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Abstract

In many food-insecure areas, such as Eastern Canada, agriculture and food production is seasonal, leaving the population to rely on the Summer and Fall harvests for the Winter and Spring seasons. With the ever-present climate change, crop production is being threatened year-round, compromising food security worldwide but specially in places such as Eastern Canada, where food production is limited by the seasons and only possible for 6-7 months of the year.

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 examines the build materials and specifications, control of parameters (temperature, humidity, and more), current issues, and client needs. From the aforementioned, the team ranked the client's need(s) using the Importance Value metric. Based on these metrics and looking at alternative solutions, the team will determine the need(s) we will target to solve while satisfying both the client, and our existing constraints.

Table of Contents

Abstract.....	i
Table of Contents.....	ii
List of Figures.....	iv
List of Tables.....	v
List of Acronyms.....	vi
1 Introduction.....	1
2 Design Research.....	4
2.1 Design Status Review.....	4
2.1.1 Existing Materials Review.....	4
2.1.2 Existing Issues and Prototype Risks.....	7
2.1.3 User Needs.....	8
2.1.4 Critical Metrics.....	9
2.1.5 Outline of Improvements.....	10
2.2 Technical and User Benchmarking.....	11
2.2.1 Existing Products.....	11
2.2.2 User Perceptions.....	13
2.2.3 Additional Constraints.....	14
2.2.4 Target Specifications.....	15
2.3 Prototype Test Plan.....	15
2.3.1 Test Plan.....	15
2.3.2 Comparison Method.....	17
3 Conclusions and Recommendations for Future Work.....	18

Bibliography 20

List of Figures

Figure 1. Root cellar exterior (February 2020).....	2
Figure 2. Materials used in the root cellar	4

List of Tables

Table 1. User Needs.....	8
Table 2. Critical Metrics.	9
Table 3. Cellar insulation and performance index design.....	12
Table 4. User Perceptions.	13
Table 5. Target Specifications	15

List of Acronyms

Acronym	Definition
DRFH	Deep Roots Food Hub
R60 or R40	The R value is the capacity of an insulating material to resist heat flow. The higher the R-value, the greater the insulating property
W	Watts (a unit of measuring power)
Wi-Fi	Wireless Fidelity
HVAC	Heating, Ventilation, and Air Conditioning

1 Introduction

Higher temperatures, water scarcity, extreme events like droughts and floods, and greater CO₂ 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 Eastern 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 investigate and analyze the existing prototype to create a design status review. This review will help us better understand the client's situation and from there, we can define the client's current need(s) and conceptualize the solution(s). This report will discuss in detail the logic behind the design features of the root cellar, the methods of temperature and humidity control, performance and target specifications, existing issues that the client currently faces and some of the risks involved, client needs, alternative technologies and solutions, and a summary list of the defined metrics and constraints that may impede the design process.

2 Design Research

2.1 Design Status Review

This subsection contains a review of the existing prototype built by the client (see Figure 2). The information was gathered from the materials provided and from a meeting with the client.

2.1.1 Existing Materials Review

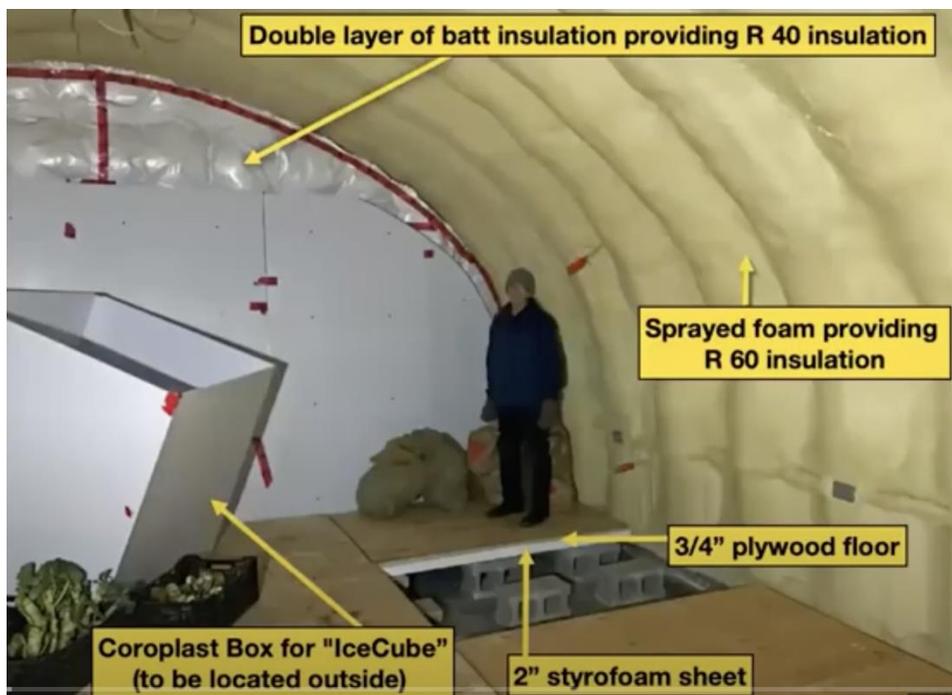


Figure 2. Materials used in the root cellar

Building materials and dimensions

The root cellar is made of galvanized steel structure. The dimension is 40'×24'×10'. And the foundation is made of poured concrete, which is 10''×18'' deep. The geothermal isolation is made of 2'' high density foam, which is covered with 12'' of granular "A" gravel. This extends 5' from

poured concrete foundation. The inside walls of the cellar are made of sprayed foam, which provides R60 thermal insulation. The wall on the side of the cellar door is double-layer batt insulation, which can provide R40 insulation. The floor of the root cellar is made of 3/4" plywood and 2" styrofoam sheet.

Power

The off-grid design utilizes three solar panels and four 12-volt vehicle batteries to capture and store energy. A backup gas generator for emergency situations is stored inside the root cellar, the client has been using it quite often to support two 250W heaters due to the frequent cold fronts in this winter.

Desired values

The user wants the temperature of the root cellar between two and four centigrade and the humidity between 90 and 95%. The humidity is maintained by the ultrasonic humidifier (Sunbeam Model SUL496 0.4 AMPS).

Monitoring devices

A Raspberry pi (microcomputer) that connects to Wi-Fi and Cellular to monitor temperature, humidity, battery levels and fan controls. And there is another software component, written in python, used to query for current temperature in the zones, to calculate averages, and to compare against external conditions. This leads to automated decisions on whether air should come in from outside (cooling), or should be circulated from under the floor (heating), or be circulated within

the ice cube chamber (cooling in spring), or simply turn on circulation fan (air flow to reduce chance of mold growth and to balance temperatures in main chamber).

Methods of heating

When the temperature of the root cellar goes down below two centigrade, it should be heated. Users can obtain heat from underground rocks. Gravel floors can provide warmth from the earth. The users built a floor over the rock and left 8 inches of space around it. There is insulation under the building so it can be compressed. The user installed two 80-watt fans near this insulated floor. The fan will bring the heat from the floor to the chamber. Fans activated when geothermal heat is needed to maintain storage chamber temperature if temperature drops below a target threshold of two centigrade. The chamber can be heated up within ten minutes.

Methods of cooling

When the temperature of the cellar is higher than 4 degrees Celsius, it is not conducive to the storage of fruits and vegetables, so it needs to be cooled. There are two ways to cool down. The first is to open the vents at night to cool the cellar with cool outside air. Because the temperature at night is low, and the temperature in the cellar is high, the air in the cellar is exhausted and the external ambient air is introduced to achieve the effect of cooling. The second method is to utilize Icehouse Strawpile, which is invented by the client. It consists of a straw bale and 3.78 antifreeze containers, which is equivalent to a device that can perform convection heat transfer. 260 of which is equivalent to 1 ton of water. Divide them into 4 layers and make with chlorine paste. Insulating and inert. The user first uses the cold air in the environment to cool the water in the container, freezing them into ice. And then closes the vents that bring in ambient air and opens the vents that

bring in cellar air. The air in the cellar can be cooled by ice cubes, and then returns to the cellar to achieve the purpose of cooling.

2.1.2 Existing Issues and Prototype Risks

The risks and issues of the existing prototype are mentioned below:

- 1) The root cellar has minimal control over humidity, and the humidifier is not enough.
- 2) Lack of sufficient off-grid power sources was addressed multiple times throughout the client meeting. The existing prototype combines large lithium batteries, solar panels, and a backup gas generator as the off-grid power source, but the performance is unsatisfactory when the heater needs to be turned on during winter evenings. And due to the very cold temperature in this winter, the client had to refill the generator several times throughout the night to keep it running which causes both physical and mental fatigue.
- 3) The client has to enter the root cellar and start the generator from time to time, so it has the issue with the season start.
- 4) The gas generator is very harmful to the environment. It also needs to be warmed up at home before getting turned on if the surrounding was very cold.
- 5) The root cellar cannot operate during the summertime. The current “Icehouse Strawpile” system works during spring, but ice being used usually melt within 2-3 days, which is not enough.
- 6) The types of produce it can store are limited. The root cellar needs separate chambers and more areas.
- 7) The root cellar project is short of money, and it needs more financial support. A business and marketing plan needs to be pushed forward.

- 8) The temperature of the root cellar may get up to nine centigrade which is higher than normal root cellar temperature during long warm spells. Because the long warm spells have no cold temperature at night, so it is hard to control the temperature in the root cellar.
- 9) Extremely cold temperatures require at least two 250W heaters to keep the chamber warm, and they are very demanding.
- 10) Mathematical proof of heat gain and distribution was not fully covered before the construction of the root cellar.
- 11) Control system's wireless connection drops and needs system reboot to reconnect, which happens occasionally, and the cause is yet unknown.

2.1.3 User Needs

Each client need is assigned with an importance value, with 5 being the most important and 1 being the least important (see Table 1).

Table 1. User Needs.

#	Need	Importance Value
1	The root cellar needs to be scaled up.	2
2	The root cellar can store a large variety of crops, vegetables, and fruits.	3
3	The root cellar has different chambers to keep stuff separately.	4
4	The root cellar has large power sources.	5
5	The root cellar stays off-grid.	5
6	The root cellar needs an eco-friendly backup power.	3
7	The root cellar needs an efficient heat source.	4
8	Making a mathematical model for heat distribution in each chamber.	4

9	A mathematical proof of the heat gains from the gravel floor during winter and summer.	5
10	The root cellar has good heat insulation	4
11	The root cellar can maintain a consistent temperature.	3
12	The root cellar can maintain a consistent humidity.	3
13	The root cellar uses less energy to run the cooler.	3
14	A better method to harvest snow or ice.	2
15	A better method to store snow or ice.	2
16	The generator can be turned on autonomously without direct human manipulation.	2
17	The root cellar needs a stable wireless control system.	4
18	The control system can use weather forecast to make decisions.	1

2.1.4 Critical Metrics

See Table 2 for the metrics involved with the client needs, units of measurement, and importance value.

Table 2. Critical Metrics.

#	Need #	Metric	Importance Value	Unit
1	1,3	Size of each storage chamber area	1	ft ²
2	1,2	Total storage area after shelves being installed	2	ft ²
3	2,3	Total chamber volume	2	ft ³
4	11	Target indoor temperature	4	°C
5	12	Target indoor humidity	4	%
6	10	Wall insulation material heat resistance	4	k/W
7	10,11,12	Total heat exchange with the outside	3	W
8	8	Heat distribution within the storage chamber	3	List

9	4,5,6	Maximum power usage	5	W
10	4,5	Power source output rating	4	W
11	4,5	Electricity storage capacity	4	Ah
12	7	Heat source output rating	3	Btu/kW
13	9	Heat gains from gravel floor	3	btu/kW
14	7,11	Time required to heat up the chamber	2	Min
15	12	Time required to stabilize the humidity	2	Min
16	14,15	Straw bale heat resistance	3	k/W
17	14,15	Time for snow/ice to melt in straw bale	1	h
18	11,13	Time required to cool down the chamber	3	min
19	13	Cooling system capacity	4	btu/kW
20	16	Autonomous control of the backup generator	1	Binary
21	18	Weather forecast integration	2	Binary
22	17	Wireless connection stability test	1	Binary

2.1.5 Outline of Improvements

The following outline of improvements is based on the existing issues and user needs:

1. The current off-grid power source needs significant improvement, batteries with larger capacities and a more efficient and eco-friendly method of power generation shall be investigated.
2. The client wants to expand the root cellar, and if possible, has it to be separated into different chambers to store fruit, crops, and vegetables accordingly to avoid sprouting.
3. Mathematical proof of the root cellar's heat gain from outside and gravel floor shall be performed. An optional improvement is to develop a mathematical model of heat

distribution within the chamber, so the client can use it as a guide to regulate the heat flow within the storage.

4. An alternative method to maintain the temperature during winter shall be investigated.
5. A better wall insulation method shall be investigated.
6. The team shall improve the cooling method, better snow/ice harvesting and storage method shall be investigated.
7. The control system requires improvement on its wireless connection stability.
8. Some optional improvements of the control system include: (1) enable an autonomous operation of the backup generator, so the client will not need to turn it on manually during the midnight. (2) an integration of weather forecasts, so the system can make decisions ahead of the time.

2.2 Technical and User Benchmarking

Due to the unique nature of this project, there are a few similar designs that exist but none of them can meet all the aspects being listed in the user metrics table.

2.2.1 Existing Products

In China, there are similar designs (but not off-grid) for growing sweet potatoes in greenhouses [4]:

- Goal: The temperature is 10~15°C, the humidity is 85%~90%, the O₂ concentration is about 4%, and the CO₂ concentration is about 3%.

- The size of the cellar: length 20 m, width 6 m, height 4.8 m, volume 576 m³, and can store 150 tons of fresh potatoes.
- The structure and materials of the cellar: The greenhouse storage cellar is composed of three parts: the cellar body, the roof and the management room. It is semi-underground, built in a north-south direction, and the materials are civil structures. The tiling material of the cellar shoulder is 200 cm×150 cm×5 cm foam board (that is, polystyrene board), with a total of 120 m², which needs to be sealed and fixed, and only one piece is left at the front, middle, and back of the top of the cellar aisle. Foam board is used as an artificial control adjustment measure for temperature increase, ventilation and moisture dissipation.

Table 3. Cellar insulation and performance index design.

Structure	Materials	Total thermal resistance (m²CW)
Cellar roof	Arch rod+0.10mm non-drip film + black shading cloth + ventilation window	0.79
Cellar body	100cm thick earth wall + cellar shoulder 50mm foam board + eight symmetrical ventilation holes	4.26
Cellar bottom	250cm (width)× 30cm (height) storage bed + 100cm aisle + 200mm diameter plastic pipe ventilation channel	-
Cellar side	400cm×300cm×200cm (height) management room	-

- Methods of heating: Open the shading cloth and the cellar shoulder movable foam board, and make full use of the solar energy resources in winter to heat up.

- **Methods of cooling:** The plastic ventilation pipes at the bottom of the cellar are connected to the outside of the cellar, and are mainly used for ventilation and cooling in addition to drainage. When the temperature in the cellar is too high, a blower can be used to blow cold air from the outside into the cellar through this pipe to achieve the purpose of rapid cooling.
- **Storage effect:** The highest cellar temperature is 17.4°C, the lowest is 9.5°C, the average is 13.5°C, the relative humidity is 85%~90%, and the storage purpose is achieved.

2.2.2 User Perceptions

Barry Bruce, the client, needs food storage that can go off-grid for days without using power. The current system generates power from solar cells, but it is not enough to keep a steady temperature inside the food storage. Barry has come up with various solutions to handle the current issues. They are not perfect as he wants them to be, but they work for now. See Table 4 for a perception of the existing solutions:

Table 4. User Perceptions.

#	Problem	Existing Solution	Perception
1	Power Backup	They have 3 large lithium cell batteries, equivalent to 5-6 truck batteries.	In extreme weather lithium cell batteries are not enough to maintain temperature between 2–4°C. Thus, someone has to rush to the food storage to replace the batteries in bad weather conditions.

2	Power Generation	6 solar cells, so 100 watts each.	Solar cells don't generate enough power. Extra batteries are needed.
3	Natural Heat Generation	Extracting heat from earth core. Gravel floor can provide warmth from the surface of the earth. He built a floor above that and gives 8 inches of space around there. With an insulating material under the building so it can be compressed. He used HD40 (R=12) and then covered it with plywood. This was useful at the beginning of the season to cool down the heat coming from the gravel. If it gets too cold, they can bring warm air out from underneath the floor with fans that ventilate the floor.	According to the client it worked well. They were able to extract heat from the floor in cold weather and were able to restrict the heat in summertime.
4	Artificial Heat	Client used a 250-watt heater to maintain the temperature.	It consumed a lot of battery energy. Even the generators were not enough to keep that heater running.
5	Cooling	Icehouse Strawpile- which is a straw bale and 3.78 anti-freeze containers. And 260 of those is equal to 1 ton of water. Put those in 4 layers and made with chloro-paste. Insulating and inert. This will hold 1 L of water. He ducted it on the side of the root cellar so they have warm air coming from chamber to the ice cube (his invention), and air comes back cool.	Melts quickly, so it only worked for 2-3 days.

2.2.3 Additional Constraints

1. Sudden climate change would cause excessive stress on the heating / cooling system, hence consuming more power.
2. Not enough solar energy is available to refill batteries.
3. Going completely off-grid will be challenging.

4. High cost of good-quality insulating materials.

2.2.4 Target Specifications

Table 5. Target Specifications

#	Metrics	Unit	Value
1	Temperature	Celsius (°C)	2-4
2	Humidity	Percentage (%)	90-95
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

2.3 Prototype Test Plan

2.3.1 Test Plan

1. Power system: The total hours the prototype can stay off-grid will be recorded. Ideally, there should be enough day time sun exposure to charge the batteries, and the night should be cold enough to require both the heater and the generator to work. The team will determine the theoretical overall power usage under different conditions (temperature, humidity, season, etc.), then it will be compared with the current generators and batteries' power output. This will provide the team with an idea of how much power the current system is lacking.

2. HVAC: The team will turn off all fans and heating/cooling appliances to determine how the storage temperature changes with time. Then, fans and heating/cooling appliances will be turned back on to measure how long it takes to reach an ideal temperature and humidity. All insulation materials specification will be used in the heat gain calculation, both extreme cold and hot outdoor temperatures will be considered to give the worst-case values. Then the team will compare the heat gain values with the heater and cooler's capacities to see how well the temperature can be maintained. The ice storage test is not practical during wintertime, and simply use a heater to melt the ice cannot simulate the summer weather, so this part will be calculations only.
3. Control system: As mentioned in the previous sections, the current control system works as expected but requires occasional manual reboot to fix the disconnection issue. At this stage, the team cannot test the stability of the system, as it requires the issue to be reproduced. Unless the client could provide the team with a system log file at the instance when the disconnection happened, a thorough inspection on the source code and the control unit would be necessary. Therefore, the control system test plan will be determined once the team receives more details on the failure cases.
4. Storage size: This part relies on the existing measurements have been gathered by the client, team will use this information to calculate the theoretical storage size, then it will be compared with the total size of the crops being stored as it is impractical for the team to weigh all crops in the root cellar.

2.3.2 Comparison Method

A table will be made for comparison purpose, it will contain all calculated data, measured data, and target specifications. This will enable the team to understand how well the prototype performs against the theoretical results, and how much it is behind the target values.

3 Conclusions and Recommendations for Future Work

Climate change poses an eminent threat to growing our crops and sustaining our population's food consumption. Therefore, it is important now more than ever to innovate creative designs to support the storage of root vegetables, especially in many food-insecure areas where agriculture and food production is seasonal such as Eastern Canada.

To address the food shortage issues during the Winter and Spring seasons, DRFH designed a prototype above-ground vegetable roots cellar with a Quonset-styled metal frame. The goal of this cellar and off-grid storage is to connect small-scale farmers and their families and provide them with a place to store their produce all-year round. This task implies knowledge of root crop preservation (such as the ideal conditions: temperature, humidity, air quality, and more), temperature and humidity control, power and energy usage, measuring data using sensors and programming tools (Raspberry Pi), and knowledge of many more sustainable methods/technologies/materials.

Throughout our research, we've come across interesting papers and articles about crop storage, heat transfer, sustainable materials, and even the benefits of building underground! We also learned a lot from the initial meeting with our client, Barry Bruce, who has been studying renewable energies and cellar architecture for the last couple of years.

After meeting with the client and analyzing his needs using the Importance Value metrics, the most productive avenues for our future work are to carry out the test plan steps, which consist of:

1) Analyzing the log file of the utilities that the client provided to us to calculate the theoretical overall power usage under different conditions. From that, we can then get an idea of how much power the current system is lacking. 2) Manipulate the HVAC system by turning the fans and heating/cooling appliances on and off at different patterns and intervals. The data registered by the sensors during these temperature changes, along with the insulation materials specification, will be used in the heat gain calculation. 3) Perform an in-depth investigation on the current control system and the reboots needed to fix the disconnection issues. Lastly, 4) Calculate the total storage size with the chambers since the client showed an interest in scaling-up.

As we progress in our research and with more meetings with the client (and possible in-person visits to the cellar), we will keep re-evaluating our Importance Value metrics and refining the client need(s) that we will be working on for the semester.

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