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December 8, 2021

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Dear Dr. Labossiere,

Please find the Final Design Report for the Vertical Farming project as completed by Group 11. This report is authorized by the Mechanical Engineering Department of the University of Manitoba's Price Faculty of Engineering, with assistance provided by Dr. Meghan Guyot, P.Eng.. We would like to thank Dr. Guyot for her time, support, and expertise throughout the project.

The purpose of this report is to present the final design for a climate-controlled, retrofitted carousel suitable for plant growth. The report focuses on detailed structural, HVAC, and renewable energy design for the carousel. The final design presented is capable of withstanding the harshest Manitoban weather conditions while maintaining optimal indoor conditions powered fully by renewable energy sources.

On behalf of Group 11, it has been a pleasure preparing this report. We would like to thank you Dr. Labossiere for your guidance throughout our degrees' and sharing your knowledge with us.

Sincerely,

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University
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Final Design Report

Vertical Farming Project

MECH 4860 ENGINEERING DESIGN

VIDIR SOLUTIONS, INC.

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Executive Summary

Founded in 1985, Vidir Solutions is a Manitoban company that specializes in vertical, motorized storage solutions. In their 35 years of operation, Vidir has become a leading manufacturer and worldwide supplier of vertical motorized storage carousels and display systems [1]. Vidir has a diverse product line offering solutions for a broad range of industries. One may even see their products being used in stores like Home Depot, Lowe's, or Menards. Being located in the rural community of Vidir, Manitoba, Vidir Solutions aims to serve the agricultural community which surrounds it. Combining mechanical design and agricultural considerations, Vidir Solutions would like to enter the vertical farming market.

In conjunction with a separate Biosystems design team, Group 11 has been tasked with aiding Vidir in retrofitting an existing carousel to be a fully climate controlled plant growth environment as there are no motorized products like this currently on the market. Specifically, the design is constrained to the existing 10×10 foot concrete pad and must maintain an internal temperature between 20 and 30°C and an internal relative humidity between 45 and 60%. The deliverables for this project include a 3D CAD model, a Bill of Materials, and associated calculations.

For ease of design, Team 11 split the design process into three focus areas: structural, HVAC, and renewable energy. Numerous concepts were explored including combinations of insulation and construction methods, heating, cooling, and combined systems, as well as a feasibility study on the use of renewable energy power sources. The design development process involved defining and integrating these focus areas. The systems were designed based on a mixture of analytical and numerical analyses to specify design details. Analysis provided a proof-of-concept based on proven methods, therefore allowing Team 11 to more effectively meet client needs of safety, structural integrity, thermal stability, and humidity control. Further, analysis allowed Team 11 to verify the design will meet relevant codes and standards.

The structural design uses a modular panel system for the walls, floor, and roof, taking advantage of Vidir's manufacturing capabilities. The panels feature a steel tubing frame, held together with rivets to achieve a permanent connection, and will house closed cell spray foam insulation. Panels, flooring, and roof are connected to the concrete pad and carousel frame using bolt connections through metal brackets. This design ensures an easy to install, well insulated, rigid structure around the carousel that can be effectively climate controlled, increasing overall energy efficiency.

A minisplit system was selected for the HVAC heating unit, consisting of an indoor wall unit and outdoor heat pump, supplying 9,000 BTUh, surpassing the required 3,035 BTUh. The heating system also includes a heat recovery ventilator to facilitate outdoor air intake and humidifier to deliver the required humidity levels. Team 11 opted to use a convection based cooling system with a vent and exhaust fan to circulate outdoor air. This HVAC system will allow for efficient climate control able to handle varying plant growth conditions while requiring minimal interaction.

Team 11 determined the entire system could be powered by five solar panels with a collective annual energy generation of 40,740 kWh, meeting 120% of the energy demand. Due to the size of these panels, they will have to be mounted externally from the main structure. For the purpose of Vidir's first enclosure it was determined that panels could be installed on their surrounding buildings. The system will be connected to the grid as a fail-safe against solar panel failure. Implementation of solar panels results in a more sustainable system and lower long-term energy costs.

The enclosure has been designed to facilitate plant growth in extreme Manitoban weather conditions. The entire system is estimated to cost \$17,304.45 for components sourced outside of Vidir's capabilities. This system is energy efficient, easy-to-implement, and has long-term sustainability. The enclosure may be adjusted to be applied to varying applications. Team 11 recommends implementing the presented solution at Vidir's Arborg location to prove the feasibility of the design in the field, further improving on any unforeseen issues that may arise.

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Glossary

Advanced Engineering Design (AED)

Advanced Engineering Design (AED) is a technical elective course running from (January to April) which Vidir has expressed interest in. The course would see this project continue into the prototyping and testing phases of the engineering design process.

Capstone

The final design course in the University of Manitoba's Mechanical Engineering degree through which Team 11 is participating in this design.

Computer Aided Design (CAD)

Design software such as Solidworks, through which 3D models are created and analyzed

Heating, Ventilation, and Air Conditioning (HVAC)

A branch of engineering related to the study of the motion, heating, cooling, and quality of air between interior and exterior spaces, and the equipment needed to control/distribute these [2].

Heat Recovery Ventilator (HRV)

A system designed to replace stale air from an enclosed space, such as a home, with fresh air from outside while minimizing the loss of heat or cold depending on the season.

LED

Light emitting diode.

Oriented Strand Board (OSB)

Is an engineered building material composed of rectangular-shaped wood strands arranged in layers at right angles to one another, the layers are then bonded together with waterproof adhesives.

Shelving Carousel (carousel)

The mechanized storage solution that will be used as the foundation for the vertical farming design.

Structurally Insulated Panel (SIP)

Commercially available pre-fabricated wall and ceiling panels which provide high insulation values and structural properties similar to traditional wood frame construction.

Vidir Solutions Inc (Vidir)

A Manitoban company who specializes in vertical storage solutions.

Finite Element Analysis (FEA)

Is a process of simulating the behavior of components or assemblies under a given set of conditions and constraints.

Thermal Analysis

Similar to finite element analysis is a process of simulating the behavior of components or assemblies under a given set of conditions and constraints.

Hollow Structural Section (HSS)

A commonly available form of steel tubing, found in a variety of standard round, square and rectangular sizes, as well as a number of different grades. Unlike pipe and other products HSS can be identified by a long welded joint, and die markings from cold forming.

1 Introduction

The following report will describe the process and details of the final design, including the enclosure structure and HVAC system, as well as descriptions of feasible renewable power options. Section 1 will provide an overview of the project objectives, scope, and constraints. Section A contains a brief summary of the structural concept selection process and a detailed description of the final proposed structural design. Likewise, section 3.3 summarizes the HVAC concept selection process and describes the final proposed HVAC design. Section 4.4 evaluates options for renewable energy implementation and includes the Team 11 recommendations. Section 6 will provide a full summary of the entire proposed design, including structure, HVAC system, and renewable energy recommendations.

1.1 Project Background

Vidir is a Manitoban company specializing in vertical storage solutions. In their 35 years as a company, Vidir has designed and built solutions for a variety of applications around the world, ranging from vertical tool storage to carpet roll storage/cutting machines [1]. Now, Vidir is exploring the possibility of using their vertical storage experience to enter the market of controlled agriculture.

Vidir is considering developing one of their existing vertical shelf carousel designs into a controlled agriculture solution. The carousel, shown in Fig. 1, provides shelf-style storage with a mechanical system that improves ease of access and safety. The carousel is made up of two towers joined by shelves which are hung from chains. A drive shaft synchronizes the chain in each tower and connects the rotating system to a pair of drive motors. With this design each shelf can be brought to an easily accessible location with the press of a button. Vidir believes that using a carousel may be a unique approach for growing fresh food in a relatively small footprint.



Figure 1: Vidir shelving carousel [3]

1.2 Problem Definition and Project Objectives

Team 11 is tasked with helping Vidir adapt an existing shelf carousel into a controlled plant growth environment. Specifically, Team 11 is to design a fully climate-controlled solution that allows Vidir to install a carousel as an outdoor, year-round growth environment in Manitoba. Team 11's design must support the growth environment in the extreme conditions expected to occur in Manitoba, both by being structurally rigid, and by regulating heat and air flow.

Part of the problem is there are currently no vertical, carousel (i.e, moving), greenhouse storage products available on the market. This attests to the unique nature of Vidir's product line.



Figure 2: Vidir's prototyping site [4]

In Arborg, Manitoba, Vidir has poured a concrete pad upon which they envision an enclosed carousel being installed. This prototype site is described in more detail in Section 1.2.1. Eventually, Vidir would like to market this enclosed solution to customers such as restaurants, homes, and remote communities to increase sustainable agriculture accessibility.

Vidir would prefer renewable energy as a power source for the project, to better meet the goal of sustainability. Team 11 has been tasked with analyzing the associated costs and feasibility.

Team 11 is working in parallel with a Biosystems Engineering student team to design the desired system for Vidir. Aspects of this project have been divided between the groups, seen in Fig. 3 below. For this project, the scope has been limited to development of the enclosure, HVAC, and a feasibility study on solar power delivery. Excluded from the scope to be completed by the biosystems group is development of the lighting and watering systems as well as determining power requirements for these systems for the solar feasibility study.



Figure 3: Scope division [4]

1.2.1 Limits and Constraints

- **Space:** The design is constrained to the existing 10 x 10 foot concrete pad at Vidir. There is no physical height constraint - just the 20ft target suggested by Vidir.
- **No major changes to existing products:** The design must be compatible with Vidir's existing carousel. Redesigning Vidir's carousel is not within the scope of this project. Minimal modifications are allowed.
- **Manufacturing:** The design is limited to the manufacturing processes, materials, and products available to Vidir. Purchased components will be limited to commercially available products.
- **Time & Resources:** The project must be completed by the end of the Engineering Design course running from September 8th, 2021 until December 10th, 2021.

1.2.2 Customer Needs and Requirements

Needs and requirements were established and prioritized based on information provided by Vidir. The requirements and their respective importance factor are outlined in Table I.

TABLE I: CLIENT NEEDS AND REQUIREMENTS

No.	Requirement Description	Rank
1	Enclosure surrounds the carousel, withstanding Manitoba weather.	5
2	System is safe.	5
3	Enclosure can be installed on a preexisting concrete pad.	5
4	Height of system is compatible with the dimensions of the concrete pad.	5
5	Internal environment calculations account for thermal properties of the un-insulated existing concrete pad.	5
6	A renewable energy source is used as an aid to electrical grid power.	5
7	System maintains temperature and humidity levels for growing.	5
8	Temperature and humidity can be adjusted to desired growing conditions.	5
9	Design can be used or modified to other locations for customers (i.e. restaurants, northern communities, homes, etc.).	5
10	Enclosure allows entrance of an external water line.	4
11	System can be made and assembled using in-house materials and tooling.	3
12	Design is adjustable to accommodate a larger area and more carousels.	3
13	System is easy to operate.	3
14	System is easy to maintain.	3
15	System is economical to implement and operate.	2

High Priority  Low Priority

1.2.3 Metrics and Specifications

After assessing the needs and consulting with Vidir, a list of metrics was established. Each metric was assigned a unit, target specification, and a priority from 1 to 5. Metrics critical to success are priority 5 while preferred metrics are a priority 1. These metrics facilitate the evaluation of the design on a measurable set of criteria by which to measure concepts as well as the proposed design at the end of this project.

TABLE II: METRICS AND TARGET SPECIFICATIONS

No.	Needs	Metric Description	Units	Specification	Rank
1	2	Safe	Yes or No	Yes	5
2	3	Concrete Pad Size	Feet (ft)	10 x 10	5
3	5,7,8	Internal Temperature	Degrees Celsius (°C)	$20 \leq \text{°C} \leq 30$	5
4	5,7,8	Internal Relative Humidity	Relative Humidity (φ)	$45\% \leq \varphi \leq 60\%$	5
5	1,7	The Enclosure Withstands Manitoba Weather	Yes or No	Yes	5
6	9	Adaptability difficulty	High to Low	Low	5
7	2,3,4	Height	Feet (ft)	≈ 20	4
8	2	Meets Standards & Codes	Yes or No	Yes	4
9	6,15	Efficiency	Percent	Maximize	3
10	6	Grid Reliance	Percent	Minimize	3
11	6	Environmental Impact	Subjective	Minimize	3
12	13,14	Requires Specialized Tools	Yes or No	No	3
13	13,14	Consumable Components	Yes or No	No	3
14	15	Cost	Dollars (\$)	Minimize	3
15	13,14	Off-the-Shelf Components	Yes or No	Yes	1

High Priority  Low Priority

Metrics were determined by Vidir’s preference and through research. Firstly, the design must be safe to operate. The size of the supporting concrete pad must be 10×10 feet as the pad has been constructed for this project. The internal temperature and humidity were determined through consultation with the Biosystems team. The enclosure must withstand Manitoba’s climate to ensure that the internal environment is maintained, and there are no structural failures under heavy wind, rain, or snow loads. Vidir has indicated a preferred height of 20 feet to be compatible with an existing design, but requirements for the size of the concrete pad will take precedence. The design should meet all codes and standards applicable to this type of agricultural structure. Efficiency of the design should be prioritized while the reliance on grid power and the environmental impact should be kept low. Cost should also be kept low so that the finished product is competitive for the market. It is also preferred that the design avoid specialized tooling and consumable components for normal use.

2 Codes, Standards, and Existing Patents

Team 11 looked into existing patents and design as a first step, as such the results of this search has been included. Further, Team 11 has decided to compile their research into applicable codes and standards to ensure that the final design satisfies the designated safety needs.

2.1 Patent Search

While there are several patents existing in the vertical farming industry, patents conflicting with the responsibilities of Team 11 could not be found. Patents specific to the lighting, watering, and other plant growth systems under development by the biosystems group were shortly investigated.

Common patents in the vertical farming industry involve moving plants along a frame supporting a track, belt, hydroponic trough, or robot, each of which moves plants from areas accessible by the operator to storage or grow areas. Examples and further reading can be found as follows:

- System and method for vertical farming [5]
- Tank housing a vertical farm [6]
- Vertical growing tower for automated horticulture and agriculture [7]
- Combined Vertical Farm, Biofuel, Biomass, and Electric Power Generation Process and Facility [8]

2.2 Applicable Standards

To ensure the needs of safety and efficiency are met the design must be in agreement with applicable sections of the Manitoba Building Code for greenhouses and other agricultural buildings [9]. In this report the code is primarily used to determine required insulation for the enclosure. The code will be referenced further to ensure compliance in other areas of the final design. In addition to the Manitoba Building Code, the Greenhouse Ventilation guideline [10] will be followed to ensure an optimum growing environment while minimizing the energy impact of excessive air exchanges. The Greenhouse Ventilation guidelines were developed by the Department of Agricultural and Biological Engineering at University of Florida in 1987 and updated in 2019.

3 Concept Development and Selection Summary

This section summarizes the overall concept development and selection for the structural and HVAC systems used in the final design. Section 3.1 describes the methodology that was used in developing concepts for both the structural and HVAC systems, followed by the approach taken to determine which concepts should move forward to final design development. Section A includes concept details, selection criteria and final chosen selection for the structural system, Section 3.3 includes the same details for the HVAC system. Renewable energy concepts were not included as Team 11 focused on the feasibility of implementing a renewable system and will be addressed later in the report.

3.1 Concept Selection Methodology

Because the project is divided into two distinct systems, structural and HVAC, two separate concepts had to be selected. The concept selection methodology utilized for both systems was identical. Firstly, concepts were generated through brainstorming and research on conventional solutions. Concept selection was completed in two phases, screening and selection. Screening involves reducing numerous concepts to a few so that more rigorous analysis can be performed in selection. Selection utilized multiple matrices to determine which concepts satisfied project requirements the best. Criteria weights were computed by comparing the importance of each criterion against each other. Next, the concepts were ranked on each criteria as either 1 (best), 3 (mediocre), or 5 (worst) and the score for each criteria was determined by Equation 3.1. Finally, the criterion scores were summed and the concept with the highest total score was chosen.

$$\text{criterion score} = \frac{\sum \text{rank}}{\text{rank}_{\text{concept}}} \quad (3.1)$$

3.2 Structural Concept Selection

This section explores the concept generation and selection process for the structural and construction aspects of the project. Each option was filtered qualitatively before being filtered quantitatively.

3.2.1 Carousel Stability

As Vidir's shelf carousel is designed for indoor use, the stability of the enclosure under severe wind loads was a significant concern in the initial stages of the project. As such, the carousels stability was investigated before the concept development process began. In Manitoba maximum wind gusts of 125 kph [11] are not uncommon. Therefore, a sustained wind speed of 125 kph has been used as a worst-case scenario for stability evaluation. Additionally, the calculations assume

an even wind distribution on the carousels broad side with no disruptions due to the surrounding buildings. The equations and results of this analysis can be found in Appendix A.

Under the worst case wind load the freestanding carousel has a minor positive, or stable, moment. The extra mass of the enclosure and carousel contents will add greatly to the structures stability by providing extra resistance to the wind. As Team 11 moves into the more detailed stages of the design the carousels stability will be assessed again to ensure the final design is stable.

3.2.2 Structural Concepts

There were four structural and five insulation concepts generated, seen in Table III. 13 combinations of insulation and construction concepts were found to be compatible. These combinations are summarized in Table A.4.

TABLE III: STRUCTURAL CONCEPTS

No.	Construction	Insulation
1	Traditional Wood Frame	Fiberglass
2	Steel Frame	Rockwool
3	SIPs	Foam Sheets
4	Custom Modular Panels	Spray Foam
5		SIPs

TABLE IV: INSULATION AND STRUCTURAL COMPATIBILITY

	<i>Traditional</i>	<i>SIP</i>	<i>Steel Frame</i>	<i>Modular Panels</i>
Rockwool				
Fiberglass				
Foamular				
Spray Foam				
SIP				
Spray Foram Pro				

 indicates compatibility

3.2.3 Structural Selection Criteria

Team 11 decided on six criterion that the concepts would be compared against. These criterion are based on what Team 11 deemed most important for an effective enclosure to include and are based on the previously stated project needs detailed in Table I.

1. **Manufacturability:** How well does the product fit with Vidir’s existing processes and capabilities. This relates to need #11.

2. **Convention:** Is the product similar to other or common industry practice. This relates to needs #9, #11, #14, and #15.
3. **Energy Efficiency:** How well do the materials resist thermal transfer in the summer and winter. This relates to needs #5 and #7.
4. **Cost:** Is the product affordable for Vidir to produce and the consumer to operate. This relates to need #15.
5. **Humidity Resistance:** Are the materials resistant to humidity and associated problems such as mold and mildew. This relates to needs #5 and #7.
6. **Ease of Installation:** Is the design something that requires minimal time on site for construction. This relates to need #15.

3.2.4 Structural Selected Concept

The highest ranked concept from the concept selection was a modular panel system supported by the existing structure of the carousel, insulated with spray foam. This design was selected for its exceptional resistance to humidity, ease of installation on site, moderate cost, and manufacturability for Vidir.

3.3 HVAC Concept Selection

This section explores the concept generation and selection process for the HVAC system. Following the same methodology as the structural system, the process begins with identifying concepts that may satisfy the client needs followed by a qualitative and quantitative screening and selection process.

3.3.1 HVAC Concepts

In total, 11 HVAC concepts were considered, including three heating, three cooling, and five combined systems. The concepts are listed below in Table V.

TABLE V: HVAC CONCEPTS

No.	Heating System	Cooling System	Combined Systems
1	Furnaces	Window Air Conditioners	Single Zone System
2	Electric Heating	Evaporative Coolers	Variable-Volume System
3	Hydronic Radiant Heating	Fans	Dual Duct System
4			Split System
5			Roof-Top Unit

3.3.2 HVAC Selection Criteria

Team 11 decided on six criterion that the concepts would be compared against. These criterion are based on the project needs in Table I and what Team 11 deemed most important for a functional system. This selection process was completed after conducting a brief concept screening process which may be seen in Appendix B.

1. **Size:** The physical size of the HVAC system should be compact, this will help keep the overall system within the given footprint. This relates to need #3.
2. **Cost:** Includes both upfront and maintenance costs. The cost should be minimized. This relates to need #15.
3. **Energy Efficiency:** The system should be energy efficient to meet the needs of sustainability. This relates to needs #5 and #7.
4. **Capacity:** The system should have the energy capacity to keep the space at a temperature and humidity adequate for plant growth. This relates to needs #5, #7, and #8.
5. **Noise and Vibration:** Quieter systems cause less annoyance, and typically have less wear. This relates weakly to needs #2 and #13.
6. **Expansion Potential:** The system should be expandable and adaptable for future variations of the design. This relates to needs #9 and #12.

3.3.3 Selected HVAC Concept

Team 11 found that a split HVAC system was the best choice for the final design as it scored the highest against the chosen criteria. A compact version of the split system will be used, called a minisplit system. The minisplit system will be used as it is capable of delivering the same air flow as a larger system, but requires less space. Minisplit systems range from approximately 1750 W (0.5 TOR or 6000 BTU) to 17,500 W (5 TOR or 60,000 BTU) which is more than sufficient based on the expected design heat load (Section 4.2.2) [12] [13].

In-floor radiant heating scored nearly as high as the split system, therefore, Team 11 decided to research this concept further for the final design. It was determined during the detailed design process that this secondary in-floor heat system would not be needed, so it was not developed further. The heat generation from a minisplit (summarized above and detailed in Section 4.2.3) was found to be sufficient for the space, and the minisplit is preferred over hydronic heating regardless since it can also control humidity.

4 Design Development

This section describes the development of the previously developed concepts into a comprehensive final design. Sections 4.1, 4.2, and 4.4 provide a description of the design process for the structural, HVAC, and renewable energy subsystems, respectively.

4.1 Structural Design

The overall construction method has been determined and so the enclosure can be broken into three separate components. A floor must be added as the existing concrete pad provides poor insulation which would result in significant energy costs if not improved. The walls will be constructed from modular panels and mounted directly to the existing carousel frame. The roof sections will be mounted in a similar fashion to the walls, but will require more insulation. The outcome of each of these designs can be seen in Fig. 4.



Figure 4: Enclosure design, transparent walls for clarity [4]

4.1.1 Structural Design Methodology

The motivations for all design choices in terms of structure and construction are:

- **Standards and safety** - all design choices must follow (and many are based on) code requirements. Relevant building code sections will be cited where applicable.
- **Minimizing time on site** - Vidir has emphasized the fact that installation time on site is more expensive than factory construction time. They have requested that as much work as possible can be done in-factory.
- **Fitting within Vidir's existing construction techniques** - visiting Vidir's factory in person provided great insight into their production line, available tools, and preferred techniques and materials. Team 11 has tried to design for these techniques and tools wherever possible.
- **Simplicity in assembly/installation** - In all cases, a simplistic solution was created for design details.

With these priorities in mind, Solidworks was used as the primary design tool. Solidworks makes it easy to create technical drawings, perform structural and thermal studies, and create a bill of materials. Beyond this, design processes for individual components are unique, and will be discussed in their respective subsections.

4.1.2 Simulation Analysis Methodology

Team 11 utilized SolidWorks to conduct FEA and thermal simulations. While a versatile software package, it is a computational and memory intensive program, and limited computer resources are available to Team 11 for this project. Due to these limited resources a variety of simplifications had to be made to the models:

- Whenever possible, symmetry was utilized and a smaller representative section was therefore analyzed.
- Detailed design features such as corner radii were removed from the simulation models to reduce the need for small mesh sizes.

A simulation software other than SolidWorks, such as Ansys may provide results for the unsimplified models more efficiently. As such, any future investigation may find Ansys to be a useful product if available. Since Team 11 did not have access to alternative software SolidWorks simulator was the best tool available.

Thermal Studies

A thermal analysis was conducted at a predefined 50 °F (27.8 °C) temperature differential for thermal resistance (R) measurements and accounts for the different thermal properties of each part of the wall [14]. Unlike a physical test for R-Value, which accounts for the thermal resistance of convection, the simulation fixed the temperature of each surface. The calculated R value should therefore be lower than the actual implemented R-Value making the results of this study conservative by comparison. Performing a Solidworks thermal study results in a plot of heat flux through the part in W/m^2 . The average heat flux through the analyzed section is converted to an average R-value using Equation 4.1. The constant in this equation, 5.678, represents a conversion factor between RSI (metric thermal resistance) and R value (imperial thermal resistance).

$$\begin{aligned} R &= 5.678 \cdot \frac{\Delta T}{q} \\ &= 5.678 \cdot \frac{27.8}{q} \\ &= \frac{157.85}{q} \end{aligned} \tag{4.1}$$

4.1.3 Insulation Method

It was determined that closed cell spray foam provided the best insulation solution for the enclosure, described in Section 2.2. Although closed cell spray foam has excellent humidity resistance and thermal resistance, it is not rated for fire protection and typically requires a top coat of flame retardant material. If Team 11 were to design an insulation system using a traditional spray foam product, some appropriately rated top surface would have to be added. A separate top surface would be undesirable because:

- Two products would need to be purchased and ordered, increasing cost and complexity.
- The manufacturing process would be more complex.
- Seams requiring insulating to be performed on-site (where panels are joined) would require an added top surface, increasing complexity and time on site.

Team 11 addressed the issues stated above by selecting a spray foam rated for fire protection. The Manitoba building code states that insulation itself must have a flame spread rating less than 500, with a surface flame spread rating less than 200 [9]. Handifoam is a company that specializes in the production of fire rated spray foams for various applications. Their flagship residential insulation product, E84 (HFO) II-105, has a flame spread rating of 20 and a nominal R value of R6 per inch [15]. In addition, Handifoam II-105 has CCMC #13455-L approval (Canadian

Construction Materials Center approved material). II-105 is available for order online at a cost comparable to non-fire rated options. Henceforth, any mention of spray foam in this report will refer to II-105. Price and source information are provided in Appendix D.

4.1.4 Floor

Vidir has installed a 10'×10', 6" thick pad comprised of concrete and rebar. The pad leaves a 1' perimeter around the base plates of the carousel, shown in Fig. 5. The pad is designed to support up to 20,000 lbs, as indicated by the complete drawing, which can be found in Appendix ???. The foundation was specified by Vidir for their carousel and designed/approved by the engineering team at Norstruc Engineering, therefore the pad is assumed to be structurally sufficient and reliable.

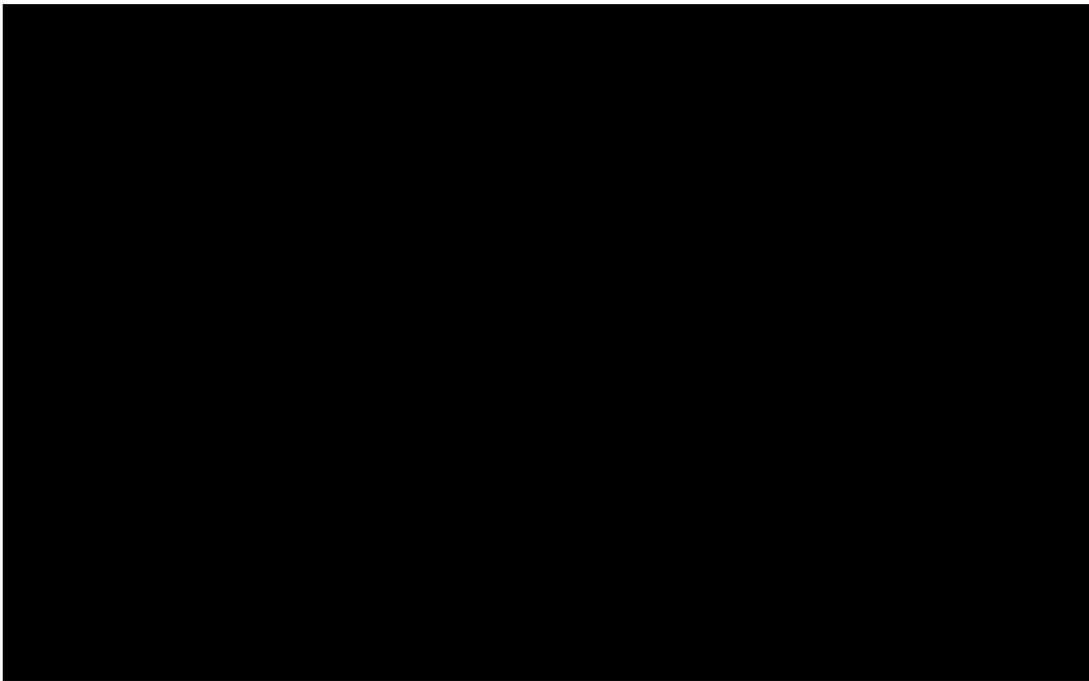


Figure 5: Concrete pad design drawing [4]

The existing concrete pad lacks a sufficient amount of insulation for the proposed growth environment. Since the enclosure will require temperature regulation, especially in harsh Manitoba winters, an insulation solution must be added to the existing concrete pad.

The carousel must mount directly to the concrete pad to ensure stability. Insulation and a top surface will act as a false floor, bearing negligible load since only the entry half of the floor will accommodate foot traffic. Therefore, most of the floor frame can be very simple, with the primary purpose of housing insulation (spray foam). The top plate of the floor will also serve as a forming guide for insulation during manufacturing. Since the entryway's floor should be suitable for walking, diamond plate will be used for the top surface material.

According to the Manitoba Building Code, an R-Value of 28.5 is required for floor insulation [9]. Nominally, this corresponds to an insulation thickness of 4.75 inches, which will be verified with a thermal study. There are only four inches of clearance between the concrete pad and the lowest point on a shelf, shown in Fig. 6. Keeping the false floor frame as simple as possible reduces thermal bridging and reduces the likelihood that leg extension would be required (in the event that the required false floor height exceeds available clearance).

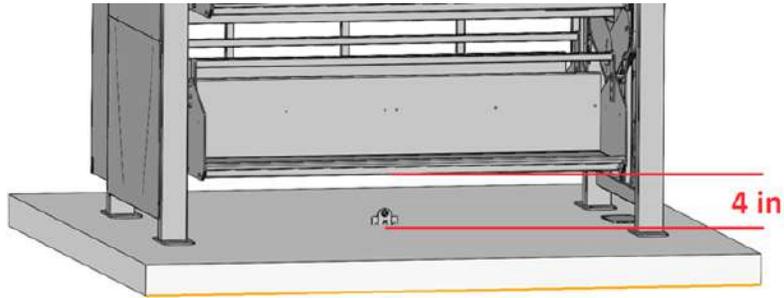


Figure 6: Clearance between lowest shelf and concrete pad [4]

Regardless of the outcome of the thermal study (used to determine required thickness), some design details were predetermined:

- 1"×1"× $\frac{1}{8}$ " tubing will be used to construct the floor frame.
- The top surface will be diamond plate so that the entryway surface is humidity resistant, yet, is not a slipping hazard.
- The false floor frame will slide between the feet of the carousel, illustrated in Fig. 7. This leaves two edges inside the enclosure that will not be covered by the frame. These edges can be filled with spray foam on site, which will also connect the floor insulation to the wall panels.

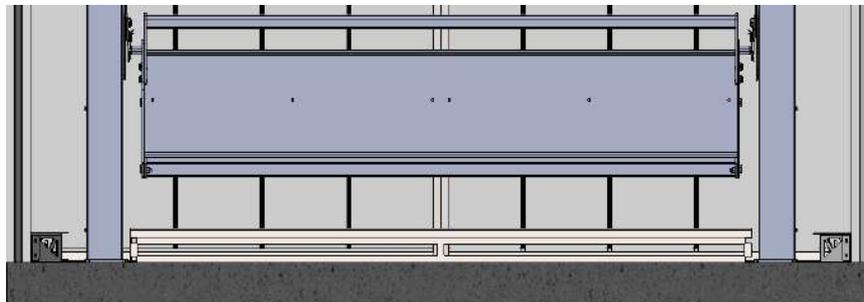


Figure 7: False floor inserted between carousel legs [4]

4.1.4.1 Thermal Study Results

SolidWorks thermal analysis was performed using an average Manitoba soil temperature of $-5\text{ }^{\circ}\text{C}$ [16] and an enclosure internal temperature of $22.8\text{ }^{\circ}\text{C}$, corresponding to the required $27.8\text{ }^{\circ}\text{C}$ temperature differential stated in Section 4.1.2. A simple assembly was created, consisting of a basic steel tube frame, four carousel legs, the cement pad, and polyurethane insulation. Since a uniform metal top will provide negligible insulation it has been excluded from the study to allow easier visualization of the frame. Although more metal will be added to the frame (Section 4.1.4.2), more insulation will be added to the edges of the floor. Therefore, the simplifications to the assembly are justified and representative of the floor thermal properties. The benefit of a simple initial design is the ability to parametrically modify the design to quickly test thermal properties at any thickness. A trial and error approach with a starting nominal thickness of 4.75" was used to determine the necessary floor thickness.

Before being able to reliably gather results from the thermal study, the mesh must be shown to produce consistent results. A mesh convergence study was conducted using mesh sizes ranging from 85 mm to 55 mm. The R value is shown to converge as mesh size decreases, Fig. 8b, indicating that the thermal study is reliable as long as a mesh size of, at most, 75 mm is used. Fig. 8a shows the mesh at 75 mm, which was used to reduce computation time in the iterative design study.

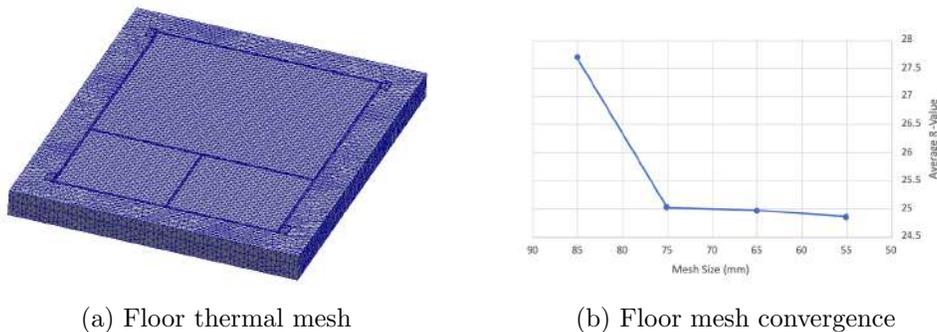


Figure 8: Floor thermal study

The thermal study results confirm expectations, the metal frame and carousel legs conduct heat through the floor much more easily than the insulation and concrete, Fig. 9. The initial study with 4.75" thickness reveals an average thermal conductivity of $4.78\text{ W}/\text{m}^2$, corresponding to an R value of R33. Therefore, the thickness of the floor can be decreased slightly. A floor thickness of 4" was studied to examine the thermal properties at the threshold height, under which legs would not need extension. For a uniform 4" false floor thickness, an average thermal conductivity of $5.67\text{ W}/\text{m}^2$ is reported, corresponding to an average R value of R27.8, just under the code requirement of 28.5. This difference is small enough that it could be attributed to the simplification of the model. The final floor will have pure insulation at the edges and is therefore expected to slightly outperform the simulation.

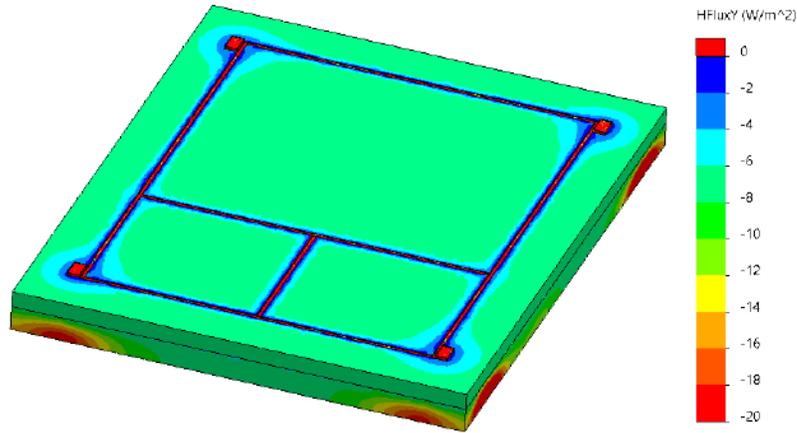


Figure 9: False floor thermal study results

Therefore, at 4" of thickness the floor is considered sufficiently insulated, however won't leave any clearance between the bottom of the carousel and the floor. The simplest solution would be to extend the carousel legs and design the entire floor to be a uniform, suitable thickness. Since the thermal performance is considered suitable, the results of the thermal study has provided a useful basis to develop further in Section 4.1.4.2.

4.1.4.2 Detailed Floor Design

A uniform floor thickness of 4" was determined to be sufficient for meeting code requirements in Section 4.1.4.1. The design can be improved by implementing a two-tiered floor frame. Utilizing a two-tier frame will provide clearance by having a floor thickness of 3.5" in the area directly under the carousel. In the entryway, where no clearance is needed, the floor height can be increased to 4.5". These changes will provide the following benefits:

- A 1" height differential will be simpler to manufacture than a uniform design since 1" square tubes have been selected as the frame material. Two simple rectangular profiles can be produced before welding one on top of the other, shown in Fig. 10.
- The manufacturing required will ensure necessary strength in the standing area.
- The average floor height will still be 4", providing suitable insulation. This is a reasonable assumption, the 3.5" thick floor will be subjected to extra heat load due to the presence of the carousel.

Floor segments on the side of the enclosure, outside the carousel legs, will be sprayed on site, joining the floor and wall panels together. This insulation can be sprayed to an arbitrary thickness (at least 4.5") to increase the floor's average thermal resistance, since there will be no foot traffic here.

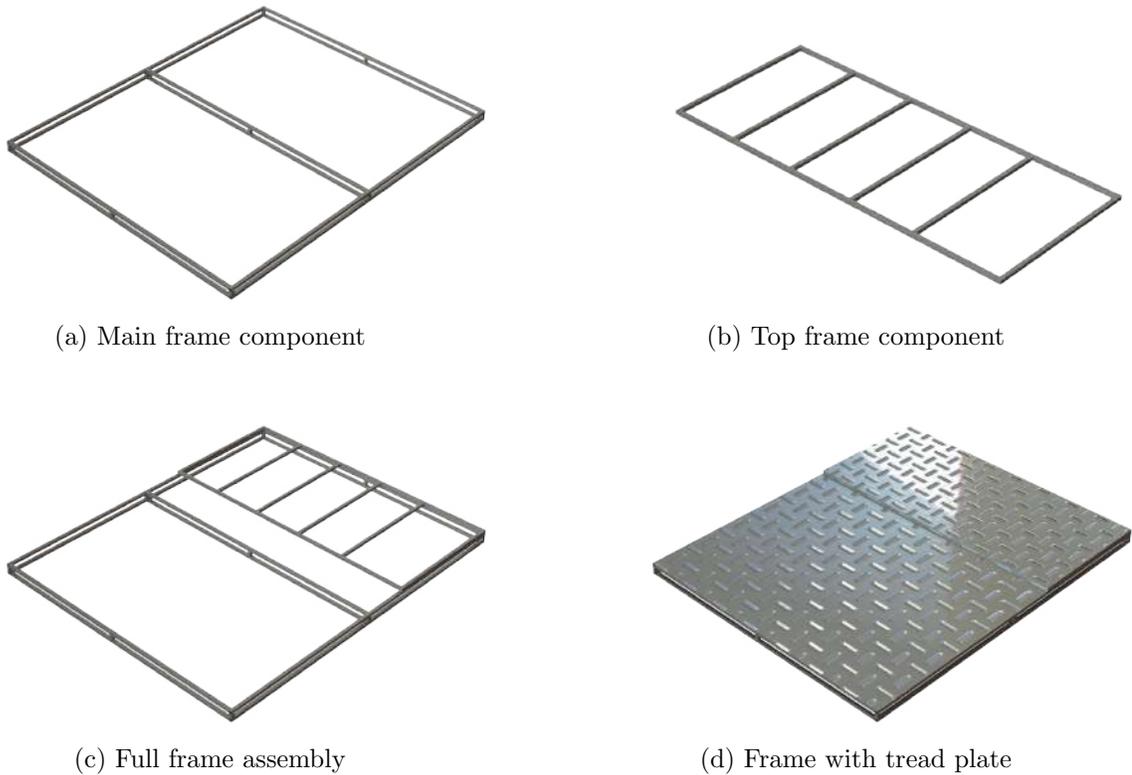


Figure 10: False floor frame components

The main (3.5" thick) frame must be sturdy enough that after being filled with insulation, that insulation will not break during transport or installation. A simple rectangular frame is considered sufficiently rigid since the addition of the top frame will serve as a supportive cross member. The top frame should be robust enough that it can adequately support human weight so that people in the entryway will not impact the insulation beneath. To ensure rigidity of the top frame 16" on center joist spacing will be used, based on common practice.

As shown in Fig. 10, the false floor is to be manufactured in two frame components. The top frame (Fig. 10b) is welded to the top of the main frame (Fig. 10a), flush at the end, before installing tread plate.

4.1.5 Modular Wall Panels

This section details the design and features of the proposed modular wall panels. The walls were designed with Vidir's existing manufacturing capabilities in mind. Shipping pre-assembled panels to the site should be simple and affordable, with this in mind Team 11's goal was to design parts that could be shipped on a flat deck trailer. Finally, installing the panels on site should be quick and simple.

Based on the initial concept development phase, summarized in Section A, the modular panels will be primarily supported by the existing carousel frame. Steel was chosen as the framing material for its strength and relatively low cost. Since steel has a high thermal conductivity reducing the effects of thermal bridging through the steel components was an important issue to address. According to Manitoba Building Code, walls must have a minimum R value of 17.5 [9]. Nominal R value refers to thermal resistance at a temperature differential of 27.8°C, outlined in Section 4.1.4.1. Since the actual temperature differential between the indoor and outdoor surfaces is expected to be higher for the walls than the floor a minimum value of R20 is used to determine the wall thickness, as suggested by [17]. It should be noted that the building code R value refers to total wall resistance, whereas the proposed R20 refers purely to the insulation without consideration of the steel frame.

4.1.5.1 Exterior Finishing of Modular Wall Panels

Tin provides an outer surface which is long lasting, durable, low maintenance, pest resistant, and is common for industrial structures [18]. Tin is also an incredibly sustainable siding material being completely recyclable, and its reflectivity improves energy efficiency by reflecting solar rays. To further capitalize on energy efficiency white tin should be used. White tin is capable of reflecting or radiating up to 59% of solar energy compared to the only 25% that more common galvanized tin will reflect [19]. For these reasons tin has been chosen over other options such as vinyl, wood, concrete board, and stucco, which are commonly chosen for aesthetic reasons rather than functionality.

The most common tin sheets are available in coverage widths of 35 and 36 inches, both of which do not fit evenly into the 120 inch width of the concrete pad. Fortunately, tin sheets are also available in 12 inch coverage widths which fit evenly along the width of the pad. For the design, components were sourced from Metal Experts Roofing & Siding. Specifically, their SNAP-TITE sheets for wall and roof applications were selected along with compatible trims. Any supplier with a 12 inch sheet could be used so long as they are able to supply sheets in white. The profile for the chosen tin sheet can be seen in Fig. 11.

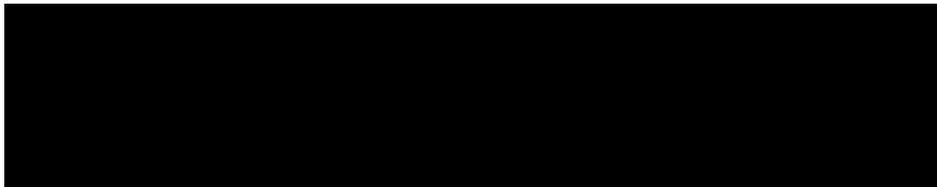


Figure 11: Example tin profile [20]

4.1.5.2 Thermal Break Washers

Given the high thermal conductivity of steel, two members in contact can easily conduct significant amounts of heat through the wall. Therefore, fiber reinforced plastic washers will be used to provide a thermal break between members. Just adding this small amount of thermal resistance can greatly improve the thermal efficiency of the structure.



Figure 12: Example of fibre reinforced washer

4.1.5.3 Fasteners

While using a fiber washer provides a thermal break, fasteners can also conduct a significant amount of heat between components. The forces on the walls due to wind are quite low (approximately 30 lbf per sq ft) and primarily applied compression, therefore a small fastener can be used to minimize the area for heat transfer.

High strength stainless steel rivets as seen in Fig. 13a were selected for the construction of the modular panels as they provide adequate strength, rapid assembly, and a permanent connection. Since connections will be covered by spray foam, using a permanent fastener is important to ensure components do not loosen during transport. Additionally, stainless steel has a much lower thermal conductivity compared to steel, with only a minor cost increase over other rivet materials.

For connections expected to be completed on site, standard bolted connections as seen in Fig. 13b will be used. Requiring a contractor to have a high power rivet gun would overly complicate installation. Additionally, bolting these connections will allow them to be used for other brackets, and allow the contractor to leave the connections loose for alignment purposes. While stainless steel fasteners would provide a small thermal advantage the extra cost makes stainless steel difficult to justify for bolts.

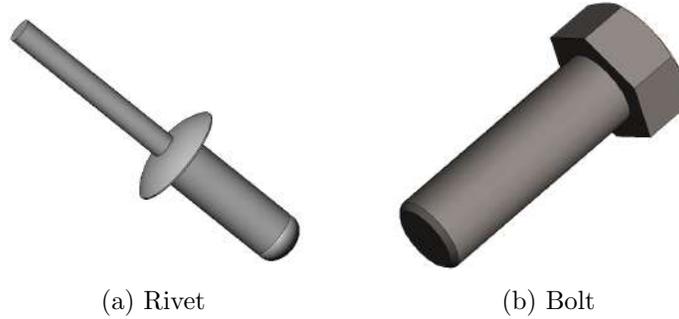


Figure 13: Fasteners

4.1.5.4 Panel Construction

Laser cut HSS A 500-C tubes with a minimum yield strength of 350 MPa (50 KSI) will be used for the majority of the panels frame to fit within Vidir’s existing manufacturing processes. Formed laser cut parts were also considered but would have required significantly more labour to form and would have limited the member length to that of Vidir’s existing break presses. Any corrosion resistant powder coat paint compatible with Vidir’s paint line will suffice, however, galvanized tubing should be used instead if possible. Galvanized tubing eliminates the need for the painting process and slightly reduces thermal conductivity. These components will not be welded and will be covered by spray foam, galvanized material will not present any extra manufacturability or appearance issues.

The exact construction of the panel had to be compatible with shipping dimensions, the width of available tin panels, and the structural requirements. As tin sheets can be made in many lengths but restricted widths, therefore the panels will be made tall rather than wide. Making the panels tall also allows for each wall to be divided into fewer vertically aligned panels compared to horizontally aligned panels.

Panels were designed with two vertical members supported by multiple horizontal joists. This design, seen turned sideways in Figs. 14 and 15, gives support to the panel vertically, and will transfer horizontal forces into the concrete pad and carousel frame. The two vertical members are made from standard $1 \times 2 \times 1.125$ HSS square tube, providing ample strength while minimizing the amount of material and thermal bridging. The vertical members are joined by several horizontal members, arranged to support the outer tin surface. Horizontal members use a standard $1.25 \times 1.25 \times 0.11$ HSS tube. A smaller tube may be sufficient structurally, however, space inside the tube is required for assembly, necessitating the use of a slightly larger tube. The initial design used $1 \times 1 \times 0.125$ tubes for both the horizontal and vertical members as a starting point for the modeling and simulation. These values were quickly adjusted due to large amounts of deflection calculated in the FEA study discussed further in Section 4.1.5.6.

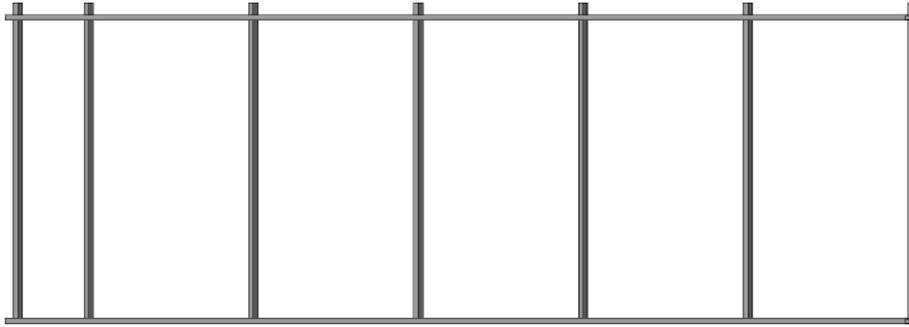


Figure 14: Modular front panel frame

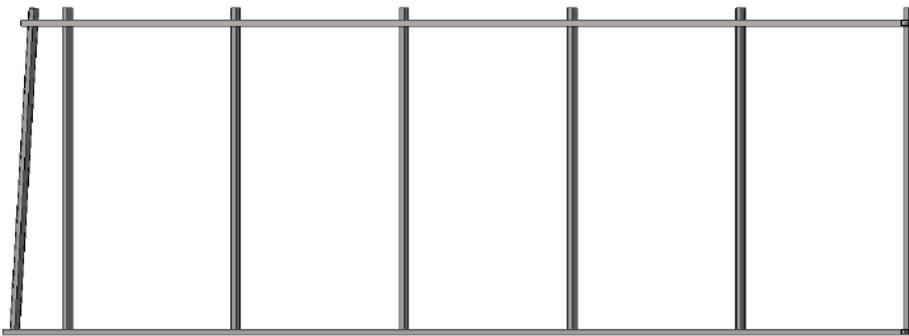


Figure 15: Modular side panel frame

4.1.5.5 Supports

Custom support brackets were designed to affix the panels to the carousel frame and concrete pad. Some brackets will also be used to fasten adjacent panels together. Brackets will be made from formed laser cut sheet metal so that they will be strong enough to withstand wind loads and will provide Vidir a simple part to manufacture. Steel connections will provide a slight thermal bridging effect, therefore fewer brackets were ideal. Each bracket facilitates easy and fast installation, connecting to components with $\frac{3}{8}$ " bolts. Engineering drawings for each of these custom parts are provided in Appendix ??.

The carousel frame will serve as a primary mounting point to keep the enclosure upright and sturdy. Three unique brackets are designed to connect the carousel to the panels. There are two vertical brackets on each wall to prevent bowing from wind forces. One leg on each side of the carousel lines up directly with the seam between wall panels. The alignment with the wall panels provides an opportunity for a simple linear bracket to fasten the carousel to the wall, as well as fastening the two wall panels together, seen in Fig. 16a. A three-point bracket can be implemented in the entryway for increased lateral stability. The front bracket is made of two identical components, installed symmetrically about the seam of the two front wall panels, seen in

Fig. 16c. The carousel is so close to the back wall that a linear bracket would be extremely difficult to access for installation. Therefore, the rear bracket is a much shorter version of the front bracket, seen in Fig. 16b. The rear bracket requires additions to the carousel frame, these additions are identical to the cage design that Vidir currently uses for the front of the carousels.



(a) Center bracket [4]

(b) Rear bracket [4]



(c) Front bracket [4]

Figure 16: Wall support brackets

The vertical panel members provide strength and stability throughout the entire panel, especially when their ends are fixed. Therefore, mounting the base of each panel to the concrete pad will greatly increase the overall stability of the enclosure. A firm attachment between the concrete pad and the panels also minimizes air infiltration at the seam. Brackets are designed to fix two adjacent wall panels together to provide extra structural rigidity, seen in Fig. 17a. FEA was performed to evaluate the performance of these brackets, detailed in Section 4.1.5.6.

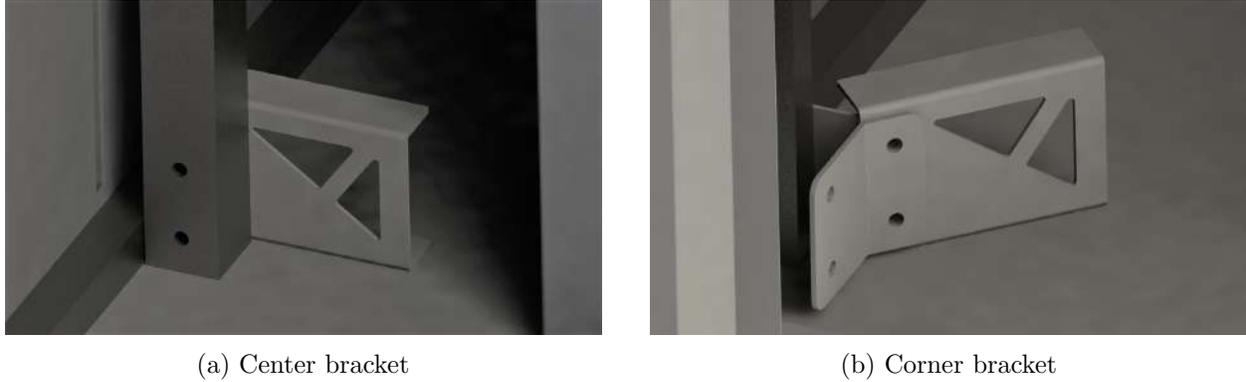


Figure 17: Floor support brackets

4.1.5.6 Wall Finite Element Analysis

The design was analyzed using FEA to ensure it provides sufficient strength and a reasonable factor of safety so that the end product is safe and reliable. Two situations were analyzed and a mesh convergence study was conducted for each to verify accuracy of results. The two scenarios explored were as follows:

1. **Standard Wind Loading:** This case assumed a sustained wind load of 125 kph with an evenly distributed pressure across the entire wall. This case is considered the normal operation case, therefore a safety factor of 3 will be required to ensure safety.
2. **End Lifting Panel:** This case assumes the worst case scenario for lifting a panel; lifting it entirely from one end while the other end is fixed. A reduced safety factor of 1.25 was used as this case would only be observed in a rare, abusive installation case where no one should be near the panel being lifted.

Standard Wind Load

Based on the assumed wind load the total expected force was 28837.3 newtons, equivalent to a pressure of 2.1 mega-pascals; the calculation for this force can be found in Section A. The force will be applied to the outer surface of the tin, exerting a force on the carousel. The carousel was constrained at each mount point using a solid fixture, however the upper mounting points were unconstrained in the vertical direction. It must be noted that the unconstrained upper mounting is a simplification of the model, which Team 11 required in order to complete the FEA analysis on computer hardware available to Team 11. Fortunately, the carousel frame is substantially stronger than the wall panels, and would add a negligible amount of deformation over the solid fixturing method used.

The initial mesh size was quite coarse, to confirm the results the mesh size was decreased until the results stabilized. The final mesh can be seen in Fig. 18, while the results of mesh

convergence can be seen in Fig. 19. Mesh sizes were tested until a percent difference of less than two percent was achieved, demonstrated in Fig. 18. The second to last mesh size was used for the final FEA analysis to minimize compute time while ensuring accurate results.

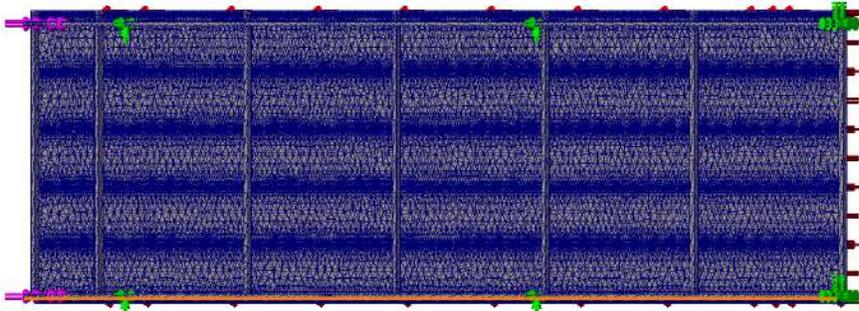


Figure 18: Standard wind load mesh

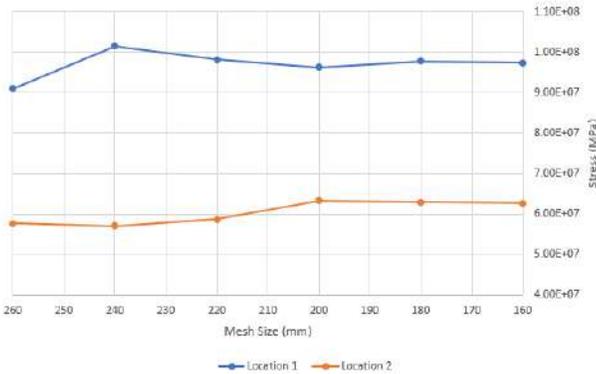


Figure 19: Standard wind load mesh convergence

Final results are presented in Fig. 20. The maximum stress observed was 115.9 MPa (16.81 ksi), using A500-C steel with a yield strength of 350 MPa (50 ksi) these results are just under the required safety factor of 3. Stress concentrations occur at the fixture points, likely caused by the coarse mesh. These stress concentrations have been ignored under Saint-Venant’s Principle [21]. An example of a stress concentration present in the analysis can be seen in Fig. 21. Saint-Venant’s Principle allows these concentrations to be ignored as they are caused by limitations of the boundary conditions caused by the mesh size. Further, mesh refinement is outside the scope of this project, but may eliminate these concentrations and better reflect stress in these areas.

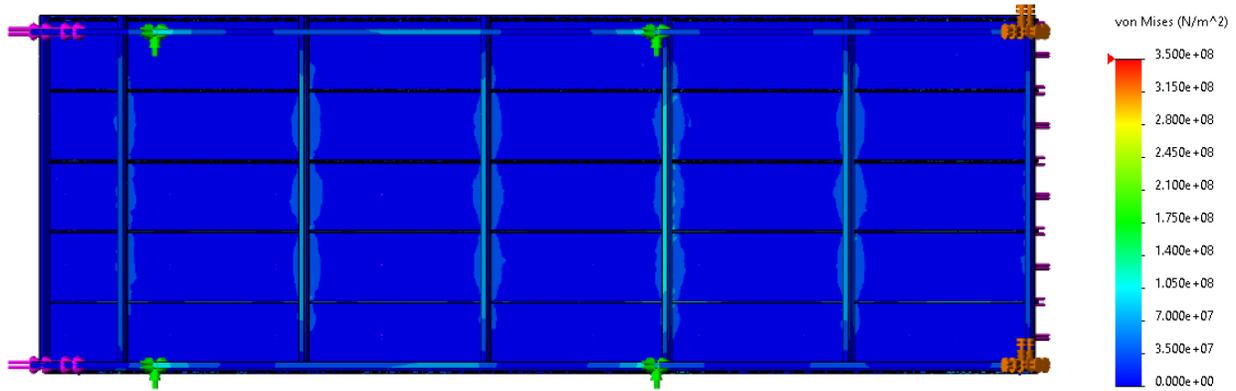


Figure 20: Standard wind load FEA results for wall

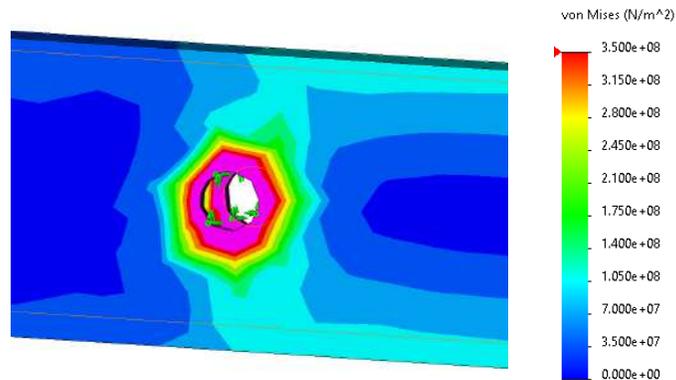


Figure 21: Example stress concentration in wall

End Lifting Panel Load

To ensure this case will be the worst possible case Team 11 assumed that one end of the panel would be fixed and the other end lifted with a force equal to half the panel weight. The force will be applied to the lower edge of the top member of the panel while the bottom member will be fixed in place. The more common lifting scenario where the bottom member is free and allowed to rotate would have significantly lower stresses.

As with the wind load scenario, the initial mesh size was coarse and slowly decreased until the study results stabilized. The final mesh can be seen in Fig. 22, while the mesh convergence results can be seen in Fig. 23. Mesh sizes were reduced until a percent difference of less than two percent was achieved. The second smallest mesh size was used for the final FEA analysis.

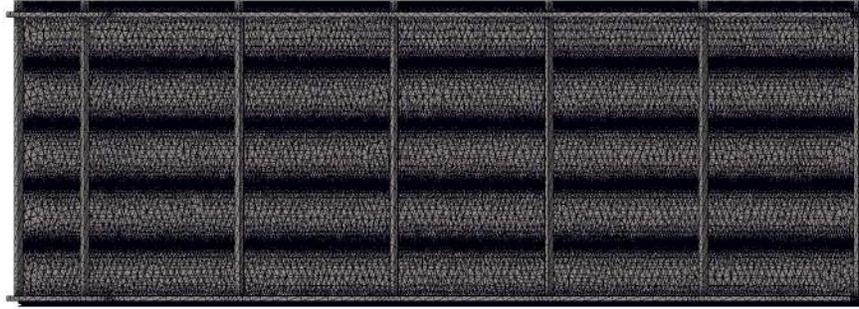


Figure 22: Wall FEA mesh

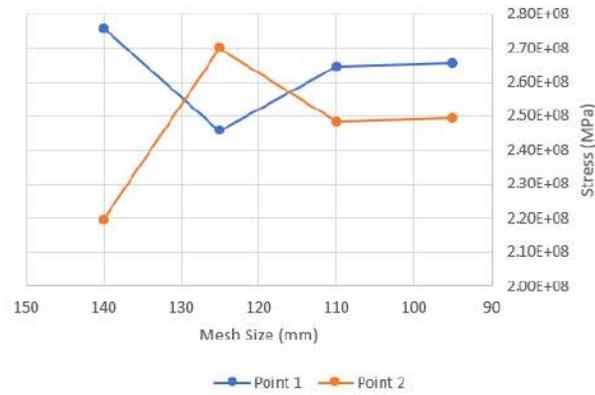


Figure 23: Wall FEA study convergence

Final results can be seen in Fig. 24. The maximum stress observed was 266 MPa (38.6 ksi), well within the required safety factor of 1.25. The material used was A500-C steel with a yield strength of 350 MPa (50 ksi).

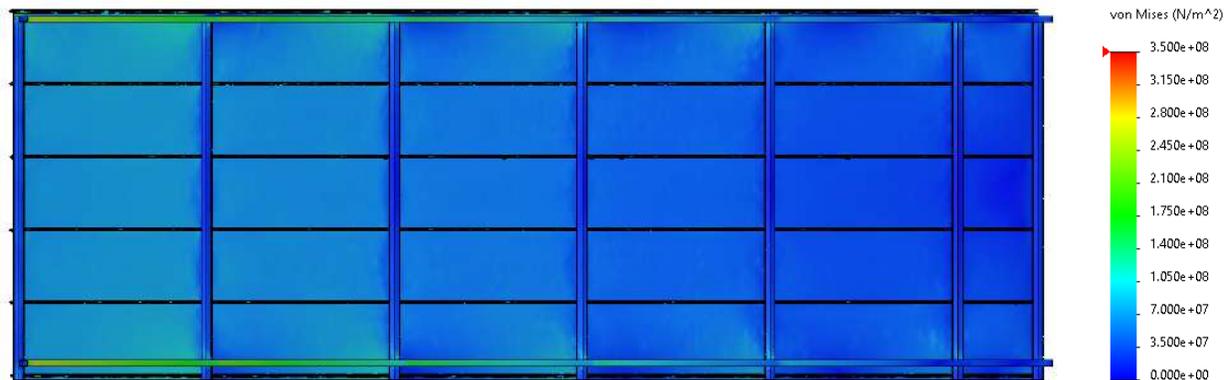


Figure 24: Wall end lifting FEA results

4.1.5.7 Wall Thermal Analysis

The desired R-value of R20 corresponds to an insulation thickness of 3.3". Walls will require insulation greater than 3.3" to account for the thermal bridging through the metal panel frames. The thermal analysis was performed using the previously stated standard temperature differential of 27.8 °C. The simplifications discussed in Section 3.1 were used and only a quarter of the model was analyzed due to symmetry. Multiple studies were run at a variety of insulation thicknesses to determine the required wall thickness. A mesh convergence study was performed with mesh sizes ranging from 85 to 55 mm, seen in Fig. 25. A percent difference of less than 1% was deemed acceptable, seen in Fig. 26.

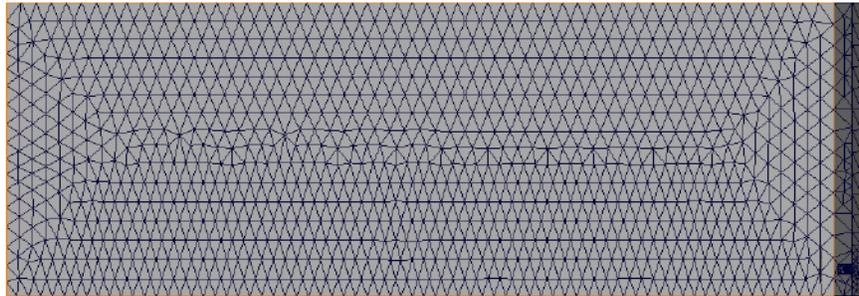


Figure 25: Wall thermal mesh

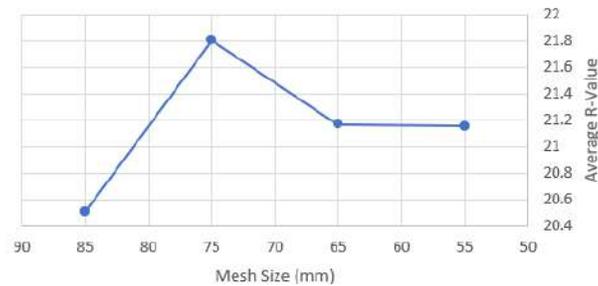


Figure 26: Wall thermal study convergence

Heat flux through the inner surface of the wall can be seen in Fig. 27. The average heat flux was $7.45 \frac{W}{m^2}$, corresponding to an R-Value of approximately 21 for 4" thick spray foam insulation. This value is above the required value of R20, therefore 4" thick insulation is deemed acceptable.

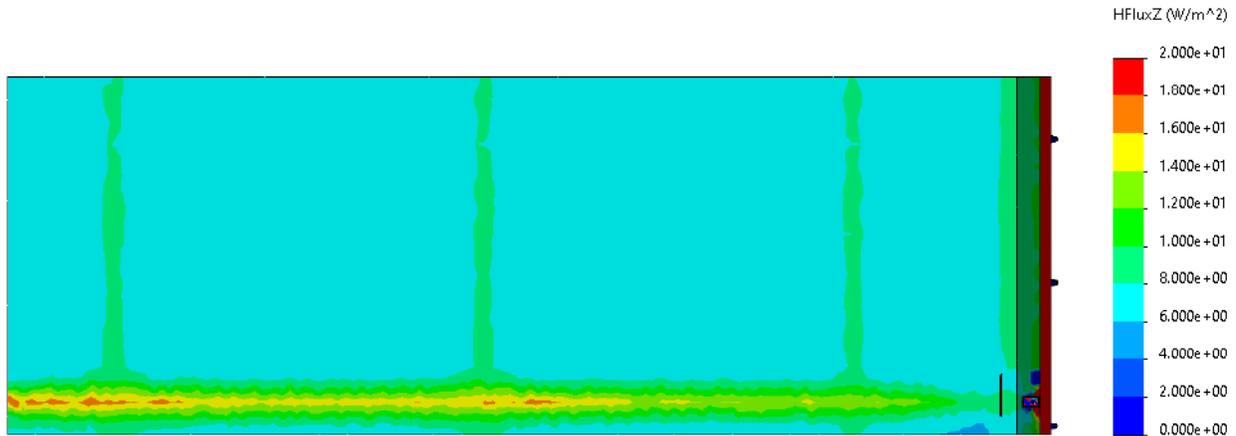


Figure 27: Wall thermal study results

4.1.5.8 Interior Finishing of Modular Wall Panels

Because the selected spray foam insulation is adequately fire rated, there is no need for any interior surface. The wall panels will therefore have bare spray foam for their interior finish, which has the following benefits:

- Simpler and cheaper manufacturing process, minimizing work time in-factory
- Exposed insulation means that any seams between panels can be easily joined during installation by quickly spray foaming the seam, minimizing work time on-site

While unnecessary, if a client requests interior finishing it may be added, provided it is compatible with the high humidity greenhouse environment. Finishing should only be added to the entrance way where the operator may interact with the walls to keep costs low.

4.1.6 Roof

The roof of the enclosure will adopt many of the features designed for the walls. There are three easy-to-manufacture roof shapes considered, shown in Fig. 48. The sloped roof was selected as the simplest design, directing water and snow away from the carousel entrance. The flat roof would have required expensive water proofing, while the peaked roof would have required a more complicated construction. A slope of 1" per foot will be used, allowing for snow and melt runoff [22], the slope corresponds to a peak height of 8".

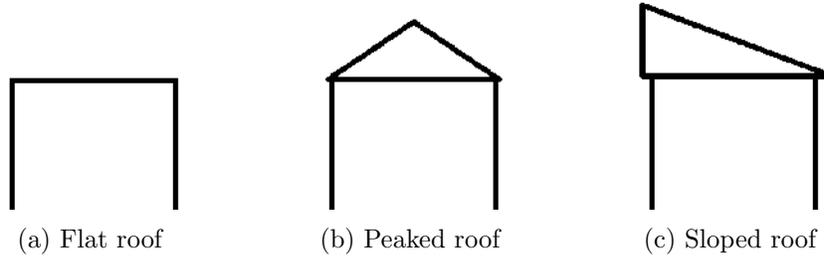


Figure 28: Roof profile concepts

4.1.6.1 Roof Construction (Adaptions from wall design)

The roof will use the same exterior tin paneling, thermal break washers, fasteners, and overall style of construction as the walls. Roof panels were shorter and cross member spacing was changed so that the roof can support heavier snow loads.

4.1.6.2 Supports

Design of brackets used to mount the roof to the enclosure followed the same methodology discussed in Section 4.1.5.5. Both the corner and center brackets fix the roof firmly to the wall panels, the center brackets join the roof and two adjacent wall panels, each can be seen in Fig. 29. The center support is located at the center of the roof, transferring loads directly into the carousel frame



(a) Center bracket

(b) Corner bracket [4]

(c) Center support [4]

Figure 29: Roof support brackets

4.1.6.3 Finite Element Analysis

According to the Manitoba building code, the worst case snow load pressure is 2.8 kPa seen in northern Manitoba. A snow load of 3 kPa has been used along with a safety factor of 3. The force will be applied to the outer surface of the tin, exerting force into the carousel. The carousel was constrained at each mount point using a solid fixture, this is a simplification of the model, required to complete the analysis on available computer hardware. Fortunately, the carousel frame is substantially stronger than the roof panels, and would add a negligible amount of deformation over the solid fixturing method used.

The initial mesh size was quite coarse, slowly decreased until results stabilized to ensure accuracy. The final mesh can be seen in Fig. 30, the results of mesh convergence can be seen in Fig. 31. Mesh sizes were tested until a percent difference of less than 1% was achieved.

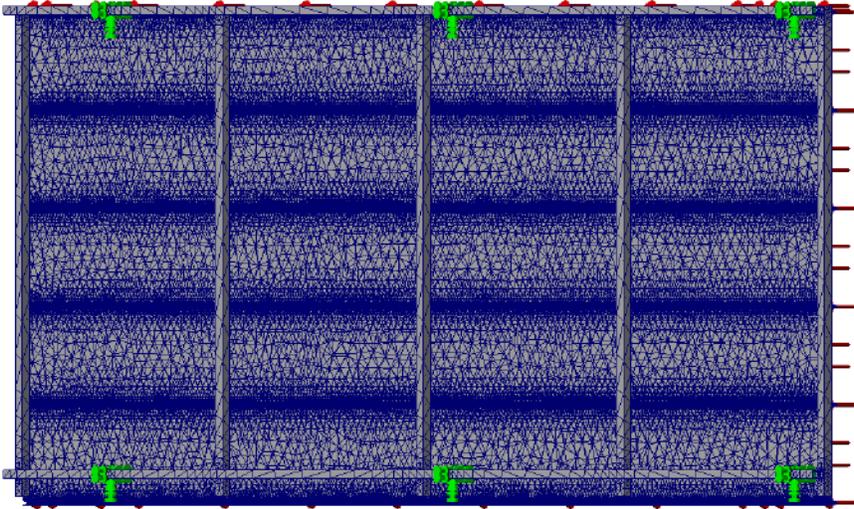


Figure 30: Roof panel mesh

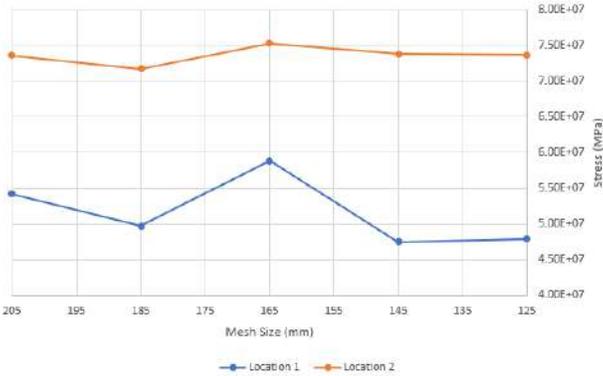


Figure 31: Roof panel mesh convergence

Final results can be seen in Fig. 32. The maximum stress observed was 116.2 MPa (16.9 ksi), just under the safety factor of 3 required for a roof constructed of A500-C steel, yield strength of 350 MPa (50 ksi).

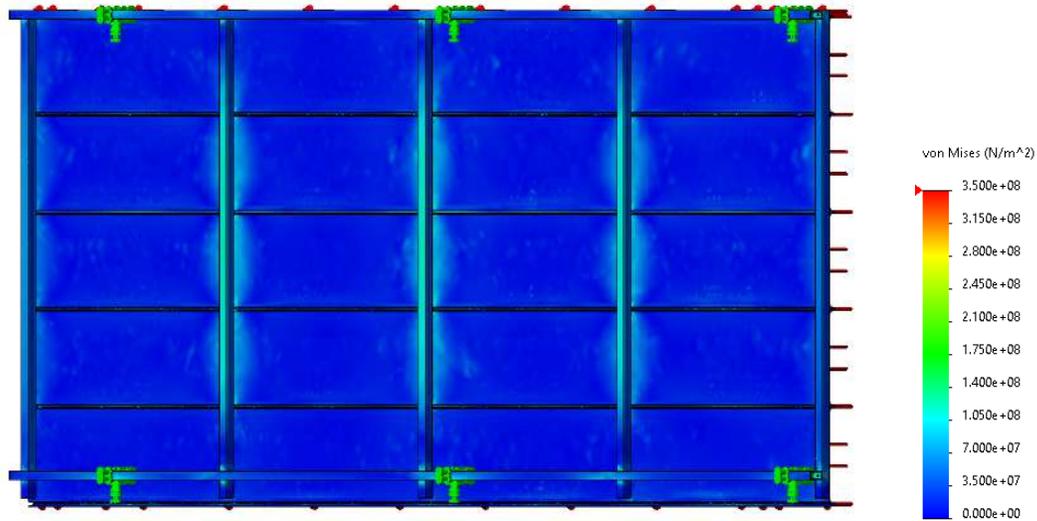


Figure 32: Roof panel FEA results

4.1.6.4 Thermal Analysis

According to the Manitoba building code an average R-Value of 28.5 is required for cathedral ceilings and flat roofs [9]. The building code requirement corresponds to an insulation thickness of 4.75", though additional thickness will be required to account for thermal bridging through the steel framing of the roof.

The thermal analysis was performed using the standard temperature differential of 27.8 °C. The simplifications discussed in Section 4.1.2 were used, the entire model was assessed since the roof panels are much smaller than the wall panels. Multiple studies were run at a variety of insulation thicknesses to determine the required thickness. A basic mesh convergence study was performed to ensure result accuracy, with mesh sizes ranging from 120 to 80 mm, see Fig. 33. A percent difference of less than 1 % was deemed acceptable criteria, see Fig. 34.

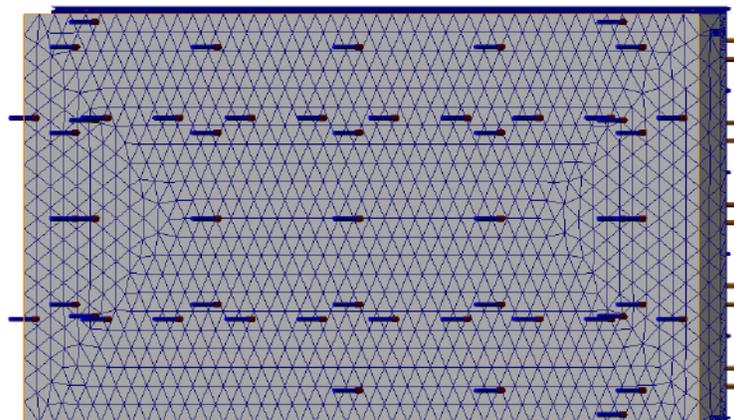


Figure 33: Roof thermal mesh

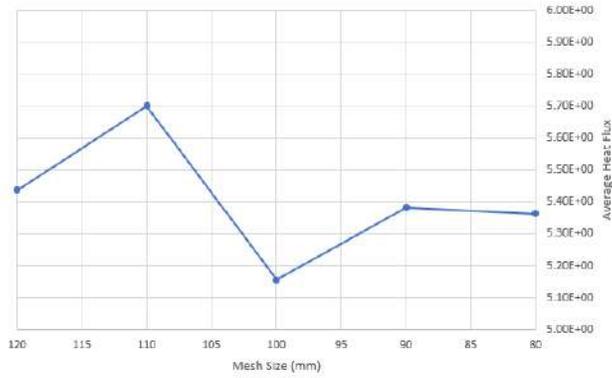


Figure 34: Roof thermal study convergence

The average heat flux through the inner surface of the roof was 5.36 W/m^2 which corresponds to an R-Value of approximately 29.5 with 5.75" of spray foam insulation. This is slightly higher than the required R-Value of 28.5, as such the spray foam thickness is deemed acceptable.

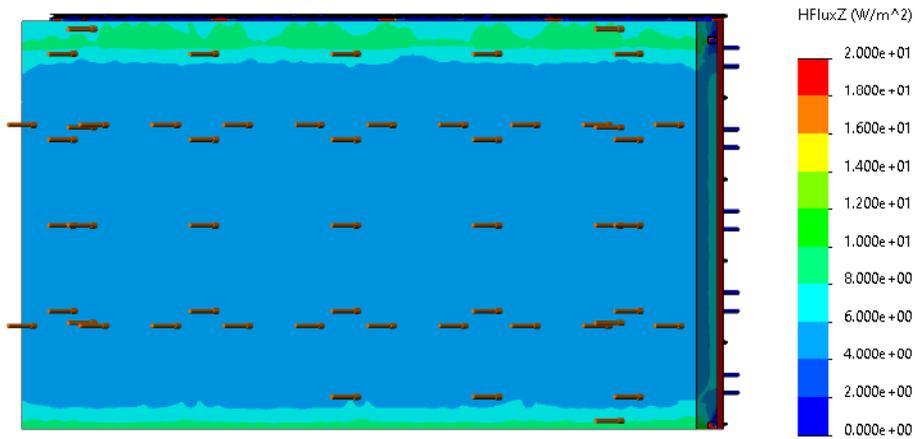


Figure 35: FEA results 2

4.2 HVAC Design

With structural design finalized, this section of the report focuses on the design of the HVAC system required to maintain an optimal environment inside the carousel. Section 4.2.1 outlines the methodology used and Section 4.2.2 calculates the heating and cooling loads required. Finally, Section 4.2.4 details the sourced unit.

4.2.1 HVAC Design Methodology

In order to source a suitable HVAC system, analysis was done to determine the heating and cooling load requirements based on the Manitoba Building Code. In addition, further motivation for design choices included:

- **Efficiency** - The design should adhere to ASHRAE Standard 62.1 for minimum energy performance.
- **Air Flow** - Sufficient air exchanges must occur for an optimal plant growth environment to be sustained. The required airflow is 2 and 30 air exchanges per hour (ACH), for the winter and summer respectively [10].
- **Humidity Control** - The Biosystems team specified a required relative humidity of 40 - 60%. In Manitoban winters, outdoor air has a very low amount of saturated water vapour, any chosen system will require an air humidification process. In-floor heat is excluded from the design as discussed in Section 3.3.3 as more humidification would be required.

4.2.2 Heating and Cooling Load Analysis

Calculating the heat losses and gains of the enclosure is necessary to determine the required capacity for a given HVAC system. Fig. 36 describes the naming conventions for the carousel faces.

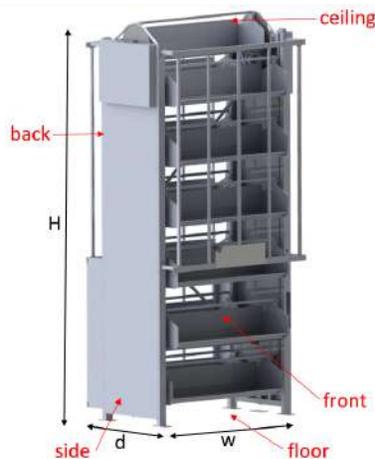


Figure 36: Naming conventions for carousel [4]

The carousel is divided into five sections to analyze the heat losses and gains through the carousel enclosure:

- The front and back, denoted with subscript ‘f, b’,
- The sides, denoted with subscript ‘s’,
- The ceiling, denoted with subscript ‘c’,
- The floor, denoted with subscript ‘fl’.
- The slab, denoted with subscript ‘sl’, which is not depicted here.

For each section defined, a thermal resistance network is created to determine the total thermal resistance and in turn, heat transfer through it. Consideration is also given to heat gain from grow lights required by the Biosystems counterpart, as well as the heat losses or gains from infiltration. The total heat loss or gain is then found by summing the effects of each.

4.2.2.1 Analysis Details and Assumptions

The heating and cooling load analysis will be completed on three design cases; two winter and one summer; the details of each case are listed below.

1. Cases 1 & 2 - Winter:

- (a) **Worst Case Scenario:** Extreme outside winter temperature with an interior temperature lowered to reduce energy usage.
- (b) **Average Scenario:** Average outside winter temperature with an inside temperature that can be maintained at optimal levels (i.e., 20°C).

2. Case 3 - Summer:

- (a) **Average Scenario:** Average outside summer temperature with an inside temperature that can be maintained within optimal levels (i.e., 20-30°C).

To analyze the heating and cooling loads for each of these cases, there are a few important assumptions that are made:

1. Only steady-state conditions are considered. This is done for a few reasons. For one, the enclosure is not overly large and will be well insulated, therefore, it should retain heat well and would not take long to heat up compared to a larger space. Secondly, for the initial heat-up of the structure, it is assumed that the plants will be removed from the structure and placed back in once at the desired interior temperature.

2. The heat gains from miscellaneous items and electrical sources are negligible. Specifically, heat produced by any pumps, motors, or electrical systems would be minimal as the carousel will not be rotating constantly. Rotation would only happen every few hours to ensure all plants are watered.

4.2.2.2 Heat Transfer through the Walls and Ceiling

The thermal resistance network for all four walls and the ceiling are modelled similarly and may be seen in Fig. 37 with the corresponding equations below. Heat transfers by convection from the outside to the carousel’s outer wall, conduction through the wall and insulation, and finally convection from the inside wall to the air space inside the enclosure. It is important to note that the effects of radiation, both on the outside and inside of the enclosure are included withing the convection heat transfer coefficients as per Table 5-2a in [23].

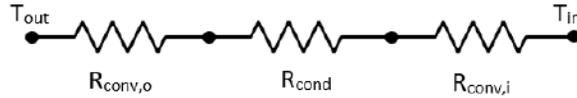


Figure 37: Thermal resistance network for the walls and ceiling

$$\dot{q} = \frac{\Delta T}{R_{tot}} = \frac{\Delta T}{\frac{1}{h_o A} + \frac{R'_{ins}}{A} + \frac{1}{h_i A}} \quad (4.2)$$

As per the thermal analysis discussed in Section 4.1.5.7, the R-values of the insulation for the walls and ceiling were determined in accordance with the Manitoba Building Code for new construction. These values are summarized below and will be used in the final calculations.

TABLE VI: THERMAL RESISTANCE RESULTS FOR THE WALLS AND CEILING

Unit	Walls	Ceiling
R	20.77	28.5

4.2.2.3 Heat Transfer through the Floor

Similar to the method followed for the walls and ceiling, a thermal analysis in Section 4.1.4.1 was completed for the floor to determine the required R-value to be in accordance with the Manitoba Building Code.

In addition to the heat transfer through the floor, heat will transfer through the outermost perimeter of the concrete slab. It is important to note that the outer structure of the carousel lines up perfectly with the edge of the pad, and the perimeter (P) of the pad has no insulation ($U' = 3.1W/mC$).

In order to determine the combined effects of the heat transfer through the floor and slab, a thermal resistance network was created which may be seen in Fig. 38. From this network, it is shown that the heat transfer through the floor is equal to that through the slab.

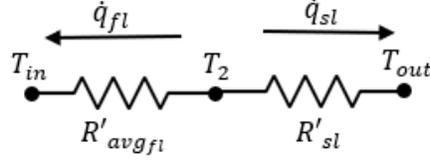


Figure 38: Thermal resistance network for the floor and slab

$$\dot{q}_{fl} = U_{fl}A_{fl}(T_{in} - T_{out}) = \dot{q}_{sl} = U_s(T_2 - T_{out}) \quad (4.3)$$

In order to determine the value of the heat transfer through either the floor or slab, which are equal, the intermediary temperature, T_2 , must be found per the following equation for each design case.

$$T_2 = \frac{U_{fl}A_{fl}T_{in} + U_sT_{out}}{U_{fl}A_{fl} + U_s} \quad (4.4)$$

$$U_{fl} = \frac{1}{R'_{avgfl}} \quad (4.5)$$

$$U_s = U'P \quad (4.6)$$

With this intermediary temperature, the heat transfer through the floor and slab may be calculated using either equation.

TABLE VII: INPUTS FOR FLOOR AND SLAB THERMAL RESISTANCE NETWORK

$\mathbf{R'_{avg}}$ [m ² C/W]	$\mathbf{U_{fl}}$ [W/m ² C]	$\mathbf{U_s}$ [W/m ² C]
5.019	0.04	37.80

TABLE VIII: RESULTS FOR FLOOR AND SLAB THERMAL RESISTANCE NETWORK

Case	$\mathbf{T_2}$ [°C]	$\mathbf{\dot{q}_{fl} = \dot{q}_s}$ [W]
1	-39.74	9.91
2	-19.79	7.93
3	29.97	-0.99

4.2.2.4 Heat Gain from Grow Lights

The Biosystems counterpart team will be using LED lights on each shelf inside the carousel. Though LED lights emit less heat than incandescent bulbs, the effect is not negligible, especially with 13 shelves. The equation below is for heat gain from electric lighting, taken from [23], where L is the number of lights, W_L is the light wattage ($W_L = 43$ W as defined by the Biosystems team), F_u is the use factor (for LED lights $F_u \approx 0.20$ [24]), and F_s is the special allowance factor..

$$\dot{q}_l = L(W_L F_u F_s) \quad (4.7)$$

4.2.2.5 Infiltration

A major consideration especially in winter is infiltration, which is air leakage. A precise method to determining the amount of infiltrating air is the Crack Method. With this method, the infiltration flow rate is calculated based on the total area of a crack, type of crack, and pressure differences across a crack [23]. The sensible heat required to heat the infiltrating air may be calculated as:

$$\dot{q}_i = \rho \dot{Q} C_p (T_i - T_o) \quad (4.8)$$

In order to calculate \dot{q}_i , the volumetric flow rate of the infiltrating air, \dot{Q} , must be known which is taken from figures in [23] based on the pressure difference, ΔP , and crack type. The total pressure difference is the summation of the effects due to the wind, stack effect, and building pressurization as seen in below.

$$\Delta P = \Delta P_w + \Delta P_s + \Delta P_p \quad (4.9)$$

As the carousel's height is less than three times its width, it is considered a low rise structure according to [23] such that the pressure difference due to the stack effect are small, the wall infiltration is low, and only the wind effects need to be considered. Additionally, the building pressurization effects are typically small such that they will be considered as negligible in the calculations. With those simplifications, the equation simply becomes,

$$\Delta P = \Delta P_w = \frac{c_p \rho}{2g_c} \bar{v}_w^2 \quad (4.10)$$

where c_p is the pressure coefficient, ρ is the density, g_c is the gravitational conversion factor, and \bar{v}_w^2 is the wind velocity.

The structure will contain one door on the front wall, a vent, and exhaust fan. The vent and exhaust fan will be considered as 'window'-type cracks. Therefore, there are three major cracks for air to infiltrate into.

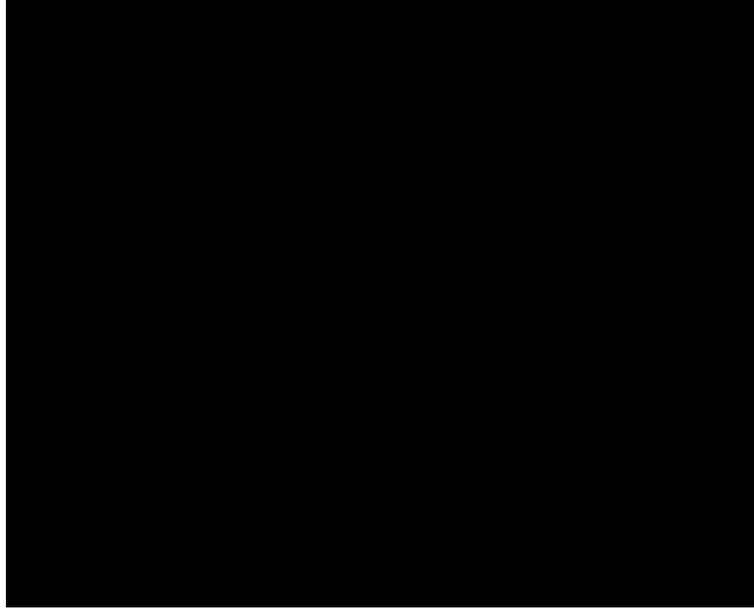


Figure 39: Window and door infiltration characteristics [23]

To use Fig. 39, the pressure coefficient, c_p , is found first using Fig. 40 with which information about the wind must be known. The design will accommodate the worst case scenario wind angle. As per Fig. 40, the worst case scenario is a wind angle of 0° for a windward wall corresponding to 180° for a leeward wall. Therefore, the pressure coefficient for the windward and leeward walls is 0.52 and -0.45 respectively. Additionally, in Winnipeg, the average wind speed in January is 18.5 km/hr (5.14 m/s) and the average wind speed in July is 14.8 km/hr (4.11 m/s) [25].

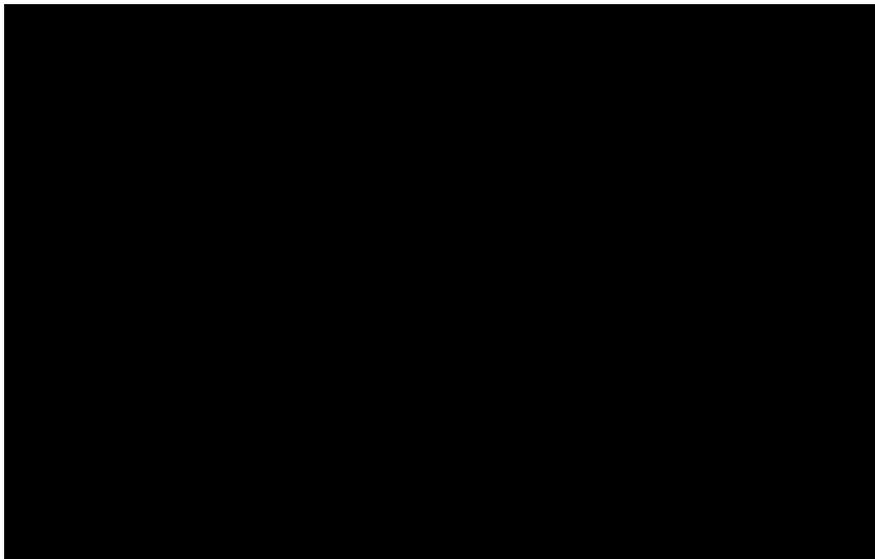


Figure 40: Variation of wall averaged pressure coefficients for a low rise building [23]

Next, the K value must be determined for the windows and door to use Fig. 39. Both the door and windows of the structure will be assumed to be tight fitting with weatherstripping. According to Fig. 41, $K_{door} = 1$ and $K_{window} = 1$ according to Fig. 42.

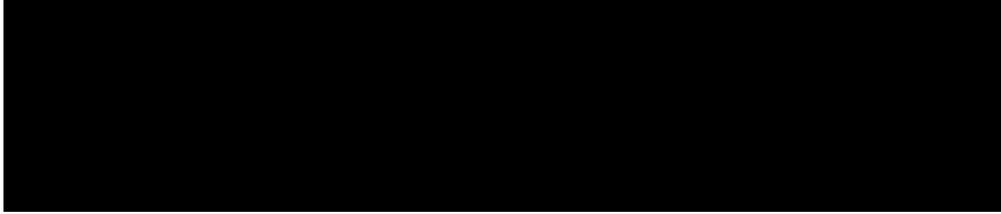


Figure 41: Door classification [23]

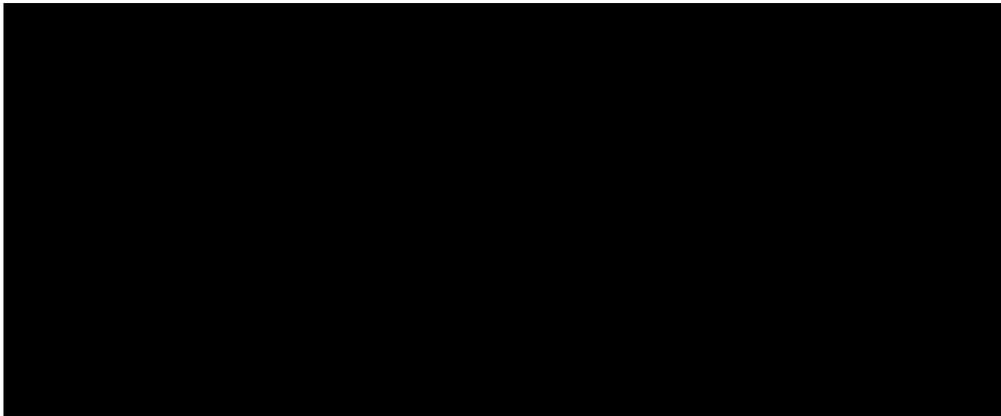


Figure 42: Window classification [23]

Designing for worst case scenario, the door and windows would be located on the windward and leeward wall respectively. Additionally, the crack lengths for the door and windows would be 5.89 meters (for a standard door [26]) and 5.74 meters (2.87 meters for the specified exhaust fan and 2.87 meters for the vent [27]). Given that information, the ΔP may be calculated for each design case, the \dot{Q}/L value may be found using Fig. 39, and the total infiltration rate may be calculated as summarized in the tables below. It is important to note for Table X that:

- The negative sign indicates exfiltration rather than infiltration. As there are no dedicated figures for exfiltration, Fig. 39 was used and a negative sign was inserted to values taken from here to reflect the scenario.
- For the summer case, the vent and window exhaust fan would be operational/open such that it would be considered ventilation rather than infiltration. Therefore, the volumetric flow rate of the infiltrating air is zero.

TABLE IX: INFILTRATION SUMMARY

Case	Door Infiltration			Window Infiltration		
	Windward Wall, $c_p = 0.52$			Leeward Wall, $c_p = -0.45$		
	ΔP [Pa]	\dot{Q}/L [L/s-m]	\dot{Q} [L/s]	ΔP [Pa]	\dot{Q}/L [L/s-m]	\dot{Q} [L/s]
1	10.41	0.25	1.473	-9.01	-0.23	-1.320
2	9.50	0.24	1.414	-8.22	-0.18	-1.033
3	5.07	0.10	0.589	-4.39	0.00	0.00

TABLE X: TOTAL INFILTRATION FLOW RATES

Case	\dot{Q}_{loss} [L/s]	\dot{Q}_{net} [L/s]
1	2.793	0.153
2	2.447	0.381
3	0.589	0.589

4.2.3 Calculations and Results

Combining the equations below, the heat losses for winter and heat gains for summer can be calculated respectively. Tables XI and XII list necessary inputs for these calculations.

$$\dot{q}_{out} = \dot{q}_{f,b} + \dot{q}_s + \dot{q}_c + \dot{q}_{fl} + \dot{q}_i - \dot{q}_l \quad (4.11)$$

$$\dot{q}_{in} = \dot{q}_{f,b} + \dot{q}_s + \dot{q}_c + \dot{q}_{fl} + \dot{q}_i + \dot{q}_l \quad (4.12)$$

TABLE XI: ESTIMATED ENCLOSURE DIMENSIONS

Dimension	Unit	Value	Dimension	Unit	Value	Dimension	Unit	Value
Front Height	m	6.07	Ceiling Length	m	3.07	A_{front}	m ²	16.51
Back Height	m	5.82	Ceiling Width	m	3.05	A_{back}	m ²	15.83
Side Height	m	5.82	Slab Length	m	3.05	A_{sides}	m ²	11.12
Width	m	2.72	Slab Width	m	3.05	$A_{ceiling}$	m ²	9.36
Depth	m	1.87	—	—	—	A_{floor}	m ²	5.09
—	—	—	—	—	—	A_{pad}	m ²	9.29
—	—	—	—	—	—	P_{slab}	m	12.19
—	—	—	—	—	—	V	m ³	58.35

TABLE XII: HEAT TRANSFER CONSTANTS

Season	Indoor conv., wall [W/m ² C]	Indoor conv., ceiling [W/m ² C]	Outdoor conv. [W/m ² C]	Slab U' [W/mC]
Winter	4.2	2.1	34.0	3.1
Summer	4.2	2.1	22.7	3.1

Finally, Table XIII lists the three design case input parameters and Table XIV shows the results of applying Equations 4.11 and 4.12 to Case 1 and 2 and Equation 4.12 to Case 3.

TABLE XIII: CASE SPECIFIC VALUES

Case	T_{in} [°C]	T_{out} [°C]	ΔT [°C]	Specific Volume [m ³ /kg]	Specific Heat [J/kg°C]
1	10	-40	50	0.660	1000
2	20	-20	40	0.723	1000
3	25	30	5	0.866	1000

TABLE XIV: HEAT TRANSFER ANALYSIS RESULTS

Case	Walls [W]	Ceiling [W]	Floor [W]	Lights [W]	Infiltration [W]	Total [W]
1	695.14	84.74	9.91	-111.80	211.62	889.61
2	556.11	67.79	7.93	-111.80	135.41	655.44
3	-69.33	-8.45	-0.99	-111.80	-3.40	-193.97

4.2.4 HVAC Unit Selection

As decided in Section 3.3, the minisplit system was chosen as the HVAC unit to use for this project. This unit is capable of either a combination of heating and cooling or solely heating. As explained in Section 4.2.4.1, an alternative system is considered for the summer months to maintain temperature and humidity plant requirements. This sections additionally includes the details on the chosen system for cooling. The heating system, including details on the minisplit system and in-floor heating, is described in Section 4.2.4.2.

4.2.4.1 Cooling System

The cooling system used for the application of plant growth must meet the requirements as provided in Table I which states that the internal temperature is ideal between 20-30°C with a relative humidity between 45-60%. When comparing this to the natural outdoor conditions in Arborg, the temperature from May to September has high averages from 14-23°C and low averages from 6-14°C, with relative humidity averages of 55-74% [28]. For the remainder of the year, temperatures historically drop below freezing temperatures, so a cooling system is only considered from May to September. Although the low averages are lower than the optimal growing conditions, plants are able to survive in temperatures down to 0°C [29] [30]. Similarly, plants can withstand temperatures exceeding 30°C and are not exposed to sun damage because the plants within the structure remain sheltered from extreme outdoor conditions. Given these conditions, natural outdoor air is sufficient in maintaining a growing environment. Therefore, an air circulation unit can be used as opposed to a cooling unit as it is not necessary for these months.

As stated, outdoor air circulation is optimal to meet the growing requirements as it is the most natural condition for plant growth. To obtain fresh air circulation within the structure, air intake and air exhaust are required. The warmest air within a structure rises to the top of the building, causing a large heat differential within the structure. On days when extreme heat is experienced, the temperature in the top of the building could exceed the required indoor temperature for plant growth, risking crop failure. Therefore, this air needs to be removed to maintain uniform conditions within the required temperature range. An exhaust unit should be installed in the wall in the upper portion of the structure to accomplish this indoor temperature condition. The summer airflow requirement of 30 air exchanges per hour corresponds to a minimum air flow of 1100 cfm. A cabinet exhaust fan from Grainger shown in Fig. 43 was chosen as it provides an airflow of 3,100 cfm with a blade diameter of 24 inches, making is compatible with the structure [27], the larger air flow will allow for greater convection and therefore cooling. In addition to the exhaust fan, Grainger’s weatherhood is recommended to protect the fan and structure interior from weather conditions, including rain and snow [31].

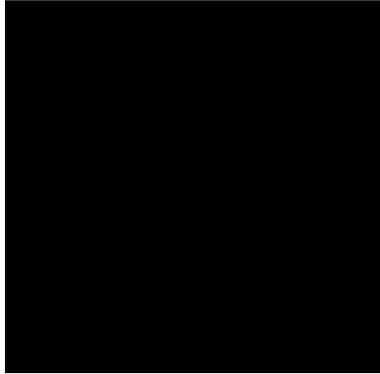


Figure 43: Cabinet exhaust fan [27]

In addition to the exhaust fan pushing air out of the top of the structure, outdoor air must also be pulled in to balance fresh air circulation and humidity levels. This could be accomplished with the use of a supply fan similar to the exhaust fan, however the height of the building allows for a pressure differential. Therefore, air can naturally be pulled into the system from the base while the exhaust fan is pushing air out from the top. By inserting a vent at the base of the structure on the opposite wall from the exhaust fan, the fresh air will naturally flow through the centre of the structure. This concept is visually described in Section 4.3.

A vent and exhaust fan system in the summer months will allow for the plant growing requirements to be met. However, the addition of these systems results in gaps in the structure that are not compatible with the heating requirements in the winter months as they would have large cold air infiltration. These gaps will be need to be sealed in the winter which is discussed in further detail in Section 4.3.

4.2.4.2 Heating System

The heating unit is responsible to meet the indoor growing environment conditions during the winter months when temperatures drop below 0°C. These months are nominally from October to April, however this range experiences large differences in temperature and relative humidity. The unit will be able to meet all temperature requirements throughout these months as long as it is able to provide sufficient heat in the most extreme cold weather conditions. However, heating units often come with a dehumidification function due to the high humidity levels in the coldest months from December to February [28]. This dehumidification function does not support the remaining months that experience freezing temperatures because they have the lowest relative humidity levels of the year. These relative humidity levels can be as low as 10%, so humidification in the structure is required.

The minisplit system was the main concept selected for heating the structure. While this unit provides both heating and cooling, only the heating function will be used throughout the winter while being shut-off during the summer. The heating unit must be able to achieve 890W (3,035 BTUh) of heating as calculated in Section 4.2.3 for the worst case average outdoor temperature. The entire system contains an outdoor and indoor unit, where the outdoor unit is a heat pump which powers the indoor wall unit to distribute the heat. The indoor unit that was chosen is the 40MPHA Infinity High Wall Indoor Unit from Carrier as shown in Fig. 44 [32]. This unit was chosen because it can supply 9,000 BTUh, meeting the heating requirements of the structure. Additionally, it has a built-in relative humidity sensor which allows for humidity customization and can be controller with a cellular device which allows for remote temperature control.



Figure 44: Heating system: Infinity high wall indoor unit [33]

Similarly, the outdoor unit chosen for this system is the 38MAR Performance Heat Pump with Basepan Heater from Carrier as shown in Fig. 45 [34]. This heat pump was selected because it is compatible with the wall unit and comes equipped with a basepan heater which eliminates system failure due to freezing.

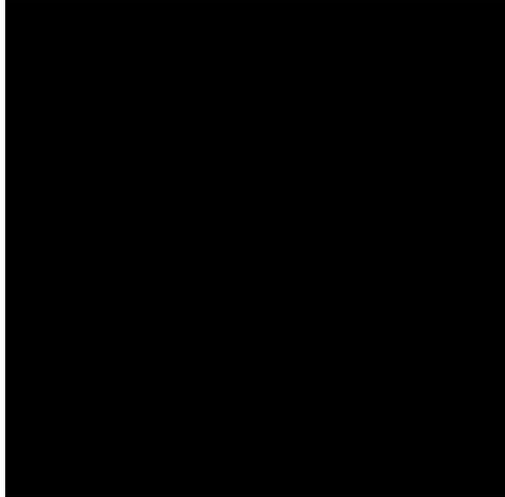


Figure 45: Heating system: Performance heat pump with basepan heater [34]

The minisplit system is not able to provide fresh air circulation which is required to maintain the growing environment. To have fresh air circulation, a heat recovery ventilator (HRV) can be installed on the wall towards the top of the building. This will allow the hot air at the top of the structure to be pulled out in order to maintain the necessary growing temperature. The HRV 160 CFM 75 SRE unit was chosen from VanEE shown in Fig. 46 because it has a 75% efficiency and can supply up to 160 cfm of airflow which meets requirements for fresh air intake that would be required in winter [35]. This unit is generally used in conjunction with ducting, however can be operated without ducts to supply and remove air.



Figure 46: Heat recovery unit: HRV 160 CFM 75 SRE [35]

A humidifier is required to deliver the relative humidity levels that are needed for plant growth. Most humidifiers are independent systems that require manual water replenishment or are specifically designed to be attached to duct-work. Although the manual-fill units would be sufficient in providing the relative humidity necessary, it is not optimal for the nature of this project as it would add a higher level of maintenance. The unit that would require the least amount of attention

and maintenance is one which allows for an auto-fill system by a connection directly to a water source. Since a water line is used by the Biosystems team as a supply for the plants, water is accessible for the application of a humidifier. The humidifier chosen is the Horticat U80 Pro as shown in Fig. 47 which is able to deliver an output of up to 40 litres per day and comes with a external humidity sensor [36] [37]. This humidifier was selected because it is able to supply the required humidity and is one of the limited options available which has the auto-fill functions available.



Figure 47: Humidification unit: Horticat U80 Pro Humidifier [36]

The combination of the minisplit unit, HRV and humidifier will allow the environment requirements to be met throughout the year where outdoor temperatures are below 0°C. These systems will be integrated into the structural design in Section 4.3.

4.3 Subsystem Integration

There are three openings in the carousel walls large enough to be considered structurally relevant; the door opening, the high flow fan exhaust, and high flow fan inlet. Additional members were added in these areas to support the door frame, cabinet fan, and air inlet. The upper and lower vents are protected by the weatherhood specified in Section 4.2.4.1. While the door opening has been left to the contractor conducting the install to determine how best to integrate the entrance into the adjoining structure. The remaining holes in the carousel are small enough to be drilled onsite for wiring, hoses, and low flow ventilation.

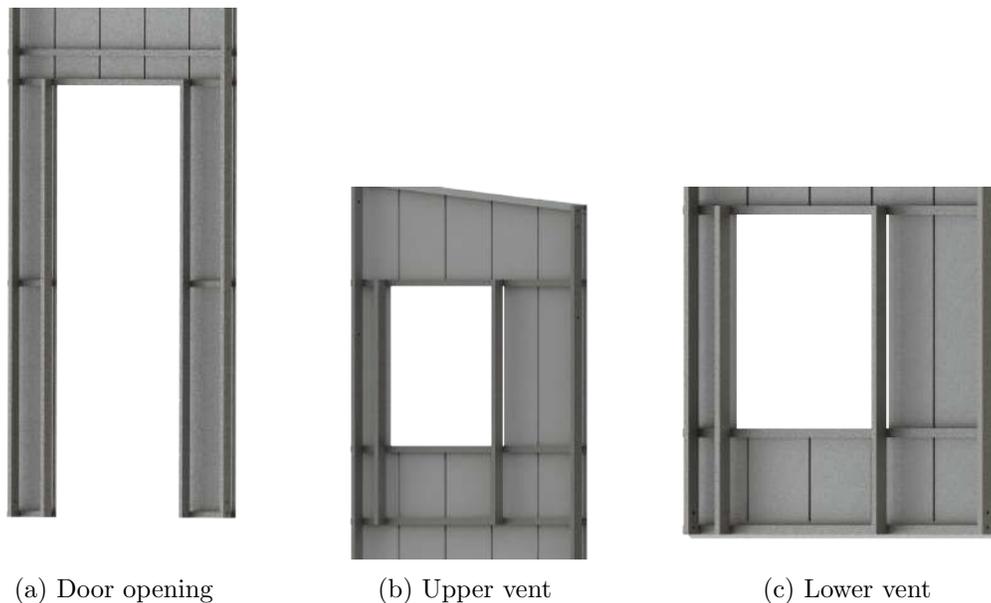


Figure 48: Large enclosure openings

The remaining HVAC components can be mounted to existing members of the enclosure:

- **HRV Unit** - The HRV unit can be hung from the uppermost horizontal support members given its compact size and its low weight due to its volume is primarily occupied by air chambers.
- **Split System Indoor Unit** - The indoor unit of the split system can be mounted to the existing object fall protection cage found on the carousel. Placing the unit here centrally eliminates the need for additional mounts protruding through the insulation. Additionally, by placing the unit high any condensation collected by unit during normal operation can be drained into the plant watering system.
- **Humidifier** - Like the split system the humidifier should be mounted to the existing object fall protection cage found on the carousel. As the humidifier can be connected to supply water there is no issue with the unit being mounted out of reach.

4.4 Renewable Energy Design

This section summarizes the concept generation, development, selection processes and feasibility for implementing a renewable energy solution for the project. Section 4.4.1 briefly describes the qualitative process of selecting solar power from the variety of renewable energy sources. Section 4.4.2 describes the process used to determine overall feasibility of solar power. Finally, Section 5.1.3 summarizes the decisions made and outlines the solar energy design.

4.4.1 Energy Generation Options

Vidir has requested that Team 11 investigate the feasibility of using renewable energy sources. Solar energy was selected by the team and approved by Vidir to pursue in this feasibility study. Alternative renewable energy sources were eliminated for the following reasons:

- Water-based renewable energy was eliminated because the land surrounding Vidir does not host water sources.
- Biomass and hydrogen fuel cells were eliminated due to high maintenance requirements which goes against the requirements set by Vidir.
- Geothermal energy was not considered due to the equipment complexity and size.
- Wind energy was eliminated as wind levels can be inconsistent and is too elaborate a solution for this project.

Although the amount of sun exposure can be inconsistent, the ease of installation and maintenance of solar panels resulted in the selection of solar energy.

4.4.2 Solar Energy

Two values are needed to determine the amount of energy feasibility of solar panels: annual energy created by the solar panels through solar absorption and the annual energy demand of the system the solar panels will power. The annual energy generated by the solar panels is determined by evaluating and comparing fixed-tilt and sun-tracking surfaces. Surface type and the total absorbed radiation for each is detailed in Section 4.4.2.1. Section 4.4.2.2 outlines the details of the selected solar panel, including the total energy generated by the panels. Section 4.4.2.3 includes the total energy demand of the system and a summary of the specific loads of the system. Finally, Section 4.4.2.4 outlines the total energy load and discusses the number of panels that will be required to meet the demand of the system. Additional details for each of these sections can be found in Appendix C.

4.4.2.1 Total Solar Radiation

The solar energy generated is dependent on the radiation that is able to be absorbed by the solar panels. This absorbed radiation is directly correlated with the angle of the sun relative to the panel's surface which can be calculated using the historical weather data provided in Appendix C.2 [38]. The total radiation comes from direct, diffuse, and reflected sun beams that are directed towards the panel's surface which is used to determine the energy generated according to the specifications of the solar panel. The amount of absorbed radiation varies between the use of a fixed-tilt surface and sun-tracking surface, so the results are determined for each in the following sections. The process in determining the solar energy attainable from the panels is based on the details found in [23] and [38]. Further details for these calculations and the detailed definitions for each variable can be found in Section C.1.

Fixed-tilt Surface

A fixed-tilt surface is a solar panel that remains in a fixed position. When set at an optimal angle to absorb the most sun rays possible, a stationary surface is able to have a large amount of energy generated, however it may not absorb as much as a sun-tracking surface. Fixed-tilt systems are often much more cost effective though, making it a positive option for the purpose of this project [39].

The amount of energy produced by the solar panels is determined according to the sun's position relative to the earth and solar panel at every hour throughout the year. Using the hour, extraterrestrial radiation, and the direct normal weather data from Appendix C.2, the angles from the sun to the solar panels are calculated according to the equations provided in Appendix C.1. These equations are based on the solar panels facing directly South with a tilt angle of 20° with respect to the horizontal plane. This angle was used as it is the assumed approximate angle of the existing roof at Vidir. Although this angle may be increased to increase the energy absorption, the installation of solar panels flush to the surface reduces the additional effects from wind on the roof's structure [40]. This angle additionally encourages a lack of snow build-up on the panels because it can slide off the panel.

The solar radiation absorbed is based on the isolation that results from the rays that are incident on the solar panels, are scattered from dust and molecules in the air, and are reflected in the air molecules as shown in Fig. 49.

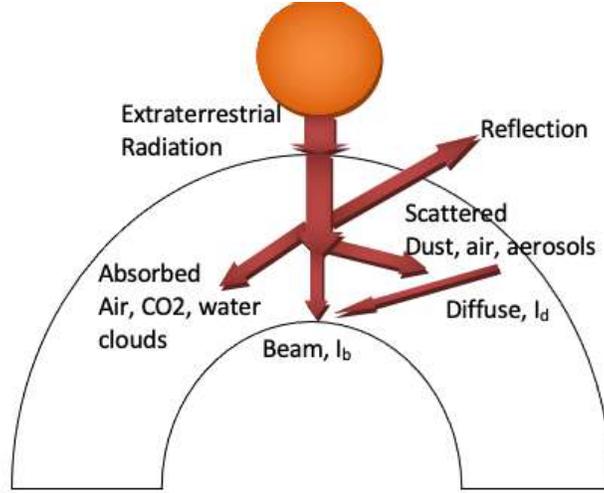


Figure 49: Forms of solar radiation [38]

These radiation values are calculated according to the angles that were previously determined. The equations used to calculate the total radiation are shown in Equations 4.13 to 4.17, with the variables first defined in Table XV.

TABLE XV: VARIABLE DEFINITIONS FOR SOLAR RADIATION CALCULATIONS [23] [38]

Variable	Definition
$I_{b,n}$	Beam radiation - radiation from the sun onto a flat surface which is not redirected and is normal to the sun's rays. Used as a constant in finding the total radiation onto a tilted surface.
I_{ext}	Extraterrestrial radiation - radiation of sun before it reaches the atmosphere. Found in historical data in Appendix C.2.
k	Diffuse factor - see Appendix C
χ	Zenith angle - see Appendix C
$I_{b,tilt}$	Beam radiation - radiation from the sun onto a tilted surface which is not redirected.
θ	Incident angle - see Appendix C
$I_{d,tilt}$	Diffuse radiation - solar radiation scattered by aerosols, dust and molecules.
C	Sky diffuse factor - see Appendix C
ϵ	Tilt angle of the plate - see Appendix C
$I_{r,tilt}$	Reflective radiation - solar radiation that is reflected off the ground, clouds and surrounding features.
ρ	Reflective index
I_{total}	Total radiation on the tilted surface.

$$I_{b,n} = I_{ext} \exp\left(\frac{-k}{\cos\chi}\right) \quad (4.13)$$

$$I_{b,tilt} = I_{b,n} \cos \theta \quad (4.14)$$

$$I_{d,tilt} = CI_{b,n} \cos^2 \left(\frac{\epsilon}{2} \right) \quad (4.15)$$

$$I_{r,tilt} = \rho I_{b,n} [\cos \chi + C] \sin^2 \left(\frac{\epsilon}{2} \right) \quad (4.16)$$

$$I_{total} = I_{b,tilt} + I_{d,tilt} + I_{r,tilt} \quad (4.17)$$

Using the equations above, the total radiation was found for every hour throughout the year. The total amount of radiation expected for each day of the year depends on the amount of sunlight exposure. The two extreme cases, winter and summer equinox, where the least and most amount of sun is expected, respectively, are used to demonstrate the change in absorbed radiation throughout the year. Fig. 50 and Fig. 51 show this variation. The data to develop these charts is included in Appendix C.2.

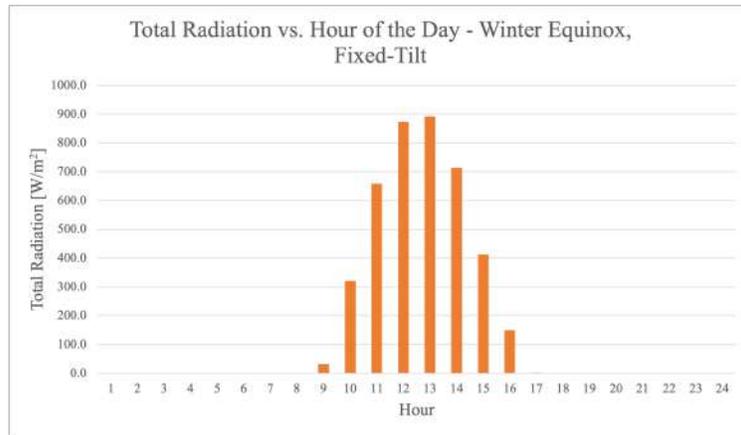


Figure 50: Chart of total radiation per hour on winter equinox for fixed-tilt surface

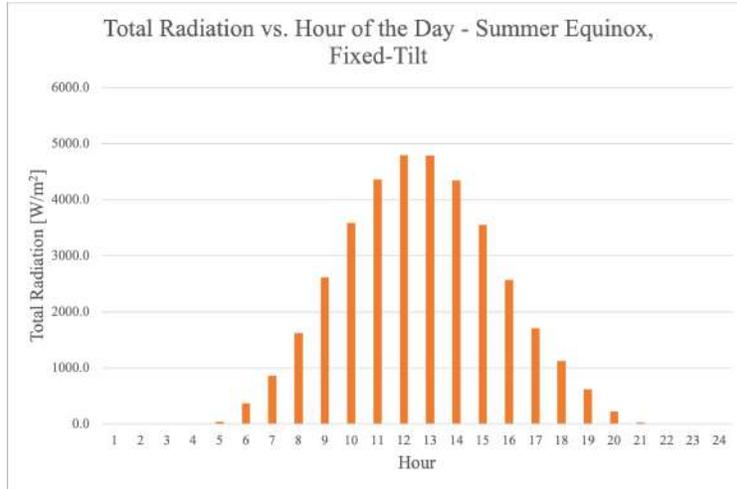


Figure 51: Chart of total radiation per hour on summer equinox for fixed-tilt surface

The total resulting solar radiation from a fixed-tilt surface is approximately $7.1 \times 10^6 W/m^2$. This value is used in Section 4.4.2.3 to determine the total energy generated by a solar panel and is compared to the sun-tracking surface in terms of the difference in energy and cost.

Sun-Tracking Surface

A sun-tracking surface is a solar panel that follows the position of the sun throughout the day using sensors within the frame the solar panels are mounted on. These systems can come as a single-axis or dual-axis tracker which offers a variation in energy absorbed depending on the application [39]. However, these systems require a higher level of maintenance compared to the fixed-tilt systems and are generally designed for climates with little to no snow.

The total radiation that is absorbed using a sun-tracking system is calculated similarly to a fixed-tilt surface. A dual-axis sun-tracking surface is used for these calculations in order to maximize the radiation absorbed. As a result, the only difference in the calculations is the zenith angle is always equivalent to zero since the panels are directly facing the sun at all hours of the day. Additionally, the tilt angle is set to zero as the tracking system follows the angle that is required for the panels to face the sun.

Equations 4.13 to 4.17 from the fixed-tilt calculations are used to calculate the total radiation onto the flat sun-facing surface. Using these equations, the total radiation absorbed throughout the year on the sun-tracking surface is equivalent to approximately $9.9 \times 10^6 W/m^2$. The amount of radiation on the winter and summer equinox can be seen in Fig. 52 and Fig. 53, respectively. In comparing these to the fixed-tilt surface, it can be assumed that the absorbed radiation throughout the day remains mostly consistent throughout the year, with the sun-tracking being slightly higher. As a result, these two surfaces will be compared in terms of energy generated and total cost to determine the surface that is optimal for this project.

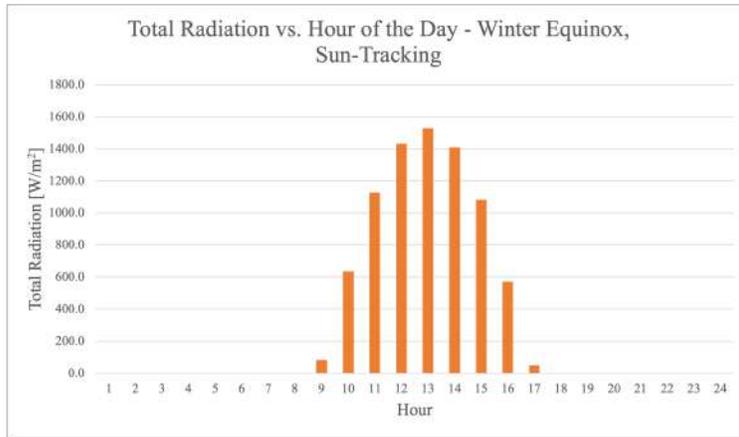


Figure 52: Chart of total radiation per hour on winter equinox for sun-tracking surface

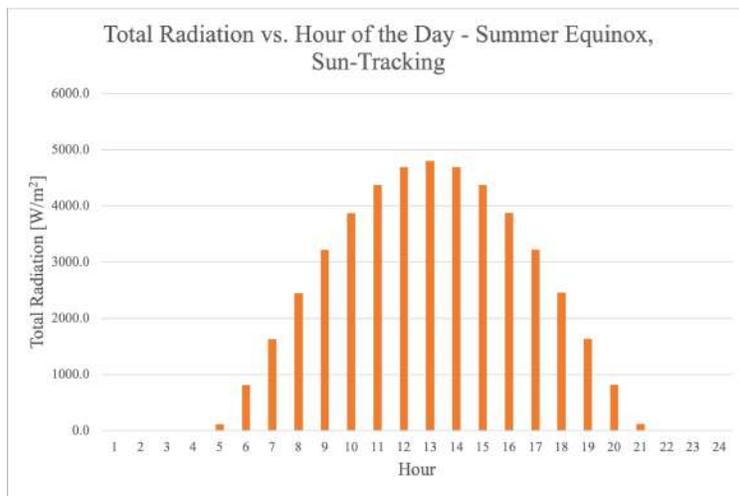


Figure 53: Chart of total radiation per hour on summer equinox for sun-tracking surface

4.4.2.2 Solar Panel Selection and Energy Generated

Three solar panel suppliers are suggested for Vidir to pursue: Canadian Solar, Solacity Inc., and Silfab Solar. Details on each of these suppliers and selected models they carry is provided in Appendix C.3. According to the details found in the section provided, Team 11 chose to pursue the Canadian Solar’s HiKu7 model because it has the highest output power for the same price range as the alternative models. Details on this model are provided in Table XVI [41].

TABLE XVI: CANADIAN SOLAR SPECIFICATIONS OF HIKU7 SOLAR PANEL MODEL [41][42]

Parameter	Unit	Specification
Output Power	W	640
Length	m	2.38
Width	m	1.30
Efficiency		25.3%
Temperature Range	°C	-40 to 85
Cost		\$250 - 270

Using these specifications, the total annual energy generated for a single panel for the fixed-tilt surface and sun-tracking surface are computed and summarized in Table XVII.

TABLE XVII: TOTAL ENERGY GENERATED BY SOLAR PANEL

Parameter	Unit	Value
Area	m ²	3.09
Rated Power	W	640
Efficiency		25.3%
I_{total} - Fixed-Tilt	kWh	22,083
I_{total} - Sun-Tracking	kWh	30,703
Annual Energy Generated - Fixed-Tilt	kWh	8,148
Annual Energy Generated - Sun-Tracking	kWh	11,536

Although the annual energy generated is 1.4 times larger for a sun-tracking surface, there are additional factors that must be considered with a sun-tracking system. As previously mentioned, these systems are designed for climates which experience little to no snow. When operated in climates with heavy snow, high levels of maintenance is required in order to operate effectively [39]. While options are available that are better suited for Canadian climates, such as dual-axis tracking models by Deger, these models are much more commercialized as they are meant for module surfaces up to 40-70 m² [43]. Smaller-scale options are not widely available in Canada, however they could cost between \$500-\$1000 per panel [44]. This additional cost is significantly more than the solar panels which, in addition to the increased maintenance requirements, is not a compatible option. Therefore, the fixed-tilt system is chosen for this project.

4.4.2.3 System Energy Demand

The system energy demand is determined according to all units that require energy to complete the operation of the entire structure. This includes all HVAC components, the carousel, and grow lights. While the units and carousel will be in use throughout the entire year, the HVAC systems are divided into summer and winter application. Table XVIII summarizes the energy demand of the HVAC units in the summer, while Table XIX summarizes the HVAC demand for

winter. Since May and October can often vary in above or below freezing temperatures, these months were added to the total amount of days for both the summer and winter case to establish a worst-case-scenario for the total energy load. As a result, 184 days was used for the summer and 243 days was used for the winter. Detailed calculations for the values presented in Table XVIII and Table XIX can be found in Appendix C.

TABLE XVIII: HVAC ENERGY DEMAND IN SUMMER

HVAC Unit	Energy Demand [kWh]
Exhaust Fan	8,125.4

TABLE XIX: HVAC ENERGY DEMAND IN WINTER

HVAC Unit	Energy Demand [kWh]
Mini-Split System	12,072.2
Heat Recovery Ventilator	583.2
Humidifier	758.2
Total	13,413.6

Using the summer and winter values, a worst-case of the annual energy demand for the complete system is summarized in Table XX. The energy demand can then be compared to energy generated to determine the solar energy feasibility in Section 4.4.2.4.

TABLE XX: ENERGY DEMAND OF COMPLETE SYSTEM

Unit	Energy Demand [kWh]
HVAC - Summer	8,125.4
HVAC - Winter	13,413.6
Lights	2,448.4
Carousel	9,916.8
Total	33,904.2

4.4.2.4 Solar Feasibility

The feasibility of solar energy is completed by comparing the total energy demand of the system to the total energy generate by the solar panels. With one solar panel, the energy generated is 8,148 kWh. In order to meet the energy demand of the whole system throughout the year, five solar panels are required. This is summarized in Table XXI.

TABLE XXI: ANNUAL ENERGY DEMAND OF COMPLETE SYSTEM

Variable	Value
Annual Energy Demand	33,904.2 kWh
Annual Energy Generated (5 Panels)	40,740.4 kWh
% of Load Met	120.1%

According to the above table, there is an excess of 20.1% energy generated with the use of five solar panels. However, the most amount of energy is generated throughout the summer months when there is a smaller demand on the system. As previously stated, the winter equinox will have the least amount of energy generated by the solar panels in a day. Therefore, the total number of panels required is determined by the difference in the energy demand and energy generated on the winter equinox. Table XXII summarizes the difference between energy demand for one day in the winter and the energy generated using five and six panels on the winter equinox. The energy generated was determined by taking the sum of the hourly generated energy in Appendix C.2.

TABLE XXII: SOLAR FEASIBILITY ON WINTER EQUINOX

Variable	Value
Energy Demand in Winter for One Day	89.1 kWh
Energy Generated on Winter Equinox	17.9 kWh
Energy Generated from 5 Panels	89.5 kWh
Energy Generated from 6 Panels	107.4 kWh
% of Load Met (5 Panels)	100.4%
% of Load Met (6 Panels)	120.5%

As a result, the implementation five solar panels results in the energy loads being met, so an additional panel is not required. As discussed in Section 5.1.3, these panels are recommended to be connected directly to the grid. Therefore, using five solar panels is recommended to meet the demand through the winter months, with electricity from the grid providing the remainder of the energy required if there is excess cloud coverage during the winter. Excess energy through the year will be able to be sold back when connected to the grid as discussed in Section 5.1.3, or energy stored in a battery-bank system as discussed further in Section 6.3. The addition of a sixth solar panel would be recommended for off-grid application when grid electricity is unavailable.

5 Final Design

With the design development completed, Team 11 has decided to summarize the decisions made to provide a quick, overall view of the design. A brief overview of the important aspects of the design are presented in Section 5.1. Suggested manufacturing steps for custom parts and assembly of the enclosure are presented in Section 5.2. Finally, a truncated bill of materials is presented in Section 5.3.

5.1 Design Overview

This section provides an overall view of the design, acting as a summary of important details from Section 4. Design justifications were presented in the preceding sections, therefore only final design details are discussed.

5.1.1 Structure

The structure was broken into floor, walls, and roof. Team 11 decided on using modular panels that can be fabricated using Vidir's existing capabilities. Overall details on each part of the structure are presented, with further details on manufacturing and assembly presented in Section 5.2.

Floor

The enclosure is built on top of a pre-installed concrete pad. The pad requires insulation and proper flooring according to relevant codes and standards. Insulation will also aid in maintaining the indoor temperature of the enclosure.

Team 11 decided on a floor with two levels: a higher level for the entryway and foot traffic, and a lower level to allow for clearance between the flooring and carousel. The higher level will have 4.5" of insulation, while the lower level will have 3.5". The overall average R-value of the floor is approximately R27.8. The two layers will be achieved by fabricating a steel frame in which insulation can be sprayed. The two frames will be welded together and filled with spray foam insulation, finally covered with tread plate to allow for foot traffic as shown in Fig. 54.

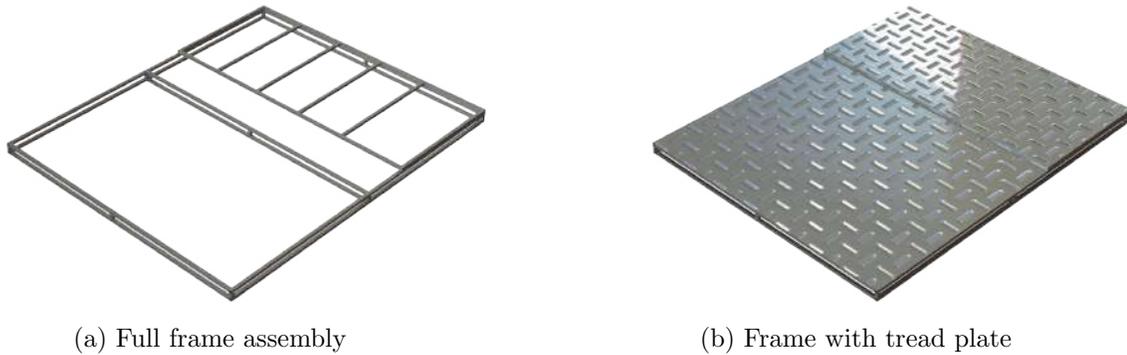


Figure 54: Flooring design

Wall & Roof Panels

Walls and the roof utilized a modular panel design. The four walls consist of two panels each. The roof is also made of two panels and has a single slope of 1" per foot to account for snowfall. Tin paneling is used as an exterior surface of the structure, applied to both the roof and walls. The interior surface is simply exposed insulation, though an interior surface may be installed if desired.

Wall and roof panels consist of a steel frame constructed from steel HSS tubes. Panels consist of two vertical members made of $1 \times 2 \times 1.125$ HSS and a number of horizontal joists made of $1.25 \times 1.25 \times 0.11$ HSS tubes. The frame is held together by rivets and once constructed, the frames will not need to be disassembled. Reinforced plastic washers provide a thermal break between frame members. Spray foam will be applied to the panel frames to provide insulation to the structure. Fig. 55 provides an example front wall panel frame construction.

Wall panels are all 60" wide with varying heights. Front wall panels have a height of 239", while rear wall panels have a height of 229". Side walls will have a sloped top from 239" to 229" to accommodate the roof. Roof panels are 60" wide and 140" long. A few large openings in the walls are required to accommodate the HVAC system and door. These openings have additional members to account for any structural weakness the holes may introduce.

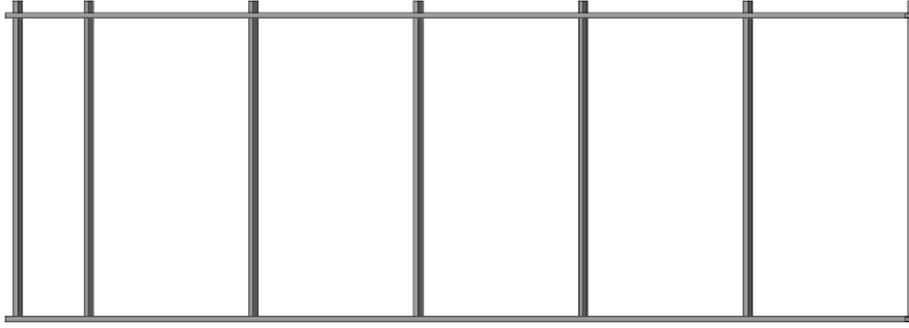


Figure 55: Modular front panel frame

Brackets

Wall and roof panels are connected to the carousel frame and concrete pad by way of steel brackets. Brackets are formed from sheet metal and secured to components with bolts. Table XXIII summarizes the types of brackets required and their function. The enclosure will be held together by these brackets and will receive some structural stability from the spray foam insulation. Brackets offer cheap and simple installation, and provide some flexibility in wall alignment to account for looser tolerances.

TABLE XXIII: SUMMARY OF BRACKET TYPES

Type	Amount	Location	Connections
Wall Front	2	Middle and top of carousel	Carousel front to wall, connects both front panels together
Wall Back	2	Middle and top of carousel	Carousel back to wall, connects both back panels together
Wall Side	4	Middle and top of carousel	Carousel sides to wall, connects two side panels together
Floor Corner	4	Enclosure corners, sits on floor	Connects walls to floor
Floor Center	4	Wall panel seams, sits on floor	Connects walls to floor
Roof Corner	8	Cieling corners, front and back wall seams	Connects carousel to roof and walls
Roof Center	2	Ceiling, side wall seams	Connects carousel to roof and walls
Central	1	Center of enclosure ceiling	Carousel to roof

5.1.2 HVAC

The HVAC system is extremely important for any indoor growing space as it is the system regulating the temperature and humidity of the space. Team 11 took into account the requirements provided by the Biosystems team to specify a system that can supply adequate heating, airflow, and humidity to the grow system.

Cooling System

The cooling system is considered for May through September based on the average temperature ranges in Arborg, Manitoba. Team 11 determined that outdoor air was adequate for plant growth, therefore airflow was the only concern to be addressed. To achieve proper airflow in the summer Team 11 determined that the enclosure would require an air intake and exhaust. It was decided that the air intake should be installed near the bottom of the enclosure and the exhaust at the top. The placement of intake/exhaust was chosen due to natural convection, hot air rising to the top of the enclosure, and to create a pressure differential to allow fresh air circulation.

An exhaust fan produced by Grainger was chosen to move air through the structure. The exhaust fan is capable of pulling 3100 cfm and has a blade diameter of 24". It is suggested that the weatherhood sold by Grainger be implemented with the fan to protect the fan and reduce infiltration in the winter. A vent is installed to act as the intake, utilizing the power of the exhaust fan and the pressure differential produced to carry fresh air into the enclosure.

Heating System

The heating system is far more active compared to the cooling system. In the cold winters of Manitoba air will require heating to achieve an acceptable indoor temperature. Intake air will also require humidification since cold intake air can not retain much moisture.

Heating will be achieved by using a minisplit system. The chosen indoor unit is a 40MPHA Infinity High Wall Indoor Unit sold by Carrier. The 40MPHA is capable of providing 9,000 BTU/h which was more than enough for the structure. The chosen outdoor unit is a 38MAR Performance Heat Pump with Basepan Heater sold by Carrier would be adequate for the heating needs of the carousel. The project required an HRV unit to achieve proper circulation. The chosen HRV unit is a HRV 160 CFM 75 SRE unit sold by VanEE. Finally, a Horticat U80 Pro was found to provide enough humidification for the enclosure and provides a solution with simple installation and operation.

5.1.3 Renewable Energy

As discussed in Section 4.4.2, the annual energy demand of 33,904.2 kWh can be met year-round through the use of five Canadian Solar HiKu7 solar panels. The total energy generated with

these solar panels will be 40,740.4 kWh.

Team 11 decided to have these panels directly connected to the grid as this has a larger compatibility with the structure that will be located at Vidir. The addition of a battery bank to store energy would be compatible for an off-grid application of this structure which is discussed further in Section 6.3. The benefit of having the panels connected directly to the grid is the energy can be sold back to Manitoba Hydro which lowers the overall cost of the system [45]. Additionally, the system will continue to run using electricity from the grid if there is not enough energy being generated through the day due to prolonged overcast. This is a necessary feature with vertical farming as any dramatic change to the conditions can cause crop failure. The current price that Manitoba Hydro will pay for excess electricity is \$0.02403/kWh, which equates to an annual return of approximately \$160, accounting for a large portion of the cost of one solar panel.

5.2 Design Assembly and Manufacturing

This section describes manufacturing and assembly procedures required to implement the design. Full drawings are provided in Appendix ?? and CAD files will be provided to Vidir, from which most parts can be directly produced.

Note: Drawings are not included in the publication version of this report since they include all technical detail required to produce the design.

5.2.1 Manufacturing

This section describes the processes required to manufacture each of the key components for the enclosure in detail. Components of these assemblies are primarily constructed from laser cut sheet and tubular steel compatible with Vidir's existing manufacturing processes, and the remaining components are sourced.

Floor

The false floor consists of five primary components; lower (main) steel frame, top steel frame, tread plates, rivets and insulation. The main frame members are designed to be cut using Vidir's tube laser, or simply with a bandsaw and drill. The thin tread plate may be cut by hand, all to the dimensions specified in Appendix ?. As shown in Fig. 54, the main and top frames should be welded up separately, before placing one on top of the other with a final weld. ¼" rivets are used to fasten the tread plate to each level of the floor frame.

Finally, the floor frame should be turned upside down (treadplate facing down), to be filled with spray foam. Foam should be applied to fill the frame completely. Slightly underfilling the edges is fine since all seams in the enclosure will be given a final coat of spray foam after assembly. If overfilled, a utility knife, hand saw, or reciprocating saw can be used to trim away excess.

Walls & Roof

These sub-assemblies consist of six primary components; vertical members, horizontal members, thermal washers, rivets, tin, and insulation. The members are designed to be cut using Vidir's tube laser cutters, and the optional use of pre-galvanized material reduces the load on the paint line. While each panel is slightly different each can be constructed using the following method.

1. Lay out all the required vertical members for the panel with the 1/4" rivet holes facing up, before laying out all of the horizontal members on top of them with the large holes facing up.
2. Fasten the structure together using an air powered rivet gun, taking care to insert the thermal washer between members before inserting the rivet.
3. Lay the tin down over the panel, taking care to insert the drip edge underneath at the bottom. Use self-drilling screws to fasten the tin to the steel members.
4. Flip the panel and apply the spray foam insulation at the required thickness; 4" for walls, 5.75" for the roof. Ensure care is taken to avoid spraying the areas close to the bolt holes which join the panels together. These areas will be insulated onsite.

Brackets

The eight brackets required to join the panels and connect back to the carousel have been designed for Vidir's flat laser cutters and break press forming. Like the tube components of the enclosure panels, these sheet metal parts can be cut from pre-galvanized material to reduce paint line load.

Door

The enclosure frame has been designed to accept a standard 36" wide door, however the door and any adaptation required to connect the enclosure to an existing building was out of scope. Should a different size of opening be desired in the future, the frame can be easily adjusted to accommodate.

5.2.2 Installation

This section briefly describes the on-site procedure for installing all components of the vertical farming design.

1. Ship all components to site

All modular panels were designed to fit on a flat-deck trailer for easy shipping. Care should be taken not to damage the spray foam insulation applied in the factory during handling, load

securement, or transport.

2. Mount carousel frame to the concrete pad

Since the carousel frame is used as the enclosure frame, the frame should be secured first. To allow easy access for enclosure components through the carousel frame, shelves are not yet added. Mounting details for this step are assumed to have been predetermined by Vidir, as the concrete pad was designed around this feature.



Figure 56: Carousel on pad, and positioning information [4]

3. Install side walls

The side walls of the carousel can then be mounted. It is recommended to install the side walls first due to their simple to install mounting brackets making for a safer job. The panels must first be gently lifted into an upright position before being moved into position to be mounted. The center brackets connecting the panel to the carousel can then be installed, locking in the panels position. Finally the floor support brackets can be installed after drilling holes in the concrete pad. This process can be repeated for each of the four wall panels making up the side walls.

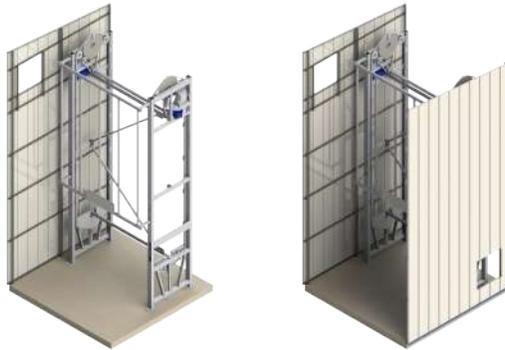


Figure 57: Side panel installation [4]

4. Install back wall

The back wall should be installed next, as once the shelves are installed, access to the mounting locations will become difficult. The rear panels are mounted using the same process as the side panels, however the rear brackets are to bridge between the carousel towers. Finally the panels can be joined in the corners using the corner brackets.



Figure 58: Back panel installation [4]

5. Slide floor panel between carousel feet

Before the front of the carousel is installed the insulated floor assembly should be positioned. Installing the floor assembly after would not be possible, requiring a new floor to be built on site.



Figure 59: Floor panel installation [4]

6. Close select seams, corners, and floor edges

Close any gaps at the rear of the carousel which may be difficult to reach after the shelves are installed. Namely the gaps between the six standing wall panels, and the gaps between the walls and floor section.

7. Install carousel shelves

Once the floor and rear wall panels have been installed and gaps sealed the carousel shelves can be installed without causing accessibility issues to any of the mounting locations.

8. Install front wall

Finally the front wall should be installed, once again using a process similar to the side and rear panels. However the extended front bracket are used and again the panels can be joined in the corners using the corner bracket.



Figure 60: Front panel installation [4]

9. Install Roof and Trim

Once the front wall panels have been installed the roof and trim sections can be added. Each roof panel is supported by the center, corner, and carousel mount brackets. These brackets can be installed before lowering the roof panel into place allowing for faster and safer assembly when working with the suspended panel. Finally, the trim sections can be added using self-drilling metal fasteners.

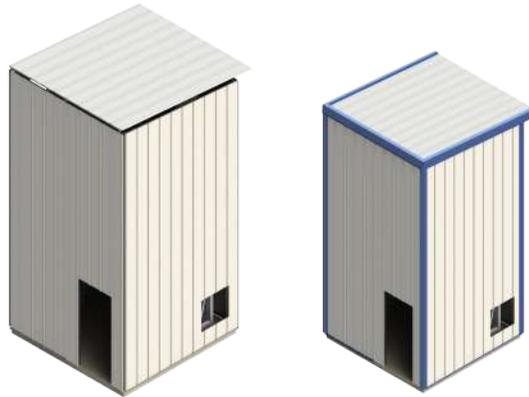


Figure 61: Roof and trim installation

10. Install all HVAC components

Now that the carousel and enclosure have been constructed, the split system (Red), HRV (Pink), humidifier (Yellow), and fan (Green) can be installed as seen in Fig. 62. Additionally, at this stage any wiring and hoses should be routed through holes drilled through the tin and spray foam in the desired locations for convenient routing into buried conduit or other structures. Holes for the HRV inlet and outlet should be drilled on a leeward wall facing away from the prevalent wind directions as much as possible.

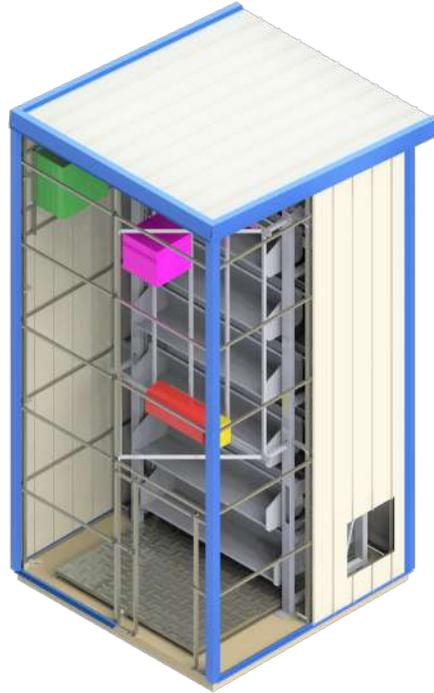


Figure 62: HVAC install [4]

11. Close all seams, corners, and floor edges with spray foam insulation

Finally the remaining gaps can be filled with spray foam to seal the enclosure.

12. Install solar panels

Lastly, the solar system can be installed following the systems manufactures directions, using their mounting system. The installation of the panels may be completed in parallel with the enclosure construction, however the installation of wiring, power converters, and breaker panel should be completed after construction of the enclosure is complete, and components located.

5.3 Bill of Materials

This section contains a truncated bill of materials (BOM) which summarizes all sourced components that must be purchased from external vendors for this design Table XXIV. The full BOM is provided in Appendix D. The full version includes all steel parts used in panel construction. Team 11 did not source these because for the prototype enclosure, Vidor is expected to be able to draw from their stock for these components.

TABLE XXIV: PURCHASED COMPONENTS BOM

Part	Quantity	Cost (CAD)	Source
1.5 Common Hardware	1		
1.5.1 Tin 12" wide	1	██████████	██████████
1.5.2 1/4" Fiber Washer	170	██████████	██████████
1.5.3 3/8" Fiber Washer	140	██████████	██████████
1.5.4 1/4" Rivets	210	██████████	██████████
1.5.5 3/8"-16 3" Grade 5 Flanged Bolt	35	██████████	██████████
1.5.6 3/8"-16 2" Grade 5 Flanged Bolt	78	██████████	██████████
1.5.7 3/8"-16 3.5" Grade 5 Flanged Bolt	2	██████████	██████████
1.5.8 3/8"-16 Grade 5 Flanged Nut	115	██████████	██████████
1.5.9 Handifoam E84 II-605 Kit	7	██████████	██████████
2.0 HVAC Subsystem	1		
2.0.1 Grainger Cabinet Exhaust Fan	1	██████████	██████████
2.0.2 Infinity High Wall Indoor Unit	1	██████████	██████████
2.0.3 Carrier Performance Heatpump	1	██████████	██████████
2.0.4 HRV 160 CFM 75 SRE	1	██████████	██████████
2.0.5 Horticat U80 Pro Humidifier	1	██████████	██████████
3.0 Renewable Energy Subsystem	1		
3.0.1 HiKu7 Solar Panel	5	██████████	██████████

6 Conclusion and Recommendations

This section brings the project to a close, and discusses some recommendations for Vidir should they continue development and implement the carousel enclosure.

6.1 Conclusion

Team 11 has based their design process and results on the client needs of Vidir. The enclosure structure has been designed to be built with modular panels. The structure is extremely implementable for Vidir’s capabilities and satisfies safety, weather shielding, insulation, manufacturing, and installation requirements. The recommended HVAC system is more than adequate to satisfy the temperature and humidity requirements for plant growth, even in the harsh winters of Manitoba. Lastly, Team 11 was able to determine that solar power would satisfactorily meet the demands of the overall system, providing a brief summary of the amount of solar panels required. The overall design has proven to be a sustainable, economical, and efficient solution, capable of housing plants year round. Table XXV restates the 15 needs along with Team 11’s solution to them and a reference to the relevant report section.

TABLE XXV: RELATION BETWEEN NEEDS AND SOLUTIONS

No.	Need	Solution	Ref.
1	Enclosure surrounds the carousel, withstanding Manitoba weather.	The enclosure is designed according to the Manitoba Building Code. Heat transfer calculations were completed on a worst case scenario basis such that any system selected using these values would be sufficient.	2.2, 4.2.2.1
2	System is safe.	The enclosure is designed according to the Wall Insulation: R-20.77 Ceiling & Floor Insulation: R-28.5	2.2, 4.1.4.1, 4.1.5.7
3	Enclosure can be installed on a preexisting concrete pad.	Dimensions of the carousel were unchanged such that the enclosure fits on the pre-existing pad.	4.1.4
4	Height of system is compatible with the dimensions of the concrete pad.	Dimensions of the carousel were unchanged.	A.1
5	Internal environment calculations account for thermal properties of the un-insulated existing concrete pad.	The concrete pad was considered a slab on grade with no insulation along its perimeter which is accounted for in the heat transfer calculations and HVAC unit selection.	4.2.2.3

6	A renewable energy source is used as an aid to electrical grid power.	five (six for Off-Grid) Canadian Solar HiKu7 Solar Panels meet 100.4% of required load	4.4.2.4
7	System maintains temperature and humidity levels for growing.	Cooling System: 3,100cfm Grainger Cabinet Exhaust Fan, Open Vent Heating System (Indoor): 40MPHA Infinity High Wall Indoor Unit Heating System (Outdoor): 38MAR Performance Heat Pump with Basepan Heater Humidifier: Horticat U80 Pro Humidifier HRV: 160CFM 75 SRE	4.2.4.1, 4.2.4.2
8	Temperature and humidity can be adjusted to desired growing conditions.	App Integration for remote operation.	6.2.3
9	Design can be used or modified to other locations for customers (i.e. restaurants, northern communities, homes, etc.).	All components are modular allowing for modification in dimension for other uses. In-floor heat is recommended for enclosure not requiring air humidification.	5.2.1, 6.2.2, E
10	Enclosure allows entrance of an external water line.	Any small hoses, cables or pipes can be integrated by drilling through the modular panel	4.3
11	System can be made and assembled using in-house materials and tooling.	Components are primarily constructed from laser cut sheet and tubular steel which is compatible with Vidir's existing manufacturing process.	5.2.1
12	Design is adjustable to accommodate a larger area and more carousels.	All components are modular allowing for modification in dimension for other uses.	5.2.1
13	System is easy to operate.	App Integration for remote control.	6.2.3
14	System is easy to maintain.	The enclosure is humidity controlled such that there will be minimal build up on the walls. The solar panels require minimal intervention.	4.2.4.1, 4.4.2.4
15	System is economical to implement and operate.	The cost of purchased parts needed to implement is \$17,304.45.	D

6.2 Recommendations

This section provides Vidir with a list of recommendations based on findings of Team 11 throughout the design process.

6.2.1 Carousel Orientation

In Section 4.2.2.5, the amount of air infiltration was calculated based on the worst case scenario, where the door and vent/exhaust would be on the windward and leeward walls respectively. As the door has a longer crack length than the exhaust fan and vent, the amount of infiltrating air would be greater in this case as the wind hits straight-on. For design purposes, the opposite is desired.

The carousel should be oriented such that the door is on a predominantly leeward wall. This will ensure there is less crack length directly facing the wind. As the wind direction varies throughout the day and year, orientation should be chosen based on prevailing annual wind directions.

In Manitoba, the wind is predominantly from the South year round and is rarely from the East according to Fig. 63 [25]. Therefore, it is suggested at Vidir’s site that the front of the carousel, containing the door face East.

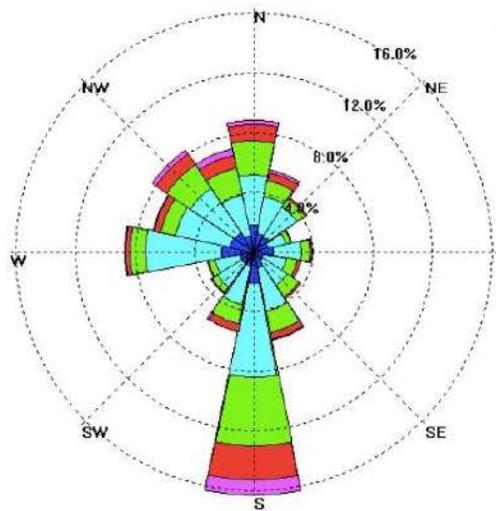


Figure 63: Prevailing wind conditions in Winnipeg, MB [25]

6.2.2 In-Floor Heating for Storage Spaces

In order to make a detailed comparison between a minisplit heating system and in-floor hydronic heating, both systems had to be sourced and designed to determine their respective heat outputs. As mentioned in Section 3.3.3, it was determined that either system could independently heat the enclosure, making the combination of them unnecessary. For this application, humidity

control is required to create a viable plant growth environment. The minisplit system was selected over in-floor heating because it satisfies this requirement.

Since the in-floor heating system is designed and source, it is included as a recommendation here for Vidir’s future work. In future applications where humidity control is not required, such as storage enclosures, in-floor heating is recommended because:

- In-floor heat may be installed directly into the concrete pad, allowing the heating system to take up virtually no extra space
- Switching to in-floor heating for this enclosure would lead to 45% reduction in energy consumption for heating.

The full hydronic system design is provided in Section E. This design would be able to fully handle the heating requirements for the vertical farm, described in Section 4.2.4.2, as summarized in Table XXVI.

TABLE XXVI: HYDRONIC IN-FLOOR HEAT SYSTEM PERFORMANCE SUMMARY

Specification	Value
Installation Cost	\$1,313.32
Heat Generation	3035 BTUh
Annual Energy	6613 kWh

6.2.3 App Integration for Remote Operation

If the product was to be offered for remote locations it may be desirable to remotely manage the enclosure. One suggested solution would be to install cameras in the enclosure that can be remotely accessed by the customer to check on growth. Customers may also desire analytics on how well the growth chamber is operating, some important metrics to measure would be temperature and humidity. A software application that can be accessed remotely would allow customers to monitor and control the operation of the enclosure without having to physically travel to the enclosure. This solution will be most useful for a customer who will have the carousel in a remote location.

6.2.4 A/C Systems for Specific Environments

The HVAC system designed for this project required high humidity levels to provide an environment that supports plant growth. This resulted in the requirement of several units to provide the appropriate environment. However, most units are not needed if the structure is used for alternative applications. Team 11 suggests Vidir utilizes only the minisplit system and HRV unit when the indoor environment does not require high humidity levels. The minisplit system can provide heating and air conditioning, while the HRV can maintain air quality. This additionally

decreases the outdoor air infiltration because the vent and exhaust fan spaces in the structure would not be required.

6.2.5 Renewable Power Generation

When implementing the solar panels, the energy will need to be converted from the DC energy AC electricity to power the system. An inverter is required for this conversion. While there are many inverters available on the market, Team 11 recommends an inverter that is also manufactured by Canadian Solar to ensure compatibility and ease of assembly. Canadian Solar’s Utility 125 kW Single Input inverter is specifically recommended which includes the details provided in Table XXVII [49].

TABLE XXVII: CANADIAN SOLAR INVERTER SPECIFICATIONS [49]

Specification	Value
Efficiency	99.1%
Power	1500 V/125 kW
Size	942x733x311 mm

In addition to an inverter, solar panel frames are required to mount the panels. There are two locations at Vidir that the solar panels can be mounted: in the field of the surrounding area or on a roof of an existing building. Since five solar panels are required that take up a total of 15.5 m^2 , it is recommended that the solar panels are mounted on the roof of an existing building for this specific project. For future projects where the structure is used in remote locations, it is recommended the panels be mounted to the ground since roof mounting on the structure has not been evaluated.

For integration at Vidir, the panels will face southward on the building indicated in Appendix C.3. The mounting brackets that are recommended by Team 11 are the Fast-Rack components available by HES PV located in Canada [50]. The necessary components may be selected by Vidir according to the roof structure. However, the specific mounting details and inverter integration is outside of the scope of this project so it is included as part of Section 6.3.

The addition of a battery-bank to store energy created by the solar panels is recommended for applications of the structure in remote settings. This would allow for year-round operation of all components when grid-connection is unavailable. Team 11 recommends CanLife 12V200AH Lithium Iron Phosphate batteries from Westrock Battery, which is located in Winnipeg, MB [51]. Lithium iron phosphate batteries are suggested as opposed to the traditional lithium-ion batteries that are typically used for the following reasons [52]:

- They have a longer battery life.
- They are built with non-toxic materials which lower environmental impacts.

- They offer a higher stability which increases the overall safety from combustion.
- They have an overall lower cost.
- They have a deeper discharge capacity which protects them from damage due to energy depletion.
- They have a higher discharge rate.

The batteries suggested require low maintenance and are among the least expensive within North America [51]. They also come with a capacity display which can be monitored through a phone app using Bluetooth. While the rated temperature for energy storage is -20 to 60°C, the charging and energy discharge temperatures are required to be above 0°C and -5°C, respectively. Since the temperatures in Arborg can drop to temperatures below these ratings, the batteries are required to be located indoors in a dry environment. To have them inside the structure, additional space may be required. An alternative option is adding a cell heater to the batteries that can be shut-off during the summer when it is not required. Westrock Battery has this internal heat option which is compatible with their lithium iron phosphate batteries [53]. This would provide the option of outdoor battery placement, provided sun-shelter is available, however may not provide the same efficiency as indoor placement.

6.2.6 Temperature and Humidity Sensors

It is imperative that the enclosure is maintained at an optimal temperature and humidity as specified by the Biosystems counterpart team as well as in Table II. Team 11 recommends the installation of a thermo-hygrometer which is a single unit able to measure both temperature and relative humidity. Fig. 64 shows an example of a thermo-hygrometer that Team 11 suggests. This product comes with three remote sensors and is able to measure temperatures from -40°C to 60°C and relative humidities between 10% and 90% [54]. It is suggested to position one sensor at the top, middle, and bottom of the enclosure to detect potential temperature and humidity variances. The unit allows a user to set minimum and maximum temperature and humidity values and is capable of providing both visual and audible alarms if these values are surpassed.

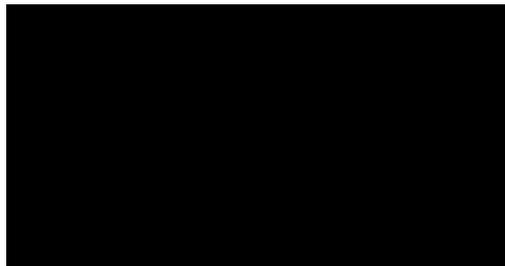


Figure 64: Recommended thermo-hygrometer [54]

6.3 Future Work

In addition to the recommendations made in Section 6.2, Team 11 suggests the following items as future work for Vidir to take on and integrate into the presented final design:

- **Solar Panel Mounting:** Team 11 suggests that Vidir analyzes the structural details of the roof the solar panels will be mounted on to ensure stability prior to integration. Additionally, it is suggested that mounting and inverter integration details be discussed with a specialist if further details beyond Vidir's capacity are required.
- **Biosystems Integration:** Team 11 suggests that Vidir closely reviews and skillfully integrates the work of the Mechanical and Biosystem's teams. It is suggested to combine the two CAD models into one as soon as possible to check for any conflicts/rebuild errors prior to prototyping.
- **Sensor and Alarm Integration:** Team 11 suggests that Vidir integrates all electrical systems, including the thermo-hygrometer sensor and alarm into the carousel's existing control board prior to operation. The sensors and alarms should also be tested prior to operation.

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Appendices

Appendix A Structural Concept Screening & Selection

This appendix explores the concept generation and selection process for the structural and construction aspects of the vertical farming project. The process begins with identifying all possible options that may satisfy the client needs. Each option is filtered qualitatively before being filtered quantitatively. For example, some options may be discarded before utilizing a decision matrix if they having glaring qualitative issues. Section A.1 evaluates the stability of the carousel against Manitoban wind conditions, to help Team 11 decide whether the carousel frame alone may be used as an enclosure frame. Section A.2 develops concepts for other aspects of the enclosure construction, and the methods used to screen those concepts.

A.1 Carousel Stability

As Vidir's shelf carousel is designed for indoor use, the stability of the enclosure under severe wind loads was a significant concern early in the initial stages of the project. As such, the carousels stability was investigated before the concept development process began. While the maximum hourly average wind speed is only 40 kph [55] in Manitoba, maximum wind gusts of 125 kph [11] are not uncommon. A sustained wind speed of 125 kph has been used as a worst-case scenario to evaluate whether the carousel will remain stable. Additionally, the calculations assume an even wind distribution on the carousels broad side with no disruptions due to the surrounding buildings. Equations A.1 through A.6 are used to analyze the stability of the enclosure under the given wind conditions.

$$P = 0.613 \cdot V_{wind}^2 \quad (A.1)$$

$$F_{wind} = AC_d P \quad (A.2)$$

$$M_{wind} = \frac{H}{2} F_{wind} \quad (A.3)$$

$$F_{mass} = 9.81 (W_{carousel} + W_{concrete}) \quad (A.4)$$

$$M_{mass} = F_{mass} \cdot LCGx \quad (A.5)$$

$$M_{differential} = M_{mass} - M_{wind} \quad (A.6)$$

While the weight of the bare carousel creates a minor positive, or stable moment, seen in Table A.1, under the worst case wind load the mass of the enclosure, and the carousels contents will add greatly to the structures stability. As Team 11 moves into the more detailed stages of the design the carousels stability will be assessed again to ensure the final design is stable. While out of scope for the project, an approximate mass of each grow shelf will be obtained from the Biosystems group.

TABLE A.1: CAROUSEL STABILITY CALCULATION

Parameter	Value	Symbol	Units
Mass of Empty Carousel	2550	$W_{carousel}$	kg
Mass of Concrete Pad	3426	$W_{concrete}$	kg
CG z	3.178	L_{CGz}	m
CG Pad x	1.524	L_{CGx}	m
CG Pad y	1.524	L_{CGy}	m
Width of Enclosure	3.048	L_{width}	m
Height	6.096	H	m
Area	18.58	A	m ²
Drag Coefficient	2.1	C_D	
Wind Speed	34.7	V_{wind}	m/s
Pressure	739.1	P	kPa
Force	28837.3	F_{wind}	N
Wind Moment	87896.1	M_{wind}	Nm
Weight Force	25015.5	F_{weight}	Nm
Weight Moment	38123.6	M_{mass}	Nm
Weight Force	58624.6	F_{mass}	Nm
Weight Moment	89343.8	M_{mass}	Nm
Moment Differential	1447.7	$M_{differential}$	Nm

A.2 Structural Concept Development

Structural concept development covers the available options for constructing the frame of the enclosure and insulating the enclosure. As the options for both the structure and insulation are interdependent, the compatible options are combined and evaluated together for the concept selection process.

A.2.1 Construction Concepts

Various methods of construction are available for the enclosure. Traditional wood frame, steel frame, structurally insulated panels (SIPs), and custom modular panels will be considered as viable options. The options will be evaluated on cost, ease of installation, and industry convention. The optimum construction method will also depend on the insulation method which will be evaluated together in concept selection.

1. **Traditional Wood Frame** - Traditional wood frame construction offers the most industry standard approach, with many contractors available to construct an enclosure around the carousel. This type of construction uses wood or composite studs (vertical) and joists (horizontal) to create a structure which can be insulated and sheet-ed with a variety of materials for weather and humidity resistance. Construction quality may create issues with air infiltration and mold and fungus growth as Vidir begins selling the design for new areas.
2. **SIPs** - SIPs are a pre-fabricated, assemble on site solution for buildings and structures, custom made to order. They are typically made of an expanded foam core surrounded by OSB or steel sheeting and are available in a wide variety of configurations for many applications. OSB panels are generally used in residential, and smaller building construction, while steel panels are typically used for large industrial buildings and industrial refrigeration. SIPs unfortunately have a high cost and a long lead-time due to their custom construction, unlike other options presented.
3. **Steel Framing** - Steel frame construction offers a solution aligned with Vidir’s current manufacturing processes and allows for ready to assemble construction, similar to SIPs. The steel frame would consist of vertical members similar to traditional wood framing, but typically with much wider spacing. The frame is then covered with insulated panels to finish the enclosure. This concept would require the design of the frame and paneling.
4. **Custom Modular Panels** - Custom modular panels are a variation on the steel frame design but rely on the carousel frame as the main structure supporting the enclosure. The design would examine the exterior panels and a mounting mechanism to the existing carousel frame. The panel design may require modifications to the carousel frame itself, such as increased leg thickness to handle the increased load. The cost of custom panels has been estimated at a value between steel framing and traditional framing due to the reduced amount of material required to support the structure. The positive moment differential found in Section A.1 shows that the weight of the carousel mounted firmly to the concrete pad is sufficiently stable, even in the most extreme Manitoban conditions.

TABLE A.2: COST OF CONSTRUCTION CONCEPTS

Concept	Cost per Sq. ft.	Ease of Construction	Industry Convention
Traditional Wood Frame	████ [56]	1	3
SIP	████ [57]	3	2
Steel Frame	████ [56]	2	2
Custom Modular Panels	████	3	1

Undesirable  Desirable

A.2.2 Insulation Concepts

Several types of insulation are readily available and are considered for the carousel enclosure. The insulation's R value per inch, approximate cost, and resistance to mold and fungus growth will be considered. As the optimum insulation used is dependent on the type of construction, they will be evaluated together in concept selection.

1. **Fiberglass and Rockwool** - Fiberglass is the most common insulation type due to its low cost, weight, and ease of installation in standard stud and joist based construction. Unfortunately, fiberglass has downsides such as porosity, which allows airflow, and can trap allergens, dust, and moisture, leading to mold and fungal growth. Rockwool is a similar product whose primary advantage is acoustical dampening, though it costs a bit more than fiberglass. Both of these products require the use of a vapor barrier to prevent air infiltration along with mold and fungal growth.
2. **Foam Sheets** - Foam sheet insulation is the lowest cost foam option. When installed as full sheets it provides a high R value, prevents air infiltration, and resists mold and fungal growth. Ease of installation decreases significantly as smaller portions of the sheet need to be installed.
3. **Spray Foam** - Closed cell spray foam has an exceptional R value per inch, provides a seal to prevent air infiltration, and resists mold and fungal growth. Due to the versatility of spray foams, ease of installation, and resistance to air infiltration, spray foam is quickly becoming one of the more popular insulation materials.
4. **SIP** - Finally, SIPs provide high R values and structural rigidity in a ready to assemble form. While the insulation typically used in SIPs is resistant to mold and fungus growth, the OSB often used as paneling is susceptible under high humidity conditions like those found in the carousel. Higher end SIPs can be ordered with weather resistant metal paneling, they are typically better suited to industrial buildings and large construction projects. As discussed in the structural concept section, cost and lead-times can be a significant downside to SIPs.

TABLE A.3: INSULATION TYPES AND PROPERTIES

Insulation Type	<i>R/inch</i>	<i>Thickness [in]</i>	<i>Required vol [m³]</i>	<i>Cost</i>	<i>Requires Extra VB</i>	<i>Plus Install</i>
Rockwool [58]	4.00	5.50	283.39		Yes	Yes
Fiberglass [59]	3.64	5.50	283.39		Yes	Yes
Foam Sheet [60]	5.00	4.00	206.10		Yes	Yes
Spray Foam (Kit) [61]	6.20	3.23	166.21		No	Yes
SIP [62]	3.08	6.49	334.59		No	No
Spray Foam (Pro) [63]	6.00	3.33	171.75		No	No

A.2.3 Construction and Insulation Selection

There are several combinations of insulation and construction concepts compatible with one another that are up for consideration. These combinations are summarized in Table A.4. Each of the thirteen concepts are then ranked from 1 (low) to 5 (high) for how well they meet the constraints seen in Table A.5, based on Tables A.3 and A.2.

TABLE A.4: INSULATION AND STRUCTURAL COMPATIBILITY

	<i>Traditional</i>	<i>SIP</i>	<i>Steel Frame</i>	<i>Modular Panels</i>
Rockwool				
Fiberglass				
Foamular				
Spray Foam				
SIP				
Spray Foam Pro				

TABLE A.5: STRUCTURAL CONCEPTS SCORING

Concept	<i>Manufacturability</i>	<i>Convention</i>	<i>Cost</i>	<i>Humidity Resistance</i>	<i>Ease of Installation</i>
Rockwool / Traditional	4	1	1	5	5
Rockwool / Modular Panels	4	5	3	5	2
Fiberglass / Traditional	3	1	1	5	5
Fiberglass / Modular Panels	3	5	3	5	2
SIP / SIP	1	3	5	4	1
Foam Sheet / Steel Frame	2	3	3	3	3
Foam Sheet / Modular Panels	2	5	3	4	2
Spray Foam Kit / Traditional	4	1	2	2	5
Spray Foam Kit / Steel Frame	4	5	4	1	3
Spray Foam Kit / Modular Panels	3	5	4	2	1
Spray Foam Pro / Traditional	2	1	3	2	5
Spray Foam Pro / Steel Frame	2	3	3	1	3
Spray Foam Pro / Modular Panels	3	5	3	1	1
Total	11	7	5	15	12

Poor ranking  Good ranking

The metrics are then evaluated based on their importance relative to the other metrics. It is desirable for the structure to fit into Vidor’s existing manufacturing capabilities, therefore, manufacturability will be considered. It’s also desirable for the structure to use concepts and features common in the construction industry already. The structure should be cost effective, not only for Vidor, but also to keep the purchase price of the end product reasonable for the end consumer. Humidity resistance is also incredibly important as the interior of the structure will be maintained as a high humidity environment, year round, which is required for optimal plant growth. Finally, it is preferred that the structure be quick and easy to install around the carousel year round.

Once the concepts are scored, it is necessary to evaluate how heavily each metric should be weighted when moving onto the concept decision matrix. This is done by comparing metrics one on one, totaling the number of times a metric is ranked more important, and normalizing to determine the metrics weight. This process can be seen in the symmetric matrix of Table A.6.

TABLE A.6: METRIC WEIGHTING MATRIX

	<i>A. Manufacturability</i>	<i>B. Convention</i>	<i>C. Cost</i>	<i>D. Humidity Resistance</i>	<i>E. Ease of Installation</i>
A. Manufacturability		A	C	D	E
B. Convention			C	D	B
C. Cost				D	C
D. Humidity Resistance					D
E. Ease of Installation					
Number of Hits	1	1	3	4	1
Weight (%)	0.1	0.1	0.3	0.4	0.1

The structures resistance to the humidity and the cost of the structure are identified as the most important metrics identified for this project. The humidity resistance is ranked more important than the all other metrics, as a structure susceptible to rust, rot, mold, or fungus is not acceptable, and would affect longevity and health. Cost, being the second most important metric, is ranked higher than all metrics except humidity resistance. The remaining metrics, manufacturability, convention, and ease of installation are weighted much lower, each only scoring well once each. With the concepts scored and the metric weighting determined the decision matrix could be formed in Table A.7.

TABLE A.7: INSULATION AND STRUCTURAL WEIGHTED DECISION MATRIX

Concept	<i>Manufacturability</i>	<i>Convention</i>	<i>Cost</i>	<i>Humidity Resistance</i>	<i>Ease of Installation</i>	<i>Total</i>
Rockwool / Traditional	2.8	7.0	5.0	3.0	2.4	3.9
Rockwool / Modular Panels	2.8	1.4	1.7	3.0	6.0	2.7
Fiberglass / Traditional	3.7	7.0	5.0	3.0	2.4	4.0
Fiberglass / Modular Panels	3.7	1.4	1.7	3.0	6.0	2.8
SIP SIP	11.0	2.3	1.0	3.8	12.0	4.3
Foamular / Steel Frame	5.5	2.3	1.7	5.0	4.0	3.7
Foamular / Modular Panels	5.5	1.4	1.7	3.8	6.0	3.3
Spray Foam Kit / Traditional	2.8	7.0	2.5	7.5	2.4	5.0
Spray Foam Kit / Steel Frame	2.8	1.4	1.3	15.0	4.0	7.2
Spray Foam Kit / Modular Panels	3.7	1.4	1.3	7.5	12.0	5.1
Spray Foam Pro / Traditional	5.5	7.0	1.7	7.5	2.4	5.0
Spray Foam Pro / Steel Frame	5.5	2.3	1.7	15.0	4.0	7.7
Spray Foam Pro / Modular Panels	3.7	1.4	1.7	15.0	12.0	8.2
Concept Weight	0.1	0.1	0.3	0.4	0.1	1.0

Poor ranking  Good ranking

The highest ranked concept from the concept selection is the modular panel system supported by the existing structure of the carousel, insulated by professionally installed spray foam. This design is selected for its exceptional resistance to humidity, ease of installation on site, and manufacturability for Vidir. The design is slightly unconventional, but with the existing structure of the carousel it would be a loss to not take advantage. Team 11 has estimated the design to have a moderate cost which is made up for by the other advantages of the design.

Appendix B HVAC Concept Development Screening & Selection

This appendix explores the concept generation and selection process for the HVAC subsystem of the vertical farming project. The process begins with identifying all possible options that may satisfy the client needs. In section B.1, each option is filtered qualitatively before being filtered quantitatively. Decision matrices and comparative discussion are included herein. In Section ??, a final selection is made for required components.

B.1 HVAC Concept Screening

To narrow down the number of concepts considered into the final design choice, the concepts in the above section required screening. This screening took into account the most important selection criteria as outlined by Vidir as well as mandatory conditions for indoor plant growth. This selection criteria includes the off-grid compatibility, system compactness, size and space taken up inside the structure, suitability for Manitoba’s weather, and ability to control humidity levels. Table B.1 below shows the scoring for each concept against the selection criteria. Each concept is considered against a furnace, which is used as the reference concept. The reference concept scoring is indicated by '0' as this concept is considered neutral, while the subsequent concept scoring is indicated by a '+', '-', or '0' which describes the selection criteria for its respective concept as being better, worse, or the same as the reference concept, respectively.

TABLE B.1: HVAC SYSTEM CONCEPT SCREENING

Selection Criteria	Concepts										
	Furnace (reference)	Electric Baseboard Heater	Hydronic Radiant Heat	Window Air Conditioner	Evaporative Cooler	HAF/VAF	Single Zone	Variable Volume	Dual Duct	Rooftop Unit	Split System
Off-Grid Capability	0	-	+	0	0	0	+	0	-	-	+
Compact System	0	-	-	-	-	-	+	+	+	+	+
Size and Space	0	+	+	+	0	+	+	0	0	-	+
Suitability for Manitoba	0	0	0	0	-	0	0	-	0	0	0
Humidity Control	0	0	0	0	+	+	-	-	0	0	0
Pluses	0	1	2	1	1	2	3	1	1	1	3
Sames	0	2	2	3	2	2	1	2	3	2	2
Minuses	0	2	1	1	2	1	1	2	1	2	0
Net	0	-1	1	0	-1	1	2	-1	0	-1	3
Rank	5	8	3	5	8	3	2	8	5	8	1
Continue?	No	No	Yes	No	No	Yes	Yes	No	No	No	Yes

Based on the results from Table B.1, the concepts of highest rank are those that will move forward to be screened using further decision criteria. These concepts include the single-zone system, split system, as well as the hydronic radiant heater and HAF/VAF as a combined system so that both heating and cooling can be achieved.

B.2 HVAC Concept Selection

Team 11 decided on six criterion that the concepts would be compared against. These criterion are based on what Team 11 deemed most important for a functional system to include.

- **Size:** The physical size of the HVAC system should be compact, this will help keep the overall system within the given footprint.
- **Cost:** Includes both upfront and maintenance costs. The cost of the system should be minimized.
- **Energy Efficiency:** The system should be energy efficient to meet the needs of sustainability.
- **Capacity:** The system should have the energy capacity to keep the space at a temperature and humidity adequate for plant growth.
- **Noise and Vibration:** Quieter systems cause less annoyance, and typically will have less wear.
- **Expansion Potential:** The system should be expandable and adaptable for future variations of the design.

Table B.2 includes all of these criterion and shows the calculation process for the relative weight of each criterion. Energy efficiency and capacity have the highest weights due to the importance of sustainability and functionality of the system. Expansion potential and size are of medium importance as Team 11 wants to stay within the given concrete pad and ideally Vidir would like a system that can be adjusted for different environments. Cost and vibration are of least importance. Vidir has not specified a cost limit for the project as it is somewhat exploratory. The space is not meant to be occupied for a long time and so noise is not a high priority.

TABLE B.2: CRITERIA WEIGHTS FOR HVAC CONCEPT SELECTION

	<i>A. Size</i>	<i>B. Cost</i>	<i>C. Energy Efficiency</i>	<i>D. Capacity</i>	<i>E. Noise and Vibration</i>	<i>F. Expansion Potential</i>
A. Size		A	C	D	A	F
B. Cost			C	D	B	F
C. Energy Efficiency				D	C	C
D. Capacity					D	D
E. Noise and Vibration						E
F. Expansion Potential						
Number of Hits	2	1	4	5	1	2
Weight (%)	13%	7%	27%	33%	7%	13%

The three best scoring concepts from Table B.1 are compared against each of the criteria. The results of this process can be found in Table B.3.

TABLE B.3: HVAC CONCEPT RANK

Concept	Size	Cost	Energy Efficiency	Capacity	Noise and Vibration	Expansion Potential
Single Zone	5	1	5	3	5	3
Split System	3	3	3	1	3	1
Radiant Heating + HAF/VAF	3	5	1	5	3	5
Total	11	9	9	9	11	9

Poor ranking  Good ranking

Once each concept had been ranked for each criterion they are scored. The equation used to find each score is as follows:

$$\frac{\sum \text{rank}}{\text{rank}_{\text{concept}}} \quad (\text{B.1})$$

The resulting score is then multiplied by the criteria weight, the weighted scores for each

concept are then summed and the results can be found in Table B.4.

TABLE B.4: HVAC CONCEPT FINAL SCORE

Concept	Size	Cost	Energy Efficiency	Capacity	Noise and Vibration	Expansion Potential	Total
Single Zone	2.2	9.0	1.8	3.0	2.2	3.0	2.9
Split System	3.7	3.0	3.0	9.0	3.7	9.0	5.9
Radiant Heating + HAF/VAF	3.7	1.8	9.0	1.8	3.7	1.8	4.1
Weight	13%	7%	27%	33%	7%	13%	100%

Appendix C Renewable Energy Calculations and Suppliers

This appendix contains details on the calculations and decision made to determine the renewable energy feasibility for this project. Section C.1 provides the calculations used to determine the total radiation absorbed on fixed-tilt and sun-tracking surfaces. Section C.3 contains details on various solar panel suppliers, the total energy generated from the solar panels, and the suggested location to mount the panels. Finally, Section C.4 outlines the calculations used to determine the total energy demand of the system.

C.1 Solar Energy Absorbed

The amount of energy produced by the solar panels is determined according to the sun's position relative to the earth and solar panel at every hour throughout the year. This section outlines the data, angles and solar radiation calculations to find the energy produced. The process in determining the solar energy attainable from the panels is based on the details found in [23] and [38].

Annual Data

Historical annual weather data is required to determine what delivered energy from the solar panels is to be expected. Data from 2014 is used, as this is the most recent data available that consisted of the greatest extreme weather conditions experienced in both summer and winter in Winnipeg [64]. This data is provided in Appendix C.2.

Sun to Solar Panel Angles

To begin calculating the amount of annual energy that can be absorbed by the sun through the solar panels, the angles of the sun relative to the solar panels need to be considered at each hour throughout the year. The amount of absorbed energy first depends on the use of a fixed-tilt surface or sun-tracking surface, where a fixed-tilt surface remains in place while a sun-tracking surface follows the sun throughout the day. Differences in values for these concepts are identified within this section.

Preliminary values including the atmospheric optical depth, k , and sky diffuse factor, C , need to first be defined for each month. The atmospheric optical depth describes typical precipitation levels and dust concentrations, and sky diffuse factor is a constant that describes the effect of dust and aerosols in the air.

TABLE C.1: SOLAR ATMOSPHERIC OPTICAL DEPTH AND SKY DIFFUSE FACTOR FOR EACH MONTH [38]

Month	k	C
1	0.142	0.058
2	0.144	0.06
3	0.156	0.071
4	0.18	0.097
5	0.196	0.121
6	0.205	0.134
7	0.207	0.136
8	0.201	0.122
9	0.177	0.092
10	0.16	0.073
11	0.149	0.063
12	0.142	0.057

There are two angles to consider for the sun's position relative to earth: hour angle and solar declination. The hour angle describes the sun's position in the sky throughout the day and is calculated using Equation C.1 where t is the solar time in hours using the 24 hour clock and α is in degrees.

$$\alpha = \frac{360}{24}(t - 12) \quad (C.1)$$

The solar declination angle tracks the season as well as the latitude of the sun when observed from earth. The solar declination angle is calculate using Equation C.2 where d is day of the year from 1 to 365 and δ is in degrees.

$$\delta = 23.44 \sin \left[360 \left(\frac{d - 80}{365.25} \right) \right] \quad (C.2)$$

The hour angle, declination angle, panel tilt and latitude of location are used to determine the amount of sun exposure the solar panels will experience. The panel tilt, ϵ is the angle off flat ground that the solar panels will be placed and is generally between 0-65°[38]. An angle of 20°is used for a fixed-tilt surface as this is the approximate slope of the roof at Vidir and positioning the panels to be flush with the roof removes added stresses from wind. For a sun-tracking surface, a value of 0°is used as it will be constantly changing with the position of the sun.

The latitude of Arborg, MB is shown in Equation C.3 [65]. When considering the energy that can be created in northern regions, it is important to apply the appropriate value of latitude into the calculations.

$$\lambda = 51^\circ \quad (C.3)$$

The angle of the sun relative to the vertical plane of the solar panel is given in degrees by the zenith angle, χ , and is dependent on the hour angle, declination angle, and latitude. The zenith angle is calculated for the fixed-tilt surface using Equation C.4, while the value of the angle is 0° for a sun-tracking surface.

$$\chi = \arccos[\sin \delta \sin \lambda + \cos \delta \cos \lambda \cos \alpha] \quad (\text{C.4})$$

The azimuth angle can be described by a solar azimuth, ξ , and the azimuth of the solar plate, ζ . The solar azimuth calculates the angle from the North direction to where the sun is vertically along the horizontal plane. The azimuth of the plate calculates the the angle from the north direction to where the tilted solar plate faces along the horizontal plane. The calculations used only require the solar azimuth which can be calculated using Equations C.5 and C.6, where ξ is in degrees.

$$\tan \xi = \frac{\sin \alpha}{\sin \lambda \cos \alpha - \cos \lambda \tan \delta} \quad (\text{C.5})$$

$$\xi = \arctan \left[\frac{\sin \alpha}{\sin \lambda \cos \alpha - \cos \lambda \tan \delta} \right] \quad (\text{C.6})$$

The solar azimuth angle equation does not account for the quadrant the final angle is within, so the value can be corrected based on the sign of the hour angle and value of $\tan \xi$ as shown in Table C.2.

TABLE C.2: VALUE OF CORRECTED AZIMUTH ANGLE [38]

Sign of α	Sign of $\tan \xi$	ξ
+	+	$180^\circ + \arctan(\tan \xi)$
+	-	$360^\circ + \arctan(\tan \xi)$
-	+	$\arctan(\tan \xi)$
-	-	$180^\circ + \arctan(\tan \xi)$

These angles are used in the following section to determine the total solar radiation the solar panels absorb. Fig. C.1 visually describes these angles relative to the vertical and horizontal planes.

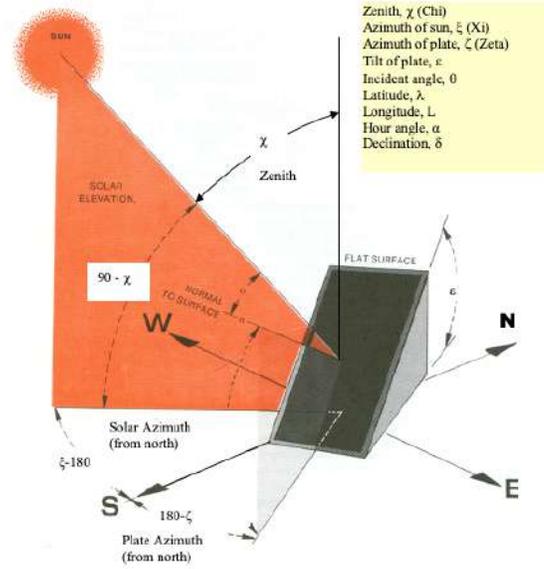


Figure C.1: Sun angles relative to solar panel [38]

Solar Radiation

The solar radiation absorbed is based on the isolation that results from the rays that are incident on the solar plate, are scattered from dust and molecules in the air, and are reflected in the air molecules as shown in Fig. C.2 following the calculations. This radiation onto the plate determines the annual energy that is generated using the angles in the previous section. These equations are used for determining the radiation for both fixed-tilt and sun-tracking surfaces.

Beam radiation normal to the sun, $I_{b,N}$, is the radiation from the sun which is not redirected and is normal to the sun's rays. This value considers the radiation onto a flat surface, so is used as a constant in finding the total radiation onto an angled surface. Beam radiation is determined as shown in Equation C.7 using the zenith angle, optical depth, and the extraterrestrial radiation, I_{ext} , which is the radiation of the sun before it reaches the atmosphere and clouds. The value for extraterrestrial radiation is a function of time of year and is obtained from the historical data in Appendix C.2.

$$I_{b,n} = I_{ext} \exp \frac{-k}{\cos \chi} \quad (C.7)$$

To account for the angled solar plate, the incident angle, θ , is used which is calculated according to the angle of the plate, zenith angle, and azimuth angle as shown in Equation C.8. The beam radiation on the tilted plate is determined by Equation C.9.

$$\cos \theta = \cos \epsilon \cos \chi + \sin \epsilon \sin \chi \cos \xi \quad (C.8)$$

$$I_{b,tilt} = I_{b,n} \cos \theta \quad (C.9)$$

Diffuse radiation, I_d , is the solar radiation scattered by aerosols, dust and molecules. It does not have a unique direction and contributes to the total energy hitting the solar panel. The diffuse radiation is found using Equation C.10 and is a function of the sky diffuse factor, beam radiation on a flat surface, and the tilt angle of the plate.

$$I_{d,tilt} = CI_{b,n} \cos^2 \left(\frac{\epsilon}{2} \right) \quad (C.10)$$

The reflective radiation, I_r , is the solar radiation that is reflected off of the ground and clouds onto the panel. The solar radiation reflected onto the panel is based on the tilt angle of the panel, zenith angle, sky diffuse factor, and the reflective index. Equation C.11 is used to compute the reflective radiation.

$$I_{r,tilt} = \rho I_{b,n} [\cos \chi + C] \sin^2 \left(\frac{\epsilon}{2} \right) \quad (C.11)$$

The total radiation that is absorbed by the solar panels is the sum of the beam, diffuse and reflective radiation as shown in Equation C.12.

$$I_{total} = I_{b,tilt} + I_{d,tilt} + I_{r,tilt} \quad (C.12)$$

The details of these solar radiations are visually demonstrated in Fig. C.2. The total radiation is converted into energy generated in Section C.3 below using the details and specifications of various solar panels.

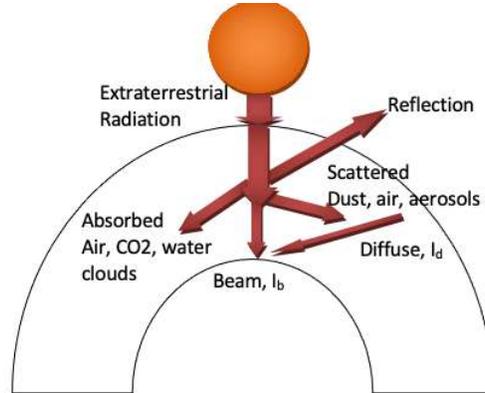


Figure C.2: Forms of solar radiation [38]

C.2 Renewable Feasibility Data

This section contains the data used to determine the total radiation absorbed by a solar panel throughout the year as well as the results from the calculations included in Section C.1. Table C.3 and Table C.4 contains the data and calculation results using the summer equinox, respectively. Table C.5 and Table C.6 contains the data and calculation results using the winter equinox, respectively.

TABLE C.3: 2014 DATA FOR SUMMER EQUINOX [38]

Month	Day	Hour	I_{ext}	Direct Normal	T_{db} (°C)	n	k	C
6	21	1	0	0	15.5	172	0.205	0.134
6	21	2	0	0	14.5	172	0.205	0.134
6	21	3	0	0	14.7	172	0.205	0.134
6	21	4	0	0	14.5	172	0.205	0.134
6	21	5	103	0	14.9	172	0.205	0.134
6	21	6	719	0	16.5	172	0.205	0.134
6	21	7	1444	369	17.8	172	0.205	0.134
6	21	8	2169	1858	20.5	172	0.205	0.134
6	21	9	2845	2830	21.7	172	0.205	0.134
6	21	10	3426	3023	22.9	172	0.205	0.134
6	21	11	3872	3145	24.4	172	0.205	0.134
6	21	12	4153	3185	25.8	172	0.205	0.134
6	21	13	4249	3038	26.2	172	0.205	0.134
6	21	14	4154	1844	26.6	172	0.205	0.134
6	21	15	3875	524	28.2	172	0.205	0.134
6	21	16	3430	2385	28.1	172	0.205	0.134
6	21	17	2851	2224	28.4	172	0.205	0.134
6	21	18	2176	369	26.6	172	0.205	0.134
6	21	19	1451	0	20.1	172	0.205	0.134
6	21	20	726	424	18.3	172	0.205	0.134
6	21	21	106	0	17.5	172	0.205	0.134
6	21	22	0	0	17.1	172	0.205	0.134
6	21	23	0	0	16.4	172	0.205	0.134
6	21	24	0	0	16	172	0.205	0.134

TABLE C.4: SOLAR CALCULATIONS FOR SUMMER EQUINOX

<i>Hour</i>	<i>Lambda (deg)</i>	<i>Hour Angle (deg)</i>	<i>Declination (deg)</i>	<i>Panel Tilt (deg)</i>	<i>Zenith (deg)</i>	<i>Sun Azimuth (deg)</i>	<i>Azimuth Corrected</i>	$I_{b,n}$	$\cos(\theta)$	$I_{b,tilt}$	$I_{d,tilt}$	$I_{r,tilt}$	$I_{total} (W/m^2)$
1	51.0	-165.0	23.4	20.0	104.4	14.2	194.2	0.0	0.5	0.0	0.0	0.0	0.0
2	51.0	-150.0	23.4	20.0	101.0	27.9	207.9	0.0	0.5	0.0	0.0	0.0	0.0
3	51.0	-135.0	23.4	20.0	95.7	40.7	220.7	0.0	0.5	0.0	0.0	0.0	0.0
4	51.0	-120.0	23.4	20.0	88.8	52.6	232.6	0.0	0.4	0.0	0.0	0.0	0.0
5	51.0	-105.0	23.4	20.0	80.8	63.9	243.9	100.7	0.4	42.3	11.5	5.4	59.2
6	51.0	-90.0	23.4	20.0	72.0	74.7	254.7	710.7	0.4	281.2	81.3	57.2	419.6
7	51.0	-75.0	23.4	20.0	62.7	85.8	265.8	1432.8	0.4	531.2	163.9	154.2	849.3
8	51.0	-60.0	23.4	20.0	53.3	-82.4	97.6	2156.1	0.5	1073.3	246.6	286.5	1606.4
9	51.0	-45.0	23.4	20.0	44.2	-68.6	111.4	2830.8	0.7	1944.2	323.8	437.7	2705.6
10	51.0	-30.0	23.4	20.0	36.0	-51.3	128.7	3410.9	0.8	2837.2	390.1	584.2	3811.5
11	51.0	-15.0	23.4	20.0	29.9	-28.4	151.6	3856.1	0.9	3558.9	441.0	700.8	4700.8
12	51.0	0.0	23.4	20.0	27.6	0.0	180.0	4136.3	1.0	3946.2	473.1	766.5	5185.8
13	51.0	15.0	23.4	20.0	29.9	28.4	208.4	4231.5	0.9	3905.5	484.0	769.1	5158.5
14	51.0	30.0	23.4	20.0	36.0	51.3	231.3	4135.7	0.8	3440.0	473.0	708.3	4621.4
15	51.0	45.0	23.4	20.0	44.2	68.6	248.6	3855.7	0.7	2648.1	441.0	596.1	3685.2
16	51.0	60.0	23.4	20.0	53.3	82.4	262.4	3409.5	0.5	1697.3	390.0	453.1	2540.4
17	51.0	75.0	23.4	20.0	62.7	-85.8	94.2	2828.8	0.4	1048.8	323.6	304.4	1676.8
18	51.0	90.0	23.4	20.0	72.0	-74.7	105.3	2151.0	0.4	850.9	246.0	173.1	1270.0
19	51.0	105.0	23.4	20.0	80.8	-63.9	116.1	1418.8	0.4	596.5	162.3	75.7	834.4
20	51.0	120.0	23.4	20.0	88.8	-52.6	127.4	609.3	0.4	270.3	69.7	17.1	357.0
21	51.0	135.0	23.4	20.0	95.7	-40.7	139.3	109.9	0.5	50.9	12.6	0.7	64.2
22	51.0	150.0	23.4	20.0	101.0	-27.9	152.1	0.0	0.5	0.0	0.0	0.0	0.0
23	51.0	165.0	23.4	20.0	104.4	-14.2	165.8	0.0	0.5	0.0	0.0	0.0	0.0
24	51.0	180.0	23.4	20.0	105.6	0.0	180.0	0.0	0.5	0.0	0.0	0.0	0.0

TABLE C.5: 2014 DATA FOR WINTER EQUINOX [38]

Month	Day	Hour	I_{ext}	Direct Normal	T_{db} (°C)	n	k	C
12	21	1	0	0	-1.6	355	0.142	0.057
12	21	2	0	0	-1.5	355	0.142	0.057
12	21	3	0	0	-1.5	355	0.142	0.057
12	21	4	0	0	-1.3	355	0.142	0.057
12	21	5	0	0	-1.4	355	0.142	0.057
12	21	6	0	0	-1.6	355	0.142	0.057
12	21	7	0	0	-1.5	355	0.142	0.057
12	21	8	0	0	-1.5	355	0.142	0.057
12	21	9	79	0	-1.4	355	0.142	0.057
12	21	10	602	737	-1.2	355	0.142	0.057
12	21	11	1069	958	-1.5	355	0.142	0.057
12	21	12	1358	58	-1.4	355	0.142	0.057
12	21	13	1449	18	-1.8	355	0.142	0.057
12	21	14	1337	33	-1.7	355	0.142	0.057
12	21	15	1027	1132	-1.4	355	0.142	0.057
12	21	16	543	1021	-1.1	355	0.142	0.057
12	21	17	48	0	-1.2	355	0.142	0.057
12	21	18	0	0	-1.3	355	0.142	0.057
12	21	19	0	0	-1.3	355	0.142	0.057
12	21	20	0	0	-1.1	355	0.142	0.057
12	21	21	0	0	-1	355	0.142	0.057
12	21	22	0	0	-0.8	355	0.142	0.057
12	21	23	0	0	-0.7	355	0.142	0.057
12	21	24	0	0	-0.7	355	0.142	0.057

TABLE C.6: SOLAR CALCULATIONS FOR WINTER EQUINOX

<i>Hour</i>	<i>Lambda (deg)</i>	<i>Hour Angle (deg)</i>	<i>Declination (deg)</i>	<i>Panel Tilt (deg)</i>	<i>Zenith (deg)</i>	<i>Sun Azimuth (deg)</i>	<i>Azimuth Corrected</i>	$I_{b,n}$	$\cos(\theta)$	$I_{b,tilt}$	$I_{d,tilt}$	$I_{r,tilt}$	$I_{total} (W/m^2)$
1	51.0	-165.0	-23.4	20.0	150.1	28.4	208.4	0.0	-0.3	0.0	0.0	0.0	0.0
2	51.0	-150.0	-23.4	20.0	144.0	51.3	231.3	0.0	-0.3	0.0	0.0	0.0	0.0
3	51.0	-135.0	-23.4	20.0	135.8	68.6	248.6	0.0	-0.3	0.0	0.0	0.0	0.0
4	51.0	-120.0	-23.4	20.0	126.7	82.4	262.4	0.0	-0.3	0.0	0.0	0.0	0.0
5	51.0	-105.0	-23.4	20.0	117.3	-85.8	94.2	0.0	-0.3	0.0	0.0	0.0	0.0
6	51.0	-90.0	-23.4	20.0	108.0	-74.7	105.3	0.0	0.0	0.0	0.0	0.0	0.0
7	51.0	-75.0	-23.4	20.0	99.2	-63.9	116.1	0.0	0.2	0.0	0.0	0.0	0.0
8	51.0	-60.0	-23.4	20.0	91.2	-52.6	127.4	0.0	0.4	0.0	0.0	0.0	0.0
9	51.0	-45.0	-23.4	20.0	84.3	-40.7	139.3	77.1	0.6	46.5	3.7	2.2	52.4
10	51.0	-30.0	-23.4	20.0	79.0	-27.9	152.1	594.2	0.7	444.9	28.9	26.8	500.5
11	51.0	-15.0	-23.4	20.0	75.6	-14.2	165.8	1058.4	0.8	888.9	51.5	58.7	999.1
12	51.0	0.0	-23.4	20.0	74.4	0.0	180.0	1345.5	0.9	1171.8	65.5	79.5	1316.8
13	51.0	15.0	-23.4	20.0	75.6	14.2	194.2	1434.6	0.8	1204.8	69.8	79.6	1354.2
14	51.0	30.0	-23.4	20.0	79.0	27.9	207.9	1319.8	0.7	988.0	64.2	59.4	1111.7
15	51.0	45.0	-23.4	20.0	84.3	40.7	220.7	1001.7	0.6	604.6	48.7	28.4	681.8
16	51.0	60.0	-23.4	20.0	91.2	52.6	232.6	613.2	0.4	254.3	29.8	4.1	288.2
17	51.0	75.0	-23.4	20.0	99.2	63.9	243.9	48.8	0.2	9.5	2.4	-0.9	10.9
18	51.0	90.0	-23.4	20.0	108.0	74.7	254.7	0.0	0.0	0.0	0.0	0.0	0.0
19	51.0	105.0	-23.4	20.0	117.3	85.8	265.8	0.0	-0.3	0.0	0.0	0.0	0.0
20	51.0	120.0	-23.4	20.0	126.7	-82.4	97.6	0.0	-0.3	0.0	0.0	0.0	0.0
21	51.0	135.0	-23.4	20.0	135.8	-68.6	111.4	0.0	-0.3	0.0	0.0	0.0	0.0
22	51.0	150.0	-23.4	20.0	144.0	-51.3	128.7	0.0	-0.3	0.0	0.0	0.0	0.0
23	51.0	165.0	-23.4	20.0	150.1	-28.4	151.6	0.0	-0.3	0.0	0.0	0.0	0.0
24	51.0	180.0	-23.4	20.0	152.4	0.0	180.0	0.0	-0.3	0.0	0.0	0.0	0.0

C.3 Solar Panel Suppliers and Energy Generated

There are three solar panel suppliers that are suggested in this section for Vidir to pursue: Canadian Solar, Solacity Inc., and Silfab Solar. These suppliers are chosen as they are all located in Canada, offer a variety of solar panel brands, are competitive in the market, and offer highly rated solar solutions.

Using the values obtained for the total radiation, the total energy generated in a year from the solar panels can be determined based on the number, size, rated power and efficiency of the selected panels using Equation C.13. The details for each individual panel as well as the energy produced from the respective panels are given in the following sections for each of the suppliers chosen.

$$W = nAP\eta I_{total} \quad (\text{C.13})$$

Where n is the number of panels, A is the area of the panel [m^2], P is the rated power [W], η is the efficiency, and I_{total} is the total radiation [kWh]. I_{total} can be converted from W/m^2 to kWh using Equation C.14.

$$I_{total}[kWh] = \frac{AI_{total}[W/m^2]}{1000} \quad (\text{C.14})$$

It is important to note that when determining the energy for more than one panel, the annual energy generated may be multiplied by the number of panels that will be purchased. Additionally, the total energy generated from each panel only considers fixed-tilt surfaces as it was decided to pursue this system.

Canadian Solar

Canadian Solar is located in Guelph, Ontario and have a line of solar products designed and manufactured by their company [41]. Canadian Solar panels are one of the top rated brands in the market from having higher efficiency than many other brands, affordable panels with an improved return on investment, and are designed to have a higher reliability in winter conditions [66]. Additionally, the panels they produce have a higher output power, as well as a wider range of output power available, for a lower cost. Table C.7 contains the specifications for Canadian Solar's most common solar panels; HiKu7 and HiHero. The HiKu7 model is the latest edition, however older versions for this model are available on the Canadian Solar website to find specifications.

TABLE C.7: CANADIAN SOLAR SPECIFICATIONS OF IN-HOUSE SOLAR PANELS [41][42]

Parameter	Unit	CanadianSolar	CanadianSolar
		HiKu7	HiHero
Output Power	W	640	430
Length	m	2.38	1.73
Width	m	1.30	1.13
Efficiency		25.3%	22.0%
Temperature Range	°C	-40 to 85	-40 to 85
Cost		████████	████████

Using Equations C.13 and C.14, the total energy generated by the solar panels is computed according to these specifications and the values are summarized in Table C.8.

TABLE C.8: CANADIAN SOLAR IN-HOUSE SOLAR PANEL GENERATED ENERGY

Parameter	Unit	CanadianSolar	CanadianSolar
		HiKu7	HiHero
Area	m ²	3.09	1.95
Number of Panels		1	1
Rated Power	W	640	430
I_{total}	kWh	22,082	13,953
Efficiency		25.3%	22.0%
Annual Energy Generated	kWh	8,148	1,935

Solacity Inc.

Solacity Inc. is based in North Grenville, Ontario and offer high-wattage Hanwha and LG brand solar panels [67]. Hanwha Q-Cell solar panels are a leader in the solar energy technology and are known for their high temperature tolerance, efficiency, and low cost [68]. The Q-Cell panels provide high efficiency modules that enhance overall system performance. Table C.9 outlines the specifications of three of Solacity Inc.’s high performing Hanwha Q-Cell panels. The LG solar panels are limited in options so are not considered from Solacity Inc.

TABLE C.9: SOLACITY INC. SPECIFICATIONS OF HARWHA Q-CELL SOLAR PANELS [67]

Parameter	Unit	Q.Peak Duo	Q.Peak Duo	Q.Peak Duo
		G8 350	L-G8.3 425	BLK-G8+ 340
Output Power	W	350	425	340
Length	m	1.74	2.08	1.74
Width	m	1.03	1.03	1.03
Efficiency		18%	18%	18%
Temperature Range	°C	-40 to 85	-40 to 85	-40 to 85
Cost		████████	████████	████████

Using Equations C.13 and C.14, the total energy generated by the solar panels is computed and the values are summarized in Table C.10.

TABLE C.10: SOLACITY INC. HANWHA Q-CELL PANEL GENERATED ENERGY

Parameter	Unit	Q.Peak Duo G8 350	Q.Peak Duo L-G8.3 425	Q.Peak Duo BLK-G8+ 340
Area	m ²	1.79	2.14	1.79
Number of Panels		1	1	1
Rated Power	W	350	425	340
I_{total}	kWh	12,792	15,291	12,792
Efficiency		18%	18%	18%
Annual Energy Generated	kWh	1,083	1,880	1,052

Silfab Solar

Silfab Solar is located in Toronto, Canada and are distributors of their in-house designed and manufactured solar panels [69]. Silfab offers high efficiency levels with a higher cost compared to other suppliers. This higher cost is a result of the solar panels being manufactured in North America. Silfab has a base model solar panel that has output power ranging from 330 to 400 W. The 400 W panel is chosen to compare to two other models Silfab manufactures, however specifications for other output powers can be found at their website. In addition to this panel, the Elite and Prime models are also chosen for comparison as they have the highest rated efficiencies. Table C.11 contains the specifications for each of the panels.

TABLE C.11: SILFAB SOLAR PANEL SPECIFICATIONS [69]

Parameter	Unit	SIL-400 NU	Silfab Elite SIL-380 BK	Silfab Prime SIL-370 HC
Output Power	W	400 W	380 W	370 W
Length	m	2.026	1.795	1.762
Width	m	1.006	0.990	1.037
Efficiency		19.6%	21.4%	20.2%
Temperature Range	°C	-40 to 85	-40 to 85	-40 to 85
Cost		■	■	■

Using Equations C.13 and C.14, the total energy generated by the solar panels is computed and the values are summarized in Table C.12.

TABLE C.12: SILFAB SOLAR PANEL GENERATED ENERGY

Parameter	Unit	SIL-400 NU	Silfab Elite SIL-380 BK	Silfab Prime SIL-370 HC
Area	m ²	2.04	1.78	1.79
Number of Panels		1	1	1
Rated Power	W	400	380	370
I_{total}	kWh	14,547	12,683	13,041
Efficiency		19.6%	21.4%	20.2%
Annual Energy Generated	kWh	1,743	1,374	1,336

The location of the solar panels was decided to be on the roof of one of the buildings on Vidir’s property. The solar panels must be angled towards the South to absorb as much light during the day as possible, so the roof-top selected must be angled in the Southern direction. Fig. C.3 indicates the roof-top which is suggested as the mounting location according to the black rectangle.



Figure C.3: Solar panel location [70]

C.4 Energy Demand

In order to determine the amount of energy that is feasible for solar panels to account for, the annual energy demand of the system must be determined. The energy demand is based on the power required to run all components within the entire system of this project, including the power required for the Biosystems design. The units that contribute to the system’s energy demand include the lights, carousel, and all components HVAC system which is divided into summer and winter components.

As indicated by the Biosystems design team, a load of 43W per shelf is required to operate the lighting components. Equation C.15 is used to calculate the energy demand throughout the year for the 13 shelves on the carousel. It is assumed that the lights will be in operation for 12

hours per day throughout the entire year.

$$W = \frac{(43W/shelf)(13shelves)(12hours/day)(365days/year)}{1000} \quad (C.15)$$

The energy demand from the carousel is calculated according to the horsepower of the motor as provided by Vidir shown in Equation C.16. It is assumed the carousel is in operation each day of the year for 12 hours per day.

$$W = \frac{(2motors)(1.5hp/motor)(754.7W/hp)(12hours/day)(365days/year)}{1000} \quad (C.16)$$

To calculate the energy demand of each HVAC component, the number of days each unit is going to be in operation must be assumed. To account for worst-case scenario, it is assumed that the heating components will be in operation from the start of October to the end of May, while the cooling components will be in operation from the start of May to the end of October. This allows for expectation of temperature fluctuation each year. As a result, 243 days is used for winter units and 184 days is used for summer units.

Using the specifications as indicated by the HVAC units, the energy demand of the winter systems are calculated in Equations C.17 to C.19 while the energy demand for the summer system is calculated in Equation C.20.

$$W = \frac{(230V)(9A)(24hours/day)(243days/year)}{1000} \quad (C.17)$$

$$W = \frac{(100W)(24hours/day)(243days/year)}{1000} \quad (C.18)$$

$$W = \frac{(130W)(24hours/day)(243days/year)}{1000} \quad (C.19)$$

$$W = \frac{(230V)(8A)(24hours/day)(184days/year)}{1000} \quad (C.20)$$

Appendix D Bill of Materials

This section includes the bill of materials for all components required for Team 11's design. It should be noted that prices are excluded for any parts that Vidir is expected to have stock of. During Team 11's site visit to Vidir's factory, it was noted that Vidir has an existing steel supplier and existing stock. Since Vidir has this material sourced already, Team 11 did not provide an additional source.

TABLE D.1: BOM

Part	Quantity	Material	Finish	Process	AUX Process	Cost (CAD)	Source
0.0 Vertical Farming Enclosure	1						
1.0 Structural Subsystem	1						
1.1 Walls	1						
1.1.1 Horizontal Member Door Top	1	1.25x1.25x0.11 A500-C	Galvanized	Tube Laser			
1.1.2 Horizontal Member Door	4	1.25x1.25x0.11 A500-C	Galvanized	Tube Laser			
1.1.3 Horizontal Member	44	1.25x1.25x0.11 A500-C	Galvanized	Tube Laser			
1.1.4 Vertical Member 229	6	2x1x0.125 A500-C	Galvanized	Tube Laser			
1.1.5 Vertical Member 233.875	4	2x1x0.125 A500-C	Galvanized	Tube Laser			
1.1.6 Vertical Member 239	6	2x1x0.125 A500-C	Galvanized	Tube Laser			
1.1.7 Vertical Member Door	2	2x1x0.125 A500-C	Galvanized	Tube Laser			
1.1.8 Horizontal Member Angle	4	1.25x1.25x0.11 A500-C	Galvanized	Tube Laser			
1.1.9 Fan Vertical Member	4	2x1x0.125 A500-C	Galvanized	Tube Laser			
1.1.10 Horizontal Member Fan	6	1.25x1.25x0.11 A500-C	Galvanized	Tube Laser			
1.2 Floor	1						
1.2.1 Diamond Tread Plate	1	7.5'x17'	Diamond Tread	Cutting			
1.2.2 Main Frame Long Member (107.3")	4	1x1x0.125 A500-C	Galvanized	Tube Laser	Welding		
1.2.3 Main Frame Cross Member (84")	6	1x1x0.125 A500-C	Galvanized	Tube Laser	Welding		
1.2.4 Main Frame Vertical Member (1.5")	9	1x1x0.125 A500-C	Galvanized	Tube Laser	Welding		
1.2.5 Top Frame Long Member (86")	2	1x1x0.125 A500-C	Galvanized	Tube Laser	Welding		
1.2.6 Top Frame Joist (38")	6	1x1x0.125 A500-C	Galvanized	Tube Laser	Welding		
1.3 Roof	1						
1.3.1 Roof Beam	4	2x1x0.125 A500-C	Galvanized	Tube Laser			
1.3.2 Roof Cross Member	10	1.25x1.25x0.11 A500-C	Galvanized	Tube Laser			
1.3.3 Center Roof Support Weldment	1	ASM	Painted	Weldment	Paint		
1.3.3.1 Center Roof Support Beam	1	3x2x0.125 A500-C		Tube Laser	Welding		
1.3.3.2 Center Roof Support Extension	2	2x1.5x0.188 A500-C		Tube Laser	Welding		
1.4 Brackets	1						
1.4.1 Center Roof Support Bracket	1	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.2 Pad Mount	8	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.3 Pan Mount Adapter	8	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.4 Roof to Panel Bracket	4	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.5 Roof to Side Panel Bracket	4	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.6 Side Wall Bracket	4	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.7 Front Wall Bracket	4	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.8 Back Wall Bracket	4	0.125" 1020 Sheet	Galvanized	Flat Laser	Forming		
1.4.9 Back Bar	2	2x1.5x0.188	NA	Tube Laser	Welding		
1.5 Common Hardware and Products	1						
1.5.1 Tin 12" wide	915 feet	Tin	White				
1.5.2 1/4" Fiber Washer	170	Fiberglass	Light Green				
1.5.3 3/8" Fiber Washer	140	Fiberglass	Light Green				
1.5.4 1/4" Rivets	210	Stainless Steel					
1.5.5 3/8"-16 3" Grade 5 Flanged Bolt	35	Steel					
1.5.6 3/8"-16 2" Grade 5 Flanged Bolt	78	Steel					
1.5.7 3/8"-16 3.5" Grade 5 Flanged Bolt	2	Steel					
1.5.8 3/8"-16 Grade 5 Flanged Nut	115	Steel					
1.5.9 Handifoam E84 II-605 Kit	7	Spray Foam	Fire Rated	Spray			
2.0 HVAC Subsystem	1						
2.0.1 Grainger Cabinet Exhaust Fan	1						
2.0.2 Infinity High Wall Indoor Unit	1						
2.0.3 Carrier Performance Heatpump	1						
2.0.4 HRV 160 CFM 75 SRE	1						
2.0.5 Horticat U80 Pro Humidifier	1						
3.0 Renewable Energy Subsystem	1						
3.0.1 HiKu7 Solar Panel	5						
Totals	943					\$ 17,304.45	

Appendix E In-floor Heat Design

This appendix describes the design of an in-floor heat system for the enclosure. The design was not implemented because after designing it enough to determine key metrics (install cost, operating energy, and heat output), it was found to not be necessary as a supplement to the minisplit system selected by Team 11. It is included as a recommendation to Vidir, who has expressed interest in the possibility of using a heated enclosure for other purposes in the future. For example, for an enclosed storage carousel where humidity control is not necessary, hydronic in-floor heating would be an excellent choice for the following reasons:

- In-floor heat may be installed directly into the concrete pad, allowing the heating system to take up virtually no extra space
- Switching to in-floor heating for this enclosure would lead to 45% reduction in energy consumption for heating, as shown in Section E.2

E.1 Design and Components

In future applications, it is recommended that Vidir include the hydronic system directly in the construction of the concrete, as shown in Fig. E.1. This reduces the installation cost and complexity since DIY kits can be zip tied to rebar instead of requiring additional mounting hardware. Table E.1 summarizes the components needed for a hydronic system to be installed in a concrete pad.



Figure E.1: Hydronic system in concrete pad [72]

TABLE E.1: HYDRONIC SYSTEM COMPONENTS

Component	Quantity	Cost (CAD)
1/2" PEX tubing	170 ft	██████████
Thermolec 3 kW electric boiler	1	██████████
Grundfos UPS 15-58 FC pump	1	██████████
Total		\$1,313.32

The layout of the tubing is generate in LoopCAD, a design tool specifically intended for HVAC and hydronic system designs. This layout, shown in Fig. E.2 is based on industry conventions, including 1/2" tube diameter and 6" tube spacing [76]. Since the carousel enclosure is smaller than most hydronic applications (residential or commercial), commercially available components are generally oversized for this application. The smallest boiler and smallest pump are selected from Hydro Solar Innovative Energy, a Canadian supplier who specializes in DIY hydronic components. Both components are more than adequate for the heat and flow demands of the enclosure.

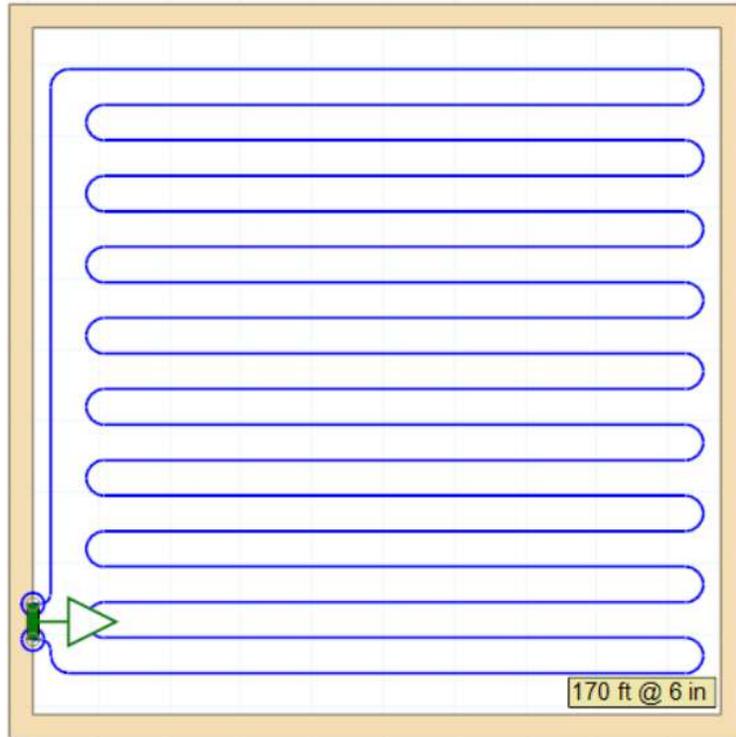


Figure E.2: Hydronic layout design for the 10'x10' concrete pad

E.2 Hydronic Analysis

The selected boiler is rated for 3kW, and able to output a maximum heat of 10,236 BTU_h. The selected pump is rated for 80W. Since the enclosure only requires 3035 BTU_h of heating, as determined in Section 4.2.4.2 the boiler would only need to run at 890W. In Section 4.4.2.3, it was

determined that heating the enclosure with the minisplit system annually requires 12,072 kWh in a worst case scenario. This includes the following assumptions:

- 243 days of the year require heating
- On those days, the heating unit runs for 24 hours

Under these same assumptions with the boiler operating at 890W and the pump operating at full power (worst case scenario), a hydronic heat system can output the same amount of heat for only 6613.16 kWh of input energy. This represents a 45% reduction in energy and therefore operating cost by switching from the minisplit system to in-floor heat.