MCGILL UNIVERISTY – DEPARTMENT OF BIORESOURCE ENGINEERING

SENIOR DESIGN BREE 495 – FINAL REPORT

NATURAL VENTILATED AUGMENT COOLING GREENHOUSE

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3. ACKNOWLEDGEMENTS

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The essence of this greenhouse design project is to contribute and respond to an agricultural and environment program initiated by the IDRC at UWI.

4. EXECUTIVE SUMMARY

Greenhouses create optimal climate conditions for crop growth, and protect crops from outside pests. To achieve good indoor crop production climate, traditional tropical greenhouse designs utilize a standard fan ventilation system to decrease temperature. The issue remains that such fans are energy intensive and are prone to failure when faced with tropical storms. The proposed solution is a natural ventilation augmented cooling greenhouse, or NVAC greenhouse. A NVAC greenhouse comprises arched, open-roof airflow improved by coupling natural ventilation with controlled aeration using a water misting system. The misting system running along the ridge, where the uprising warm air meets the incoming fresh air, floods the air mass with a fine mist causing the cooled air mass to flow down the side and collapse into the lower space of the greenhouse. No other mechanisms are involved. Temperature, relative humidity and solar radiation sensors, placed in key areas throughout a NVAC greenhouse prototype, provided data to detect air movement and cooling. Overall, from 2.3°C to 7.0°C of cooling was observed at the time of highest solar radiation (11:00am-3:00pm) on the warmest (>30°C) and most humid days of 2012 at the Macdonald Campus of McGill University in Montreal. Such results were obtained by comparing outside temperatures to inside temperatures with the misting system functional. Two design configurations of the same greenhouse were considered: open roof and open roof with misting system running. Maximum cooling was observed on the warmest days with the misting system operational. This design is economically and environmentally viable as it reduces energy costs, general pesticide use, and provides optimal growing conditions.

Competition video abstract available here.

5. INTRODUCTION

Crop production in greenhouses is a growing industry, especially in mild climates, and is very important for local populations as a source of income and fresh food [1]. Moreover, greenhouses provide the possibility of integrated production and protection (IPP) [1], which focuses on the importance of finding alternative solutions to improve yield and quality in crop production. Von

Elsner has proposed that optimization of a greenhouse design with respect to local climatic and economic conditions still remains a challenge [2]. Challenges with growing crops in tropical regions such as Trinidad include dramatic heat, high humidity, and high precipitation. Due to sensitivity of germination and sprout growth, these undesirable environmental characteristics make agricultural production difficult, expensive, and energy consuming. Thus utilization of greenhouses is beneficial in specific control of microclimates, to provide optimal growing conditions and increase crop yield. Controlling ventilation allows for temperature control, prevention of plant pathogens, and fresh air for photosynthesis and respiration. Having control of the growing environment in an enclosed structure reduces need for chemicals and pesticides used in pest control. Yield potential reduces at temperatures above 26.0°C, with fruit set being one of the first processes that is negatively influenced by supra-optimal temperatures (32.0°C/26.0°C day/night) [3] [11]. A detailed review presented by Kumar et al. indicates that existing cooling technologies are not enough and widely accepted to cater the needs of greenhouse grower and that there seems to be a necessity to develop cheap and effective technology suitable to local climatic conditions to boost up the greenhouse industry [5]. Traditional cooling alternatives for greenhouses depend upon exhaust fans to remove excess energy to decrease inside temperature [9]. Shen and Yu reported that the best cooling method for greenhouses in tropical region is ventilation with fans and using roof covering materials having near infrared reflection [7]. Detrimental effects from intense, tropical storms are reduced by implementing greenhouses and providing safer growing conditions for seedlings. Greenhouses in the Caribbean focus on temperature reduction rather than Canadian greenhouses which must consider cooling effects in the summer and heating systems in the winter.

Many existing designs include an opening in the roof for further air circulation, facilitated by convection. When convection alone is not sufficient, mechanical fans are utilized to force the air circulation and provide climate control within the greenhouse. However, these designs face many impairing issues. First off, using fans for ventilation is very energy intensive. Secondly, fans are placed on the sides of the structure, and occasionally along the opening of the roof, causing them to be subjected to damaging tropical storms.

Natural ventilation is the direct result of pressure differences created and maintained by wind or temperature gradients. It requires less energy and equipment and is the cheapest method of cooling a greenhouse. The present paper brings forth a natural ventilation process enhanced with an alternate version of a fog or mist cooling system. In previous studies, Montero et al. used an air water fogging system to cool a greenhouse with shade screen of 45% perforations. It was reported that maximum temperature reduction during sunny days was 5.0°C. Arbel et al. tested the efficiency of the fog system with a droplet size of 2–60 micrometers in a 16 m by 24 m greenhouse under rather hot but dry climatic conditions. The results were compared with fan and evaporative pad system. They concluded that performance of fog system was better than fan-pad system as temperature and relative humidity variations were <5°C and 20%, respectively [8]. A study by Rault considers the most commonly used cooling technologies as unsatisfactory for application in the humid tropics [6].

With this in mind, considering the very high relative humidity in tropical climates, a standard fog or mist system would simply drench the air mass and plants with water. As seen in figure 1, the side space suggested is designed to channel the humidified air, drive it down to collapse into the lower area and collect any condensation. This prevents any extra, unneeded humidity from reaching the crop area and allows for the possibility of harvesting and reuse of the condensed water. The misting system location is indicated with a red dot.

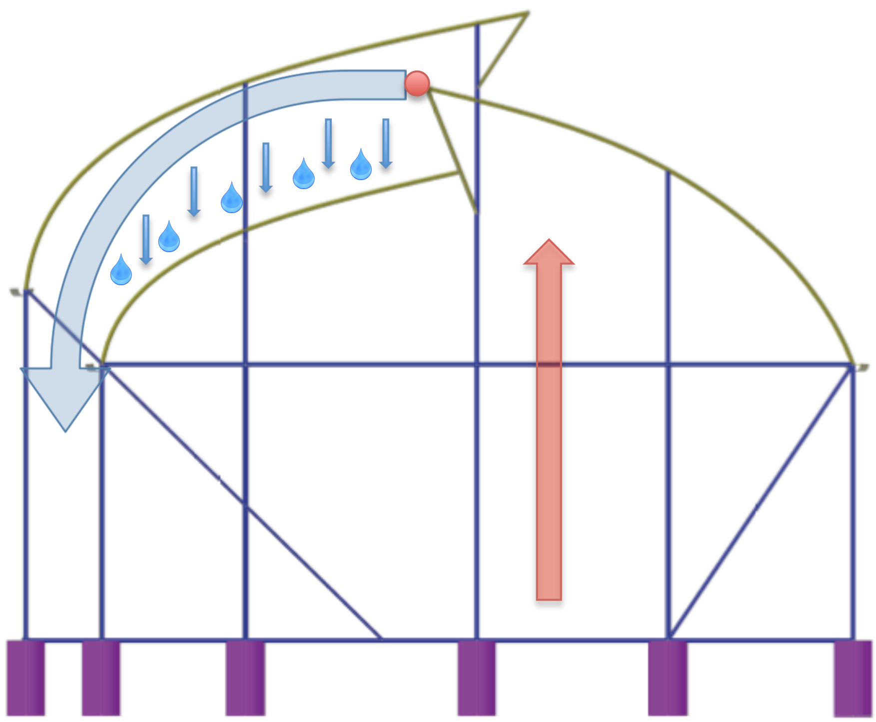

Figure 1 – Condensation in the greenhouse side space and misting system location (red indicator)

6. EVALUATION AND COMPARISON OF POSSIBLE SOLUTIONS

6.1 *Natural Ventilation*

Natural ventilation arises from pressure difference created by temperature and wind changes within the greenhouse structure. The necessity for wind gradients implies that all greenhouse designs utilize insect screening to allow airflow. Natural ventilation is the most cost effective method of cooling, and is profoundly reliant on evapotranspiration from the crop. A study by Tietel et al. found that the ventilation rate increased linearly with wind speed [10]. However, The direction of wind entering the structure, strongly affected the rate of ventilation, airflow, and crop temperature circulation. This causes inconsistent airflow, and thus is not an ideal solution on its own.

6.2 *Evaporative Cooling*

Evaporative cooling is the most proficient method of cooling while also maintaining control of the humidity within a greenhouse. However, this process is unsuitable for our design due to the high humidity levels within the Caribbean.

6.2.1 *Fan-pad system*

This technique utilizes a negative pressure fan and pad system to prompt airflow. This idea is also disregarded due to high-energy consumption, and damage caused to such machines in detrimental tropical storms as the Caribbean region often encounters.

6.2.2 *Fog/mist system*

This process entails spraying water droplets using high pressure nozzles. As the droplets evaporate, air temperature is reduced. However, this method alone, without consideration to structural design often prompts water collection in stagnant air, especially for tropical regions with high humidity.

6.2.3 *Roof Evaporative cooling*

Roof evaporative cooling is the method of placing a thin layer of water atop the surface of the structure to create evaporation. However, due to the high humidity of our chosen environment, evaporation rate for this mode of cooling will not be fast enough to suffice significant temperature decrease within the greenhouse.

7. EXPERIMENTAL SECTON

7.1 *AutoCAD design*

A three dimensional AutoCAD model was prepared to provide computer generated images and dimensions of the three-roofed design, in preparation for prototype construction. The radii of curvature of the roofs were chosen as such to facilitate convective air movement as seen in Figures 2 and 3.

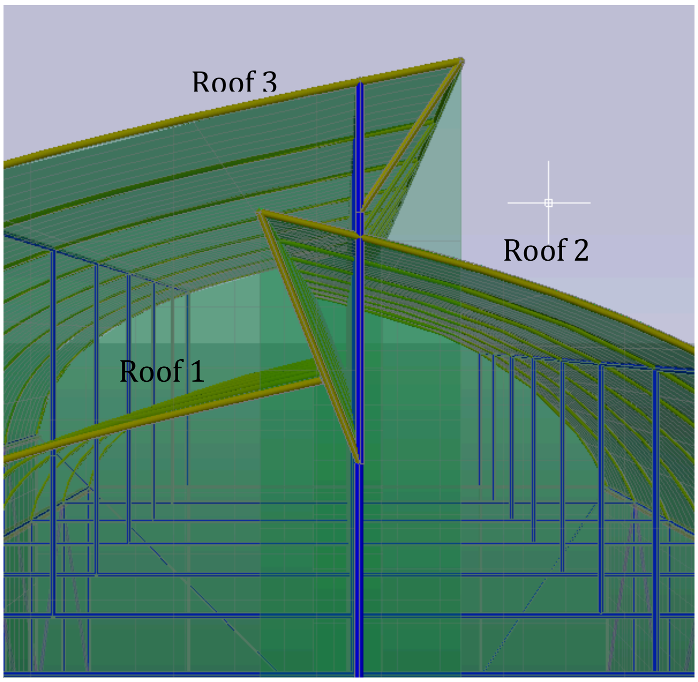

Figure 2 Side view of roof arrangement

Special attention to roof structural support was needed to account for the alternate roof design. Main vertical columns are used, as they are used in standard greenhouses, except they branch off to suitably support the three unusually angled roofs, as seen in figure 4.

7.2 *Prototype I*

Prototype construction began in spring 2012. A10 feet by 20 feet downsized version prototype greenhouse was built to attempt to investigate the air movement and cooling effect first hand. ¾ inch (19 mm) white PVC piping was used as structural components. High load bearing PVC segments were reinforced with rod-iron segments inserted into the hollow pipes. Additional support within the arched roofs

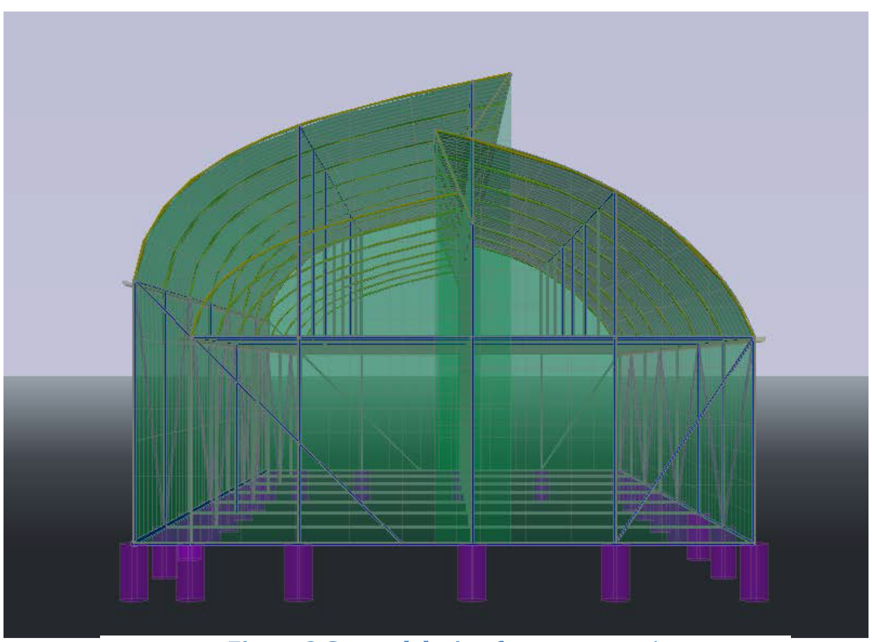

Figure 3 General design for prototype 1

was provided by inserting flexible bamboo sticks within the PVC piping. Intersecting PVC pipes were joined using standard corner, t-sections and 4-way sections. Solvent PVC cement was used for fastening. 4 vertical supports were used for roof support. 4" by 4" ground-anchored wood posts were used for the structure's front and back walls and 2 ¾ inch (70 mm) steel pipes were used in between for inside roof support and to prevent sagging. Steel square-angled flanges branched off from the wood posts to provide support to the roofs and hose-clamps were used to attach the roofs to the steel pipes within. Proper roof curvature was attained by tightening rope from roof edge to roof base. This allowed the PVC pipes to be bent to the required radii and the rope ensured the pipes held their shape. This however produced immense stress in the joining components and caused occasional cracking and failure of the joints when subjected to windy conditions. Regular maintenance involved repairing or replacing the joining components. The open sidewalls of the greenhouse were covered in a mesh to keep rodents and insects out. The rest of the area was covered with a standard polyethylene, clamped to the PVC tubing with plastic snap-clamps. Obviously, wind was a significant issue when ensuring structural stability. Hence, the base PVC segments running along the ground were anchored down using bent rod-iron sections pushed into the ground and each wooden post remained secured with post anchors. Figure 4 shows an image of the actual first prototype.

Figure 4 NVAC Greenhouse Prototype 1 Summer 2012

The opening of the third roof was designed to be adjustable in the case of changing airflow and to close during unfavorable weather conditions. Therefore it was built in a flexible fashion by attaching its upper edges to the wood posts using cable which was fed through a round hook screw located at the top of each wooden post. This cable could be pulled or loosened as one would a flagpole to alter the angle of the roof. The inside structural steel pipes could be extended accordingly. Throughout the greenhouse, cord lengths were used to fasten the roofs to the rod-iron anchors to stabilize and solidify in the event of strong winds. The side cables could also be fastened to prevent the roof from opening.

The misting system was a professional outdoor cooling 3/8 inch (9.5 mm) pipe misting system from Orbit® Irrigation Products Inc. The piping was installed along the edge of the second roof using hose clamps. Brass *Slip Lok Tee*s were the nozzle type used. The nozzles were positioned uniformly to spray water down the side space. 8 nozzles were installed at a 2-½ feet (0.762 m) interval. Each nozzle is designed to use 1.89 liters per hour. Standard line pressure was utilized.

7.3 Re-designing prototype II

The same misting system and overall design in maintained in the redesigning for the second prototype. The key difference is the enlargement of the left hand side space. See Figure 5 and 6 for illustrations and dimensioning of this. This space is what can be called the active portion of the greenhouse, where the driving force of the ventilation happens and has been increased to be two-thirds the length of the side of the greenhouse, while the right hand side is minimized to one-third of the side length. This expansion of the side space is to avoid stagnant air on the right hand side of the greenhouse, as seen in the first prototype. Moreover, the second prototype is designed to be half scale; twice the size of the first prototype. The second prototype is meant to be pseudo-permanent, and will be comprised of hardier materials such as EMT conduit piping. We will lay a concrete foundation with Sonotubes two feet beneath the ground for structural stability. The top and middle roof will be primarily conduit piping, bent using a wooden jig, with some PVC sections to fill gaps between EMT conduit segments. The lowest roof will be made completely of PVC piping because it is not exposed to harsh environmental conditions, and this material is cost-effective.

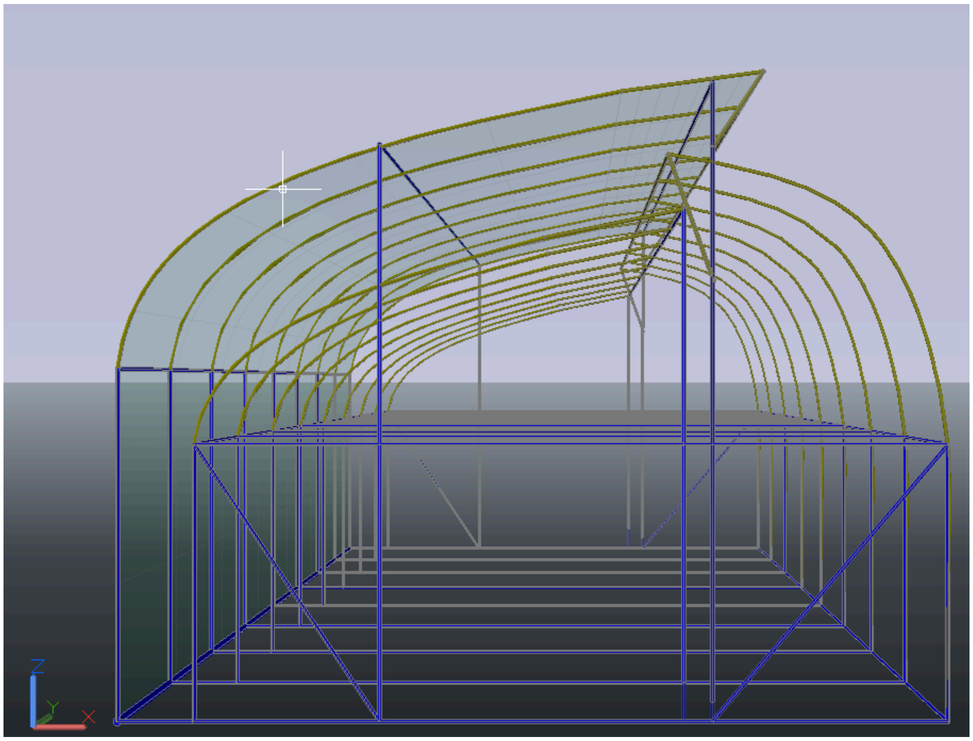

Figure 5 General design for prototype 2

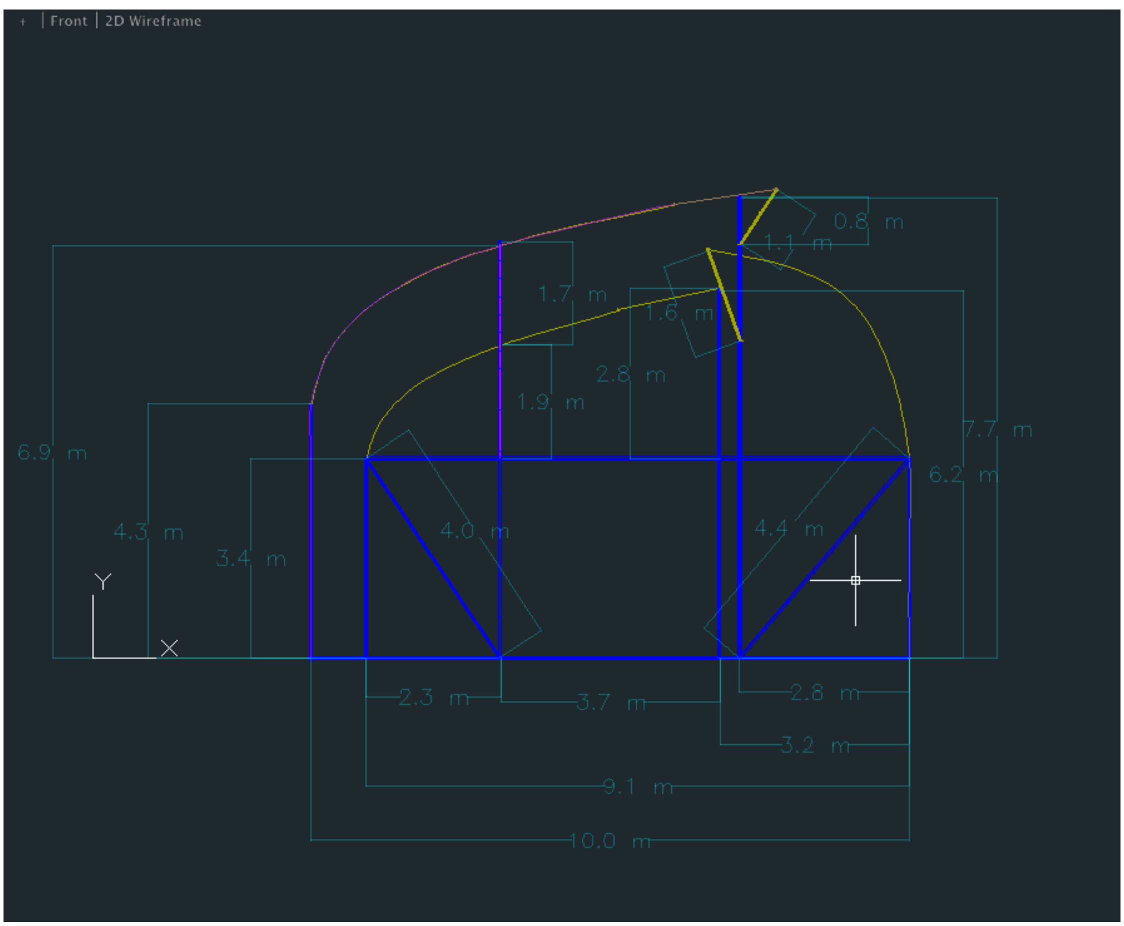

Figure 6 Side View of Prototype 2

8. DATA COLLECTION AND TESTING

An Onset Hobo data logger with appropriate sensors was used to collect temperature, relative humidity and solar radiation data. Data was collected 24 hours a day at a 2-minute interval. 9 sensors in total were placed in key areas in the greenhouse, such as at the roof opening and in the left hand side space, to track temperature differences. A diagram and description of the location of the sensors can be found in the appendix. On warm and humid days, preferably above 30 degrees centigrade and beyond 50% relative humidity, particular attention was taken to ensure that the third roof was open and that the misting system was on or off, according to the type of data collection decided upon. The Orbitz Arizona Misting system, utilizing 10 fine-mist nozzles, which were installed along the edge of the middle roof, ran at a minimum from 11a.m. to 3p.m. during misting days, since maximum solar radiation was experienced during that interval. This interval of maximum solar radiation meant highest inside temperatures, thus misting was to be most effective during this period, and hence it was crucial to have the misting system running during this period. The 9 gpm flow was controlled by hand by turning the water valve open or closed.

Our second prototype shall comprise of many more sensors, specifically placed in the side space area and at the opening of the roof to further study the air movement and the quality of the air at these locations. With our major modification of extending the left hand side of the structure, we are hoping to promote ventilation and temperature reduction in the right hand side of the greenhouse as well. Therefore, sensors will be placed to monitor the effects of these changes. Additionally, we look forward to programming a relay to control the misting system to run two minutes on, two minutes off, and turn off completely when unnecessary; this is especially useful as night. This will reduce human error in our data, while also reducing water buildup along the bottom roof. An extra set of nozzles will be necessary if the second greenhouse prototype is built twice the size of the first one. A total of 18 to 20 nozzles will be required to simulate a similar system as was used in the summer of 2012.

9. RESULTS AND DISCUSSION

9.1 *Results from prototype 1*

As a general rule, greenhouse temperatures should be limited to less than 30 to 32 °C (86 to 90 °F) unless tropical, cool season or shade plants are to be grown. For tropical plants, an upper limit of 35

°C (95 °F) should be considered from the standpoint of worker comfort and safety [9]. All inside temperature sensors in the study of the first prototype were compared to the outside temperature sensor (control) to show temperature differentials.

Table 1 Greenhouse temperature differences, relative humidity and solar radiation on days without misting system running

Trial Days No Misting Summer 2012						
Data taken 11:00am-3:00pm						
	1 (Aug 8)		2 (Aug 9)		3 (Sept 13)	
Sensor ID	**Average ΔT**	**S.D.**	**Average ΔT**	**S.D.**	**Average ΔT**	**S.D.**
(2-1)	5.37	0.67	5.71	2.45	2.36	0.63
(3-1)	-1.26	0.61	-1.25	1.20	1.02	0.48
(4-1)	1.39	1.26	2.34	2.02	0.91	0.51
(5-1)	0.98	0.92	1.18	1.06	0.82	0.99
(6-1)	3.15	0.54	5.32	2.44	1.09	0.84
(7-1)	2.34	0.58	2.82	1.48	1.75	1.03
(8-1)	5.75	0.89	5.80	2.85	3.17	0.81
(9-1)	0.37	0.90	2.59	1.53	1.37	0.79
Relative Humidity	Avg%	S.D.	Avg%	S.D.	Avg%	S.D.
RH 1 out	44.20	6.78	42.04	5.33	37.38	3.62
RH 2 inside	40.38	6.16	36.07	6.21	43.89	3.06
RH 3 up	46.93	7.43	46.03	7.03	41.81	3.11
Solar Radiation[1]	Avg PAR uE	S.D.	Avg PAR uE	S.D.	Avg PAR uE	S.D.
S1	1442.05	193.10	1258.89	397.36	1032.58	196.24
S2	1441.51	168.35	1242.58	391.03	1151.59	99.43
[1] Measured in PAR uE. PAR: Photosythetically Active Radiation						

Table 2 Greenhouse temperature differences, relative humidity and solar radiation on days with the misting system running

Trial Days With Misting Summer 2012

Data taken 11:00am-3:00pm						
	1 (Aug 24)		2 (Aug 28)		3 (Sept 6)	
Sensor ID	**Average ΔT**	**S.D.**	**Average ΔT**	**S.D.**	**Average ΔT**	**S.D.**
(2-1)	3.46	0.75	1.15	0.59	1.73	0.74
(3-1)	-2.32	1.10	-7.00	2.03	-0.43	0.84
(4-1)	-3.27	1.43	1.21	1.03	0.57	1.59
(5-1)	-2.98	1.17	-0.95	0.48	0.33	1.11
(6-1)	0.57	0.68	-0.44	0.54	1.50	1.25
(7-1)	1.48	0.64	-0.16	0.43	0.81	0.69
(8-1)	2.01	0.87	0.62	0.76	1.44	0.99
(9-1)	-2.86	1.04	0.54	0.97	0.09	0.87
Relative Humidity	Avg%	S.D.	Avg%	S.D.	Avg%	S.D.
RH 1 out	53.70	4.11	43.70	7.49	58.99	4.55
RH 2 inside	40.16	2.18	44.04	4.64	55.06	3.41
RH 3 top	47.90	3.45	82.23	6.88	62.78	6.24
Solar Radiation[1]	Avg PAR uE	S.D.	Avg PAR uE	S.D.	Avg PAR uE	S.D.
S1	1198.00	98.76	1250.93	389.41	1102.36	293.53
S2	1220.31	112.97	1244.80	394.31	1092.63	301.42

[1] Measured in PAR uE. PAR: Photosythetically Active Radiation

With the third roof open, but no misting system running, little temperature decrease is noticed within the structure, as seen in table 1. The average temperatures between 11a.m. and 3p.m. on the studied days of August 8, 9 and September 13 were 31.7°C, 30.1°C and 30.4°C respectively. As expected, the temperature within the greenhouse was greater than outside temperature. An average temperature difference did show a decrease as much as 1.2 °C at the opening of the top roof. This implies that there was light air movement, possibly being fresh air entering the structure at this point by means of wind. Below this opening (at sensors 5 and 9), although the temperature is higher than the control, the average difference is less than 1.2°C. This prompts an assumption that once the air enters the greenhouse, it falls along the left hand side. All other sensors read a noticeable increase of temperature within the structure, especially sensor 8 on the right hand side, where there may be stagnant air. Over 5.0°C increase of temperature was recorded on two of the test days. Such sensor data supports the fact that the natural ventilation augment cooling greenhouse does not function appropriately nor to its full potential without the misting system in operation, however the arched roof design does provide a little air movement.

As seen in table 2, once the misting system is operational, a more significant temperature decrease is noticed between sensors. The average temperatures between 11a.m. and 3p.m. on the studied days of August 24, 28 and September 6 were 30.8°C, 28.5°C and 30.8°C, respectively. The average temperature decrease at the opening of the third roof was between 2.3°C and 7.0°C, showing a heavy air pull at the said opening. The temperature differences at the base of the airflow space (sensor 5 and sensor 9) was on average between -3.0 and 0.3 °C, and -2.9°C and 0.7°C, respectively. The greater temperature differentials being noticed on the warmer day, implying that the warmer the conditions, the more effective the system is at cooling. The temperature readings at sensors 6 and 7, just below the middle roof and at the base of of the bottom roof, were very similar to the outside. Both show an average range in temperature differences of -0.4 to 1.5°C and -0.2 to 1.5°C; exposing a less significant, but noticeable cooling effect. This shows air movement in the structure along the right hand side of the structure, in addition to the left hand side. Just above the base of roof 1, sensor 9 also shows minor air movement. The temperature decreased by as much as 2.9°C, when compared to the control. The average temperature difference at sensor 8 is not significant and could once again further imply stagnant air at the lower right hand side of the greenhouse.

9.2 *Approach for Prototype 2*

Upon analysis of the relative humidity data taken both on misting and non-misting days, some data suggests that this NVAC method reduces the relative humidity of the cool falling air in the side-space, therefore counterintuitively reducing the overall relative humidity in the greenhouse. For instance, 50.70% RH was measured outside, compared to 40.16% RH inside and 47.90% RH at the top roof opening on August 24. This demonstrates how there may be a humidity exchange occurring between 2 masses of air in the side space; this phenomenon is explained in section 9.2 Approach for Prototype II.. The misting of the warm air causes some of the newly humid air to actually further rise in the side space, as opposed to immediately falling. This forces humid air to mix with the warm rising air from the greenhouse room, and allows it to escape from the top roof opening, as can be suggested in the data with the 47.90% RH measured. On the other hand, some dense cool air resulting from the misting will fall down the curvature of the first roof and collapse in the greenhouse main area, while dumping humidity along the way into the mass of warmer air rising above it. Figure 7 shows a schematic of this proposed process. This method of misting becomes a mild conditioning system of some sort, given that it reduces air temperature and keeps the relative humidity of the greenhouse air at par with the outside RH, or in some cases even lowers the RH. Although still an observation, further testing with sensors on the second prototype shall be done and more data will be taken in order to further understand the process and pinpoint the quality of the air in the side space and in the greenhouse main area.

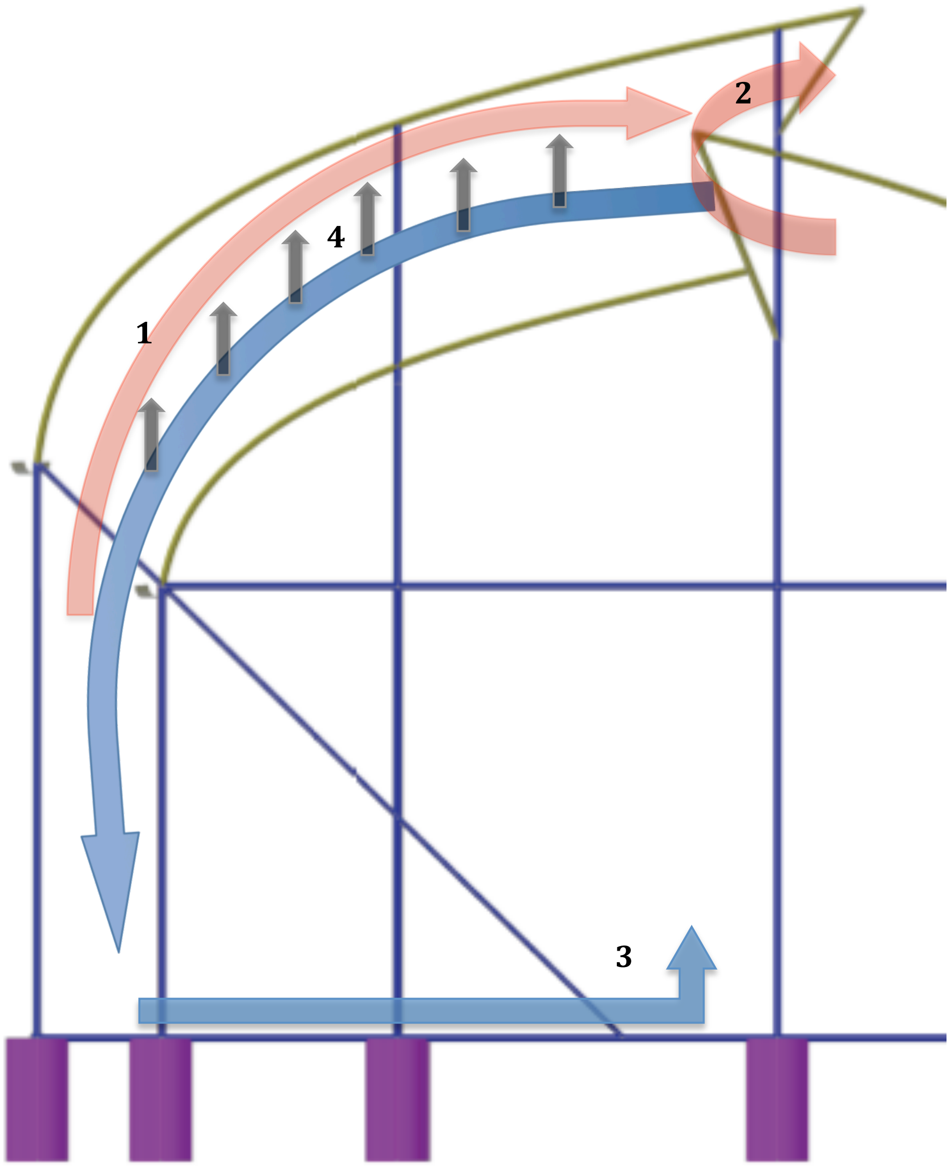

Figure 7 Possible convective movement of air in 1,2 and 3 and humidity transfer between air masses in the side space in 4.

10. EFFICIENCY AND ECONOMICS

10.1 *Efficiency*

The second NVAC greenhouse prototype to be built is to have the dimensions of 9.0m wide, 12.1m long and a maximum of 5.5m in height, considering the top roof. According to standard greenhouse design with fans, an air exchange of 20 000 cubic feet per minute is necessary to ensure optimal plant growth (see calculations below). With this air exchange in mind, a certain set of fans is required. 4 variable speed louvered exhaust 24in diameter fans with a capacity of 6487-2400 (at maximum and minimum capacity respectively) cubic feet per minute each are required to guarantee an air exchange of 20 000 cubic feet per minute (AFC Greenhouses).

- Each fan of this size costs roughly $299.00
- Aluminum frame
- 0.5HP each, 110V and 4.8 amps
- Conversion of 1 horsepower = 745.699872 watts
- Consumption per fan per year:

$$Bottom\ volume: 8m \times 12.1m \times 4.3m = 416.24\ m^3$$

$$Top\ volume: \frac{\pi(2.6)^2}{2} \times 12.1 = 128.48\ m^3$$

$$Total\ volume: 416.24m^3 + 128.48m^3 = 544.72\ m^3$$

For the purpose of this calculation, this value of 544.72m^3 per second will be converted and rounded to 20 000 cubic feet per minute.

$\boldsymbol{Eq. 1}$

$$kW\ consumed = \frac{0.746 \times rated\ HP}{eff\ (\%)}$$

$$kW\ consumed = \frac{0.746 \times rated\ HP}{eff\ (\%)} = \frac{0.746 \times 0.5}{0.96} = 0.3885$$

$\boldsymbol{Eq. 2}$

$$kWh = kW \times hours/day\ used \times days/year\ used$$

$$kWh = 0.3885 \times 6\ \frac{hours}{day} \times 365 \frac{days}{year} = 850.8\ kWh\ per\ year$$

$$850.8\ kWh = \frac{3600J}{Wh} \times 1000 \times 850.8\ kWh = 3MJ\ per\ year$$

$$3MJ\ per\ year \times 4\ fans = 12MJ\ energy\ per\ year\ to\ run\ 4\ fans$$

The misting system pump uses a small electrical motor, rated at 87.6 kWh per year, comparable to a 40Watt light bulb.

$$87.6\ kWh = \frac{3600J}{Wh} \times 1000 \times 87.6\ kWh = 315.4kJ\ per\ year$$

$$\frac{3MJ\ per\ year}{315.4kJ\ per\ year} \times 100 = 951\%\ difference\ in\ energy\ consumption\ over\ a\ period\ of\ 1\ year$$

As mentioned, our second prototype will include a relay system that will be able to control the rate of the misting system. The second prototype with a relay system will allow us to test the effectiveness of the system with intermittent misting. Moreover, if the relay system is connected to a HOBO weather station, if the weather conditions are cooler or simply unsuitable for the misting system, the system can be autonomously shut off.

10.2 *Economics and Cost Analysis*

A total of $8500.00 CAN is a cost estimate for materials to build this second prototype. Because this second prototype is to be built in Trinidad, at he UWI Campus, a cost estimate was done for the entire project, assuming Polina Fateeva and Lucas McCartney, with the help of Dr. Mark Lefsrud, will be constructing. The total cost, including materials, transport, stay and labor is shy of $30 000.00 CAN. Refer to appendix 4 for total and detailed cost breakdown. A Gantt chart for the schedule of construction is provided in appendix 3. Construction is to start in May 2013.

11. CONCLUSION

An alternate arched roof design promoting natural ventilation coupled with misting augment cooling system provides a cooling effect. The average temperature decrease at the opening of the third roof at sensor 3 was between 2.3°C and 7.0°C on trial days with the misting system running. Cooling was barely noticeable or non-existent on days with the misting system not functional. More data must be collected to study the air movement and cooling effect of the NVAC greenhouse. The prototype will be built again for the 2013 summer months. Following this current study, improvements in design and testing are to be considered. A more solid structure needs to be built to ensure the prototype survives strong winds and more sensors need to be placed in the side space area to further explain the air movement and humidity effects in the structure. If optimized, this design will be vastly beneficial for agricultural production in tropical regions.

We were very blessed and lucky to be able to successfully present our design at the 2013 Quebec Engineering Competition on Chicoutimi and at the 2013 Canadian Engineering Competition in Ottawa. The project earned 2nd place in Innovative Design at the QEC and earned a special mention award for Environmental Awareness. The project has been accepted by the Forces Avenir Award and will be presented at the McGill internal Forces Avenir competition on the 24th of April 2013. Lastly, we will be presenting the project at the 2013 ASABE International Meeting, in Kansas City Missouri, on July 24th, 2013.

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13. APPENDICES

APPENDIX 1. DESCRIPTION OF SENSOR PLACEMENT

1. Outside temperature sensor (serial 9701946). 1m off the ground. 5m away from corner of greenhouse.
2. Main room temperature sensor 1, (serial 9952171). 1.6m off the ground. Left-hand side with respect to the center point of greenhouse.
3. Top roof air inflow area temperature sensor. Highest placed sensor (serial 9701949). Placed at the edge entrance of the inflow of air.
4. Upper air-flow space temperature sensor (serial 9952175). Top part of the area between roof 1 and roof 3.
5. Lower air-flow space temperature sensor 1, (serial 9952170). Lower part of the area between roof 1 and 3.
6. Mid-roof temperature sensor (serial 9952176). Placed on the ridge of the second roof.
7. Main room temperature sensor 2, (serial 9952174). 1.6m off the ground. Left-hand side offset from the center of greenhouse.
8. Main room temperature sensor 3, (serial 9952168). 1.6m off the ground. Right-hand side with respect to the center point of greenhouse.
9. Lower air-flow space temperature sensor 2, (serial 9956048). Lower part of the area between roof 1 and 3.

There were 3 RH% sensors. One placed outside with the temperature sensor (#1), one placed at the top roof inflow (#3) and one placed at the lower air-flow space (#5).

N.B. All sensors were fitted with an aluminum foil sun radiation protector to help reduce heating of sensors due to sunrays.

APPENDIX 2. SENSOR PLACEMENT

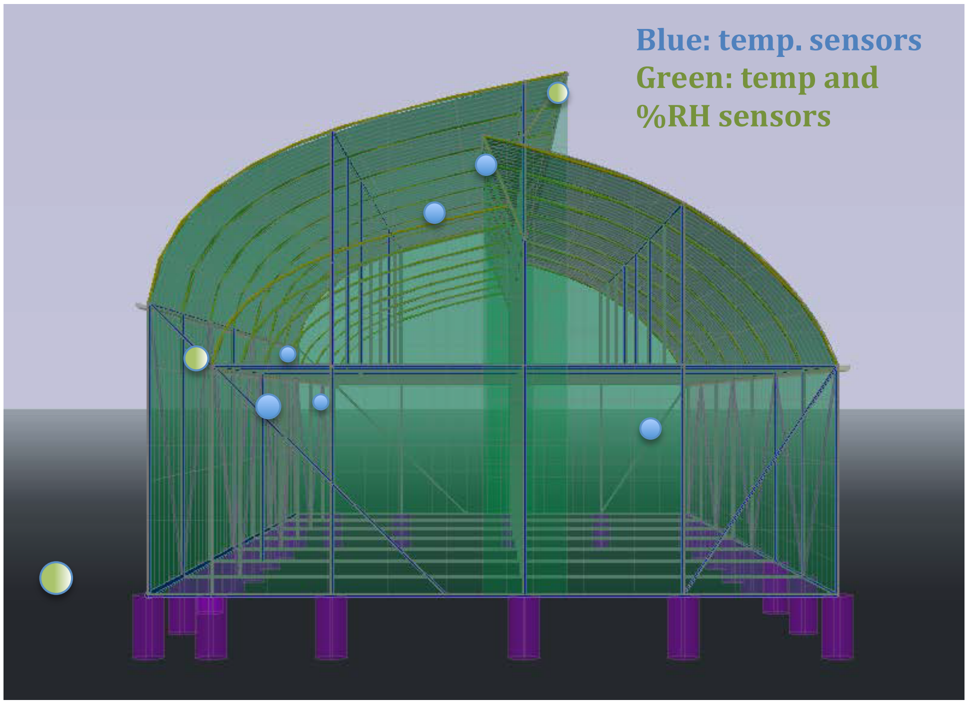


Figure 4 Side view of roof arrangement with sensor placement

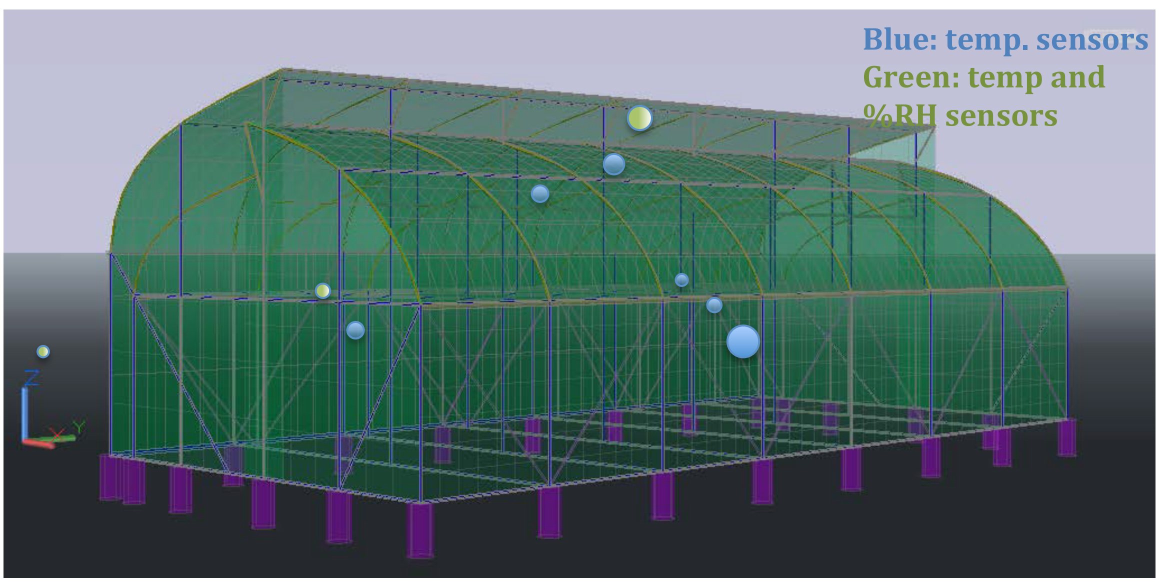


Figure 5 Angled view with sensor placement

Blue: temp. sensors
Green: temp and
%RH sensors

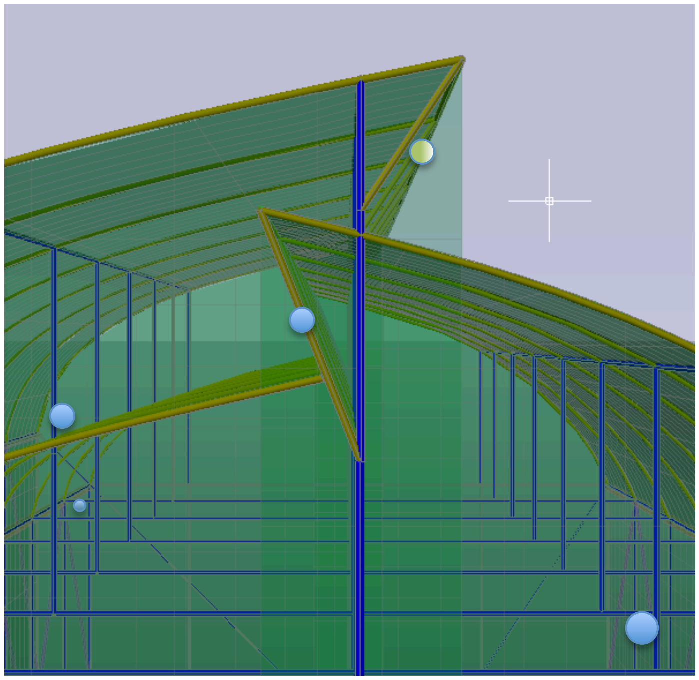
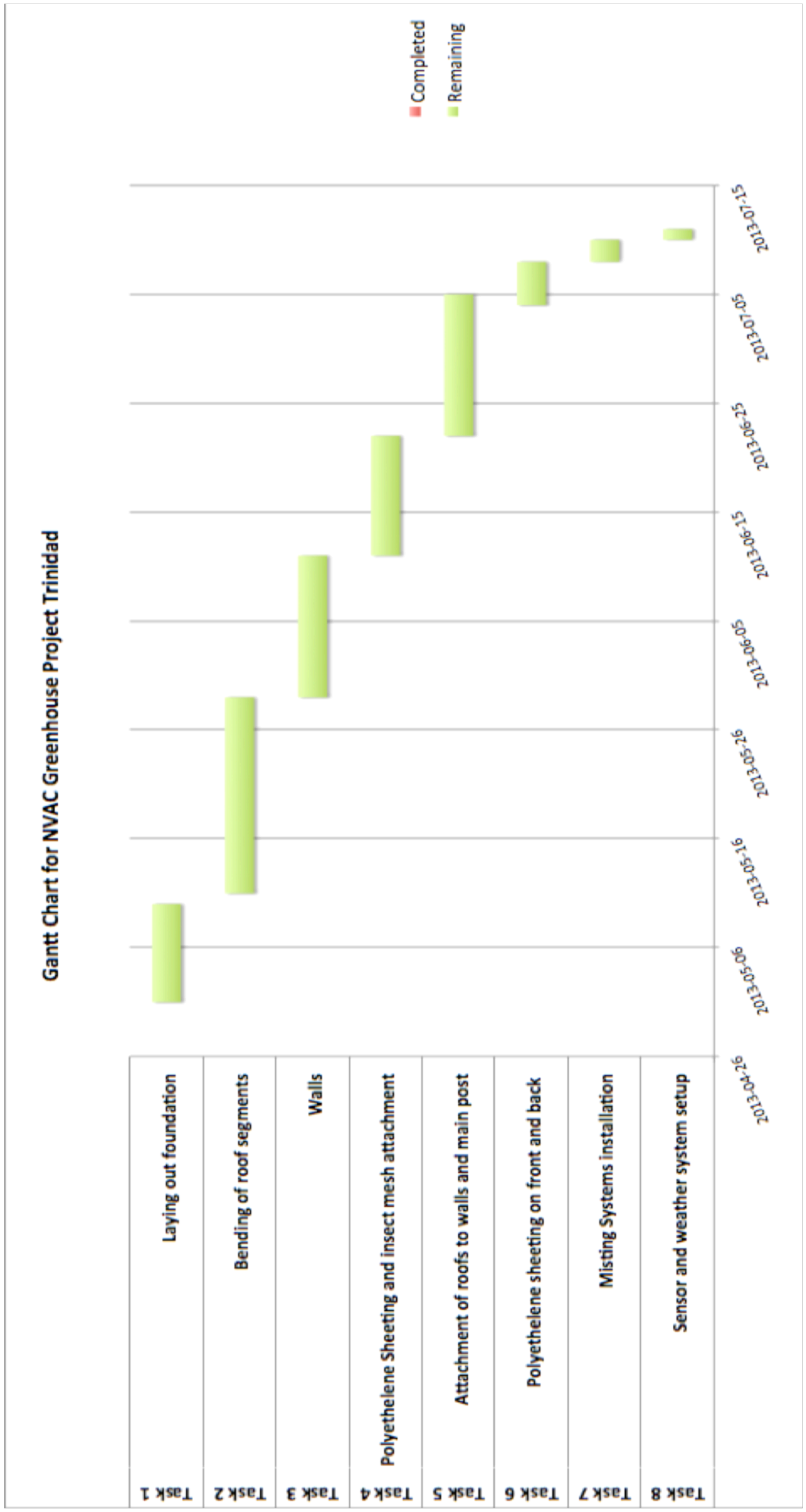


Figure 6 Alternate structure with sensor placement

APPENDIX 3. TIME FRAME FOR CONSTRUCTION SUMMER 2013



APPENDIX 4 MATERIALS AND COST SPECIFICS

Table 3 Lengths of Various Materials

	1" EMT Conduit		1" PVC	
	length in m	length in ft	length in m	length in ft
Base	27.5	90.2	0	0
Middle support	52.5	172.2	0	0
Arcs 1	11.4	37.392	7.6	24.928
Arcs 2	13	42.64	12.26	40.2128
Acrs 3	13.2	43.296	8.8	28.864
Front/Back	14.5	47.56	0	0
Side	53.5	175.48	10.7	35.096
Totals	185.6	608.768	39.36	129.1008
In 10 ft seg		60.8768		12.91008

Table 4 Cost Breakdowns

Building Materials	**Amount**	**Cost per Unit**	**Cost per unit TRINIDAD**	Total CAD
Gravel bags of 30 kg	6 bags (3 cubic feet)		$400 a yard	
concrete/foundation of 30 kg bags	60 baggs (30 cubic ft)	10		600
jig:				
Adjustable C-clamp	5	20		100
Wood: 2x12 16'	5	14.79	**375**	**73.95**
Gorilla glue 18 oz for wood	1	26	$50/quart	26
Hammers	4	10	**35**	**40**
Nails (2000)	1	10	15/ BOX	10
Screws	1	10	20cents/screw	10
U-bolt	30	5		150
Drill (Dewalt, cordless, set)	1	149	**995**	**149**
Sonatube (concrete) (10" by 12' long (48 Ft total)	4	21.84		87.36
EMT conduit pipe 1" 10 ft long	60.8768	11.28	$12/10ft	686.690304
PVC 1" (10 ft long)	12.91008	1.73	$65 (high perssure) or $40 (regular)	22.3344384
Polyethylene tape	2	15		30

polyethylene sheeting (20x25) semi clear white mcmaster	$56 & $78	one 20 by 50 & one 20 by 100	$350 a roll - 100 ft by 10ft wide	134
Wiggle wire (8 foot piece Puckett Greenhouses)	52	8.16		424.32
Insect screening (138") per foot	22	2.5		55
PVC cutter	2	15.99	95	31.98
Jig saw	1	120	795	120
Hack saw	1	30	75	30
Misting system (can bring from mac)				
bolts 2" (pkg of 25) (mcmcaster)	7	11.42		79.94
nuts (pkg of 28) 1/4" wide	7	7.11		49.77
PVC cross joint 1"	20	2.35		47
washers (pkg 100)	2	5.21		10.42
Water filter				
Hose pipes				
Research Materials				
HOBO (U12 Temp/RH/Light/External Data Logger)	2	125		250
Sensors				
temperature/RH (8m)	16	193		3088
Solar Radiation (3m)	3	220		660
HOBO weather station starter kit	1	1399		1399
pump	from mac campus			
air speed kit: Airspeed Kit with MPXV7002DP (3D robotics)	2	24.95		49.9
Smoke candles (3 minutes, pkg of 12; mcmaster)	2	9.26		18.52
relay- program				
		Total:		2967.764742
Absolute Total:	**27123.18474**			**8433.184742**

Labour	Amount		Cost
Lucas			1900
Polina			1900
Living L&P ($/day)		25	2250
			540
Travel	details		
Lucas	round trip		650
Polina	Mtl- Port of Spain		650
Lefsrud			1300
Car			1500
stay	details		
Polina	Holiday Inn: 151.52/Night for 2 queen beds		4000
Lucas	residence for 1 semester ~4000		4000
	Total:		**18690**