

Project Deliverable J: **Final Design Report**
Engineering Design
GNG 1103

Construction of a Net-Zero Shed

Angelica Gendron	8844085	agend090@uottawa.ca
Adam Kanellakis	8734024	akane029@uottawa.ca
Meaghan O'Neill	8622118	monei023@uottawa.ca
Haotian (Mike) Mai	8670743	hmai048@uottawa.ca
Alexandra (Ally) Marchese	8659597	amarc108@uottawa.ca
Paul Miller	8703913	pmill018@uottawa.ca



Faculty of Engineering
University of Ottawa
April 11, 2017

Abstract

This project required us to design a zero carbon emissions shed that would be livable in all Canadian weather conditions. This means the shed needed to have access to heat, hot water, and electricity, all powered by energy the structure produced for itself via a solar panel. This shed would act as a prototype for future zero carbon emissions homes. To complete this task we divided ourselves into three subcategories, a construction group, a solar group, and an automation group. This report will explain in detail the design process of the construction group. The report will look closely into every challenge and decision that was made from our first client meeting, establishing a list of needs and design criteria, critically analysing the calculations that needed to be considered, developing a conceptual design and a series of prototypes, and finally, presenting our product to our client. The report will also discuss technical details such as our budget, project plan, and prototyping testing strategies. Finally, this report will discuss what we learned as a group through this design process, what we would do differently if we were to start over, and how we could improve our current design moving forward.

Contents

List of Figures	3
List of Tables	3
1. Introduction	4
2. Design Process	6
2.1. The Client and the User	6
2.2. Problem Statement	7
2.3. Identifying What to Build	7
2.3.1. Needs Identification	7
2.3.2. Benchmarking	8
2.4. Design Criteria	11
2.4.1. Customer Needs and Design Criteria	11
2.4.2. Target Metrics	12
2.5. Conceptual Design	13
2.5.1. Comparison of Conceptual Design Ideas	13
2.5.2. Concept Sketches	16
Concept Version #1 - Door on Short Wall	16
Concept Version #2 - Addition of Mud Room	16
2.6. Project Plan and Cost Estimate	17
2.7. Technical Explanation of the Selected Concept	18
2.8. Prototypes and testing strategy	20
2.8.1. First Prototype - The 3D Model	20
2.8.2. Second Prototype - The Mudroom	23
2.8.3. Third Prototype - The Shed	24
2.9. Final Product	26
3. Conclusion and recommendations for future work	28
4. References	30

List of Figures

- Figure [1] - Version 1 of the Shed's Conceptual Design Page 16
- Figure [2] - Version 2 of the Shed Design, including 3 orthographic projections Page 16
- Figure [3] - Illustration of airflow in the shed Page 19
- Figure [4] - AutoCAD Representation of Prototype 1 Page 20
- Figure [5] - 3D Printed Representation of Prototype 1 Page 21
- Figure [6] - The Mudroom under Construction Page 23
- Figure [7] - Left Hand side Page 26
- Figure [8] - Right Hand Side Page 26
- Figure [9] - Interior of the Shed Page 26
- Figure [10] - Front of the Shed Page 26

List of Tables

- Table [1] - CUSTOMER NEEDS Page 8
- Table [2] - BENCHMARKING AND METRICS OF 3 SHED DESIGNS Page 9
- Table [3] - ANALYTICAL BENCHMARKING OF 3 SHED DESIGNS Page 10
- Table [4] - CUSTOMER NEEDS AND DESIGN CRITERIA Page 11
- Table [5] - TARGET METRICS Page 12
- Table [6] - COMPARISON OF CONCEPTUAL DESIGN IDEAS Page 13
- Table [7] - PROJECT PLAN Page 17
- Table [8] - COST ESTIMATE Page 18

1. Introduction

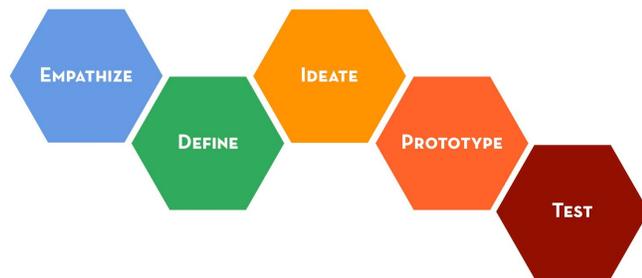
Shelter is one of the most basic human necessities; protection from the weather is essential to survival, especially under harsh conditions like the Canadian winter. Many developing countries lack the resources or economy to build adequate shelter, and as a result the task of designing low-cost, renewable, and energy-efficient housing has become a world-scale problem. But, as resources become more scarce and carbon dioxide pollution continues to enact climate change, it is clear that shelter construction must also work to minimize pollution into the surrounding environment - the general aim is to create housing with a “net zero” carbon footprint.

In January 2017 our lab section of 14 people was approached by Dr. Muslim Majeed of the uOttawa Civil Engineering Structures Laboratory, who asked us to design and construct a net zero shed (a less ambitious version of a net zero house). The intended purpose of this project was to prove that this type of housing is viable to construct, and that it could one day be implemented elsewhere in the world. The shed would be designed with the mindset that people could live in it in a developing country, and that their electricity, heat, and water heating would all be produced off-grid by solar energy collectors installed on the shed. This would work to improve people's lives by providing shelter, reducing fossil fuel use (to save money and the environment), and to eventually create a cleaner planet.

Our lab section was formed into three teams, with the six authors of this report forming the Construction Team. The purpose of our team was to design and assemble the shed, whereas the other two teams (Solar, Automation) were responsible for the solar collectors and automated systems. Dr. Majeed provided our team with very specific constraints for construction: the shed would be constructed in a length/width/height space of 8'x4'x15'; it would be built as cost-efficiently as possible; it would have a net-zero carbon footprint; and, it would be livable in all Canadian weather conditions.

Our team approached this problem by following the five-step design thinking model presented in the lecture component of the course. We began by empathizing with our client and potential user

base to identify needs and understand why they existed. We completed significant research and benchmarking on various shed types before moving onto the define stage where we created a problem statement and developed design criteria.



These criteria, interpreted from Dr. Majeed’s original meeting, allowed us to develop a chart of target specifications which we would reference for the remainder of the project.

However, it was not until the ideate stage of the design thinking model that the project began to take shape. In this stage we put our research to work to develop several conceptual sketches of the shed; these sketches would in turn lead to revisions, a 3D CAD drawing in AutoCAD, and a 3D printed prototype which allowed us to perform small-scale tests on the shed. Once we had completed these prototypes, we were confident to proceed in constructing the full scale shed.

Several concepts make our shed unique among other designs: the unusual “L” shape (incorporating a foyer/mud room), which was designed to minimize heat loss through a double-door system; the singular window on the western wall, which allowed the solar team to install solar collectors on the southern wall instead of exclusively the roof; the black painted exterior, which was designed to soak up the sun and keep the shed warm; and the construction itself, which was made extremely strong by our decision to double-stud end pieces and space our studs every 16”.

Construction took approximately two months to complete and involved collectively almost 100 hours outside of our regularly scheduled lab section. The finished prototype was completed for March 29, 2017 for the uOttawa Design Day competition, where the shed was put on display and our combined efforts yielded a 1st place prize in the shed category. The Construction Team is very pleased with our results and would like to invite you to read our final design report.

2. Design Process

2.1. The Client and the User

We first met our client, Dr. Muslim Majeed, at our client meeting on January 25, 2017. Dr. Majeed provided us with a very specific outline of the project scope: to design and construct a net-zero carbon footprint home. His needs were to minimize fossil fuel use to save the environment, to improve people's lives by providing easy-to-build shelter, to create a cleaner planet by minimizing construction waste, to have the shed function in all Canadian and developing world



Dr. Muslim Majeed [Online Image]. Retrieved April 10, 2017 from <https://carleton.ca/cee/people/majeed-muslim/>

weather conditions, and to minimize costs. We would be given limited workspace in the structures laboratory (8'x4'x15'), recycled spruce wood would be provided, and the shed must have be constructed to feature solar and automated systems.

After Dr. Majeed explained his needs as a client, we decided to empathize with potential users. We researched a variety of weather scenarios that the shed would have to withstand - in Canadian weather it would have to survive extreme cold temperature, whereas the eastern world might be extremely hot - and the shed would have to maintain a stable internal temperature to achieve this. Users would want the shed to resist outdoor temperatures.

To begin, we gathered all of our client and user information and prioritized it - it became apparent that our number one concern should be to make the shed net-zero and self-sustaining, as well as satisfy the users' functionality requirement. We were then able to take these requirements and create a Problem Statement, perform Needs Identification, and benchmark.

2.2. Problem Statement

After our client meeting with Dr. Majeed, we moved onto the define stage of the design process, and we were able to prepare the following problem statement:

“The students of the class Engineering Design are asked to design a zero carbon shed which will use no fossil fuels, produce no greenhouse gasses, have the potential to be used in underdeveloped countries, and will generate a revenue.”

This problem statement was effective throughout the design process, as it highlighted the core goal of our project. Although we developed a long list of customer needs and later complementary design criteria, it was crucial for us to have a clear, concise statement to look back on periodically as the project progressed to ensure we were solving the real, basic problem.

2.3. Identifying What to Build

2.3.1. Needs Identification

After creating the problem statement, we decided to analyze our clients' and users' needs, determine the functionality of each need, and rank their importance overall. The prepared Table [1] below demonstrates both the functionality of a need - functional being useful and measurable, whereas non-functional being unnecessary overall - and our rank of its importance. We measured the importance of each need by ranking them on a scale of one to five, five being the most important and one being the least important. We picked the most important needs based on our problem statement and critical limits such as space. We then scaled our less-important items based on what we and the customer expressed as wants. In the

process of building the shed we prioritized what we needed to get done based on this original table, and it significantly helped us to get tasks done efficiently.

Table [1] - CUSTOMER NEEDS			
#	Need	Functional or Non-Functional	Importance (1-5)*
1	Stay within dimensions	Functional	5
2	Stay within the budget	Functional	4
3	Make the shed zero carbon emission	Functional	5
4	Produce more energy than required for operation (for selling purposes)	Functional	2
5	Use recycled material	Non-Functional	3
6	Aesthetically pleasing	Non-Functional	2
7	Be livable in all Canadian weather conditions	Functional	5
8	Able to produce hydro/utilities using only solar energy	Functional	5
9	Must have running water	Functional	4

2.3.2. Benchmarking

After identifying our most important needs, we began looking for concepts to start ideating for our design. The reason for benchmarking as we did in Table [2] below was to compare shed ideas that others might have used in the past - after all, we were obviously not the first team in history to build such a structure. Benchmarking was a useful tool in this case, as it gave us the opportunity to compare various researched products that are on the market today. In Table [2], we compared three types of sheds and analyzed metrics such as cost, size, and structural stability. This provided us with a visual of the advantages or disadvantages of each shed design.

Table [2] - BENCHMARKING AND METRICS OF 3 SHED DESIGNS			
SHED SPECIFICATIONS	RONA'S "roughneck" garden shed 	Sunflower Cedar Shed 	Fox News Numbers 
BUILDING COST (cad)	939\$	2737\$	8720\$
SIZE	50 square feet	54 square feet	378 square feet
CONSTRUCTION MATERIALS	Plastic sheets (roof and structural walls)	Wood (red cedar)	Wood structure (SPF) and
INSULATION	None	Yes	1500\$
WINDOWS AND DOORS	1 large window at the back	On each wall (8 windows total)	1000\$
STRUCTURAL STABILITY	80%	100%	100%
EXTRAS	2 front doors (large entry)	Resistant to insects and decay	Aesthetically appealing
Appliances	None	None	Yes (all of the appliances found in a home: running water, heating and more)

Table [3], by contrast, shows analytical benchmarking. In this table, we ranked the quality of the three comparisons: green (good), yellow (okay), and red (bad).

Table [3] - ANALYTICAL BENCHMARKING OF 3 SHED DESIGNS			
SHED SPECIFICATIONS	RONA'S "roughneck" garden shed	Sunflower Cedar Shed	Fox News Numbers
BUILDING COST (cad)	939\$	2737\$	8720\$
SIZE	50 square feet	54 square feet	378 square feet
CONSTRUCTION MATERIALS	Plastic sheets (roof and structural walls)	Wood (red cedar)	Wood structure (SPF) and
INSULATION	None	Yes	Yes
WINDOWS AND DOORS	1 large window at the back	On each wall (8 windows total)	3 windows
STRUCTURAL STABILITY	80%	100%	100%
EXTRAS	2 front doors (large entry)	Resistant to insects and decay	Aesthetically appealing
Appliances	None	None	Yes (all of the appliances found in a home: running water, heating and more)

Both of these tables were useful to the design process because they helped to visualize which aspects of our researched sheds that we might want to incorporate into our own, and which bad qualities we might want to stay away from. It was during this benchmarking phase that we developed our initial idea for the foyer/mud room, because we realized how easy heat could escape through an open door. The benchmarking phase was thus incredibly beneficial to the final product.

2.4. Design Criteria

2.4.1. Customer Needs and Design Criteria

After completing Benchmarking, our team began progressing to the ideating phase of the design process. Table [4] was created to assign design criteria to our list of needs, which would help to assign achievable goals to each big idea.

Table [4] - CUSTOMER NEEDS AND DESIGN CRITERIA		
#	Need	Design Criteria
1	Stay within dimensions	4' * 8' * 15'
2	Stay within the budget	Low cost materials
3	Make the shed zero carbon emission	Use recycled material
4	Produce more energy than required for operation (for selling purposes)	High efficiency appliances, good insulation
5	Use recycled material	Use recycled material
6	Aesthetically pleasing	Painting after construction finished
7	Be livable in all Canadian weather conditions	Insulated, durable, weatherproof siding, breathable
8	Able to produce hydro/utilities using only solar energy	Strategically design structure to maximize solar gain
9	Must have running water	Method of gathering water

2.4.2 Target Metrics

Design criteria was then further analyzed in Table [5], where measurable objectives and units were identified. The purpose of creating this metric chart was to assign a value to needs when possible.

Table [5] - METRICS AND UNITS			
Metric #	Needs #	Metric	Unit
1	1	Needs to be within 8'x 4'	ft
2	2	Budget to be determined and approved	\$
3	3	Energy produced is <= Energy Used	kWh
4	7	Insulation R factor: Windows-3 Walls 30-35	R factor
5	7	Temperature stability-maintain a desired internal temperature	°C

It is important to note that at this stage we still had not been assigned a budget and thus continued to reference an arbitrary budget in our table. Even by the time of this report, we were never assigned a budget overall (and are thus forced to approximate costs of construction), but cost remains an important metric if the project were to be repeated in the future. It remains on this table and others for legacy purposes.

2.5. Conceptual Design

2.5.1. Comparison of Conceptual Design Ideas

It was clear to us by the time metrics had been identified that it was time to begin conceptual design of the actual prototype (hereafter referred to as “the fun part”). Due to the nature of the lab schedule, we had actually already constructed a foundation at this time; however, this is not relevant as Dr. Majeed insisted upon an 8’x4’ base so it would have been required either way.

We performed a group brainstorming session for features we could add to the shed. It became apparent to us that we should record and compare these ideas, and evaluate which ones would be best suited. The following Table [6] is an excerpt from our original brainstorming session, and it breaks the shed down into components (ex. Roof, walls, windows, etc.). Different concepts are presented (ex. For roof, we wished to decide if we would have a flat or slanted roof). Our final decision, decided by group favourable vote, is also indicated.

TABLE [6] - COMPARISON OF CONCEPTUAL DESIGN IDEAS				
Component	Option	Pros	Cons	Decision
Roof	Flat Roof	<ul style="list-style-type: none"> ● Good for garden/ terrace. ● Helps with the zero carbon emission ● Maximizes ceiling height 	<ul style="list-style-type: none"> ● Bad for heavy snow falls (possibly easy for collapsing) ● Hard to install solar panels on 	
	Peaked Roof	<ul style="list-style-type: none"> ● Good for installing Solar panels ● Good for heavy snowfall ● Maximized ceiling height 	<ul style="list-style-type: none"> ● Using more material than flat roof 	
	Slanted Roof	<ul style="list-style-type: none"> ● Good for installing solar panels on (largest surface which can be set to the optimal angle) ● Good for heavy snow fall 	<ul style="list-style-type: none"> ● Bad for ceiling height 	✓
Walls	Material: Spruce	<ul style="list-style-type: none"> ● Most structurally sound ● Easy to work with ● Light weight 		✓

		<ul style="list-style-type: none"> Renewable Resource Readily Available 		
	Number of studs: 16" Single studs	<ul style="list-style-type: none"> Structurally simple 	<ul style="list-style-type: none"> May not carry all of the loads 	
	16" Double studs	<ul style="list-style-type: none"> Structurally simple 	<ul style="list-style-type: none"> Possibility of overestimation (use of wood that is not necessary) 	
	16" Single Braced	<ul style="list-style-type: none"> Structurally stable and simple 	<ul style="list-style-type: none"> Complicated to install the braces 	
	16" Double Braced	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Complicated to install the braces 	✓
	Insulation Type: Asbestos	<ul style="list-style-type: none"> Fire Resistant Produced here in Canada 	<ul style="list-style-type: none"> Difficult to Install Hazardous if Disturbed 	
	Fibreglass	<ul style="list-style-type: none"> Easy to get 	<ul style="list-style-type: none"> Not appropriate for somewhere humid. 	
	Roxsul R24		<ul style="list-style-type: none"> Cost 	✓
	Sprayfoam	<ul style="list-style-type: none"> Good for irregular shaped areas 	<ul style="list-style-type: none"> Necessitates specialized personnel 	
	Styrofoam	<ul style="list-style-type: none"> Cheap Good Insulator High insulating value for relatively little thickness 	<ul style="list-style-type: none"> Can block thermal short circuits 	
Windows	Size: Big	<ul style="list-style-type: none"> Creates more natural light 	<ul style="list-style-type: none"> Allows more cold air in the winter 	✓
	Small	<ul style="list-style-type: none"> Allows less cold air in the winter than a big window Cost less 	<ul style="list-style-type: none"> Loss of natural light 	
	Location: Sides (larger sides)	<ul style="list-style-type: none"> Permits for the automation group to install their equipment facing the sun 	<ul style="list-style-type: none"> Greater heat loss because of lower R factor (little to no insulation) 	
	Ends (smaller sides)	<ul style="list-style-type: none"> Maximizes light in the shed 	<ul style="list-style-type: none"> Less sun comes into the shed Less heat will enter the shed 	✓

Door	Size: Large door	<ul style="list-style-type: none"> Large entry way that permits a person to store large things in the shed 	<ul style="list-style-type: none"> Large amount of heat is lost when the door opens in the winter Large amounts of cold air is lost when the door is opened in the summer 	
	Small door	<ul style="list-style-type: none"> Smaller amounts of air are lost 	<ul style="list-style-type: none"> It is difficult to store large elements in the shed. 	✓
	Location: Small wall	<ul style="list-style-type: none"> The space in the shed is better utilized as it will use less space when we open it 	<ul style="list-style-type: none"> We only have the opportunity to install a small, standard size door. If the client wants to install a larger door, it is not possible 	
	Long wall	<ul style="list-style-type: none"> Possibility to install a larger door 	<ul style="list-style-type: none"> There will be less storage on the walls 	✓
	Material: Wood	<ul style="list-style-type: none"> Aesthetically appealing 	<ul style="list-style-type: none"> More expensive and will deteriorate faster if not maintained 	
	Aluminum	<ul style="list-style-type: none"> Less expensive 	<ul style="list-style-type: none"> Will get cold when it is cold outside 	✓
	Glass	<ul style="list-style-type: none"> A lot of natural light 	<ul style="list-style-type: none"> Not insulated 	
	Foyer: Double door	<ul style="list-style-type: none"> Reduces heat loss when the door is opened 	<ul style="list-style-type: none"> Sticks out of the 4x8 footprint 	✓
Exterior Finishing	Colour: Black	<ul style="list-style-type: none"> Absorbs heat from sun which is preferable for the winter 	<ul style="list-style-type: none"> Reflects heat from the sun 	✓
	White	<ul style="list-style-type: none"> Reflects heat from sun which is preferable for the summer 	<ul style="list-style-type: none"> Reflect heat from sun during winter 	
	Material: OSB panels	<ul style="list-style-type: none"> Lowest cost 	<ul style="list-style-type: none"> Not aesthetically appealing 	
	Plastic siding	<ul style="list-style-type: none"> Aesthetically appealing 	<ul style="list-style-type: none"> Costs a little more 	✓
	Brick	<ul style="list-style-type: none"> Aesthetically appealing 	<ul style="list-style-type: none"> Extremely costly 	
	Stucco	<ul style="list-style-type: none"> Aesthetically appealing (for some - others think it looks ugly) 	<ul style="list-style-type: none"> Extremely costly 	

2.5.2. Concept Sketches

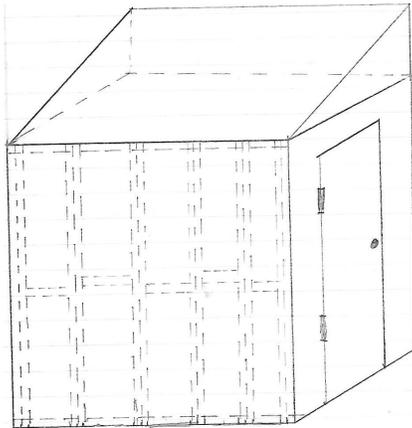


Figure [1] - Version 1 of the Shed's Conceptual Design

Concept Version #1 - Door on Short Wall

Our first true visual of the shed did not appear until a meeting in early February, when we collapsed the selected features from Table [6] into a shortlist and began generating sketches to fulfill it.

Our initial attempt to do this resulted in Figure [1].

Characteristics of this initial design include the slanted roof (slanted at 30 degrees to the south), a door on the eastern wall, and a window (hidden) on the western wall.

Most of these features were actually carried through to the final product, but notably the door would change significantly with the next concept.

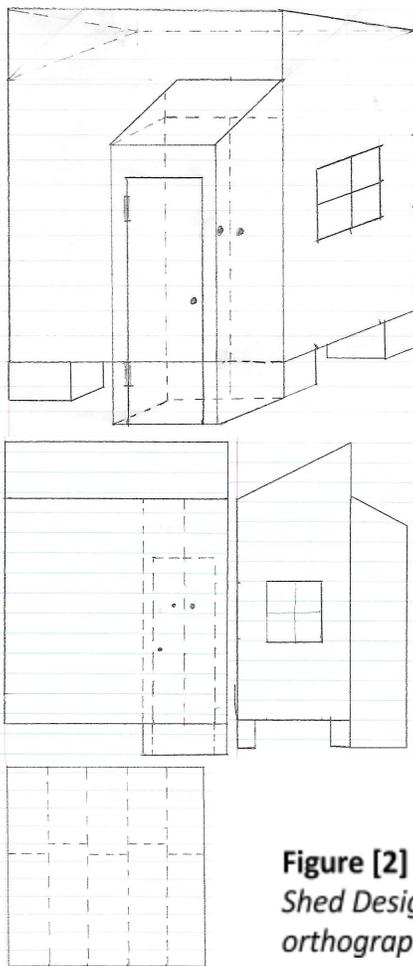


Figure [2] - Version 2 of the Shed Design, including 3 orthographic projections

Concept Version #2 - Addition of Mud Room

Since the benchmarking phase (section 2.3.2), our team was wary of the the problem of massive heat loss every time the door would be opened. We sought to solve this problem by breaking one of our core rules - the rule that the base would be 8'x4'.

The "mudroom" or "foyer" as we would refer to it later provided a double door design to trap heat inside the shed rather than expose it directly. The idea behind this concept was that the user would enter the mudroom, close the door behind him/her, and then enter a second door or thermal curtain to get into the shed.

In this concept we envisioned the mudroom on the right-hand side of the north wall, but we would later move it to the left-hand side to give the automation team space near the window.

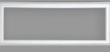
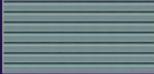
This was also the first time that proper orthographic projection views were drafted alongside an isometric sketch.

2.6. Project Plan and Cost Estimate

With a concept in mind to present to Dr. Majeed, we prepared a project plan and cost estimate. This plan is based on a document which Dr. Majeed provided us with at the beginning of the lab section, however we refined it to be of greater use to the project deliverable. The plan served as a pseudo-gantt chart which we used for time management. If we believed ourselves to be behind schedule, we planned to work overtime at the lab to get caught up. If we were ahead of schedule, we would keep going. Table [7] is a visual representation of the project plan.

Table [7] - PROJECT PLAN			
Task	Duration (days)	Task	Duration (days)
Create List of Materials	1	Build Prototype 2-Mud Room Addition	2
Create Budget	1	Insulate floors and walls	2
Order Materials	1	Add Siding	2
Inventory of Materials (insure all arrived)	2	Install Window	1
Create to Scale Prototype	5	Frame Roof	3
Present Prototype to Client and Receive Feedback	1	Add Roofing	2
Frame Walls	2	Install Door	1

Our cost estimate was a different problem entirely - since Dr. Majeed kept the project budget a secret, we weren't entirely sure what we could and could not spend. We attempted to estimate our expenditures based on the cost of materials, however an obvious error was made with regard to the cost of roofing shingles. We estimate the final amount spent on the shed to be approximately \$1,000 as opposed to the \$3,263 seen in Table [8] below, but once again this mistake is provided for legacy purposes.

Table [8] - Cost Estimate					
Material/Fee	Cost (CAD)		Material/Fee	Cost (CAD)	
Wood	Provided		Flooring	\$40.00	
Nails	Provided		Roofing	\$80.00/square foot (roughly 32 square feet) TOTAL: \$2 560	
Window	\$124.00		Insulation	\$275.00	
Door	\$35.00		Exterior Siding	\$3.00/square foot (roughly 168 square feet) TOTAL: \$504	
Total				\$3 263	

2.7. Technical Explanation of the Selected Concept

Based upon our project plan and concept generation, we were able to select a concept (version 2, section 2.5.2) to proceed with. As mentioned above, we critically analysed many of the different features that would be integrated into the design of the shed. While benchmarking and researching, we determined four different and important concepts that are present in the shed. The first is (as previously mentioned) the fact that our roof has a slant of 30° in order to maximize the amount of sun that contacts the solar panel on the roof throughout the day, all while minimizing the effects of the snow load on the structure. Furthermore, we decided that we would install one small window as opposed to many large windows. Our research proved

that walls have an “R” insulation factor of around 35/40 and windows have an “R” insulation factor of about 3/40. It is therefore apparent that a great amount of heat is lost through the windows which is why we decided to only install only the single small one. Additionally, we decided to paint the shed in black, as this colour absorbs heat from the sun. In the winter, the main dilemma is heating the shed. This colour, as well as being aesthetically appealing and modern, ensures another way for the shed to maintain a high temperature. Lastly, in order to minimize the amount of heat that is lost when the main door is opened, we decided to build the mudroom extension. Between this extension and the shed, there would be a thick material that would act as a heat shield. The following figure illustrates this concept.

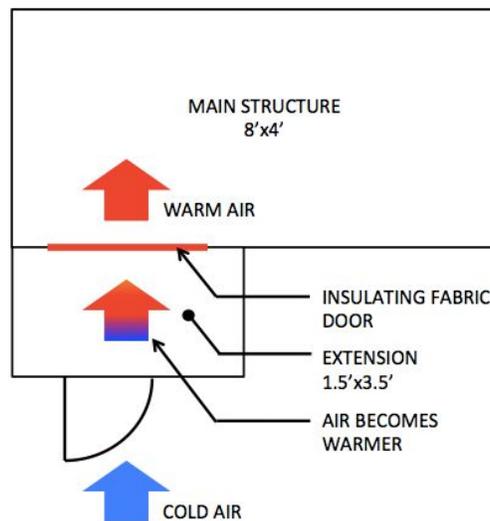


Figure [3] : *Illustration of the airflow in the shed*

A person entering the shed would stand in this extension for a few seconds as it heats up and would then enter the shed by walking through the material. This feature also set us apart from the other groups, as it made our structure look different and gave it a characteristic “L” shape which can be seen in later photographs.

2.8. Prototypes and testing strategy

With the selection of our concept complete, it became time for us to begin prototyping. During this process, we elaborated three different prototypes to ensure that our client Dr. Majeed was satisfied with the product as we designed it.

4.8.1. First Prototype - The 3D Model

The main goal of our first prototype was to clearly communicate our design to our client, to receive feedback, to ensure that we were building a structurally sound design, as well as to determine the to-scale layout of our shed. We did this in the earliest possible prototyping stage to reduce the risk of miscommunication with our client early on in the shed's development. This prototype took the initial form of a 3D model in AutoCAD, with the intention that we would 3D print a small-scale version to show to Dr. Majeed.

By using a small and cheap prototype, we were able to visually reach a mutual understanding with our client. When our client liked our first prototype, we knew that we were able to move on and develop a more comprehensive one. We also used this first prototype to test the layout of our shed. By using a

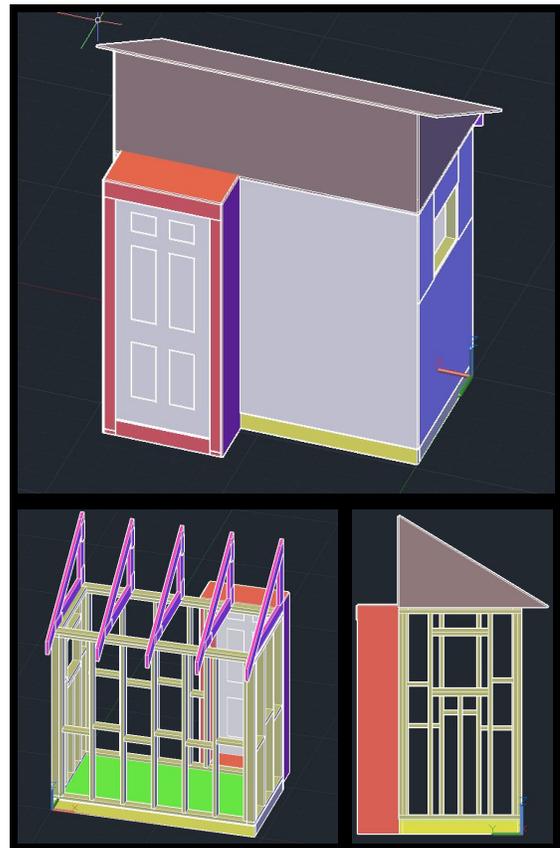
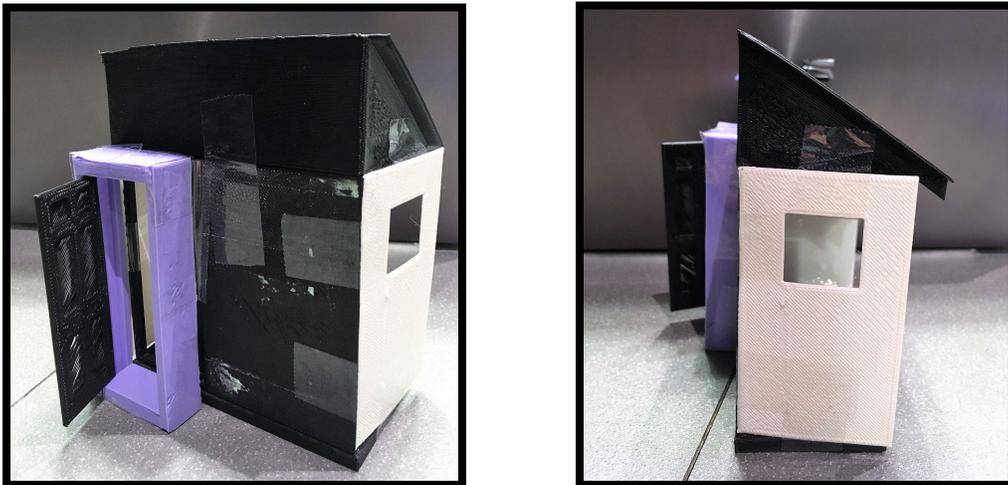


Figure [4] - AutoCAD
Representation of Prototype 1

small-scale model, it was simple to reposition the door or window to produce the most aesthetically pleasing and functional design.

The specific objectives of our tests on this prototype were to determine if our client was pleased with our design so that we could confidently proceed to the next stage in prototyping, as well as to finalize our shed design to the most minute detail. Our result was verified primarily through customer feedback, such as if our client liked what he saw and felt comfortable with the stability of the design. Due to the fast-paced nature of the lab schedule, a significant portion of our real shed (prototype 2) was already constructed by March 5th, 2017 when the 3D model of prototype 1 was finally printed in the makerspace lab:



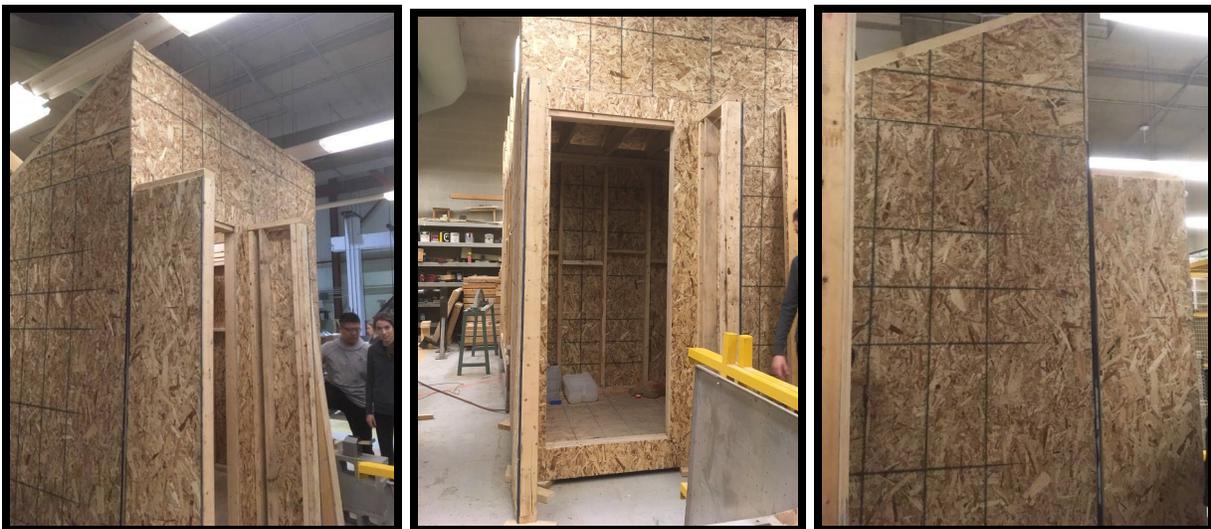
**Figure [5] - 3D Printed
Representation of Prototype 1**

As shown, the model did not yet include interior walls as we had yet to decide where various hookups to heating, electrical, and water were to be installed. The fact that prototype 2 had been underway since long before the 3D model was printed meant that a lot of thought had

already been put in the initial design of the shed, but this first prototype gave us an opportunity clearly talk to our Dr. Majeed about what our vision of prototype 2 was. Dr. Majeed presented a major concern with mudroom addition; he preferred that this structure would not be apart of the shed's super structure, but rather be built out of light materials and attached to the outside - in essence, he did not want it to be added to the foundation directly. This was noted and refined, and we were capable of moving on completely to the second prototype.

2.8.2. Second Prototype - The Mudroom

For the second prototyping phase we decided to create a focused prototype. For this we identified the most critical component of our shed as the mudroom on the front. We concluded that this was the main selling feature of our shed and hence we needed to verify that it fulfilled its purpose. We wanted to make sure that the way we were framing the shed would be stable, so we decided to assemble the mudroom first as per Dr. Majeed's suggestion, but then use it as a proof-of-concept that the rest of the shed would be sturdy. Prototype 2 is essentially the mudroom.



**Figure [6] - The Mudroom
under Construction**

There were two main goals of this prototype, the first to verify the assumption made about the functionality of the mudroom. For this we wanted to test the addition when it was actually mounted to the shed; this would allow us to test whether cold air could leak in between the cracks between the mudroom and the shed. The second aspect, as described already, was that we wanted to verify the overall structural integrity of the shed. In the construction of the

mudroom, we followed all of the same principles as in the construction of the rest of the shed - they are both constructed of spruce, studs spaced 16" apart in the floor, doubles studs in all corners, similar truss design). This meant that the addition shared very close structural properties to that of the rest of the shed.

The benefit of testing prototype 2, the mudroom, is that it is smaller and lighter than the rest of the shed which allowed for easier testing. It was, after all, considerably easier to maneuver. After the addition was verified to be structurally sound and functional, we felt confident in the rest of the shed design and were ready to move on to complete the third and final prototype.

2.8.3. Third Prototype - The Shed

The third prototype is in actuality the finished product of the shed, but it was completed roughly a week in front of our project deadline so we had some time to reflect. The goal at this stage was to make sure that we had met all of our customer needs and design criteria, which we established at the beginning of this project (sections 2.3, 2.4). We moved the shed outside on March 28, 2017 to ensure that our product was able to withstand all Canadian weather conditions, maintain a comfortable internal temperature, and was able to completely function off of the energy which it produced for itself. The main purpose of this prototype was to communicate with the various members of the community who would be present at Design Day and to receive customer feedback on the final product. On March 29, 2017 we brought the prototype 3 to Design Day for just this purpose. The goal of this testing iteration was to test all of the aspects outlined in our design criteria to ensure the most accurate results. We focused mainly on testing the internal temperature of the shed overnight and testing the amount of

weight the structure could withstand - it was capable of flawlessly supporting a number of workers on the roof in addition to a hefty solar panel.

2.9. Final Product



Figure [7]: Left Hand side



Figure [8]: Right Hand Side

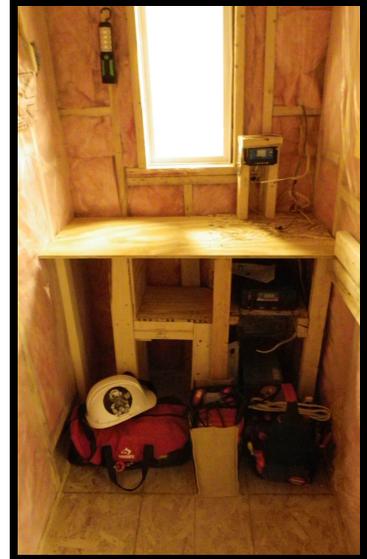


Figure [9]: Interior of the shed



Figure [10]: Front view of the shed

Overall we were very pleased with our final product. As a group we felt we were able to effectively incorporate all of our client's needs and the design criteria we established at the beginning of the project. One major criteria we determined through listening to our client was that the shed must be livable in all Canadian weather conditions. We achieved this primarily through the addition on the front of the shed. This addition minimized the heat lost when entering and exiting the shed, which helps improve the efficiency of our air heating system. Another major criteria we incorporated into our shed was the 30° slanted roof. By doing this we created the optimal surface for absorbing solar energy as well reducing the snow build up on the roof. Other minor criteria that we successfully incorporated was the use of black paint on the three un-sided walls to maximize heat absorption in the winter, insulated walls, and an overall structurally sound and functional shed. Our satisfaction with our product was verified on the University of Ottawa Design day where we placed first in the zero carbon shed category, and second overall. These results and the feedback received from the judges and the public verified that we created an effective design that would likely be successful if we were to continue developing our prototype into the future. Though the course of this project we learned a significant amount about project planning and the design process. Moving forward we would implement what we learned through the design process effectively to improve upon our product as will be discussed in the conclusion.

3. Conclusion and recommendations for future work

To conclude, our goal for this project was to design a zero carbon emissions shed that would act as a prototype for future zero carbon emissions homes. We did this by first meeting with our client, Dr. Majeed, and developing a list of needs and requirements to be included in our design. We then translated these needs into a set of actionable design criteria. We then analyzed specific mathematical and technical properties our shed such as the ability to withstand a the necessary loads as well as meet certain safety specification. These criteria and calculations were then used to develop a variety of possible conceptual designs. From these possible designs, we reevaluated our customer and analytical needs as well as our design criteria, and selected the design that met these criteria the most effectively. We then developed a series or three prototypes, implementing specific testing strategies as well as receiving customer feedback between each prototype before developing the next. Finally, we constructed our final product reviewing each step that was taken along the way to ensure each was properly implemented in the final design. Through this process we learned skills such as communication and time management as well as identified mistakes made and what can be done on our design if we were to develop it further in the future. First, we learned the importance of communication as was one of our crucial strengths we had as a team. As a group we were sure to exchange contact information in the first lab section. This allowed us to begin to get to know each other before any of the critical work began. Furthermore, we developed a facebook group to exchange important information as well as organized all of our deliverables on google drive. By doing these two things, it allowed us to have a constant open line of communication between group meetings, which allowed us to be much more efficient and productive when we did meet in person. We also learned the importance of adaptability and time management. At the beginning of this project we developed a clear project plan of all the tasks that needed to be completed and strict deadlines of when each task needed to be finished. However, things did not always go as planned, for example, in the early stages of construction we planned to

install a small square window on the short wall. However, upon receiving our materials we realized the window we received was significantly shorter in width and taller in height than the one originally planned for. This cost us significant time as we had already made the cut in the wall of where we planned the smaller window to go. This taught us the importance of adaptability and time management. In the end we had to work with the materials we had available to us which meant adapting our design to satisfy them. This adaptation also took time, more than we had originally allotted in our project plan for installing the window. This showed us the importance of time management, it would have been beneficial if we had left room for error in our original project plan as opposed to a strict schedule where everything was expected to work properly. To accommodate for this we performed a project burndown to identify what we had completed, what we still needed to complete and how much time we had to complete them. Doing this allowed us to alter our original project plan in a way that allowed us to still complete our product by the deadline. Moving forward, if we had more time and money, there are a few aspects of our design we would add to or improve upon. First, we would completely weatherproof our shed. To do this we would complete the siding on the remaining three walls, finish insulating, and add an insulating blanket between the addition and the interior of the shed. We would also improve the aesthetics of our product by adding components such as drywall and flooring. Overall, we are very pleased with the outcome of our zero carbon emission shed design and look forward to seeing its possible implications as a prototype for future zero carbon emission homes.

4. References

Dr. Muslim Majeed [Online Image]. Retrieved April 10, 2017 from <https://carleton.ca/cee/people/majeed-muslim/>