings the total coroplast boxes to 384. Each coroplast box can store 18-24 kg of produce. If we take the average (21 kg), all the coroplast boxes can hold up to 8,064 kg of produce. Barry has mentioned that he estimates the cellar can hold 50,000 kg of food. So, this design is not sufficient as it can only support about 16% of the aforementioned.

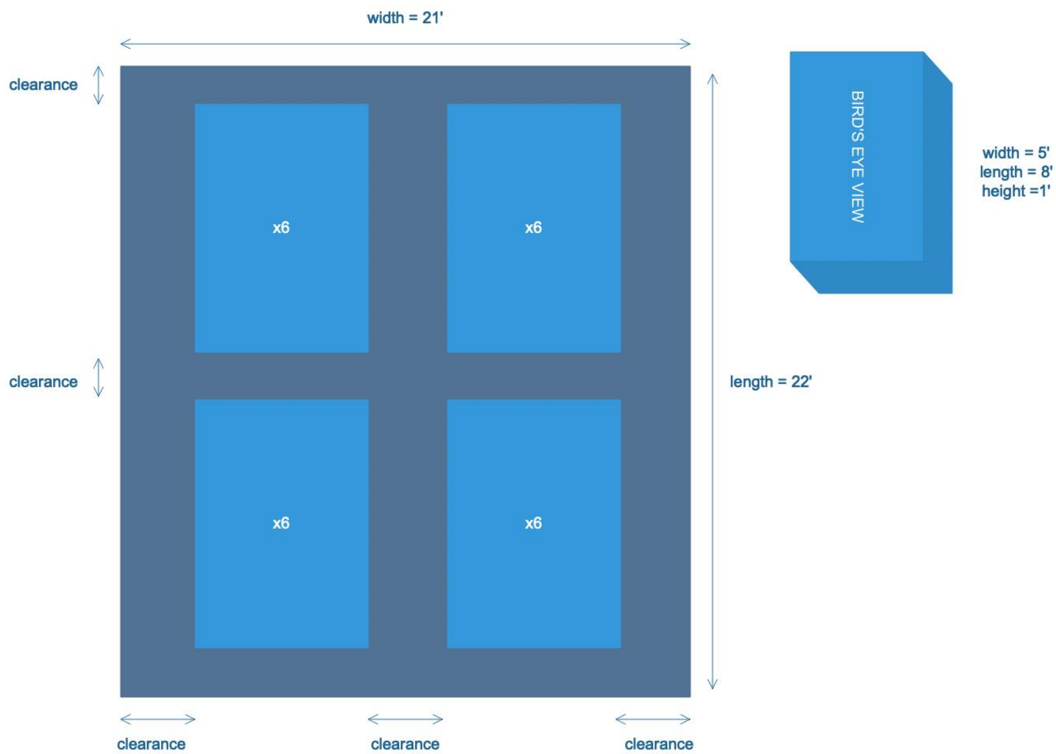


Figure 4. Bird's eye view of the produce chamber. The light blue boxes with 'x6' are 6 individual plywood boxes stacked. The dimensions of 1 plywood box are on the right of the diagram.

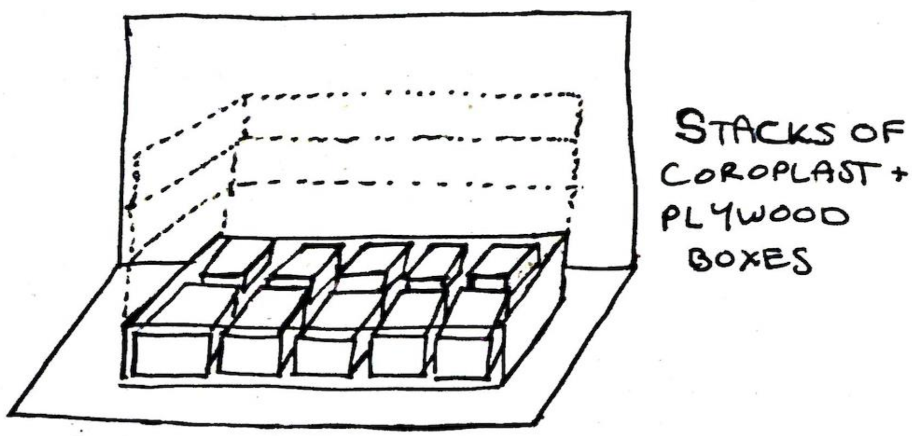


Figure 5. Sketch of the plywood box with space for coroplast boxes. The dashed lines represent the other plywood boxes that would be stacked.

Figure 6. Plywood box with coroplast boxes inside. The box is located near the back of the root cellar.

To increase this percentage and get closer to 100% (which represents 50,000kg, or full capacity), the team came up with 3 innovative solutions, which will be further analyzed and compared against the appropriate criteria in the next project deliverable.

3.1 Storage Solution #1

One of the goals of the space is the ability to safely access and retrieve the produce. This has to be achieved by leaving a significant amount of free space for people to move around and carry boxes. Having empty, unusable space, wastes a lot of potential space for storing. There are systems that have racks that can slide; these systems can store up to 75% more material as you gain valuable storage space when stacking racks side-by side (with no gap between them), and leave enough empty room on the system for the racks to be pushed laterally. These systems also provide easy-access to any of the material stored on the racks. After some research, we found 2 companies that offer the system we had envisioned: Levrack (see Figure 7) and Space-Trac (see Figure 8).

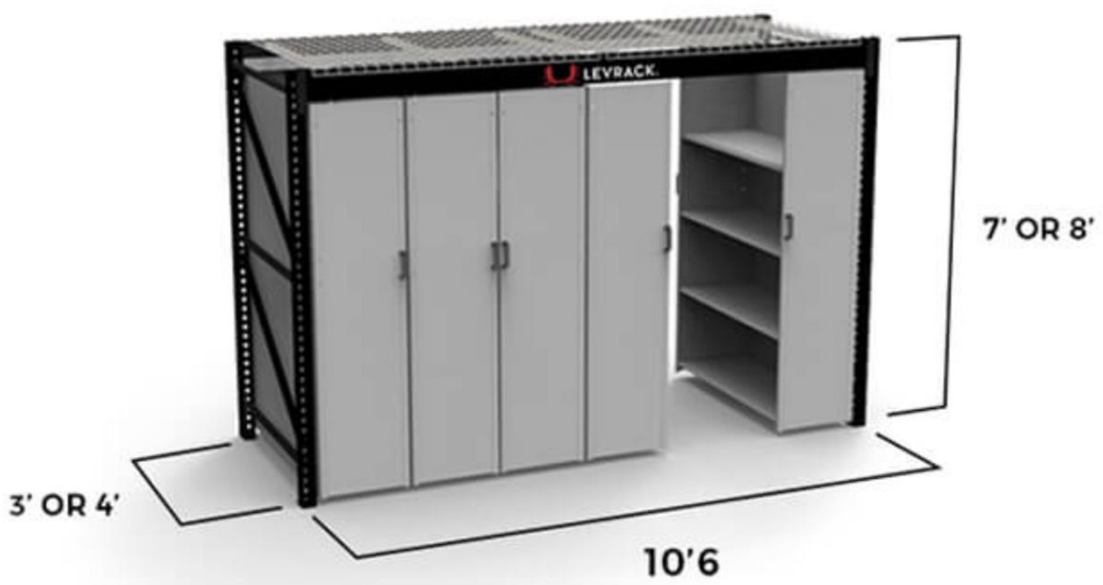


Figure 7. Levrack sliding storage racks system.

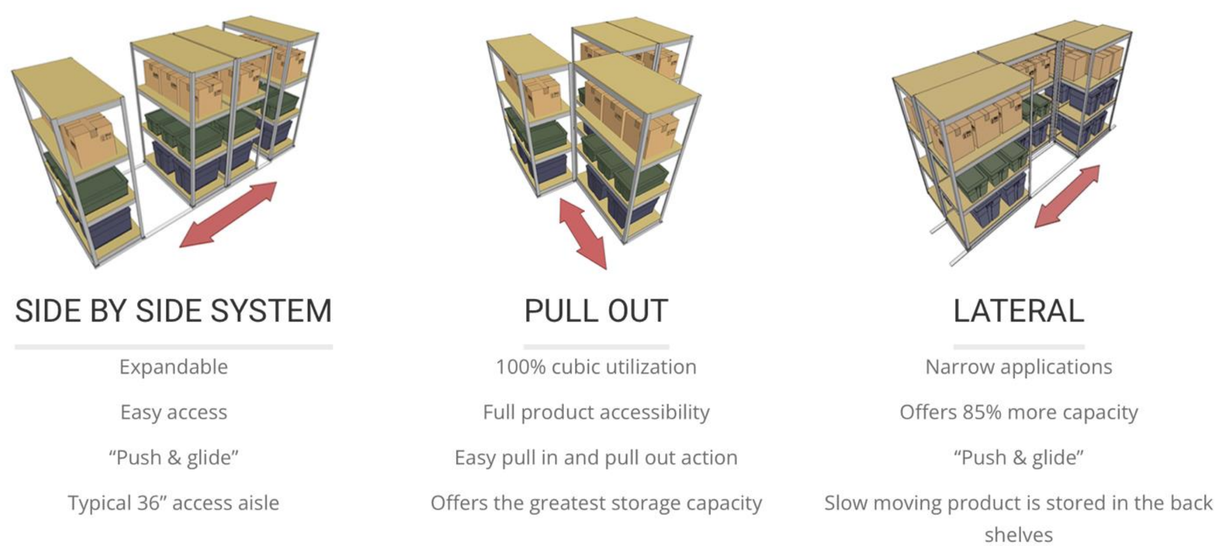


Figure 8. Three configurations of Space-Trac Nexel Wire Shelving.

Both systems provide the extra storage needed while maintaining easy-access to the produce. A table summarizing some of the cost, and the pros and cons of the two systems can be found below (see Table 3).

Table 3. Comparison of the pros, cons, and cost of the two sliding rack systems: Levrack and Space-Trac.

	Levrack	**Space-Trac**
Pros	- Easy to assemble - Sturdy - Sliding rack system - Floor to ceiling system - Can store things on top	- Comes in different designs: lateral model (best for a square area), side-by-side model, pull-out model - Easy to install - Open shelving (no metal sheets) - Additional rack models can be used. i.e. standard/universal shelves can be used with this system. - More robust
Cons	- Not open-concept - Racks are covered on the sides by a metal sheet (less air flow for distributions of hot/cold air)	- Maybe less sturdy since it's not floor to ceiling? - Only floor rails
Cost	The cost varies on the size of system you get. For example: $4000 USD for an 8-foot storage (equivalent to 16 equivalent linear feet)	- $118-188 per unit (sliding rail system for one rack)
Company Website	https://www.levrack.com/product/10ft-levrack/	http://www.space-trac.com/product-overviewhome-2.html

With this design, the estimated amount of produce that can be stored will be higher than the in the initial design (see section 3.1) given that there is less of a need to leave "hallways" or empty space for people to walk through the racks. Instead, the racks can be side-by-side ("sandwiched") and only moved when something needs to be accessed. This design will be compared against the other designs mentioned in this report and a final design will be chosen in the next project deliverable. The aforementioned design could be a combination of the best ideas found in each of the three designs presented in this report.

3.2 Storage Solution #2

Introduction:

The storage is designed to optimize the space in the root cellar. The storage is designed with a slight curve to utilize the curvature of the root cellar and optimize space.

Prototype:

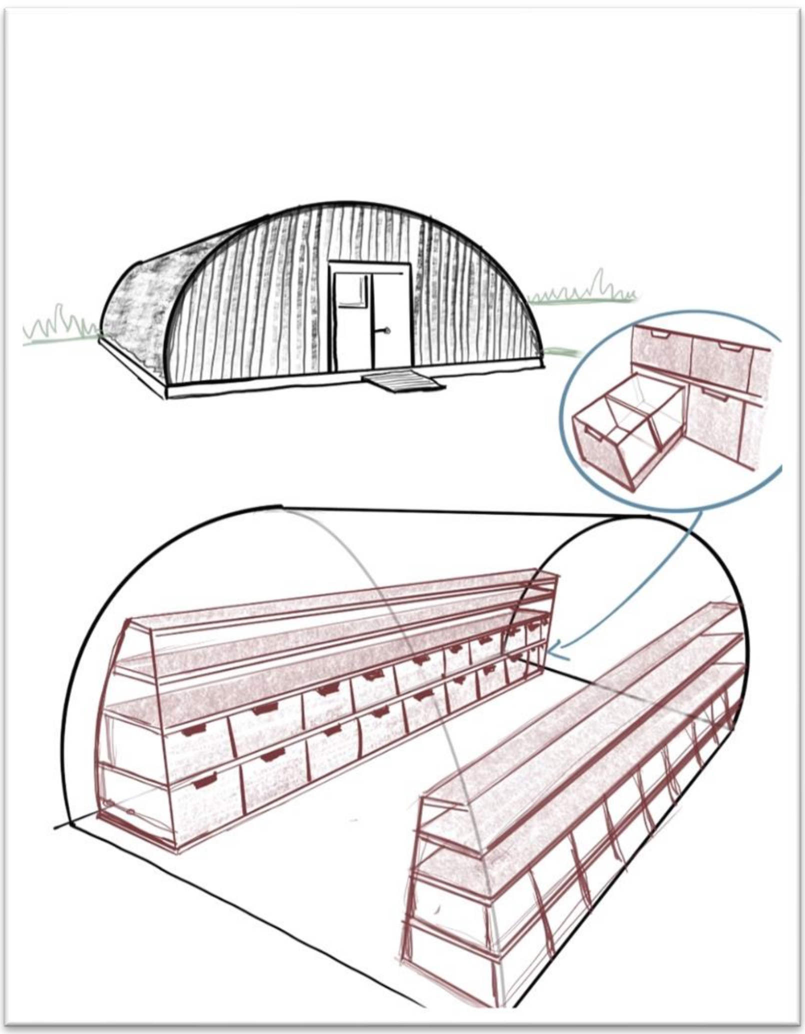


Figure 9. Design view of the cellar.

Features of this root cellar:

1. Curve-shaped shelves to accommodate more food as per the root cellar design.
2. Drawers has been made in the lower to shelves to easily access the food stored.
3. Open selves at the top to stack more food
4. A rack in the middle to store more food and access it from both the ends.
5. Enough space to walk around.

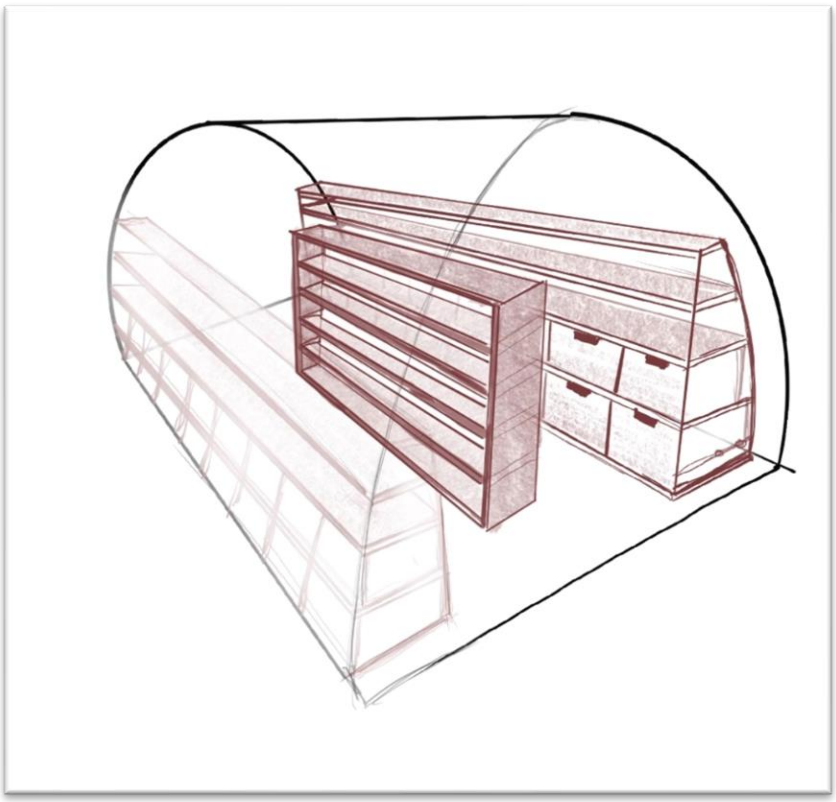


Figure 10. Design view of the shelves.

3.3 Storage Solution #3

A few tips for cluttering in the cellar:

To relieve the pressure on Barry and his team, volunteers can be found to share some of the day-to-day work in the cellar.

Volunteer a is responsible for the management of the daily work of the cellar, the management of warehouse entry and exit, and is responsible for the inventory materials. And through SharePoint Excel, the real-time material status in the cellar is reflected to Barry. Volunteer b is responsible for cellar management products in and out of the warehouse. Volunteer c is responsible for the identification of products in stock. Different kinds of products need to be classified and labeled. Volunteer d is responsible for checking the products entering and leaving the cellar, and also ensures that the products in the cellar are not lost. Volunteer e is responsible for the sanitation of the cellar. Clean up the garbage in the cellar in time to save space for more food that needs to be stored.

In addition, the arrangement of the shelves in the cellar can also be designed. During the design process, the following principles were followed:

1. The basement shelf has a large bearing capacity, is not easily deformed, is reliable in connection, and is easy to disassemble and assemble;

2. The three-dimensional structure can make full use of the warehouse space, improve the utilization rate of warehouse capacity, and expand the storage capacity of the cellar; The goods are easy to access and can be first in first out;

3. To meet the storage and centralized management needs of large quantities of goods and a wide variety of products, and with mechanical handling tools, the storage and handling work can also be stored in an orderly manner;

4. The goods stored in the shelves do not squeeze each other.

Therefore, in this design, the material of the shelf is made of stainless steel. The column of the shelf is made of C-shaped steel, and the column piece is equipped with transverse braces and diagonal braces, and the laminates fall on 2 P-beams, which have a larger force area, and their stability and bearing capacity are relatively strong, suitable for storage. food products.

The rack adopts the structure of the column piece and the beam hanging, all of which are plug-in combined type, with simple structure and convenient installation and disassembly. The material is of good quality but expensive. According to the topography of the cellar, it is designed as two rows of shelves on the left and right, leaving an aisle for the staff to walk in the middle. The shelves are designed to be easy to install and remove. Each column of shelves is divided into upper, middle and lower layers. The height of each layer is 3 feet, and the load capacity of each layer is 2500-8000kg. Shelves are 7 feet wide and 15 feet long. The reason why the shelves are divided into left and right columns is that different temperature and humidity can be designed according to the food types according to the left and right shelf areas. For example, fruits and vegetables have different humidity requirements. The reason for designing different layers of shelves is that different vegetables can be classified according to the label, which is convenient for future search.

Figure 11. Detailed view of the shelves in the cellar.

3.4 HVAC

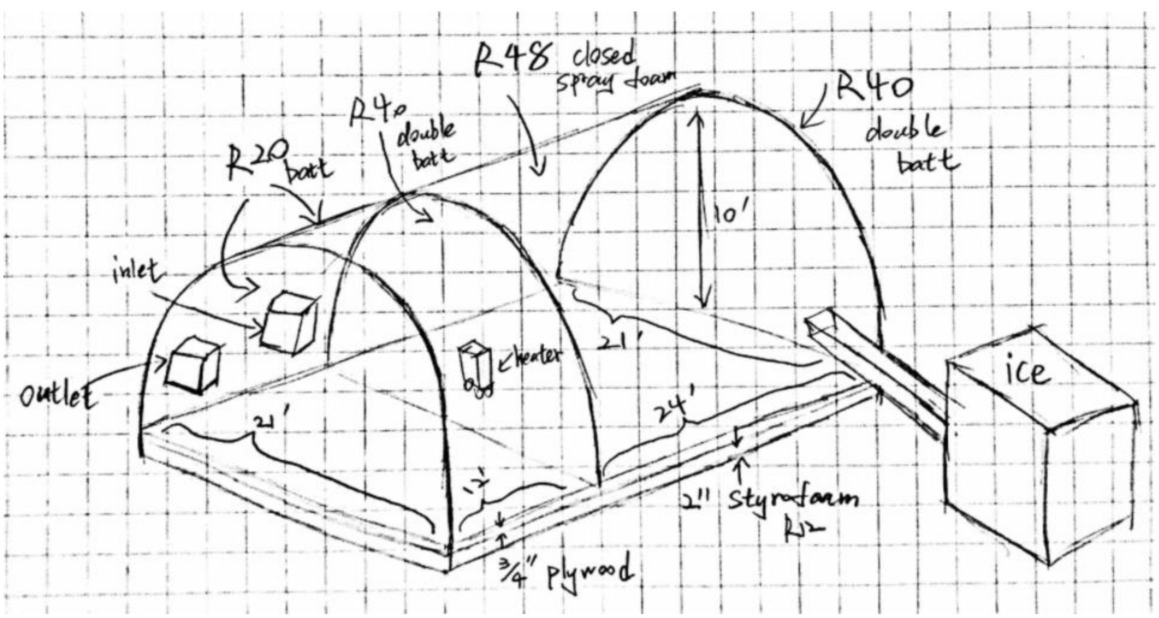


Figure 12. Detailed view of the HVAC system.

The main component of HVAC is wall insulation, but regardless of how well the root cellar is insulated, there will always be some heat conduction. Therefore, after determining the heat transfer from walls in winter and summer, additional heating and cooling elements shall be added to compensate the heat gain/loss so that the indoor temperature can stay between 2-4^{o}C. For ventilation purpose, the root cellar also has air inlet and outlet on the front wall. When the outside temperature is cooler than inside (and indoor temperature > 4 ^{o}C), both ports will be turned on until the room temperature stabilizes, this method is normally used during warm winter evenings. For hotter days, client will turn on a DIYed strawbale ice chamber to blow cold air into the chamber. The ice chamber contains 2000 pounds of ice, and it is insulated with R60 straw bale. As shown in Figure 13, warm air from outside and produce chamber is let into the ice chamber to get cooled before being fed into the produce chamber. For heating in winter, two 250W heaters are selected.

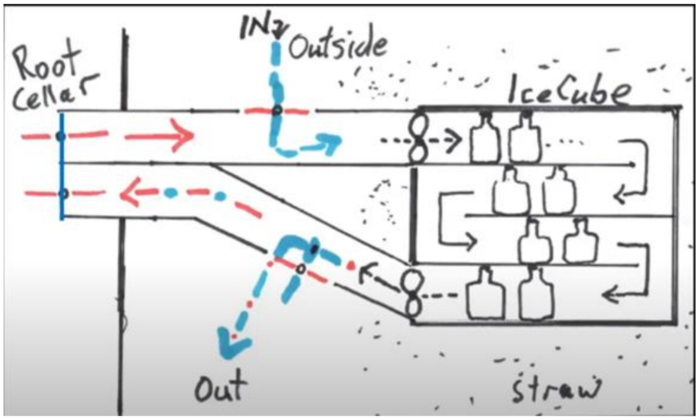


Figure 13. Schematic of the ice chamber.

Figure 12 shows the insulation materials being used on each wall. The insulation is R40 (double batt) for the rear wall and the wall dividing the main chamber from the antechamber. The front wall and side walls are R20 in the antechamber. The spray foam (8 inches thick) is about R 48, on the side walls of the produce chamber only. The gravel and the produce chamber are separated by

8’’ tall concrete bricks, R12 Styrofoam pads, and ¾’’ plywood. The construction material for the hard wall is 1/8’’ galvanized steel. Figure 14 shows that the insulations are installed on the hard wall by using metal and plastic pins.

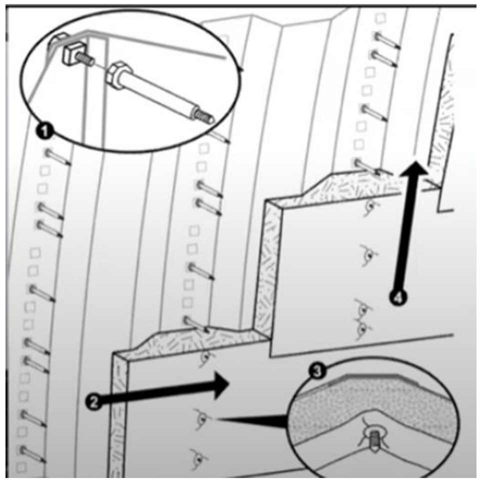


Figure 14. Wall insulation installation.

Due to the size of insulation materials, the actual usable area is less than the outside dimensions:

Outside dimensions: 37’(L) x 24’(W) x12’(H)

Produce chamber usable area dimension: 24’x 21’x 10’

Antechamber usable area dimension: 12’x 21’x 10’

3.5 Test Result #2 (Storage)

1. Space between the shelves: To test this parameter I am planning to make a CAD design and put some stimulations to verify that the space is enough for people to walk around.

2. Depth of shelf: This can be tested by making some calculation on the volume available to put stuffs. We can make a detailed CAD design and test this parameter.

3. Bottom shelve is large enough: We can consider the dimension of buckets client is planning to keep here.

3.6 Test Result #3 (Storage)

The load capacity of each layer is 2500-8000kg. According to its maximum carrying weight, the carrying weight of each layer is 8000kg, and the total carrying weight of the left and right rows of goods is 48000kg. If the estimated cargo volume is 50,000k, we multiply it by a factor of 1.2 to get 60,000kg as the ideal weight that the shelf should carry. The 48000kg we designed is 80% of the 60000kg, which basically meets the design requirements.

3.7 Test result #3 (HAVC)

Heating and cooling loads:

This part verifies the effectiveness of wall insulation by calculating the heat being transferred in some extreme temperature conditions. The whole calculation process is documented because it was later used for developing a HVAC design software to simplify the computation process.

Assumptions:

- Desired room temperature: 2 - 4 ^{o}C, here use 3 ^{o}C or 37.5^{o}F
- Relative humidity: 90% - 98%
- Outside temperature: -36 ^{o}C ~ 36 ^{o}C
- Elevation 236ft (average elevation in Ottawa), ignore air correction factor because it is nearly 1
- Heat from lighting is ignored because it is rarely turned on

- Heat from people is ignored because the client only visits the chamber for short period of time
- Fenestration is none because the structure is well insulated from inside
- 500 lbs of potatoes are brought in
- 10000 lbs of potatoes are already stored in the chamber

Heat gains to be calculated:

1. field heat from food (food just brought in) qc1
2. heat of respiration from food (already stored food) qc2
3. heat through walls qc3
4. heat through the floor qc4

- Field heat qc1

The first source of heat is the warm produce brought into the cooling facility. The heat energy it contains is called field heat. Assume food is brought into the root cellar at an average temperature of 20 ^{o}C or 68 ^{o}F, and it takes 24 hours to cool it down. The formula is:

$$qc1 = SH\ (Btu/lb/F) \times DT\ (F) \times W\ (lb) / H,$$

where SH is the specific heat of the food (numbers can be found in Appendix A), DT is the temperature difference, W is weight of the food, H is hours to cool down the food.

$$qc1 = 0.84 * (68 - 37.5) * 500 / 24 = 533.75\ Btu/h = 156.42W$$

- Heat respiration qc2

The second source of heat is the respiration of the crop itself. Horticultural crops are alive and give off heat as they respire. Note that this value is different for warm and cold crops, and less refrigeration is required to remove the heat of respiration when produce is cool than when it is warm. Here the stored potatoes are already at 3 ^{o}C, so cold heat respiration value is used.

$$qc2 = HR(Btu/h/lb) * W(lb),$$

where HR is heat respiration of a food, and W is the weight.

$$qc2 = 0.028 * 10000 = 280 \text{ Btu/h} = 82W$$

- Heat through wall qc3

Here only the temperature in the produce chamber is considered, so the antechamber is seen as a multi-layered wall with an air gap in the following calculation. Note that R value unit is ft2·°F·h/BTU for commercial insulation materials in North America, divide it by 5.678 to get SI unit m2·K/W. The specification of each insulation materials has already been given in the prototype section. Heat load from wall:

$$q = U(Btu/h/(ft^2*F)) * A(ft^2) * T(°F),$$

U is materials' u factor, it is an inverse of thermal resistance. A is the wall surface area, T is temperature difference.

To find the total qc3, three sections are considered, they are front wall to dividing wall, produce chamber side wall, and produce chamber rear wall. And the first one is comprised of the front wall, the whole antechamber, and the dividing wall.

- Front wall + antechamber + dividing wall

$$U_{fw} = 1/(R_{si} + R1 + R2 + R3 + R4 + R5 + R_{so})$$

Rsi is inside surface thermal resistance 0.12 $m^2 \cdot K/W$ = 0.68136 $ft^2 \cdot °F \cdot h/BTU$

Rso is outside wall surface thermal resistance 0.06 $m^2 \cdot K/W$ = 0.34068 $ft^2 \cdot °F \cdot h/BTU$

R1 is the thermal resistance of 1/8'' galvanized steel wall = length/thermal conductivity = 0.00318m / 52 (W/m*k) = 0.0000612 $m^2 \cdot K/W$ = 0.000347 $ft^2 \cdot °F \cdot h/BTU$

R2 is the R20 batt insulation = 20 $ft^2 \cdot °F \cdot h/BTU$

R3 is the thermal resistance of the usable area of the antechamber (air) = 3.6576m / 0.024(W/m*k) = 152.4 $m^2 \cdot K/W$ = 865.3272 $ft^2 \cdot °F \cdot h/BTU$

R4 is another galvanized steel wall used for the dividing wall = 0.000347 ft2·°F·h/BTU

R5 is the R40 batt insulation on the second wall = 40 $ft^2 \cdot °F \cdot h/BTU$

Ufw = 0.0011 Btu/h/(ft^2*F)

- Produce chamber side wall

$$U_{sw} = 1 / (R_{si} + R1 + R2 + R_{so})$$

Rsi is 0.68136 $ft^2 \cdot °F \cdot h/BTU$

Rso is 0.34068 $ft^2 \cdot °F \cdot h/BTU$

R1 is the thermal resistance of 1/8'' galvanized steel wall = 0.000347 $ft^2 \cdot °F \cdot h/BTU$

R2 is the R48 closed spray foam insulation = 48 $ft^2 \cdot °F \cdot h/BTU$

Usw = 0.0204 Btu/h/(ft^2*F)

- Produce chamber rear wall

$$Urw = 1 / (Rsi + R1 + R2 + Rso)$$

Rsi is 0.68136 ft2·°F·h/BTU

Rso is 0.34068 ft2·°F·h/BTU

R1 is galvanized steel = 0.000347 ft^2·°F·h/BTU

R2 is R40 batted insulation = 40 ft^2·°F·h/BTU

Urw = 0.0244 Btu/h/(ft^2*F)

For wall areas, assume the cross section of the chamber is an ellipse, use the usable area dimensions for calculation (ellipse's perimeter is estimated by using Ramanujan's formula):

Afw = pi*21*10/2 = 329.87 ft2

Asw = 100.47/2*24 = 1205.62 ft2

Arw = pi*21*10/2 = 329.87 ft2

qc3 = (Ufw * Afw + Usw * Asw + Urw * Arw) * TD

Winter: qc3 = 2320.35 Btu/h = 680W (from inside to outside)

Summer: qc3 = 1957.49 Btu/h = 575W (from outside to inside)

- Heat from floor:

The reported under floor temperature is constantly at around 3 ^{o}C, which means that the heat transfer between floor and chamber is 0 if the chamber is maintained at 3^{o}C, but the actual under floor temperature during different seasons still needs more investigation. Therefore, the calculation steps are included here for future testing use.

$$Uf = 1 / (Rsi + R1 + R2 + Rso)$$

Rsi and Rso are the same as previous part.

R1 is the thermal resistance of ¾'' plywood floor, the thermal conductivity is 0.1154 (W/m*k), so the R1 is = 0.01905/0.1154 = 0.165 $m^2\cdot K/W$ = 0.937 $ft^2\cdot°F\cdot h/BTU$

R2 is the thermal resistance of styrofoam which is 12 $ft^2\cdot°F\cdot h/BTU$

Uf = 0.072 Btu/h/(ft^2*F)

Qc4 = Uf * Af * TD = 0

- Total heat transfer:

$$Q\ winter = -(qc1 + qc2) + qc3 + qc4 = 442W$$

$$Q\ summer = qc1 + qc2 + qc3 + qc4 = 813W$$

Ice chamber:

The storage size is 6'x6'x6' and it is constructed by using ¾'' plywood. The outside is insulated by using 7.5cm thick straw bales, which equals to R60 thermal resistance. 2000 pounds (or 907.2kg) of water is already frozen in plastic containers. For the simplicity of finding the minimum time before ice completely melts into water, it is assumed to be at 0^oC (or 32 ^oF) and only the heat of fusion is considered.

Other assumptions:

- ice chamber is turned on during a warm winter day, daytime temperature is at 5^oC (or 41^oF), evening temperature is at -2^oC
- the produce chamber air enters the duct at 4^oC, it then mixes with outside air before entering the ice chamber.
- the air is supplied at 1750CFM. It is impossible to predict the volumes of airflow from two inlets without using proper measurement tool, so the mixed air temperature is assumed to be at 4.5^oC, and it leaves the ice chamber at 3.5^oC.
- The heat transfer process is isochoric because the volume of air being fed is constant, so the heat capacity of air is about 0.717 kJ/(kg ^oC).

Here, there are two heat gains to calculate: one is heat absorption from the intake air, and the other one is heat absorption from the outside.

- Intake air:

Stored ice volume = 907.2 (kg) / 0.917 (kg/m^3) = 0.987 m^3 = 34.86 ft^3.

Volumetric flow rate of air = 1750CFM = 0.826 m^3/s

Mass flow rate of air = 0.826 (m^3/s) * 1.273 (kg/m^3) = 1.05 kg/s

Heat gain from intake air q1 = mass flow rate * heat capacity * temperature difference =

1.05 (kg/s) * 0.717 kJ/(kg ^{o}C) * (4.5 - 3.5 ^{o}C) = 0.752kJ/s = 752W

- Outside air:

$$U = 1 / (Rsi + R1 + R2 + Rso)$$

Same as before,

Rsi is 0.68136 ft2·°F·h/BTU

Rso is 0.34068 ft2·°F·h/BTU

R1 is the R60 straw bale

R2 is the thermal resistance of ¾'' plywood floor which is 0.937 ft^{2}·°F·h/BTU.

U = 0.0161 Btu/h/(ft^{2}*F)

The contact area with outside air is A = 6*6*6 = 216ft^{2}

q2 = 216ft^{2} * 0.0161 Btu/h/(ft^{2}*F) * (41F-32F) = 31.3 Btu/h = 9.17W

- Time it takes to melt the ice:

To melt the ice, the total heat absorption is = weight of ice * heat of fusion = 907.2kg * 333.55 kJ/kg = 302596000 J

Time = heat absorption / (q1+q2) = 302596000 / 761.17 = 397541s = 110.4 hours

This means that it would take 4-5 days to completely melt the ice when the outdoor temperature is constantly at 5^{o}C, and at the same time the produce chamber is kept at below 4^{o}C. Compare the intake air heat gain and the summer heat gain from previous section, it shows that the ice chamber works well for cooling.

3.8 Results comparison (modify the table, add your own metrics accordingly)

Table 4. Results comparison.

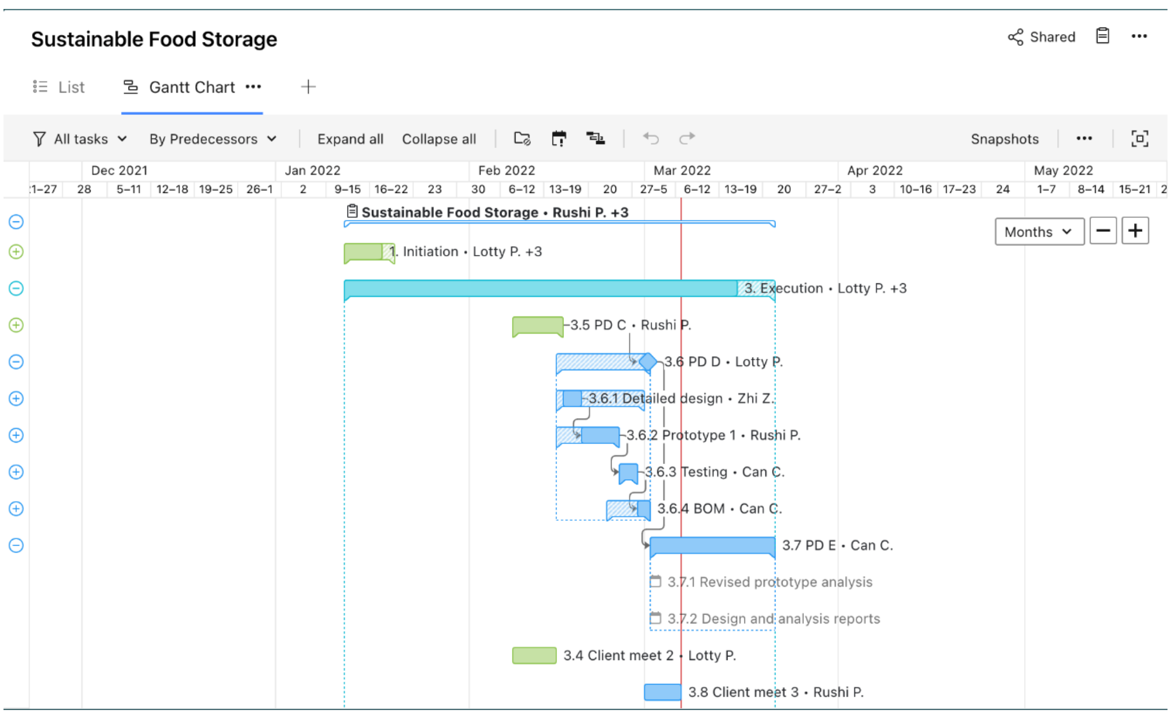
	Metrics	Unit	Expected Value	Tested Value and Comments
1	Temperature	Celsius (°C)	2-4	Hard to maintain at above 3 in winter, but easy to stay below 4 in summer. The wall insulation needs improvement to reduce heat loss in winter.
3	Power Generation	Watts (W)	>500	
4	Storage Capacity	Tons	>150,000	
5	Off-grid time	Hours (hr)	>72	
6	Cost	Canadian ($)	<20000	
7	Total storage area after shelves being installed	Ft^2	>20	
8	Maximum power usage	Watts (W)	<500	Uses > 600W for cold winter days, the heater uses more power than current system can provide.

3.9 Bill of materials

Table 5. Bill of materials.

Name	Amount	Unit cost (CAD)	Total cost (CAD)
1750CFM Fans [7]	6	30	180
R48 closed cell foam [8]	1205.62 ft2	Needs quote	Estimated 10700
R40 double batt [9]	659.74 ft2	2.30 per ft2	1517.40
R20 batt [10]	989.61 ft2	1.03 per ft2	1019.30
R12 Styrofoam [11]	504 ft2	2.66 per ft2	1340.64
¾'' plywood [12]	800 ft2	3.09 per ft2	2474.50
500w Heater [13]	1	44.99	44.99

4 Updated Project Plan



5 Conclusions and Recommendations for Future Work

In this project, the team made some suggestions for the cellar renovation based on the opinions given by the client. Recommendations are mainly for storage space and HVAC systems. There are three different proposals for storage space, each of which describes a new arrangement for the cellar. These methods serve the purpose of making the products in the cellar more orderly. However, the designed scheme cannot meet the storage requirements, and future research should focus on how to increase the space utilization in the cellar. In addition, the team performed calculations on the convective heat transfer system in the cellar, which showed that the walls dissipated most of the heat, and future research needs to strengthen the insulation.

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Appendix A

Table A.1. Specific heat and respiration for food

		Respiration (Btu/lb/hour)	
Commodity	Specific Heat (Btu/lb/°F)	Cool	Warm
Apples, summer	0.87	0.018	0.340
Apples, fall	0.87	0.012	0.240
Asparagus	0.94	0.245	2.523
Beans, butter	0.73	0.123	0.716
Beans, string	0.91	0.161	0.885
Beets, topped	0.90	0.028	0.092
Blueberries	0.86	0.028	0.748
Brambles	0.87	0.092	0.711
Broccoli	0.92	0.092	1.376
Cabbage	0.94	0.023	0.257
Cantaloupes	0.94	0.025	0.305
Cucumbers	0.97	0.119	0.170
Grapes	0.86	0.014	0.179
Green onions	0.91	0.096	0.704
Leafy greens	0.90	0.100	1.034
Okra	0.92	0.257	1.583
Peaches	0.91	0.023	0.466
Peas, garden	0.79	0.177	1.651
Peas, field	0.73	0.160	1.554
Peppers	0.94	0.046	0.252
Potatoes	0.84	0.028	0.055
Squash	0.95	0.161	0.751
Strawberries	0.92	0.069	0.872
Sweet corn	0.79	0.186	1.644