MCGILL UNIVERSITY

Canadian Integrated Northern Greenhouse for National Food Security

BREE 495 – Engineering Design 3

Final Report

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Executive Summary

The goal of this paper is to help develop a replicable design that would enable northern communities located above the Canadian 60th parallel to benefit from locally produced food on a year-round basis. In a previous report, the decision to combine a northern greenhouse with the characteristics of a growth chamber into a hybrid system, entitled the Canadian Integrated Northern Greenhouse (CING), emerged. The system would therefore act as a greenhouse during the day and benefit from the long sunlight hours during the summer. It would then transform into an insulated greenhouse during the cold dark nights and winter months.

The unit will be housed in a shipping container which becomes part of the structure of the integrated greenhouse with the addition of a glazed wall and roof. A reflective panel will also be attached across the bottom of the south-facing glazed wall which will increase direct beam solar transmittance. The floor, the north wall and the side walls will mainly be insulated using extruded polystyrene rigid foam to an optimal RSI value for efficient northern buildings (RSI-10 for the floor and ceiling; RSI-5 for the walls). In order to reach the desired RSI value on the glazed parts during the winter, a radiant insulation blanket will be deployed when the unit transforms itself into a growth chamber. Using vertical farming principles to maximize the use of available space, the plants are placed on three different height levels using motorised nutrient film technique (NFT) hydroponic systems that track the sun throughout the day. Built with PVC pipes, each individual system hosts 7 lettuce heads for an overall production size of 483 heads of lettuce per month. LED arrays providing 25 μmol/s of photosynthetically active radiation will be incorporated to each individual hydroponic system to provide supplemental lighting. The heating, ventilation and cooling (HVAC) system was sized and partially physically prototyped.

The capital cost of the first CING prototype was estimated at $35,700 leading to a price of $1.45/lettuce considering an operational cost of $4,860 (excluding maintenance labour costs) and a 10 year payback period. Considering maintenance labour costs, the price rises to $5.77/lettuce. The main barriers for the implementation of the CING (its initial cost; the availability of energy and water sources; social acceptance) will mostly be present in isolated communities rather than in the industrial sector. Awareness of the economic, environmental and health benefits will have to be done to promote this special agricultural facility that has the potential to be the world’s most volume and energy efficient enclosed food production system. The CING is currently undergoing a patent process by Dr. Lefsrud from McGill University.

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1. Introduction and Objectives

Food insecurity is a critical issue faced by more than 2 million Canadians (De Schutter, 2012). This problem is especially important in northern regions where food prices, particularly fresh produce in isolated communities, can be substantially higher (by up to 200%) than in southern cities. This is mostly due to the reality of the food distribution system where a large percentage of products are imported by truck or flown in by plane and because of significant storage costs associated to this (Indian and Northern Affairs Canada, 2008). Producing food *in situ* across northern communities would decrease their dependency on imported goods. Locally grown food is likely to be more affordable, of higher quality, and have a longer shelf-life, which in turn will contribute to the accessibility to a healthier diet (Thouez et al., 1989).

In the first part of this project, three potential solutions to perform agriculture in northern climates were analysed and compared to the importation of food via road transportation. Small plot intensive farming, a greenhouse adapted to northern conditions and a growth chamber were the three options considered to reach the desired goal of developing a replicable design that would enable northern communities located above the Canadian 60th parallel to benefit from local agriculture practices on a year-round basis. All three design ideas were an improvement over the current situation; however none of them was markedly superior to the others in the final ranking.

The idea that came out of this analysis was to create a hybrid system combining the concept of a northern greenhouse with that of a growth chamber. The principle is to make an innovative unit that would behave as a greenhouse throughout the growing season, but would transform into a growth chamber during the cold, dark months. Therefore, this hybrid system would benefit both from the energy of the sun during the warm season, and from increased insulation when supplemental heating and lighting is provided to sustain crop production during the winter.

This report is part of an ongoing process to design and evaluate a unique northern agricultural facility whose prototype is currently named the “Canadian Integrated Northern Greenhouse” (CING) with huge marketing potential. In this report, each major engineering component is sized and analysed; a heating, ventilation and air conditioning (HVAC) prototype is tested, the cost of a potential first operational CING prototype is estimated and future recommendations for the success of this project are made.

2. Analysis and Specifications

2.1 Implementation of the Technology

2.1.1 Targeted consumers and crop production

The Canadian Integrated Northern Greenhouse is a proposed method of delivering nutritious, locally grown food all year round to northern populations including First Nations communities and mining workers. Vegetable consumption is low in First Nations communities compared to the rest of Canada and therefore the implementation of this technology will need to be coupled with an educational process centered on nutrition and cooking practices to be successful. The greenhouse also needs to be seen as something that benefits the whole community and accepted by well-respected individuals. Only then can the transition from the consumption of large amounts of non-nutrient dense foods to healthier diets be realized (Agriteam Canada Consulting LTD, 2013). As for the mining companies, they are often conducting their operations in remote and isolated places, making them a potential customer of the CING. Moreover, they might be the most promising customers due to their purchasing power and could acquire the first CING prototypes and then finance its further development.

Among the most common greenhouse vegetables grown in Canada and globally are tomatoes, cucumbers, sweet peppers and lettuce (Agriteam Canada Consulting LTD, 2013). This also corresponds to vegetables consumed in the northern regions of Canada. These crops have a high yield and revenue per square meter of production. Other crops that could be grown would include strawberries, green onions, broccoli and herbs. This selection would need to be optimized for maximum production capacity and demand. For the purpose of simplifying calculations, the analysis in this report was conducted with lettuce being considered as the sole crop being harvested in the integrated greenhouse. Below is Table 1 showing estimates of fresh produce consumed in the Northwest Territories.

Commodity	NWT Stores ('000kg/year)	Non-Store Trucking ('000 kg)	Total NWT Market ('000 kg)
Potatoes	489	575	1,064
Onions	120	210	330
Peppers	96	144	240
Tomatoes	120	168	287
Cucumbers	40	51	91
Lettuce	142	108	250

Table 1: Estimate of annual fresh produce consumed in NWT (adapted from Aurora Research Institute, 2013)

2.1.2 CING overall system

The units will be manufactured in southern cities - where resources are readily available - and transported to customers in the northern communities. To facilitate the implementation and the transportation of the CING, the whole unit will be housed in a standard high cube 13.72 m x 2.44 m x 2.90 m (45 ft. x 8.0 ft. x 9.5 ft.) shipping container. The shell of the shipping container is therefore going to be designed as the base structure of the unit with an added glazed roof and wall (see Figure 1). This design combines the concept of a greenhouse with that of a growth chamber into a new hybrid system that can transform when needed. When the outside weather is suitably warm and sunny, the unit is open and can act like a typical greenhouse, however, at night or during the colder months, the unit is closed and operates as a growth chamber. Therefore this system takes advantage of the long daylight hours during the summer and limits the harsh winter conditions by having insulated walls and employing supplemental lights. The CING therefore decreases the energy losses that a regular greenhouse would incur and removes the energy demands for lighting during the day required by a normal growth chamber.

When needed, high efficiency LED lights will be used as well as a heating system with heat recovery and heat storage. Humidity and carbon dioxide levels will also be monitored and controlled. The growing method will consist of a hydroponic system with nutrient delivery stacked in mobile vertical columns to maximize space and production. Currently, the unit will also need to be placed next to accessible sources of electricity and water which meet the requirements of production. A 3D model built using Google SketchUp giving a general overview of the first CING prototype can be seen on the following link: (click to see video 1). The major components of the CING will be further described in the following sections.

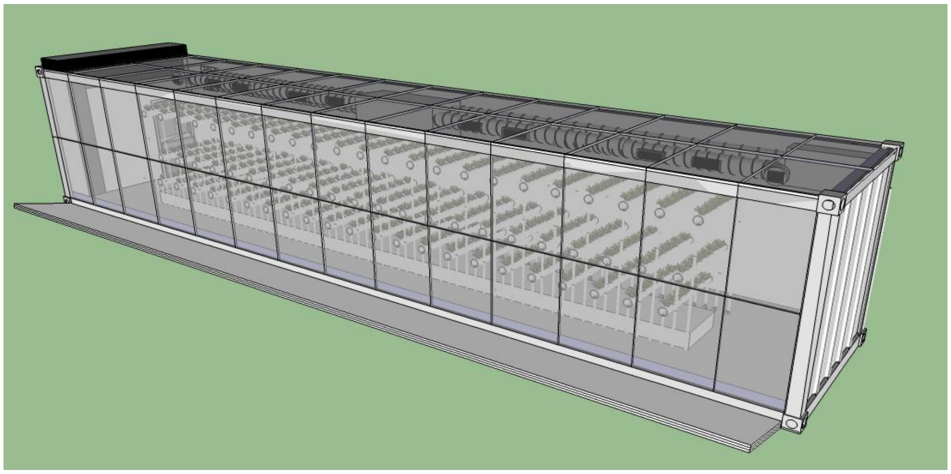

Figure 1: The CING general overview

2.2 Hybrid technical components

2.2.1 Outershell

The unit will be placed above ground on an east-west axis with the glazed wall facing south. This will allow for maximum solar exposure during the day. Additionally, a motor operated variable-angle reflective panel 1 m in length will be attached across the bottom of the south-facing glazed wall which will increase direct beam solar transmittance by up to 11% according to research done for Professor Mark Lefsrud at McGill University (Sara Tawil, unpublished data, 2013. Sainte-Anne-de-Bellevue, Quebec: McGill University, Macdonald Campus, Department of Bioresource Engineering).

One of the reasons why a rectangular shape was chosen, with a glazed roof and wall as opposed to an inclined wall, was to facilitate the transition from a greenhouse to a properly insulated growth chamber (see Figure 2). Preferably, this transition should be able to occur within minutes. The steel shutters, which will operate electrically, or by default with a manual crank, will have proper insulation attached to them. They will be stacked together at the end of the greenhouse when the system is open and will progressively release when the system is closing (click to see video 2).

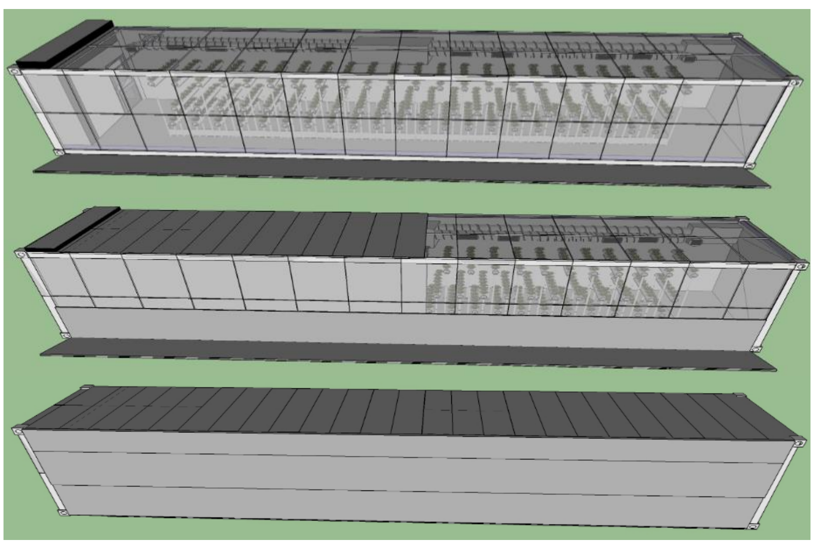

Figure 2: The CING transforming from a greenhouse (top) to a growth chamber (bottom)

2.2.2 Insulation

Since the CING is going to be subjected to extremely harsh wintry conditions during an extended period of time, the minimization of heat loss will be of paramount importance. Logically, a thicker insulation will increase its effectiveness, but will also reduce available space to grow plants, which is already scarce in such a confined shipping container. Therefore, the insulation thickness should be optimized accordingly as well as an air lock design.

As per the Guide of Energy Efficiency for New Buildings (2012), an RSI-7 (R -40) for the walls and an RS-10 (R-60) for both the ceiling and the floor would be required for this unit to be energy efficient. However, an earlier model of the AgNorth modular – a similar project to the CING - suggested that excess heat will be produced by the facility, which permits to lower the wall RSI value to 5 (R-30) (Aurora Research Institute, 2013). This information is key in the design of the CING, since the thickness of the north and south wall insulation layers are the most important dimensions affecting the net inside available volume; which in turn impacts the quantity of plants that can be produced.

The corrugated metallic surface of a shipping container does not allow framed constructions to be performed. Therefore, the best insulation principle currently available is to use extruded polystyrene (XPS) rigid foam insulation held in place by vacuum foaming acting as a plastic interior moulded to the corrugated shape of the container. A 15 cm (6 in) of XPS would be required to reach the desired RSI-5 (R-30) for the wall and 30 cm (12 in) for the ceiling and the floor to reach RSI-10 (R-60) (The Dow Chemical Company, 2013). A vapour barrier and a thin finishing material (such as 2mm corrugated steel) will also have to be layered in order to prevent moisture produced by plant evapotranspiration from affecting the insulation material and to provide protection and durability to the walls. Note that aerogel with an RSI value of 6.9/cm (R-10/in) is an emerging technology that could eventually be used instead of XPS when it becomes more affordable; this would therefore reduce insulation thickness by half (Shukla et al, 2012).

As explained before the hybrid unit will transform itself from a greenhouse to a growth chamber when needed to enhance the insulation value of the glazed sections. However, the steel material (RSI-0.06 or R-0.33), the 3 mm polycarbonate glazing (RSI-0.15 or R-0.88) and the air trap in between the two (RSI-0.18 or R-1) will not be sufficient to reach the desired RSI value of 5 (R-30) (RSCP, 2013; Israeli, 2007; Adaptive Plastics Inc., 2013). Therefore, additional insulation will be placed on the inside of the glazing in order to increase the energy efficiency of the unit.

A radiant insulated blanket currently used in traditional greenhouses could be used, which can reach RSI-5 (R-30) by itself (Radiant Barrier Journal, 2010). This insulation blanket will be incorporated to an automated folding system enabling the insulation blanket to be deployed or rolled away in the airlock depending on the outside environment. This automated system will consequently be coupled with the one controlling the external closing system. Again, aerogel might be used in the near future instead of the conventional blanket. The development of a soap bubble insulation technology conducted by the University of Vermont is another promising alternative to insulating the glazing (Parker and Skinner, 2011). It would require a double layer of polycarbonate glazing spaced at 30cm and the soap bubble system with an anticipated cost of $16,000. The soap bubbles are generated in order to fill the gap in the glazing and provide a minimum of RSI-5 (R-30) insulation. The bubbles are then destroyed and regenerated at will. However, the most realistic additional glazing insulation currently available for the first CING prototype would be the conventional blanket.

2.2.3 Irrigation system and plant distribution

Considering the thickness of the insulation, the net space available to grow plants will now be considerably reduced to 13.26 m x 2.05 m x 2.10 m. A method introduced in the previous report was evaluated as an ideal way of growing plants in a confined environment: vertical hydroponic farming. A very inexpensive way to construct such a system would be to use polyvinyl chloride (PVC) piping. But the sizing of these pipes cannot be done before knowing if the plants should be distributed along the N-S or the E-W axis.

The plant distribution axis has to maximize the amount of light absorbed by the foliage while minimizing the amount of shading created by the plants. These parameters are of particular importance in the northern regions due to the very short growing period that needs to be capitalised upon. Conventional greenhouse plant distribution and orientation systems may not necessarily be adapted to northern geographical conditions. Thus, innovative systems will need to be developed specifically for the CING.

As scientific literature is very limited regarding row orientation for greenhouse plants at and above the 60th parallel, conclusions have to be drawn from the closest related conditions. A Japanese experiment comparing daily canopy irradiance in the summer months at 35, 45 and 55°N of latitude was the closest related study found. For the 55°N, it was concluded that the North-South orientation should be privileged over the East-West one (Kurata & Takakura, 2000). Based on this assumption, an experiment conducted for Dr. Mark Lefsrud (Patricia Gaudet, unpublished data, 2013. Sainte-Anne-de-Bellevue, Québec: McGill University, Macdonald

Campus, Department of Bioresource Engineering) tested and compared several North-South distribution and orientation systems that could be incorporated in the CING. Using the perpendicular angle of incidence of the solar rays entering the greenhouse front glass panel and roof from March to September, the limitation of height and depth distribution of the plant was assessed. It was found that there were no significant limitations for both the lowest and largest horizontal and vertical distances of light ray penetration within the container's boundary (see Appendix C). Therefore, plants can be placed all along the North-South and the elevation axis of the container during those months and receive the same amount of sunlight. On the other hand, the East-West axis will be subjected to different amounts of sunlight with more sun towards the east in the morning and more towards the west in the evening.

This led to the development of an individual motorised nutrient film technique (NFT) hydroponic pivoting system that tracks the sunlight abundance east to west throughout the day (click to see video 3). Furthermore, this experiment concluded that this pivoting system would enable to grow a larger volume of plants than the usual fixed hydroponic system. A 1.22 m (4 ft) long PVC pipe with a diameter of 10 cm (4 in) would be placed on the N-S axis. This would leave 60 cm (2 ft) on the south wall which is sufficient for an employee to circulate within the unit. Distributed every 15 cm (6 in) center-to-center, 7 lettuce heads will be hosted by each hydroponic pivoting unit (see Figure 3).

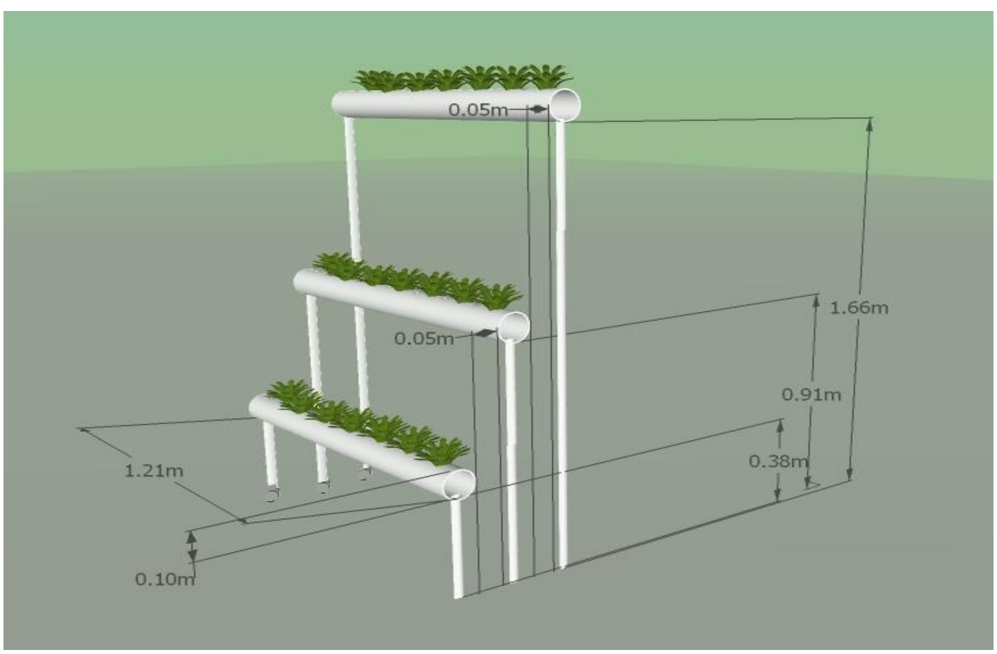

Figure 3. Individual nutrient film technique (NFT) hydroponic pivoting system

The experiment supervised by Dr. Mark Lefsrud also proposed using a vertical farming distribution. The hydroponic pivoting unit will therefore be composed of 3 levels: the smallest will be 38 cm (15 in) of height, the intermediate one will measure 91 cm (36 in) and the tallest one 166 cm (65.5 in) (see Figure 3). Placed above the 30 cm (12 in) floor insulated material, this will leave 0.44 cm (17 in) between the highest level and the insulation blanket during winter. The lateral spacing between each level will be of 5 cm (2 in) for a total of 23 units in each level. The total would then amount to 69 hydroponic pivoting units with a production size of 483 heads of lettuce per cycle.

In order to irrigate those plants with a constant flow of 6 cm (2½ in) of water– which is required for a NFT hydroponic system (Coolong, 2012) – a total of 800 liters of water will be needed. Two separate 400 liter tanks with dimension of 0.3 m x 4.6 m x 0.3 m (2 ft x 15 ft x 1 ft) will be placed underneath the smallest hydroponic system. One tank will supply calcium nitrate and the other will provide the remaining nutrients as prescribed by Coolong (2012).

2.2.4 Supplement lights

As already assessed in the previous report, a light-emitting diode (LED) lighting system would be more advantageous to use compared to the usual high-pressure sodium (HPS) lamps in arctic conditions and can lead to $0.28/m^2 ($3/ft^2) in annual saving (Chena Hot Spring Resort, 2012). The installation of the LED system in the hybrid design would follow the same configuration used for the Chena Hot spring Resort study which provided well suited economic benefits with a higher plant growth rate:

Color	Wave length	LED %
Red	630nm	40%
Far Red	660nm	60 %
Blue	460 nm	20 %
Yellow	610 nm	10%
Orange	615 nm	20 %

Table 2. Optimal LED configuration for growing lettuce (Chena Hot Spring Resort, 2012)

The LED array system will be placed 60 cm higher than the canopy to provide the needed plant light requirements (for lettuce, 16 hours of light at 100-200 µmol/m^2/s of photosynthetically active radiation (PAR) which represent a total of 17 mol/m^2/day of PAR) (Brechner and Both, 2012). Considering the vertical farming arrangement of the plants, shading will sometimes be observed. To provide a uniform light distribution across the plants in the

CING, LED panels will be permanently placed underneath each of the highest and the intermediate hydroponic levels. This will lead to the creation of an integrated hydroponic-LED pivoting unit (see Figure 4). Note that some LED panels will unfold near the roof during growth-chamber form to provide light to the plants on the highest level. To meet the suggested 17 mol/m^2/day of PAR, each LED array should provide an output of 25 µmol/s or 2.16 mol/day to the growing area of the hydroponic unit below (see appendix A). Therefore, custom made LED panels should be built specifically for the CING using the light configuration of Table 1Table 2 and PAR output aforementioned. Furthermore, a nursery area - which is essential to grow the seedlings - will be installed next to the water tank underneath the lowest level. Conventional LED panels will be installed in the nursery to meet lettuce seedling light requirements (24 hours of light at 250µmol/m^2/s of PAR) (Brechner and Both, 2012).

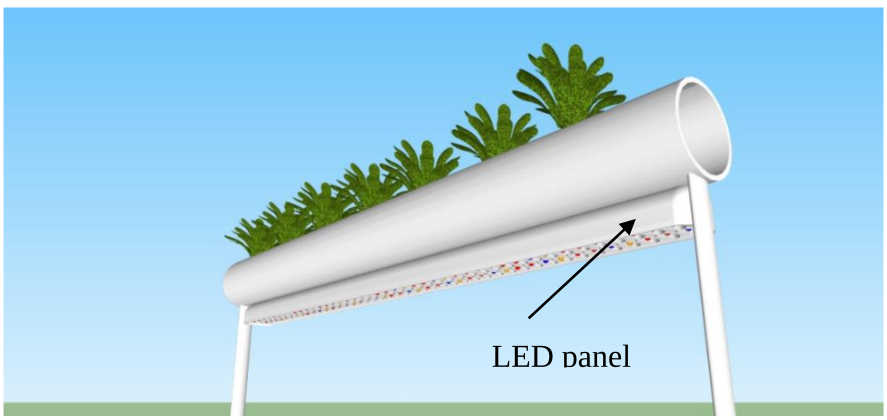

Figure 4. Integration of an LED panel on the hydroponic system

2.2.5 HVAC and Environmental Control

2.2.5.1 HVAC overview

The heating, ventilation and air conditioning (HVAC) system and the integrated climate control system of the CING are its backbone as they allow together for the automated regulation of the internal greenhouse environment to meet optimal growing conditions for plants.

A mini weather station collects information on the environment outside of the CING and relays the information back to the integrated climate control system so that it can process it using a logic control system, possibly using fuzzy logic control, to determine the best operational point for the cooling fans, the heaters and the movable insulation layers. A system of electronic switches and actuators can then configure the system to the desired level for precision and to save on labour costs. The control system would strive to achieve ideal values for temperature, relative humidity and gas concentrations. Typically, an internal temperature of 15 to 20^{o}C, a relative humidity rating of 50 to 70% and a CO_2 concentration of 1000 ppm are best for plant growth although atmospheric CO_2 concentrations of 380 ppm is also suitable (Vaisala, 2011).

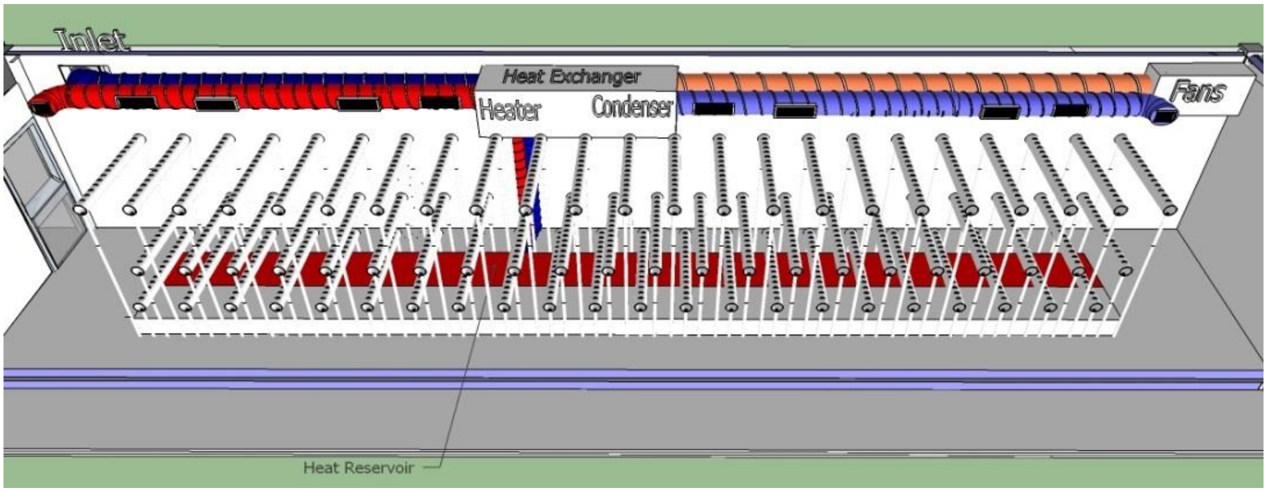

Figure 5. CING HVAC system. The heater, condenser and heat exchanger box is representative and does not suggest the actual configuration or design of the units.

The physical HVAC system is mainly composed of the inlets, the outlets, the communicating ducts, the fans, the heat exchanger, the heaters, the condenser and the water tank.

As can be seen in Figure 5, outside air is sucked in by the main inlet and passes through the heat exchanger for preconditioning before being heated, if necessary, by the duct heater and then distributed into the inside environment. Stale inside air is subsequently circulated outside, making its way through the heat exchanger to either transfer heat or suck in heat, depending on temperature gradients and has its excess moisture due to plant evapotranspiration removed in the condenser to be recycled in the system before being exhausted to the outside environment. All ducts have closable inlets or outlets so that there may be increased flow in the system when needed. Furthermore, when high air flows are necessary to cool down the greenhouse in the summer, air flow must be redirected as the heat exchanger does not tolerate such flows. As such, the adjacent ducts can communicate by slots that can be opened between them for the additional air to flow through from inlet to fan and outlet. This characteristic of the ducts also allows for slight heat exchange between the incoming and outgoing air streams, further conditioning the air. Finally, the preheater mostly acts as a backup heater in case the main heater malfunctions or if additional heat over design heat loads is required due to unforeseen circumstances. The air moves in and out of the system from the top of the container so that there is more growing space on the bottom. Figure 6 is a simple diagram representing air flow through the HVAC system.

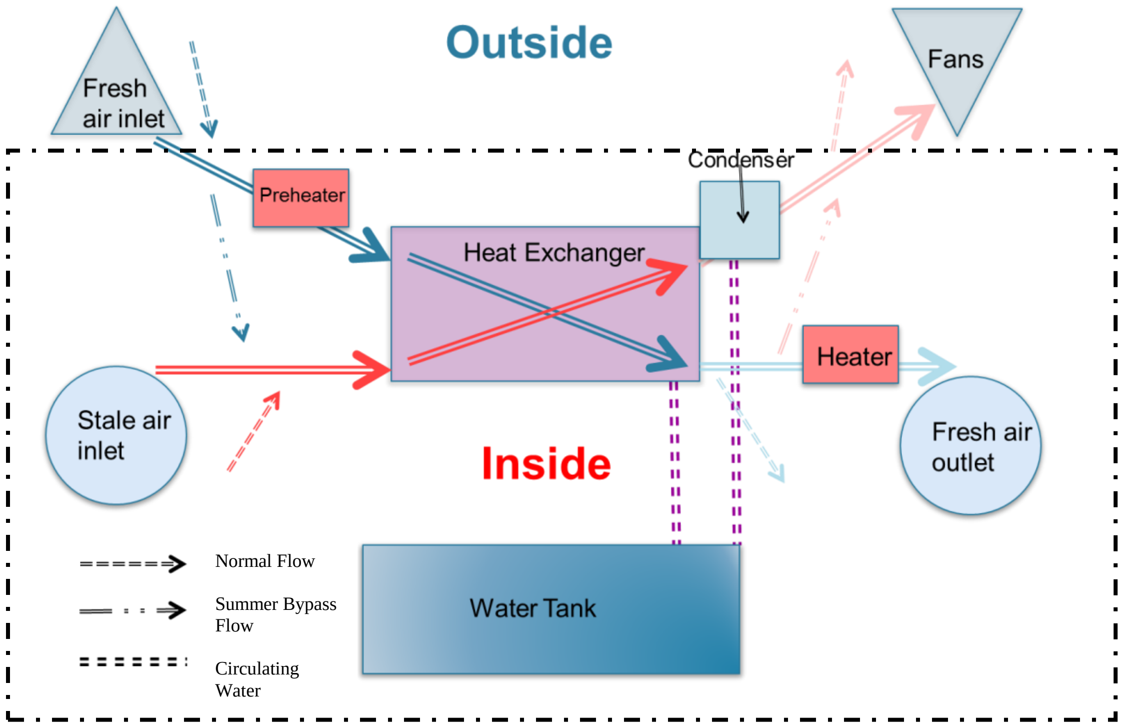

Figure 6. Simplified HVAC diagram. Red indicates hot while blue indicates cold. The darker a color the more hot or cold it is. This diagram better represents winter operation although the summer bypasses are indicated.

2.2.5.2 Inlets and Outlets

Inlets and outlets on the outside of the CING are equipped with louvers, gravity ones at the outlet and motorized ones at the inlet, and a small housing that opens at the bottom such that the fine northern powdery snow will not be sucked in or backdraft into the greenhouse. The main inlet and outlet are at opposite ends of the north side of the CING while secondary ones are spaced in between and can be opened or closed remotely.

On the inside of the CING, the position of inlet and outlets are reversed as the streams crossover at the heat exchanger. There are also secondary intakes and delivery openings for higher flows or more even distributions of air.

2.2.5.3 Ventilation Fans

Fans are a crucial part of the design as they allow us to cool down the inside of the greenhouse by acting as a forced air blower during the summer when the extra insulation on the top and south side of the container will be removed. They also allow for the circulation of air through the greenhouse to get rid of the stale air and control gas concentrations.

Auxiliary wall mounted fans blowing through the plant canopies can also ensure that there is appropriate air circulation in the boundary layers around the leaves for plant health (Clayton and Vandre, 2013).

Stage #	Air Flow	Operation Mode	Outside Temperature
Stage 1	0.25 ACH	Minimal air flow	-20^{o}C>T
Stage 2	1 ACH	Gas control	-10^{o}C>T>-20^{o}C
Stage 3	3ACH	Heat recovery	0^{o}C>T>-10^{o}C
Stage 4	0.1 ACM	Heat recovery	10^{o}C>T>0
Stage 5	0.5 ACM	Flow through	20^{o}C>T>10^{o}C
Stage 6	1-2 ACM	Flow through	T>20^{o}C

Table 3. Proposed fan stage air flows

It is desirable to have the flexibility of various operational stages such that different operating conditions can be met, as seen in Table 3. Higher air flows with a direct flow through the greenhouse will provide ventilation cooling whereas intermediate air flows will be preferred to take advantage of heat recovery from the heat exchanger which functions at lower air flows. Finally, at the more frigid temperatures, background air flows allow for the control of gas content in the air, such as volatile organic compounds, CO_2 and ethylene (Clayton and Vandre, 2013).

A 30.5 cm (12 in) diameter fan with a maximum air output of 56.6 m^3/min and a 40.6 cm (16 in) diameter fan with a maximum air output of 85 m^3/min, both capable of variable speed control, were chosen to provide the target airflows (McMaster-Carr, 2013).

2.2.5.4 Ducts

The ducts used in the CING design are rigid metal ones to reduce losses due to bends in corrugated or flexible ducts. They should be at least 300 mm or 12 in. in diameter to reach desired air change numbers in the system while respecting recommended air speeds (Engineering Toolbox, 2013). Inbound and outbound air ducts communicate through a slot which can be opened or closed. Instead of a slot, it could be a secondary duct.

2.2.5.5 Heat Exchanger

Since heat exchanging is favoured at intermediate air flows when significant heat recovery can be made, it is not necessary to purchase more expensive high air flow heat exchangers. 0.1 ACM or 6 ACH would mean that around 516 m^3/h of air would have to be circulated through the heat exchanger which can accommodate about 545 m^3/h in the case of the Venmar AVS HE 2.6 HRV. It would therefore be sufficiently sized. Furthermore, the Venmar has a sensible recovery efficiency of at least 0.70 (Venmar, 2013).

2.2.5.6 Heaters

In the right conditions, heating the CING could be inexpensive, for example after taking into consideration exhaust heat from nearby buildings or waste heat radiated by the LEDs, one could end up with enough heating to maintain the system (Aurora Research Institute, 2013). However, if that is not the case, the use of electric duct heaters allows for a flexible supply of heat while saving space. Taking into consideration the construction and insulation materials to be used for the CING, it was possible to determine that the maximum required heating load, such as during the dark months of winter with no sunlight acting on the closed system with freezing temperatures of -50^{o}C and winds of 24 km/h, would be about 2.2 kW (see Appendix A) (Straube, 2003). By installing a primary Electro Industries 5 kW, 595 m^3/h duct heater on the duct situated after the heat exchanger bringing air into the system, it would be possible to not only keep the temperature constant but also increase it at a good rate (Electro Industries, 2013). Furthermore, the addition of a backup heater before the heat exchanger, allows the system some flexibility if ever the main heater malfunctioned or if additional heating was required due to unforeseen circumstances. The duct heaters have been sized to match the air flow of the heat exchanger.

2.2.5.7 Water Tank and Condenser

The final main components of the HVAC system is the nutrient free water tank and the condenser. Due to plant evapotranspiration, much of the water in the system would be lost with system ventilation and frequent water resupplying would be required, on top of incurring higher operational costs. The placement of a condenser unit after the heat exchanger would thus allow for the removal of most of the moisture in the outgoing air stream by cooling the air down to its dew point. Doing so also avoids the formation of ice around the fan outlet, since the moisture in the air would immediately condense and freeze in the frigid northern winter climate, potentially creating blockage in the ventilation system. The condensed water could then be captured and recirculated to a nutrient free water tank. The water can also be used to resupply the other tanks if needed. The tank, which is separate from the nutrient water tanks for the hydroponic system, is used to store thermal energy during the day from the sun, the LEDs, the outgoing air or the internal CING environment to then release it at night when temperatures are lower and higher heat losses are incurred. Essentially, it acts as a heat sink when hotter and a heat source when colder. A small 124 W (1/6 HP) pump and 0.038 m diameter aluminum pipes circulate the water (Rona, 2013; McMaster-Carr, 2013). Alternatively, a glycol loop could serve the same function.

3. Prototyping, Revision, Testing and Optimization

Figure 7: Prototype of the HVAC system

3.1 Prototyping

As building the whole CING would be very time and resource consuming, it was decided that a simple version of the HVAC system would be constructed instead to give an idea of its appearance as well as what kind of performance could be expected of it. Since operation at high and frigid temperatures is simple (full venting, minimal heat versus minimal venting and high heat), this basic design will instead inspect the system flows at intermediate temperatures (from -10 to 10^{o}C) during operational stages 3 and 4 when air flow through the heat exchanger is favoured and when a balance between fan speed and heating is more challenging. Thus, the prototype would allow us to physically validate the sizing of ducts, heaters and fans.

The prototype, as seen in Figure 7, was situated in a renovated room in the Swine Complex at the Macdonald Campus of McGill University in Sainte-Anne-de-Bellevue, Quebec, Canada. This was decided, as it was the closest analog at our disposal to a shipping container in the North since we cannot afford one. Furthermore, the temperature ranges in the late fall and winter would be close to the intermediate temperatures we are interested in. Finally, our design supervisor, Dr. Lefsrud, who is also funding us, had requested that we conduct our prototyping there since the room did not currently have a functional HVAC system and that this, or some parts of it, could serve as a low budget alternative for a future project to be housed there too.

3.2 Construction

The construction of the prototype was done over several weeks and took longer than anticipated, therefore cutting into our testing and optimization schedule. Work would be done throughout the week depending on each teammate's availability. Everybody worked at least in pairs for safety. The room was first partitioned using blue tarpaulin to roughly the size of a shipping container using the existing screws and washers to hold it up. The ordered fans were hardwired to an extension cord and mounted to the available holes in the wall left from old ventilation units. Next, 30 cm in diameter (1 ft) rigid and flexible ducting, including bends, were secured from Dr. Lefsrud's experiment supplies and mounted. The fans were then enclosed in a plywood box. The ducting linked the outside from the inlet side and the fans to the heat exchanger which was essentially a cardboard box with an aluminum foil partition in the middle to separate incoming and outgoing flow while allowing for some heat transfer. Two 115 mm (4 in) holes were then made, one leading to each side of the partition. The incoming air would be delivered through a hole in the bottom of the left side of the heat exchanger while outgoing air would be sucked out through a hole in the top of the right side. A set of three 1.5 kW heaters were used to heat up the incoming air flow and the room. Two of the heaters were placed at each end of the room while the third one was located inside the heat exchanger box to act as the duct heater.

3.3 Testing

Once the construction of the prototype was done, there was only time for one test day. The system was tested for temperature, relative humidity and air speed, all important parameters of the system. Gas concentration was not measured as we did not have plants growing but it could be done in a more complete prototype. The control points for the test were three locations in the container section to obtain an average ambient reading, the inlet and outlet on the exterior side of the external wall as well as the heat exchanger inlet and outlet. All heaters were set on full load while both fans were set on medium. The test was performed for over 1.5 hours until plugging an extra heater in the hopes of increasing the plateaued temperature caused the breakers to flip. Without access to the breaker box, that event concluded the test day. Using the data collected from the test, it is possible to investigate air flow throughout the system in addition to temperature and relative humidity changes. A portable Reed anemometer which also records temperature and relative humidity was used to perform all measurements.

3.4 Results

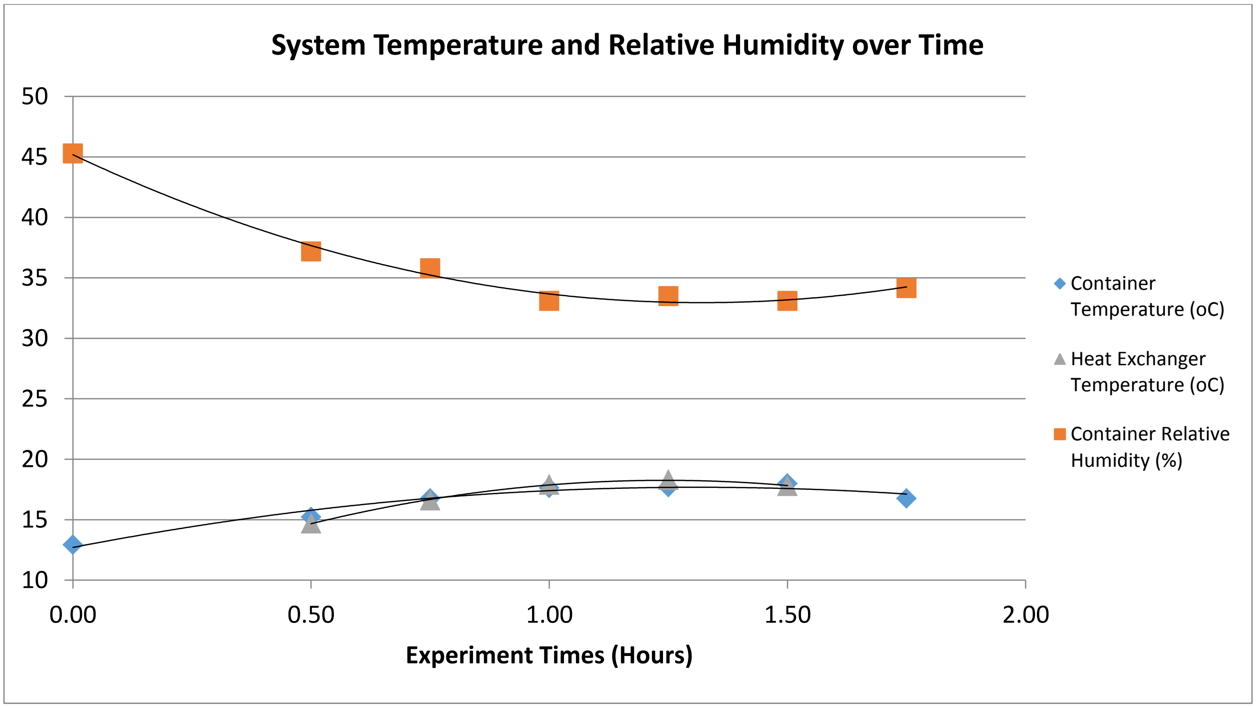

Figure 8. System temperature and relative humidity over time

	Outside				Heat Exchanger					
	Inlet		Outlet		Inlet			Outlet		
Time	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	Air Speed (m/s)	T (°C)	RH (%)	Air Speed (m/s)
0.00					4	72.7	1.5	---	---	---
0.50					20.3	31.4	2.6	14.7	40.5	1.6
0.75			10.1	51.5	18	29.2	2.5	16.6	36.6	1.8
1.00	4	56.7			17.7	30.2	2.4	17.9	30.2	2.9
1.25					18.9	29.4	3	18.3	31.5	3
1.50					18	28.1	4	17.8	33.7	2.8
1.75			Average Air Speed		18.58	29.66	2.9	17.06	34.5	2.42

Table 4. Heat exchanger measurements

	Inlet	**Outlet**	**Flow Loss**
Hole Diameter	1152 mm	1152 mm	
Air speed	2.90 m/s	2.42 m/s	
Air flow	108.82 m^3/h	90.81 m^3/h	16.55 %
	Fan (medium)	**Outlet**	
Total flow	120.3 m^3/min (4250 cfm)	90.81 m^3/h	98.74 %

Table 5.Loss analysis in the heat exchanger and the system

3.5 Data analysis

From Figure 8, it can be seen that a temperature of 18^{o}C was reached after 1.5 hours of experimentation. Furthermore, the heat exchanger outlet temperature matched the room temperature profile, suggesting that indeed the whole room was evenly heated. Relative humidity on the other hand decreased perhaps because the heater acted as a dehumidifier. The slight dip in opposing directions on the last data point indicates the end of the test when doors were being opened and the breakers jumped from overload. In other words, the heating was put to off. By comparing external temperatures to inside temperatures in Table 4, it can be seen that the air was warmed up by 14^{o}C from outside to inside. Temperatures at the inlet and outlet of the heat exchanger hovered mostly between 17 and 20^{o}C. Although relative humidity in the system remained between 30 and 35%, the value would be much higher with plant evapotranspiration occurring.

Although the temperature objective was achieved for our prototype in the test, there is evidence of much loss and inefficiency in the system as reports Table 5. The 16.55% air flow loss between the inlet and outlet of the heat exchanger suggest that air from the container partition might be leaking out. Furthermore, substantial flow loss of 98.74% is observed between the rated fan air flow at medium setting and the air flowing into the heat exchanger to be exhausted. These can be explained by non-airtight seals in the container partition and opening doors which add external air infiltration either from outside drafts or the rest of the room, as well as the rough construction leading to turbulence and loss in the ducting. The partition in the heat exchanger was also found to partially obstruct the air flow exiting the system. Finally, there might have been leaks in the fan enclosure which might have been detrimental to air flow through the ducts. To verify the influence of the rest of the room on the container partition, its temperature and relative humidity should have been measured for comparison, and possible infiltration points should have been located using the anemometer.

The hopes are that for further development, with more time and resources, it would be possible to construct an exact prototype of our envisioned design concept so as to test its actual performance. This includes the addition of automated controls, a true heat exchanger, more materials and better construction. Dampers would be required for regulating the flow of air through the ducting. In the tests, the outside wind, which was variable, would drive the air through our system, causing erratic air flows. Air-tight seals and insulation, which our prototype room and HVAC lacked, are crucial components.

In future developments, a detailed model and simulation of the heat distribution throughout the year for the container, together with its energy consumption should be attempted. This would enhance the project by allowing the diagnostic of potential problems and formulation of improvements for the system. It would streamline the developmental process by testing out solutions analytically before physically implementing them. In such a way, it would be possible to determine when opening the foldable system for sunlight is worth the increased heating load at certain times of the year. Finally, meeting ergonomic standards for occupational health will be good practice for the few if not the single operator of the CING.

3.6 Optimization

Simple overall design optimizations are removing the small fan from the design as the large fan can deliver 85 m^3/min of air versus the recommended 86 m^3/min for 1 ACM. Both heaters could also be downsized or the backup one could be eliminated, however oversizing the system has advantages in higher heating rates and in case of future need. The thickness of insulation on the east and west sides of the CING could also be reduced without having a great impact on the heating load due to the small surface area of those sides. Though the economic impact of less than $800 of these changes would be small compared to the rest of the capital cost, additional design optimization could result in significant combined reduced costs.

4. Cost Analysis

4.1 Capital cost

The capital costs of the first CING prototype was estimated to be around $35,700. The breakdown of this cost was organized into 5 main sections: the outer shell, the insulation, the hydroponic system, the lighting and the HVAC system. The detailed calculations are found in the Appendix B. The summary is presented in Table 6 below.

Component	Parts	Size	Cost	Quantity	Total
Outer Shell	Shipping container	12.036m x 2.350m x 2.393m	$1950 (used)	1	$1,950
	3mm thick glazing	0.61m x 0.91m	$26	104	$2,700
	Reflective panel	$1m^2$	$10	12	$120
sub-total					$4,770
Insulation	Extruded polystyrene	0.6m x 2.4m x 0.15m	$23.33	156	$3,640
	Vapour Barrier (Polyethylene sheeting)	3m x 0.3m x 0.006m			$60
	Vacuum foaming	Kit			$475
	Insulation blanket	System			$4,000
sub-total					$8,175
Hydroponic System	PVC pipe	3m x 0.1m	$12	35	$420
	PCV slip cap	0.1m	$7.71	138	$1,064
	HDPE pipe bundle	30m x 0.04m	$18	5	$90
	PVC pipe support	0.0381m x 3m	$4.97	136	$676
	Small wheels	0.02m	$1.80	69	$124
sub-total					$2,374
Lighting	Philips LED growing lights		$180	69	$12,420
Control System	Weather station and automated controls				$2000
HVAC System	Fans	300 mm multi-speed	$173.66	1	$174
		410 mm multi-speed	$259.17	1	$259
	Heat Exchanger	Venmar AVS 2.6 HE 168.48 L/s (357 CFM)	$1,835.23	1	$1,835
	Duct Heaters	Electro Industries 5kW, 200 mm, 165.18 L/s (350CFM)	$513.00	2	$1,026
	Condenser	A/C Condenser	$200.00	1	$200
	Ducts	300 mm dia. by 1.52m long	$32.17	12	$386
		200 mm dia. by 0.6m long	$9.64	2	$19
	Duct Elbows 90	300 mm	$23.60	4	$94
	Rectangular ducts	200 mm x 200 mm x 1200 mm	$35.39	2	$71
	Registers with Louvers	200 mm x 150 mm	$22.65	10	$227
	Reducers	300 mm/ 200 mm	$18.12	1	$18
		300 mm/150 mm	$19.58	1	$20
	Increasers	200 mm/300 mm	$18.58	1	$19
		150 mm/300 mm	$17.72	1	$18
	Vortex Inline Duct Blower Fan 12"	387 L/s (820 CFM)	$338.95	3	$1,017
	Wall-mount fans for circulation	300 mm 424.75 L/s (900 CFM)	$46.73	4	$187
	Aluminum Piping	380 mm dia. by 1.83m long	$79.60	4	$318
	Pump	124.2 W (1/6 HP)	$74.99	1	$75
sub-total					$5,962
TOTAL					$35,701

Table 6: CING capital cost

4.2 Operational Costs

The total area being cultivated employing the stacked hydroponic system is a little over 8.4 m^2. This gives a total of 483 heads of lettuce (7 heads per hydroponic unit with a total of 69 units) produced each cycle. Each cycle will consist of 4 weeks with a total of 12 growth cycles per year (Bailey, 2013). Therefore the entire system delivers a total annual production of 5796 heads of lettuce.

The operational costs related to maintaining this system include electrical power, water requirements, nutrient, seed and organic growth medium considerations as well as maintenance labour costs. The calculations can be found in Appendix B. The information is summarized in Table 7 below:

Category	Cost	Notes
Electrical Power	$4,263	115W/month/6 heads@ 0.1599$/kWh
Water	$26	$0.00299/liter
Nutrients	$116	$0.02/head of lettuce/cycle
Seeds (lettuce)	$152	1.5$/m2/cycle
Organic growth medium	$303	3$/$m^2$
Maintenance Labour	$25,000	1 person
Total Cost	$29,860	Annual

Table 7: CING operational cost

4.3 Marketability

If we consider capital costs of $35,700 and annual operational costs of $4,860 (excluding maintenance labour costs), then the price of lettuce could be set at $1.45/head. This would also imply a 10-year payback period to cover capital costs. If however a $25,000 salary is included in the operational costs then the price per head of lettuce rises to $5.77. Therefore ways to reduce costs to make this design more profitable in order to provide low cost vegetables to northern regions has to be found and implemented on subsequent CING prototypes. As stated before, some upcoming developing technologies offer promising solutions to increase the CING energy efficiency and decrease the lettuce cost. Another option is to combine the integrated greenhouse with volunteer community programs which could then provide the labour needed to maintain the required operations for minimal costs. It is finally important to mention that since food will be produced locally and in close proximity to consumer outlets, transportation, storage and packaging costs are minimized.

5. Other considerations and future perspective

5.1 Risk Management

The risks of an electrical breakdown is most probable - but also most problematic - during winter conditions. A backup diesel generator and propane burner could then be incorporated to the system on a later prototype to account for this risk. Such a system costs around $5,000 (Aurora Research Institute. 2013).

An anticipated problem involves the foldable closing system failing to close during winter. This would make the heat loss significantly higher to a point where the energy required to regulate the inside temperature might not be cost effective anymore. An analysis was conducted to help choose between letting the crops die or saving them by maintaining the inside temperature just above the freezing point - which lettuce can handle (Smith, 2011). These parameters were taken into account: outside temperature of -50°C; inside temperature of 3°C.

In such a situation, the heat load of the CING would be 13,880 kW instead of the usual 2,222 kW in optimal conditions (see Appendix A). As of now, the CING design can supply 10 kW of heating. By adding an additional 5 kW duct heater for another $513 and running all heaters full blast for 24 hours until the technician comes, at a cost of $0.1599 kWh for electricity, the total cost to save the crop would be $570.56 (Aurora Research Institute, 2013; Ecomfort, 2013). This would give a total value of $3,357.47 to the lettuce crop of that month. If the cost of having that same number of lettuce imported would be superior, for example $3,907.47 in Paulatuk, NWT at $8.09 per lettuce, then it is worth investing to save the crop (Ryder, 2013). If the cost is lower to import, such as in Yellowknife, at $724.50 for $1.50 per lettuce (from a phone call to Extra Foods in Yellowknife), then the crop should not be saved and the replacement supply should be delivered instead. Costs for saving the crop would be distributed over multiple occurrences and could therefore decrease. Also, if losing the crop is not a problem to food security, then simply losing the crop would also be possible. This would reduce the losses.

Finally, there is a potential risk of human error in the maintenance of the system. To account for that, most of the system is automated, thus minimal human input will be needed. Moreover, proper training will be offered to make sure the customer is qualified to operate this technological unit.

5.2 Barriers to Implementation

The very first barrier to the implementation of the CING in northern regions will be its cost. It might not be an issue for most of the industrial customers, but some remote northern communities might not want to invest in this facility if the payback period is currently 10 years. Awareness of the long term advantages of the CING will need to be raised and integrated in its marketing, including long term economic, health and environmental benefits. Governmental subsidies would be an interesting way to mitigate the financial burden of the initial cost of the CING. Some subsidies could come from the Nutrition North Canada program established by the Government of Canada which aims to decrease the price of perishable fresh produce in isolated northern communities. The development of a governmental policy supporting northern agriculture would help to implement the CING (Aurora Research Institute, 2013).

Aside from the initial cost barrier, the CING might have to cope with low energy and water availability. Once again, this is less of an issue with the industrial customers - that usually have their own generator - and more of an issue with remote communities. Developing an energy autonomous system might be of possible interest in the future, but would certainly increase the initial, operating and final product costs significantly. For now, the CING will have to be placed near a reliable source of water and electricity. As stated in the previous report, using geothermal sources when possible for heating would considerably reduce the annual heating cost.

Another barrier that the CING will have to consider is the case of social acceptance. This system is very unique and will involve an adaptation period from the community. There will need to be a strong educational process raising consciousness about the CING and training volunteers to help out when needed. Therefore, the CING will have to be easy to operate and become integrated in the food distribution network of the community.

Finally, the waste produced by the CING will have to be taken into consideration before its implementation by the consumer. The amount of waste is estimated to be very similar to the one found from the life cycle analysis (LCA) conducted in our previous report for a northern greenhouse (fertilizer salt, leached water, plant debris, framing, glazing or used rockwool). The LCA conclusion was that the valorisation or safe elimination of that waste was achievable, but should be planned for and anticipated.

5.3 Implementation plan

It is important to make the Government of Canada an active stakeholders in the CING project, since it has the potential to subsidize and promote project related to food security and agriculture in northern communities. If governmental funding or a governmental program is not made available, partnership with the industrial sector (e.g. mining companies) might provide the first investments needed to start this project.

The prime step to build the first CING prototype is to acquire a shipping container. Tests will be conducted in Montreal, as it was proved to be a suitable testing ground for the HVAC system. Afterwards, the other components described in this report will be added to the container structure. Once optimized after several prototypes, the CING will be manufactured and shipped to Yellowknife where the units will be stored and distributed to more remote customers. Because this agricultural facility is housed in a shipping container, its transportation to places located near an accessible road or airstrip will not pose any problems. To reach more isolated communities - which are generally located near the coast - barges will be used.

It will be the customers' duty to make sure they possess reliable energy and water sources and that they will be able to handle the aforementioned wastes. Training on how to properly use the CING will be provided before or upon arrival. Monitoring and evaluation of the CING will be a constant process in order to improve its design and provide the best experience to the customers.

6. Conclusion

The construction of the first CING prototype could potentially begin in spring 2014, under the supervision of Dr. Mark Lefsrud from McGill University. This depends if different sources of funding (both private and governmental) are awarded or not. In the meantime, a Canadian patent process conducted by Dr. Mark Lefsrud is underway to protect this very innovative and unique design. If accepted, this patent will serve as a basis for an eventual US one.

The development of new technologies (aerogel, soap bubble glazing insulation and LED efficiency) and optimization of the HVAC system will allow for the improvement of this special agricultural facility that has the potential to be the world's most volume and energy efficient enclosed food production system. These technologies will also permit to decrease the cost of production per head of lettuce lower than the price achieved by the first CING prototype (between $1.45 and $5.77).

Implemented on a large scale, the CING will improve food security above the 60th parallel by being one - if not the sole - method of producing year round affordable *in situ* fresh produce.

Acknowledgements

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We hope to submit the CING design project at various paper and design competitions after Dr. Lefsrud's final review. Some tentative competitions are the 2014 Quebec Engineering Competition as well as several CSBE and ASABE design competitions. Also, this report – or some parts of it – might be used for future funding applications.

References

Aboriginal Affairs and Northern Development Canada. 2008. Revised northern food basket – highlights of price survey results for 2006 and 2007, 2008. Gatineau.: Government of Canada. Available at: www.aadnc-aandc.gc.ca. Accessed 2 February 2013.

Adaptive Plastics Inc. 2013. Solexx™ Greenhouse Covering. Farm Wholesale Ag. Available at: http://www.farmwholesaleag.com/greenhouse_covering.shtml. Accessed 29 November 2013.

Agriteam Canada Consulting LTD. 2013. Understanding Sustainable Northern Greenhouse Technologies For Creating Economic Development Opportunities And Supporting Food Security. Agriculture And Agri-Food Canada.

Albright, L. D. 1990. *Environment Control for Animal and Plants*. St. Joseph, Michigan, USA: The American Society of Agricultural Engineers.

Aurora Research Institute. 2013. Agnorth modular farm concept: market study and technical design. Prepared for the Canadian northern economic development agency.

Bailey, J. 2013. NASA plans to grow lettuce in international space station. The Atlanta Journal-Constitution. Available at: www.ajc.com/news/news/national/nasa-plans-grow-lettuce-international-space-statio/nZtcc/. Accessed 24 November 2013.

Brechner, M., A.J. Both. 2012. A handbook for the production of CEA-grown hydroponic lettuce. Cornell University. Biological and environemental engineering. Available at www.cornellcea.com/resourcesPublications/growersHandbooks/lettuce.html. Accessed 29 November 2013.

Chena Hot Spring Resort. 2012. Improved vegetable growth in greenhouses by using tuned LED lights to enhance photosynthesis.: ChenaFresh controlled environment production greenhouse. Available at: dnr.alaska.gov/ag/Grants/ChenaHotSprin gsLEDSystem.pdf. Accessed on 16 April 2013.

Clayton, L. and W. Vandre. 2013. Controlling the greenhouse environment. University of Alaska Fairbanks. Available at www.uaf.edu/files/ces/publications-db/catalog/anr/HGA-00336.pdf. Accessed 2 December 2013.

Coolong, T. 2012. Hydroponic lettuce. University of Kentucky. College of Agriculture. Available at www.uky.edu/Ag/CCD/introsheets/hydrolettuce.pdf. Accessed 29 November 2013.

De Schutter, O. 2012. Special Rapporteur on the right to food: Visit to Canada from 6 to 16 May 2012 - End-of-mission statement. Office of the High Commissioner for Human Rights.

United Nations. Geneva.: United Nations. Available at: www.ohchr.org. Accessed 2 February 2013.

Ecomfort. 2013. EM-WX0515R Electric Duct Heater 5KW 8" Pipe Section 350CFM, 240V. Available at: www.ecomfort.com/em-wx0515r-electric-duct-heater-5kw-8-pipe-section-350cfm-240v-112.html. Accessed 2 December 2013.

Electro Industries. 2013. Duct Heaters. Available at www.electromn.com/res/html/duct.htm. Accessed 2 December 2013.

Elite Buildings. 2009. ISO Shipping Container Specifications/Materials. Available at www.elitebuildings.com/userfiles/ISO_Container_Specifications.pdf. Accessed 2 December 2013.

Engineering Toolbox. 2013. Design of Ventilation Systems. Available at: www.engineeringtoolbox.com/. Accessed 25 November 2013.

Evergreen Marine Corp. 2013. Container Specifications. Available at www.evergreen-marine.com/tei1/jsp/TEI1_Containers.jsp#Dry_4. Accessed 2 December 2013.

Guide of Energy Efficiency in Request for Proposals for New Buildings. 2012. Arctic Energy Alliance. Available at aea.nt.ca. Accessed 17 November 2013.

Haines, Roger W. and C. Lewis Wilson. 1998. *HVAC Systems Design Handbook*. United-States of America. McGraw-Hill Companies.

Hui, S.C.M. 2012. Load and Energy Calculations. Department of Mechanical Engineering, University of Hong Kong. Available at www.mech.hku.hk/bse/bbse2008/bbse2008_1112_03-load_energy.pdf. Accessed 2 December 2013.

Israeli, A. 2007. Insulation value of polycarbonate sheets. International Association of Plastics Distribution. Available at www.iapd.org. Accessed 29 November 2013.

Kurata, S. L. K., & Takakura, T. (2000). Direct solar radiation penetration into row crop canopies in a lean-to greenhouse. *Agricultural and Forest Meteorology, 100*, 243.

McMaster-Carr. 2013. Duct. Available at www.mcmaster.com/#duct/=pnhzpp. Accessed 2 December 2013.

NSSMC. 2013. Cor-ten. Nippon Steel & Sumitomo Metal Corporation. Available at www.nssmc.com/product/catalog_download/pdf/A006en.pdf. Accessed 2 December 2013.

Parker, B, and M. Skinner. 2011. Soap bubbles to insulate greenhouses: a new approach to energy conservation. *Small Farm Quarterly* (October 3 2011): 5.

Plasti-Fab. 2004. How to Calculate Thermal Resistance and Overall Thermal Transmission through Building Sections. Available at www.plastifab.com/technicallibrary/docs/pdf/0406_How%20to%20Calculate.pdf. Accessed 2 December 2013.

Radiant Barrier Journal. 2010. Why Radiant Barrier Don't Have R-values. Radiant Barrier & Reflective Insulation Info & Advice. Available at www.radiantbarrierjournal.com. Accessed 28 November 2013.

Residential Shipping Container Prime (RSCP). 2013. R value: insulation values for selected materials. Available at www.residentialshippingcontainerprimer.com. Accessed November 28 2013.

Ryder, Cassina. 2013. Cost of lettuce accidentally doubled in Paulatuk store. Available at www.nnsl.com/frames/newspapers/2013-04/apr8_13let.html. Accessed 2 December 2013.

Shukla, N.C., Ali Fallahi, and Jan Kosny. 2012. Aerogel for Thermal Insulation of Interior Wall Retrofits in Cold Climates. Fraunhofer Center for Sustainable Energy Systems. Available at cse.fraunhofer.org/. Accessed 28 November 2013.

Smith, R., M. Cahn, and O. Daugovish. 2011. Leaf lettuce production in California. University of California Davis. Available at http://ucanr.org/freepubs/docs/7216.pdf. Accessed 28 November 2013.

Straube, J.F. 2003. Heat Flow Basics. University of Waterloo. Available at www.civil.uwaterloo.ca/beg/arch264/arch264%20heat%20flow%20basics.pdf. Accessed 2 December 2013.

The Dow Chemical Company. 2013. STYROFOAM™ Brand SM Insulation Extruded Polystyrene. Dow North-America. Available at: http://building.dow.com/na/en/products/insulation/sm.htm. Accessed 28 Novembre 2013.

Thouez, J.P., A. Rannou, P. Foggin. 1989. The other face of development: native population, health status and indicators of malnutrition-the case of the Cree and Inuit in northern Quebec. *Social Science and Medicine* 29 (8): 965-974.

Vaisala. 2011. Greenhouse climate measurements ensure optimal plant growth. Available at www.vaisala.com/Vaisala%20Documents/Application%20notes/CEN-BAU-Greenhouse-Climate-Application-Note-B211142EN-A-LOW-v3.pdf. Accessed 2 December 2013.

Venmar. 2013. Venmar AVS HE 2.6 HRV. Available at: www.venmar.ca/43-air-exchangers-he-2-6-hrv.html. Accessed 2 December 2013.

Appendices

Appendix A – Technical components sizing calculations

LED PAR requirements per system:

Lettuce PAR needs: $17\frac{mol}{m^2 * d}$ (Brechner and Both, 2012)

Growing area per hydroponic unit: $Length * \ diameter = 0.10m * 1.22m = 0.122m^2$

LED PAR output per hydroponic unit: $\frac{Lettuce\ light\ need}{Growing\ Area} = \frac{17\frac{mol}{m2*d}}{0.122m^2} = 2.07\frac{mol}{d}$

Put in $\frac{\mu mol}{s}$ which is the industry standard: $\frac{2.07\ mol/d}{60s*60minutes*24\ hours} = 25\frac{\mu mol}{s}$

<u>Therefore each LED panel should have an output of 25 $\mu mol/s\ PAR$</u>

Hydroponic Water Tank sizing:

Radius of PVC pipe: 0.1m

Height of water needed for lettuce in the NTF gullies: 0.0635m **(**Coolong, 2012)

Circular segment area (using basic trigonometry): 0.00857m^2

Volume of water needed per unit: $segment\ area * length$

$$0.00857m^2 * 1.2192m \ = \ 0.01\frac{m^3}{unit}$$

For the whole system 0.01$\frac{m^3}{unit}$*69$units$ = 0.721m^3 or 721 litres

Adding a bit of extra so the tank will not dry up when the water flows in the pipes

<u>Water tank size of 800 L or two 400 L</u>

Exhaust Fan Specifications

McMaster-Carr Part Number 19455K21 & 19455K22

COMMERCIAL EXHAUST FANS

COMMERCIAL DIRECT DRIVE EXHAUST FAN

LPEV

LPES

- 115V, 1Ø, totally enclosed permanently lubricated motor.

- LPES - Shutter mounted fan - Reduces installation time by eliminating inside and outside framing when a shutter is going to be used.

TYPE	BLADE SIZE	OUTSIDE DIMENSION	CFM AT 115V HIGH MED LOW	AMPS (HIGH)	SHIP WT (LBS.)
19455K21	12"	15" Sq.	2000 / 1600 / 1150	1.1	16
19455K22	16"	19" Sq.	3000 / 2650 / 2250	1.1	25
	24"	27" Sq.	5000 / — / 4200	2.2	44
	30"	33" Sq.	7800 / — / 6600	2.5	51

(McMaster-Carr, 2013)

Fans 19455K21 and 19455K22 were used in our design.

<u>Air flow calculations:</u>

We would like a maximum air flow rate between 1 and 2 ACM (through our greenhouse for cooling in the summer and a minimum air flow rate of 0.25 ACH in the winter as background flow for controlling gas concentrations (Albright, 1990).

Container Inner Volume: 86.02 m^3
0.25 ACH = (86.02/4) m^3/h = 21.51 m^3/h
1 ACM = 86.02 m^3/min
2 ACM = (86.02 m^3*2)/min = 172.04 m^3/min

From the fan specifications, combined maximum air output is 141.6 m^3/min or 5000 ft^3/min which meets our desired specifications. For minimal flow, although the lowest setting of 1954 m^3/h far surpasses the desired 21.51 m^3/h, by using variable speed controller for the fan, it would be possible to operate at the lower required air flow.

Heating Load Calculations

ISO standard shipping containers generally use Corten A weathered carbon steel for the exterior shell (Elite Buildings, 2009). Corten NAW 490 steel has thermal conductivity of 60.44 W/(m*K) at 0^{o}C, which is the closest value found to Corten A (NSSMC, 2013). The true value would be higher as carbon steels have decreasing thermal conductivities with higher temperatures (Engineering Toolbox, 2013).

It will be assumed that there is also no airlock so as to simplify calculations. By taking it into consideration, the airlock would add to the insulation of the shipping container due do the extra wall and the thick layer of air trapped between and the container entrance door. Latent heat transfers will be ignored as the air outside is much dryer than the air inside the container.

Since the glazing will be held in place by steel, a mixed thermal resistance value for the ceiling and South sides will take into consideration a 10% area of steel in the proportional thermal resistance calculation. There is also a layer of air trapped within the two.

	South Side	**North Side**	**West Side**	**East Side**	**Ceiling**	**Floor (above grade)**
Exterior Air film	0.03	0.03	0.03	0.03	0.03	0.03
Weathered corrugated steel		$7.114*10^{-4}$ (43 mm)	$1.324*10^{-3}$ (80 mm)	$1.324*10^{-3}$ (80 mm)		$1.638*10^{-3}$ (99mm)
Glazing (3 or 8 mm)	0.15				0.15	
Foam (25.4 mm)		0.83	0.83	0.83		0.83
XPS Panels		4.17 (127 mm)	4.17 (127 mm)	4.17 (127 mm)		9.17 (279.4 mm)
Interior Air Film	0.12	0.12	0.12	0.12	0.11	0.16
Plywood (19 mm)						0.165
Total Wall Thickness (t)	3 mm	195.4 mm	232.4 mm	232.4 mm	3 mm	422.8 mm
Total Resistance, RSI	0.3	5.151	5.151	5.151	0.29	10.36
Thermal Conductance, U W/(m^{2}*K)	3.33	0.194	0.194	0.194	3.45	0.0966

RSI values in m^{2}*K/W of container sides and thickness of materials in mm
(Plasti-Fab, 2004; RSCP, 2013; Evergreen Marine Corp, 2013; Straube, 2003)

	Container Dimensions			
	Length (m)	Width (m)	Height (m)	Volume (m^3)
External	13.716	2.438	2.896	96.84
Internal	13.556	2.352	2.698	86.02

45’ High Cube Container Dimensions
(Evergreen Marine Corps, 2013)

	Container Sides						
	South	North	West	East	Ceiling	Floor (above grade)	
U (W/m^2*K)	0.2	0.194	0.194	0.194	0.1	0.0966	
Area (m^2)	39.72	39.72	7.060	7.060	33.44	33.44	
ΔT (°C)	70						
Q (W)	556.10	539.42	95.88	95.88	234.08	226.12	Q = U*A*(ΔT)
$Q_{total\ flow}$ (W)	1747.48						
$Q_{Infiltration}$ (W)	30.11						= 0.02*Volume*0.25 ACH* ΔT
Safety allowance of 25%	444.40						= ($Q_{total\ flow}$ + $Q_{Infiltration}$)*0.25
Q_{total} (W)	2221.98						= $Q_{total\ flow}$ + $Q_{Infiltration}$ + Safety Allowance

Heating Load Calculations for Optimal Operation
(Hui, 2012)

	Container Sides						
	South	North	West	East	Ceiling	Floor	
U (W/m^2*K)	3.33	0.194	0.194	0.194	3.45	0.0966	
Area (m^2)	39.72	39.72	7.060	7.060	33.44	33.44	
Delta T (°C)	53						
Q (W)	7010.45	408.42	72.60	72.60	6114.43	171.20	Q = U*A*(ΔT)
$Q_{total\ flow}$ (W)	13850						
$Q_{Infiltration}$ (W)	30.11						
Q_{total} (W)	13880						= $Q_{total\ flow}$ + $Q_{Infiltration}$

Heating Load Calculations for Container Malfunction
(Hui, 2012)

Experiment Data

<table>
<tr><th colspan="3"></th><th colspan="4">Outside</th><th colspan="6">Heat Exchanger</th></tr>
<tr><th></th><th colspan="2">Container</th><th colspan="2">Inlet</th><th colspan="2">Outlet</th><th colspan="3">Inlet</th><th colspan="3">Outlet</th></tr>
<tr><th>Time (h)</th><th>T (°C)</th><th>RH (%)</th><th>T (°C)</th><th>RH (%)</th><th>T (°C)</th><th>RH (%)</th><th>T (°C)</th><th>RH (%)</th><th>Air Speed (m/s)</th><th>T (°C)</th><th>RH (%)</th><th>Air Speed (m/s)</th></tr>
<tr><td>0.00</td><td>12.93</td><td>45.3</td><td rowspan="7">4</td><td rowspan="7">56.7</td><td rowspan="6">10.1</td><td rowspan="6">51.5</td><td>4</td><td>72.7</td><td>1.5</td><td>---</td><td>---</td><td>---</td></tr>
<tr><td>0.50</td><td>15.23</td><td>37.2</td><td>20.3</td><td>31.4</td><td>2.6</td><td>14.7</td><td>40.5</td><td>1.6</td></tr>
<tr><td>0.75</td><td>16.77</td><td>35.8</td><td>18</td><td>29.2</td><td>2.5</td><td>16.6</td><td>36.6</td><td>1.8</td></tr>
<tr><td>1.00</td><td>17.63</td><td>33.1</td><td>17.7</td><td>30.2</td><td>2.4</td><td>17.9</td><td>30.2</td><td>2.9</td></tr>
<tr><td>1.25</td><td>17.7</td><td>33.5</td><td>18.9</td><td>29.4</td><td>3</td><td>18.3</td><td>31.5</td><td>3</td></tr>
<tr><td>1.50</td><td>18</td><td>33.1</td><td>18</td><td>28.1</td><td>4</td><td>17.8</td><td>33.7</td><td>2.8</td></tr>
<tr><td>1.75</td><td>16.77</td><td>34.17</td><td colspan="2">Average Air Speed</td><td>18.58</td><td>29.66</td><td>2.9</td><td>17.06</td><td>34.5</td><td>2.42</td></tr>
</table>

End of experiment occurred due to electrical breaker flipping on the addition of a 4th heater to the system in hope of further raising the temperatures.

Appendix B – Cost calculation

Insulation
There are no 30cm (6 in) XPS panel commercialized. Two layers of 15 cm (6 in) of dimension 0.6m x 2.4m x 0.15m (2 ft x8 ft) , RSI-2.5 (R-15) per panel were used for the wall and four layers for the floor to approximate the cost of the insulation.

<u>XPS</u>

North wall:

Area to cover:

$$(container\ height - floor\ insulation\ thickness) * container\ length$$

$$= (9.5\ ft - 1\ ft) * 45\ ft = 382.5 ft^2$$

Number of panels for one layer : $\frac{382.ft^2}{(8ft*2ft)} = 24\ panels$

For two layer, 48 panels

End-wall:

Area to cover: $\left(container\ height - floor\ insulation\ thickness\right) * container\ side\ lenght$

$= (9.5\ ft - 1\ ft) * 8\ ft = 68ft^2$

Number of panels for one layer: $\frac{68\ ft^2}{(8ft*2ft)} = 5\ panels$

For the two end-walls and for two layer, 20 panels

Floor

Area to cover:

$$(container\ side\ lenght - north\ wall\ insulation\ thickness) * container\ side\ lenght$$

$= (8\ ft - 0.5\ ft) * 45\ ft = 337.5ft^2$

Number of panels for one layer: $\frac{337.5\ ft^2}{(8ft*2ft)} = 22\ panels$

For four layers, 88 panels

Total

North wall + end-walls+ floor = (48 + 20 + 88) panels

Total: 156 panels

(Home Depot, 2013a) XPS total cost: 156 panels @ 23.33 $ = 3639.48$

<u>Vapour barrier</u>

Area to cover: $382.5ft^2 + 68ft^2 + 337.5ft^2 = 788\ ft^2$

One 10 ft. x 100 ft. would be enough = 60$ (Home Depot, 2013b)

Home Depot. 2013a. PlastiSpan HD EPS Rigid Insulation 96Inch X 24Inch X 3. Available at http://www.homedepot.ca/product/plastispan-hd-eps-rigid-insulation-96inch-x-24inch-x-3/940436. Accessed 29 November 2013.

Home Depot. 2013b. Husky 10 ft. x 100 ft. Clear 6 mil Polyethylene Sheeting. Available at http://www.homedepot.com/p/Husky-10-ft-x-100-ft-Clear-6-mil-Polyethylene-Sheeting-CFHK0610C/100651788#.UpLAteyqD8o. Accessed 29 November 2013.

Insulation blanket

This system is approximated to be 4000$ according to Parker and Skinner (2011).

Vacuum foaming

Froth-pak 200 Foam Insulation Kit cost 475$ (Home Depot, 2013c)

Home Depot. 2013c. Froth-pak 200 foam insulation kit. Available at http://goo.gl/k4ucnJ. Accessed 29 November 2013.

INSULATION TOTAL CAPITAL COST: 8120.48$

LED

As stated in the report, special LED arrays should be built for the NING. However, in order to give an approximate cost of the LED system, a currently available panel was used in the cost estimation. The Philips Pro Hydroponic LED Grow Light Production using 30W of power and providing 50 $\mu mol/s\ PAR$ were used (180$/unit) (Amzon.com, 2013).

$$\text{LED capital cost: } 180\frac{\$}{unit} * 69\ units = \ 12\ 420\$$$

LED TOTAL CAPITAL COST: 12 420$

Amazon.com, Inc. 2013. Philips Pro Hydroponic LED Grow Light Production Module DR/B 120cm 110V 30W. Available at http://www.amazon.com/Philips-Hydroponic-Light-Production-Module/dp/B00BFPXQEQ. Accessed 29 November 2013.

Hydroponic System

PVC

Using 3 m x 0.1 m PVC pipe, it would require 35 pipes for the 69 units of 2.2192 m long

Total cost = 35 PVC pipe @ 12.17$ (Home depot, 2013c)

PVC cost: 419.87$

Small irrigation black pipe to connect water tank to PVC:

A total of 6 m per three systems is required for a total of 141 m

5 3/4 in. x 100 ft @ 18.16$ would be required (Home depot, 2013d)

Small irrigation pipe cost = 90$

End pipe:

For the 69 units, 0.1 m fitting @ 7.71$ (Home depot, 2013e)

End pipe cost: 1063.98$

PVC hollow support

Total length: height of each level (38cm + 91 cm + 166cm) *2 supports * 69 units = 407.1 m of PVC support needed

Using 3.81 cm (1½ in) x 3m (10 ft) pipe @ 4.97$ (Home depot, 2013f), it would require 136 pipes

PVC hollow support cost: 674.43$

Small wheel

With 1 wheel for each 69 units @1.80$ each (Home depot, 2013g)

Small wheel total cost: 124.2$

HYDROPONIC SYSTEM TOTAL COST: 2372.48$

Home depot. 2013c. 4 in. x 10 ft. PVC Sch. 40 DWV Plain End Pipe. Acessible at http://www.homedepot.com/p/Unbranded-4-in-x-10-ft-PVC-Sch-40-DWV-Plain-End-Pipe-531103/100156409#.UplmyOyqD8p. Accessed 29 November 2013.

Home depot. 2013d. Advanced Drainage Systems 3/4 in. x 100 ft. 80 PSI Poly Pipe. Available at http://www.homedepot.com/p/Advanced-Drainage-Systems-3-4-in-x-100-ft-80-PSI-Poly-Pipe-7580100/202282478?MERCH=RV-_-RV_search_plp_rr-1-_-NA-_-202282478-_-N#.UplncuyqD8p. Accessed 29 November 2013.

Home depot, 2013e. 4 in. PVC Slip Cap. Available at http://www.homedepot.com/p/Unbranded-4-in-PVC-Slip-Cap-447-040HC/100175802#.UploKOyqD8p. Accessed 29 November 2013.

Home depot. 2013f. 1-1/2 in. x 10 ft. PVC Sch. 40 DWV Plain End Pipe. Available at http://www.homedepot.com/p/Unbranded-1-1-2-in-x-10-ft-PVC-Sch-40-DWV-Plain-End-Pipe-531111/100135041#.Uplr8eyqD8o. Accessed 29 November 2013.

Home depot. 2013g. 1-1/4 Inch General Duty Swivel Casters. Available at http://www.homedepot.ca/product/1-1-4-inch-general-duty-swivel-casters/968131. Accessed 29 November 2013.

Appendix C - Hyperlinks to resources related to the CING project

Video 1 : CING_3D_overview: http://goo.gl/v4R8ug
Video 2: CING_FoldableClosingSystem: http://goo.gl/VgM1wG
Video 3: CING_3D_HydroponicTrackingSun: http://goo.gl/zidm

Report of the Prototype of Adaptive Greenhouse/Growth chamber Shell Design:
http://goo.gl/58aOnl
Report of the Pivoting Hydroponic System Prototype and System Orientation:
http://goo.gl/bZy7bf

View of the prototype testing phase