Bio-Inspired Design for Ventilation of SBS West

Northern Arizona University

March 15, 2019

BIO-INSPIRED Energy Efficiency- 18F16

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DISCLAIMER

EXECUTIVE SUMMARY

The Social Behavioral Sciences (SBS) West building at the Northern Arizona University (NAU) mountain campus is not up to the ventilation code standard for modern buildings and is inefficient with its annual energy usage, with heating and cooling being a major factor of consumption. The Bio-Inspired Energy Efficiency (BEE) team is to develop an electro-mechanical system to bring SBS West up to ventilation standards and reduce its energy consumption through analyzing the natural world. The team will use a pre-existing Solar Ventilation design developed by members of the team to implement into SBS West. The design will be paired with the current HVAC system to improve efficiency of the system as a whole, along with fulfilling the ventilation standards. The system involves using adjustable vents and solar panels to generate electricity using natural air and the sun. For ventilation, the system utilizes motors and/or temperature dependent components to expand and contract the panel based on the ambient temperature and the temperature inside of the building. The outcome of the system is to ease the use of the current HVAC system, generate addition electricity to aid the current system and bring the building up to current ventilation standards. Additionally, the ventilation and solar array will ease the cost of the system's implementation. The process of determining this final design includes preliminary research, project management, understanding the issue presented, concept generation, analytical calculation, cost analysis, resolving potential ethical issues, prototyping and future work. Presented in the following document is the process that was followed to reach the Rooftop Ridge Ventilation Housing to replace the current system installed at SBS West.

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1 BACKGROUND

In this section background information, motivation for the project and details of the processes taken by the team to generate the final design are laid out. The processes used to generate the final design are separated into sections which depict, in detail, the steps taken for each process.

1.1 Introduction

The Bio-Inspired Energy Efficiency (BEE) team was tasked with making Northern Arizona University's (NAU) mountain campus more energy efficient. The team decided to focus on Heating, Ventilation and Air Conditioning (HVAC) systems, specially focusing on the Social and Behavioral Science West (SBS West) building. This building was selected because it is not up to code with current ventilation standards and the current HVAC system in the building is outdated and energy inefficient. The client for this project is Jon Heitzinger, whom coordinates with NAU facilities maintenance to assist in resolving issues such as code violations and energy inefficiencies. Any steps taken towards the completion of this project will be reviewed by the client. Upon meeting with the client on September 28th, 2018 it was decided that ventilation was to be the focus of this design project. Upon completion of this project, documentation of the project will be provided to the client and professors for evaluation, along with a presentation. Finally, a presentation will be given at NAU's Undergraduate Symposium to communicate all findings regarding the final design, and to provide a networking platform.

This Project was motivated by the need to increase energy efficiency. Universities have a substantial amount of buildings, which makes HVAC systems a vital factor when analyzing a University's energy consumption and efficiency. With Northern Arizona University (NAU) mountain campus being located at 7,000 feet and experiencing all seasons, HVAC systems are important and necessary. Through studying the effects of equipment size, surrounding environment, and fiscal impacts using thermodynamics, kinetics, and economics, an innovative design with efficient power and heating can be produced. Outdated HVAC systems are costing NAU financially and environmentally. By improving or redesigning current HVAC systems in older buildings, such as SBS west, through modern concepts and designs, NAU can resolve these costs by reducing annual expenses and their carbon footprint.

1.2 Project Description

In this section, an updated problem statement is provided. The team was tasked to find ways to bring SBS West to the proper ventilation codes and increase the energy efficiency at Northern Arizona University (NAU). Additionally, the team has set a goal to use aspects of nature to inspire designs.

The NAU Mountain Campus has buildings which are not up to the proper ventilation codes and are inefficient with their energy consumption. Northern Arizona University has buildings on campus that are over 100 years old. Some of these buildings still have systems from the mid-1900s, which have been deemed energy inefficient, compared to modern technology. Jon Hitzinger, our client and a stakeholder, has tasked the team with reducing the energy consumption of SBS west by bringing the building up to ventilation code. He assigned the team to construct an electro-mechanical solution that would provide the building with present day standards.

1.3 Original System

Based on an audit that the team was provided, the HVAC system in SBS West currently runs off pneumatic systems that runs constantly, all year to keep the temperature of the building at a constant temperature of 72 ℉. To allow outdoor air to enter the building, a pneumatic motor controls the position of dampers to regulate the intake of outdoor air. During the summer, these dampers are fully closed to retain the air inside the building and open during the spring to allow for ventilation of the building [1]. The pneumatic motor can be seen in figure 1.

Figure 1: Pneumatic Motor

1.3.1 Original System Performance

Currently, the SBS West buildings ventilation does not work. As a result, the building does not meet proper ventilation standards. The buildings ventilation system consists of exhaust/relief vents along with intake vents. The vents are located on the top of the building with a ridge covering them to prevent debris from falling in. The intake vents are located on the south side of the building while the exhaust/relief vents are located on the north side of the building. Figure 2 shows the blueprints of the intake and exhaust/relief vents of the building. Figures 3 and 4 display how air is taken in and exhausted in the SBS West building.

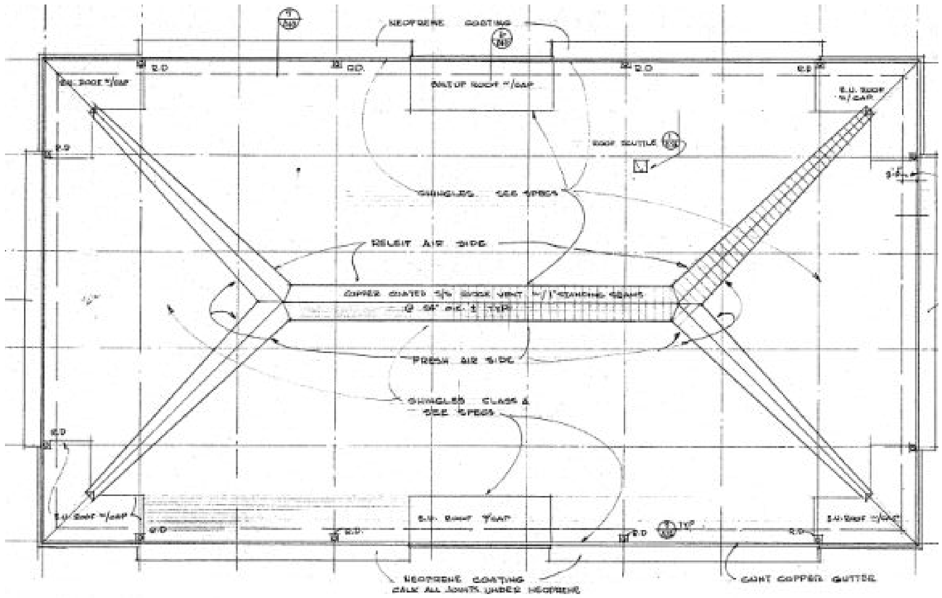


Figure 2: Intake and Exhaust/Relief Vents

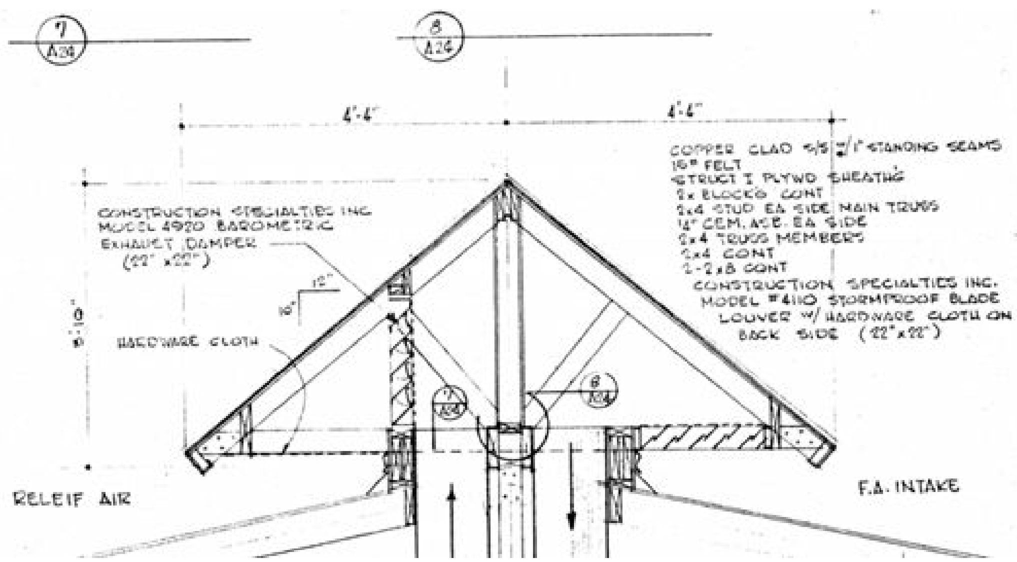


Figure 3: Blueprints of the Air intake and Exhaust on the ridge of SBS West

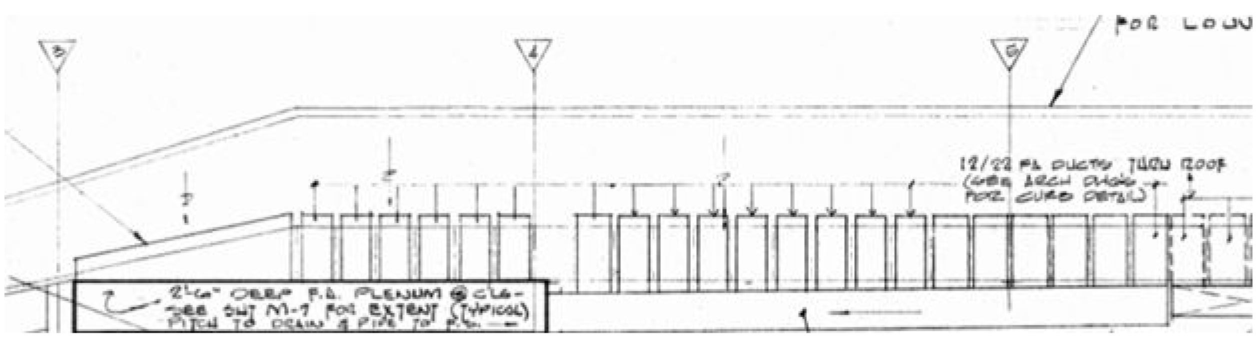


Figure 4: Blueprints of a Section of the roof displaying a side view of the ducting of the Intake/Exhaust.

1.3.2 Original System Structure

The HVAC system that is currently installed in SBS West is fully integrated into the building. The first floor HVAC intake and air handler is housed in a mechanical room on the first floor. The second and their floors system is housed in the attic of the building. In the attic is where all the exhausting air is collected in the plenum before being exhausted out of the vents in the ridge of the of the building’s roof.

2 REQUIREMENTS

Given the project description the team was able to generate customer requirements and engineering requirements. These were then used to create a house of quality model to compare the requirements. Additionally, design solutions for HVAC systems were found and benched marked versus the customer requirements.

2.1 Customer Requirements

The customer requirements are a list of wants and needs based on the requirements of the client and problem statement. These requirements are given in no specific order.

1. **Must be bio-inspired:** The system must incorporate aspects of a bio-inspired design. Ideas can be taken from how nature works an incorporated into an engineering design.
2. **Must increase energy efficiency:** The system must reduce the overall energy consumption of the building resulting in an increase in energy efficiency.
3. **Must decrease pressure in building:** The system must relieve the excess pressure within the plenums of the HVAC system currently in SBS West.
4. **Must be able to exhaust air:** The system must be able to exhaust air in the building.
5. **Must provide the same services as the current system:** The system must provide the same heating and cooling as the current system. It must have the same inputs and outputs as the current system.
6. **Must be easy to maintain (Durability):** The system must be easy to perform maintenance and repairs when needed.
7. **Must be space efficient:** The system must not take up more space than the current system.
8. **Must have adjustable times:** The system must be able to turn on and off depending on the demand times for heating and cooling.
9. **Must be safe:** The system must be safe to use and safe for the public.
10. **Must bring building up to code:** The system must bring the SBS West building up to it's ventilation code.
11. **Must be durable:** The system must last a number of years with minor maintenance to the ventilation.
12. **Must reduce the temperature of the building:** The system must be able to bring down the temperature of the building to a temperature of 72℉.

Each customer requirement was weighted on a scale of 0-100% based on its importance. The higher the weight, the more important the customer requirement was. The most important customer requirement is having the system being bio-inspired and increasing the energy efficiency of the SBS West building. The weights of each customer requirement is shown in table 1.

Table 1: Customer Requirements

Customer Requirement	**Weight (%)**
Must be bio-inspired	15%
Must increase energy efficiency	15%
Must decrease pressure in building	10%
Must be able to exhaust air	9%
Must reduce the temperature of the building	9%
Must be durable	8%
Must be easy to maintain	7%
Must be safe	7%
Must bring building up to code	7%
Must provide the same services as the current system	6%
Must be space efficient	4%
Must have adjustable times	3%

2.2 Engineering Requirements

The engineering characteristics are derived from the customer requirements that include quantifiable statements.

1. 5-year payoff estimate (5 years): Depending on the total cost of the system, it must provide a financial saving based on the consumption of energy on the building. This is again not including some aspects of the design because meeting the ventilation codes are more important than the cost.
2. New Thermal output = Old thermal output (72 ℉): With the amount of consumed energy being reduced, the new system's thermal output must be equal to the old system's thermal output.
3.Energy efficient (EER): The system must increase the energy efficiency of the building by reducing the amount of energy being used.
4. Size <= Current size (ft^3 *or* m^3 **):** The size of the new system must be equal to or less than the size of the old system.
5. Easy to repair/ replace parts and check systems (Durability): The system must be able to provide easy maintenance and repairs to ensure proper functioning of the system.

6. Temperature Management (℉): The system must be able to control the temperature of the building to ensure a comfortable work environment for people in the building.
7. System runtime (turn on and off): The system must be able to turn off and on depending on the demands of heating and cooling of the building. Energy must not be wasted when there is not a need to heating or cooling.
8. Display usage (℉ and kWh): The system can display how much energy is being generated and used while also displaying the temperature of the building.
9. Mechanical system/ Bio-Inspired: The system must be mechanically engineered with bio-inspired design incorporated into the design
10. Must be Reliable: The system must be able to produce the same efficiency and ventilation for 15 to 20 years.

The engineering characteristics where then given measurable values which we then later compared to the system developed or the were analyzed to ensure these requirements were met. These target values can be seen below in table 2.

Table 2: Engineering Characteristics and Target Values

Engineering Requirement:	**Target Values:**
5-year Payoff	<5 years
New Thermal Output = Old Thermal Output	Maintains (=) 72 ℉
Energy Efficiency	Seasonal Energy Efficiency Ratio (SEER): 13 to 21
Size<= Current size	Compatible with 22” x 22” venting area
Durability	Can operate 24/7 with regular maintenance once a month
Temperature management	Desired temperature(72℉) = Operation temperature (72℉)
System Runtime (turn on and off)	24/7, unless manually shut off
Display Usage	℉ and kWh
Mechanical System/ Bio-Inspired	
Reliability	Last 15 to 20 years

2.3 Testing Procedures

Once the engineering requirements were set, testing procedures to quantify their success were established. Presented below are the testing procedures for each engineering requirements.

2.3.1 5-Year Pay off

To ensure that the system will pay off in five years, a series of calculation will be conducted. The proposed energy reduction based on the team's design will be analyzed using; the current electric bills, estimated reduction in electric bill due to the HVAC operating more effectively, money saved by the production of solar energy, and the air quality of the building and the improved environment inside the building. These will all be assessed to see if a five year pay-off is both monetary and in the health and safety it occupants. This decision will be made by the client.

2.3.2 Equivalent Thermal Output

The thermal output of the new system needs to be that of the old system. Using the proposed final design a thermal analysis will be conducted to ensure the temperature of the building is held at a constant 72 °F (equaling the temperature of the previous system). This will be done with the electric bill and IRT(Infrared thermometer) temperature measurements inside the building making sure each rooms temperature is the same without increased electricity usage. Additionally, due to the design the team is developing being a ventilation system, the system will be analyzed to see how increased ventilation affects the temperature of the return air of the system. This will be done using methods of finite differencing in MATLAB.

2.3.3 Energy Efficiency

The system needs to increase the energy efficiency of the building. The electric usage of the building will be recorded, and the estimated energy usage of the new system will be analyzed against each other to see if there is a reduction in energy usage. Energy consumption of the new system will be estimated and then compared to that of the current system. Additionally, any adaptations, such as solar arrays, will be analyzed to calculate the energy which is going back to the system. This will be done using a solar PV analysis.

2.3.4 Size

To redesign the HVAC system the new system must not be intrusive to the buildings function. Its current space consumption inside the building needs to be retained or reduced. Final designs will be measured for volume and impact to the buildings occupants. The client will deem a system too big or too intrusive to the building and its occupants.

2.3.5 Easy to Repair and Replace Parts

The ease of repair or replacement to the new system is a qualitative metric but can be expressed in hours to complete tasks of repairing the system. The team will simulate repairs that could potentially be done and record the time taken for each repair. The times will then be presented to the client to be deemed satisfactory.

2.3.6 Temperature Management

Temperatures in the building will need to be controlled in some manner. The team will use IRTs to take temperature measurements of a simulated building and see the response of the temperatures when the system is activated or implemented.

2.3.7 System Run Time

The system needs to have the ability to turn on and off. When the design is created, the team will determine if the system can turn on and off automatically based on the demands of the HVAC system. This will be done by generating a code which uses a series of conditions which are dependent on the variables which control the HVAC and elapsed time of the system. These variables include but are not limited to; the temperatures inside and outside the building, the pressures inside and outside the building, the humidity inside and outside the building, and the current HVAC measurements.

2.3.8 Selective Heating and Cooling

As seen in section 2.3.6 the system will be simulated with being active and or adjusted to see the effects in temperature. Temperature measurements will be taken by IRT to determine if the system can change temperature as desired. Due to the description of this project being changed, the team may not have control over whether selective heating and cooling will be an option.

2.3.9 Display Usage

The system will attach a computer display to the system to track the energy usage of the system and the energy created by the solar panels. This information will be used in other tests to determine the efficiency of the system and system pay off.

2.3.10 Mechanical System

The design must be mechanically designed and bio-inspired. This will be tested by having the approval of the client that it is indeed a bio-inspired mechanical system.

2.3.11 Noise Pollution

Once the design is constructed the system will be ran with a decibel meter to determine the amount of noise produces and then compare the findings to the standards for noise pollution which commercial buildings are to meet.

2.3.12 Solar Simulations

To find the optimal solar design, the System Advisor Model (SAM) will be used to simulate multiple scenarios of the solar panel design. With the SAM software, financial calculations will be made to see the annual energy production, levelized cost of energy (LCOE), net present value (NPV), and the payback period. With these values, it will indicate if the solar panel design is a good idea to implement into the system or not.

2.4 House of Quality

The Quality Functional Display (QFD), is a form of House of Quality and seen in Appendix A figure A.1, whose main job is to show the relationships between the customer requirements and the engineering characteristics by using a 9-3-1 scale, nine being most and one being the lowest significant impact. Each of the customer requirements has a weighted score from 1-5, one being the least important and five being the most important, which are then multiplied by the designated relationship scale. This is to show the overall importance of each engineering requirement. Along with creating these weightings, the QFD compares how the engineering characteristics compare against each other by showing positive and negative impact (-- largest negative impact and ++ largest positive impact). Finally benchmarking takes products on the market and compares them with the customer requirements showing how well they work. The QFD is a useful tool in any design project because it gives the team an idea on what they should and should not do.

After comparing the customer needs to the engineering requirements, it was found that the mechanical system/Bio-inspired was the most important. Therefore, the design, which was developed was a mechanical system, along with having a bio-inspired aspect. The next aspect which was found to be the most important was the energy efficiency of the design. Meaning that the system which was designed is improving the energy efficiency of SBS west’s HVAC system. Using the QFD it was also found most of the engineering characteristics benefitted the other engineering characteristics in a positive way. This made sense due to all characteristics focusing on some way to improve the ventilation of the building, as well as energy efficiency. This allowed the team to fulfill requirements simultaneously. When it came to the benchmarking of other energy efficient HVAC systems, it was found that all of these systems were acceptable in fulfilling the customer needs or they excelled at it. This makes sense considering these systems were designed by professional engineers and that most current HVAC systems are designed to be energy efficient. Additionally, the team noticed the use of solar panels by a lot of different energy efficient HVAC systems. Which made the team feel more secure with the solar ventilation system designed.

3 EXISTING DESIGNS

With a better understanding about the requirements the design must meet, the next step was to research existing designs. This was to provide a way for the team to better understand the components needed for their design, along with understanding what kind of designs are used as HVAC systems.

3.1 Design Research

By improving or redesigning the current HVAC systems in SBS west with modern concepts/ designs, NAU can resolve these costs by reducing annual expenses and their carbon footprint. Before any improvements can be made, research about state of the art (SOTA) designs have been done and conveyed through this section. The team researched major components of energy efficient systems and key methods and techniques used to increase efficiency. This research led the team to evaluating solar panels, heat capture techniques, and unique ways to vent a space. The team's findings are presented below.

3.1.1 Data Furnace

Passive HVAC systems use nature or pre-existing systems to cool and/or heat a building to replace current HVAC systems. A current leading passive system is the Data Furnace [2]. These systems use subsystems to redirect airflow. This allows for the passive system to displace thermal energy throughout a room or building. Passive systems are known to be environmentally friendly and cost-effective. These systems do not have to generate additional thermal energy; however, this system can be unreliable and may struggle keeping a room or building at a consistent temperature.

3.1.2 Utilizing Pre-Existing systems

This design is a unique way to utilize a pre-existing system in a building to provide heating. Most commercial buildings have some sort of data center, which wastes a large amount of thermal energy. Although the exact design is still being designed, the way the design works is by redirecting the heat generated by data centers [2]. This concept has been interpreted in many ways, from single-room heating to building heating [2]. This design will overall reduce the waste of a data center and pre-existing HVAC systems.

3.1.3 Radiative Systems

Radiative system design uses thermal energy generated by the sun. However, a Radiative System explores the uses of the sun further. Additionally, the Radiative system fulfills the functions of an HVAC system.

3.1.4 Beyond Solar Panels

By using the circulation of heated fluid along with additional sub functions and ventilation the Radiative system can heat and cool to a user’s specification. This design heats and cools off buildings by using radiative panels (seen in Figure 5), which are panels that collects and amplifies solar energy to heat and pump fluid (e.g. water) throughout the building [3]. The pipes circulate the fluid through the floor, walls, and/ or the ceiling (depending on a customer's need or price range). Moreover, this design has a function, which cools down the fluid in the pipes, cooling both the building and the existing air conditioning (AC) unit [3]. Although this design is efficient and has radiative panels that can allow for lower airflow, this design does not meet the air ventilation and air quality standards [4]. Therefore, it should be accompanied by an all air AC unit. This design will optimize the ACs functionality resulting in an increased efficiency of the unit.

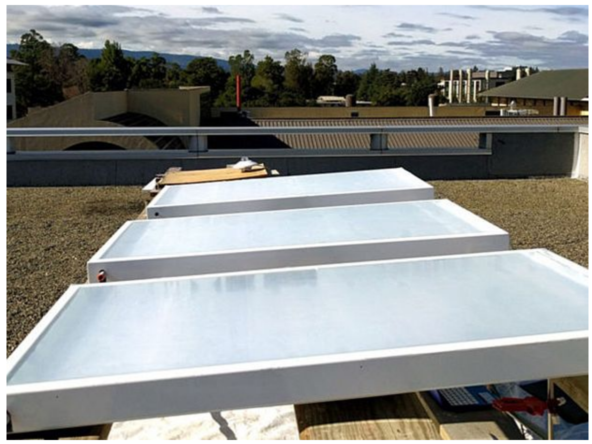


Figure 5: Radiative Panel with Ventilation Example [2]

3.1.5 Breathable Workout Suit

The Massachusetts Institute of Technology has designed a workout suit that allows for ventilation. There are vents on the workout suit that reacts to the temperature and humidity of the human body. Once the user has an increase in body temperature and humidity, the microbio cells in the suit expand and once the temperature and humidity of the user decreases, the microbio cells contract [5].

3.2 System Level

Due to the uniqueness of the project there are not many systems published on the internet similar to ours, but there are systems that correlate to separate functions of the overall system that would not be considered true subsystems. The three systems that will be analyzed are a photovoltaic solar panel, commercial ventilation system, and an active monitoring system.

3.2.1 Photovoltaic Solar Panels

Photovoltaic (PV) solar panels are the most popular form of solar panel on the market. They take solar energy and convert it to electricity using the photons emitted by the sun [6]. To produce a significant amount of solar energy for a commercial sized building an array of PV solar panels is needed. This is typically seen in the form of solar fields. PV panels are being implemented because they would aid in supporting the buildings load during peak hours of electrical use. The array would hopefully supply enough electricity to support the addition of the ventilation system.

3.2.2 Commercial Ventilation Systems

After research into the standard commercial ventilation system, it appears that there are four main parts the make up a commercial ventilation system, the filtration, the conditioning, and the distribution, and the removal of air [7]. In the filtration process air that is being deducted from the outside or the return of stale air from the building is filtered for air quality. Once the air is filtered it is then sent to be heated or cooled depending on the need of the building. Once it had been conditioned to the proper need of the building it is distributed through a series of ducts distributing the fresh air to the rooms of a building. Finally, once the rooms are in need of air circulation or a change in temperature then the old air is vented out of the room and is removed to be either filtered and conditioned or is exhausted form the building to the surroundings [7]. This standard format of ventilation will be used in the designing of the ventilation portion of the final design.

3.2.3 Active Monitoring Systems

Active monitoring systems are energy management systems that's purpose is to reduce the overall energy use of a building. The largest two uses of active monitoring systems can be seen in the monitoring of temperature and lights [8]. In the case of heating and cooling, temperature gauges are placed in various parts of the building constantly checking on the temperature. If one part of the building needs its temperature changed but others do not the system will direct the flow to that part of the building without having to hear or cool other parts of the building that do not need it. This significantly increases the energy efficiency of a building because energy is not waisted heating or cooling pats of the building that do not need it. This can be helpful in the design of the ventilation system if we can have the power to pick and choose what is heated, cooled, and ventilated then there would be an increase in energy efficiency.

3.3 Functional Decomposition

With a better understanding of the HVAC systems and overarching systems contained within the HVAC, a functional decomposition was done. First the problem was decomposed to allow for a better understanding of what is needed. From there the general function of the system was generated using a Black Box model and was then expanded into a hypothesized Functional model. This is not the actual Functional model because there are functions of the system that can't yet be determined. The models allow for a better understanding of how the system will overall function.

3.3.1 Problem Decomposition

Problem Decomposition is where one decomposes a complex problem into smaller solvable problems. There are two main types of Problem Decomposition, Functional and Physical (the Problem Decomposition for the team is represented in Appendix B: Figure B.1). Our complex problem is to design an efficient HVAC System and provided proper ventilation for Northern Arizona University (NAU) SBS West building. This complex problem can be broken down into smaller solvable problems such as provide heating/cooling, protect user and operator, reduce energy consumption and pays off in the long-term. One of the major functions of the proposed system is to reduce energy usage, which means to reduce emissions, reduce electricity and reduce the amount of fuel used for energy production. Providing heat/cooling requires that our system must provide the same services, controlled with ease, ventilated throughout the entire building and is able to maintain the desire temperature. Safety plays a large role in the decision-making process. The proposed system must be able to control the temperature, provide and maintain safe air quality and must be easily accessible. The system must be able to pay itself off within a four-year time span or prove to be cost effective, efficient with energy consumption and continues to save energy and money for NAU in the future.

3.3.2 Black Box model

The black box model is the most basic form of display that shows how system operates. Inside the “black box” is the objective of system. In the case of this project, that objective is to ventilate air and increase the energy efficiency of a building. On the left of the box there are the inputs of the system. Included in these are the materials, energy, and signals that the system is being driven off. In the case of this project the material input is the outside air which will be ventilated to the building. This process will be made possible through solar and electrical energy inputs to help deliver this outside air. This process will be guided by the signal inputs which are the outside conditions such as outside air temperature and humidity. Once the process is completed there will outputs from the system in the same form as the inputs. Clean air and stale air will be outputted as the physical materials. Electric energy will be produced and used because of the systems function. Finally, the outgoing signals of the systems will be displayed as new inside conditions for the building. This all can be seen visually in figure 6.

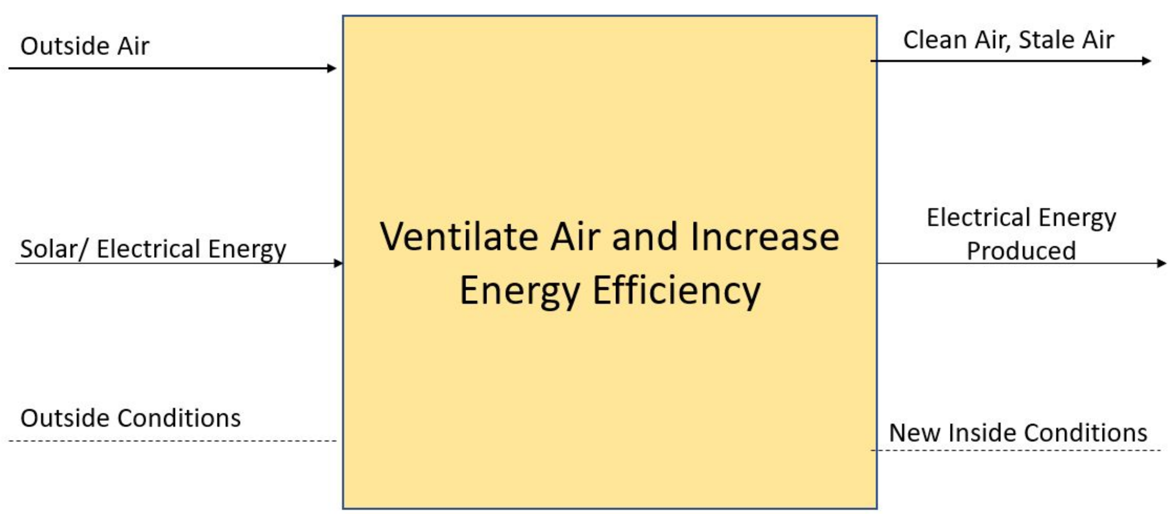


Figure 6: Black Box model of a ventilation system

3.3.3 Hypothesized Functional Model

Once the black box model was completed and the inputs and outputs of the system are classified, then the inside can be broken down which is classified as the functional model. In this breakdown the materials, signals, and energy are tracked through a series of subsystems that make up the complete system or process. In the functional model, seen in Appendix B: Figure B.2, we can track the outside air, electrical energy, solar energy, outside temperature, and outside humidity through the system and see how they change into the outputs of stale air, electricity, digital humidity display, and digital temperature display. The clean air is an output of a subsystem but does not physically leave the system. Outside air can be tracked entering the system and then being filtered and conditioned. Once conditioned it is then distributed around the building. The outgoing vents then collect the now stale air and either recondition it or remove it from the building. Electricity in used in the filtering, conditioning, distributing, and venting or removal of this air. Solar energy is collected and then converted into electricity via solar panels and is then integrated into the power grid. The outside temperature and humidity values are collected as signals. Once collected, they are evaluated to direct the system to actuate the ventilation process.

3.4 Subsystem Level

Once the functional model was created three subsystems of ventilation presented themselves as questions. How is the air filtered? How will it be collected? Finally, what is the method to complete this collection? Out of these questions came three subsystems which are: air filtration, Ventilation profiles, and Actuation methods.

3.4.1 Air Filtration

There are three main types of air filtration which our team decided to consider, and they are fiberglass air filter, polyester and pleated filters, and high efficiency particulate arrestance (HEPA) filters.

3.4.1.1 Fiberglass Air Filter

A fiberglass air filter is made of fiberglass material which is designed with small fibers which restricts dust from going through the filter [9]. There is an adhesive added to the filter to keep the fibers from air ducts. Additionally, it is called a “throw away filter” because they are cheap and have short life cycle. For maximum efficiency, manufacturers of these filters highly recommended that these filters should be replaced after 30 days of use.

3.4.1.2 Polyester and Pleated Filters

Polyester and pleated filters are made up from cotton, synthetic, and Polyester [9]. This is similar to the fiberglass air filter; however, polyester and pleated filters have high resistance of airflow and it is more efficient in stopping the dust from going in. Thus, for the maximum efficiency it should be replaced after three months.

3.4.1.3 High Efficiency Particulate Arrestance (HEPA) Filters

High Efficiency Particulate Arrestance (HEPA) filters are made up from small fibers that forces the particles to stop from going forward by three ways:

interception, impaction, or diffusion [9]. HEPA has the best type to purify the air from the microscopic particles and dust, such as, having the ability to remove the bacteria which its micrometer width is 0.3. Moreover, HEPA filter can prevent up to 99% of the dust that might go in the building.

3.4.2 Vent Style

There are many types of vent style in the market, however, the main three vent styles that our team have focused on are box vent, wind turbines, and ridge vent.

3.4.2.1 Box Vent

The box vent, which is also known as low profit vents, is designed for an open hole in the roof to vent the building and it should has higher impact once the box vent is installed as close as possible to the open hole in the roof [10]. Also, the box vent is static vents which implies it has no moving parts in the design.

3.4.2.2 Wind Turbines

Wind turbines are designed to have circular movement relying only on the wind power. This movement helps the wind turbines to produce cool air to the building and exits the heat from it [10]. Thus, this vent style does not have motors because it is only relying on the wind to move. Moreover, wind turbines are considered as a dynamic vent because it has the top parts moving in a circular way when the wind is in touch with it. Wind turbines are offered in variety of degrees of quality to satisfy different customer needs.

3.4.2.3 Ridge Vent

Ridge vent is inspired from an opened book which its face is down to the ground, that means it has a static design with no moving parts [10]. The length of the ridge vent is as the length of the roof in a horizontal way. Ridge vent provides an even distribution of temperature whereas the other vents designs create cold and hot zones in the roof. Most importantly, ridge vents do not rely on the wind, that means the changing in wind direction or speed does not affect the performance of ventilation.

3.4.3 Actuation Methods

There are three main types of vent actuation methods that the team researched or addressed based on their pre-existing knowledge. These were hydraulics, gear trains, and smart materials.

3.4.3.1 Hydraulics

Hydraulics are made up of three basic components, the piston, cylinder, and pump. The pump provides pressure to the cylinder creating the piston to extend or contract based on the pressure direction of the pump [11]. The pistons would be attached to the vents and would open and close them as directed form the pump. The accuracy and reliability of the hydraulic design is high, but the cost is all well making it hard to implement.

3.4.3.2 Gear Trains

Gear trains in conjunction with a motor is one of the more popular forms of increasing or decreasing the surface area of a vent. A electric motor would be attached to a gear train that would open and close vents in a torsional manner. The gear train is designed to each vent applications based on the size of vent its opening and the angular velocities on each end of the train. Different motors would be selected based on the torque and speed and would be controlled on a voltage input. The gear train would then transfer that torque and speed to vent which would open and close it [12]. This system like the hydraulics is very accurate in providing the right ventilation area and is simpler than the hydraulics which needs hydraulic fluid. The cost to operate and implement is less than that of the hydrologic making it more feasible for the application at hand.

3.4.3.3 Smart Materials

The final mode of actuation would be through a smart material. There are some materials for sale that expand in warm temperatures and contract when experiencing cold temperatures. Smart materials such as shape memory alloys can either contract or expand at lower temperatures, but can convert to their original shape when heated [13]. Implementing this into a ventilation setting is not a new concept but is one that is not being readily used currently. Further research into the exact material will be done to determine what will fill the need of the application. If chosen for the final design, then more research would be done as well to determine if using the material by itself is sufficient to provide the proper amount of ventilation or if another method in conjunction with the smart material. The largest upside to using the smart material rout for this project is that it will fulfill the bio inspired requirement that is present.

4 DESIGNS CONSIDERED

With a better understanding of the different subsystems and systems, various ventilation designs were generated. First, each member of the team was tasked to generate designs for the subsystems. The team then narrowed down, using methods mentions in figure C.1 in appendix C, the designs done independently to 16 complete subsystem designs. These designs were then categorized and used to create four complete system designs. This was done using a Morph matrix.

4.1 Design Category #1: Smart Material Actuation

This design utilizes a smart material which expands when its temperature increases and contracts when its temperature decreases. The design uses layering of a smart material and a material not dependent on temperature to allow for the desired expansion to be calculated. Figure 7 below is a subsystem design that was drawn up by a member of the team.

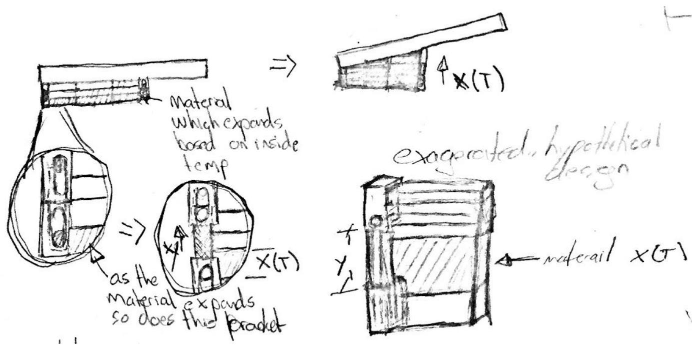


Figure 7: Actuation Using Thermal Smart Material

Figure 8 below, is a design developed by a member of the team which is similar to the previously subsystem design which used a smart material to actuate the vent. However, this design also uses a hydraulic arm to assist with actuation because it was assumed that the smart material itself would not be enough to lift the panel. This design’s hydraulic design would not only be actuated by a hydraulic arm, but the hydraulic arm was proposed to actuate using a function of the smart material’s expansion.

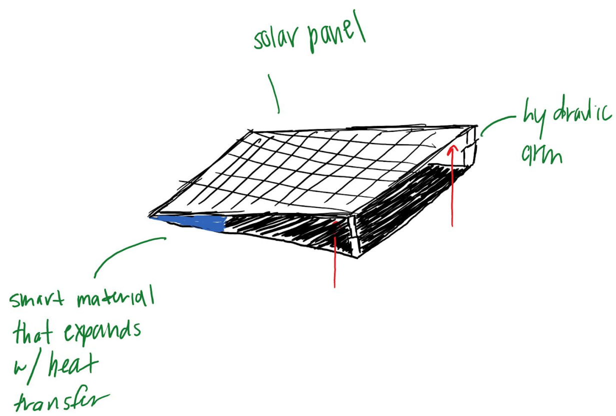


Figure 8: Panel Actuated by a Smart Material and Hydraulic Arm

4.2 Design Category #2: Vent Specification

Figure 9 below depicts two concepts for vents which are subsystems of the complete ventilation system. Number one uses vents on top of the panel and would be actuated by motors depending on the temperature and humidity of the inside and outside air. Number two is a design in which would be actuated by any sort of arm that would lift the panel from the building. Additionally, the design utilizes a net which would filter the outside air and any sort of debris like the way fish gills work.

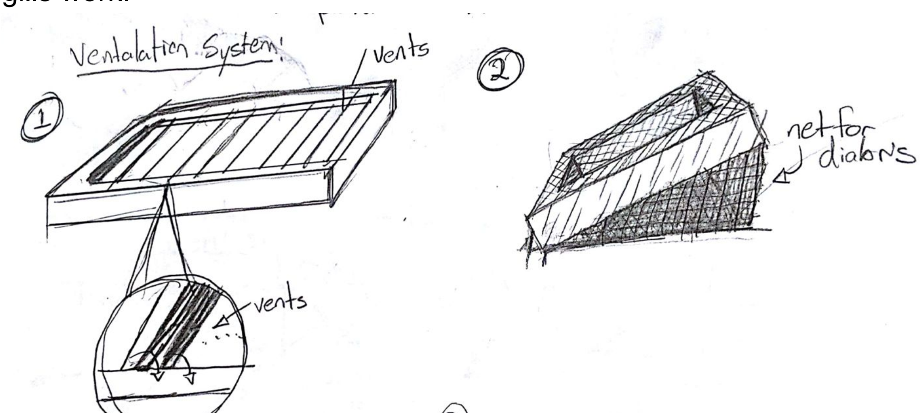


Figure 9: Sample of Vent Design

4.3 Design Category #3: Bio-Inspired Designs

Figure 10 below, is a design for vents for the ventilation system that was designed by a member of the team. They based their design on how flowers will rotate open or rotate closed based on the humidity and temperature of the ambient air. This design is bio-inspired and allows for the ventilation of the building to be controlled by an active monitoring system, which would analyze the humidity and temperature of the air inside and outside the building. This design would then (theoretically) adjust its diameter to meet the desired ventilation

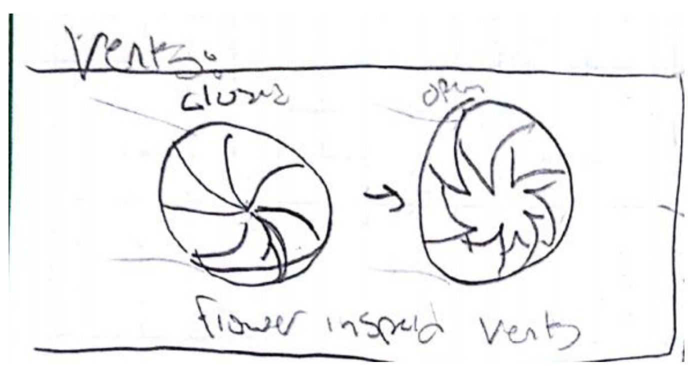


Figure 10: Vents Based on Flowers

In figure 11 below, the design depicted utilizes whale fins as blades for the fan for the ventilation system. This design was developed by a member of the team who used their knowledge about bio-inspired design and recalled that similar designs have modeled their designs after whale fins. Whale fins are known to be efficient when moving through a fluid and was hypothesized to be a way to effectively displace the air in or out of the building.

Figure 11: Fan Based on Whale Fins

4.4 Morphological Matrix Generation and Analysis

In Appendix C, figure C.1, is the Morph Matrix which was generated to provide a platform for the team to come up with complete system designs. The team choose four main subsystems to focus on, then four designs were chosen from those the team developed individually, for each subsystem. The four categories were as follows; vents, actuation, implementation, and Air economizer and/or filter. An air economizer can dampen (soften) the air, as well as filter, to meet the ventilation codes for commercial buildings. With these four complete systems, a list of their advantages and disadvantages are listed in figure C.6 in appendix C.

These concepts were either combinations or iterations of the team's original independent designs. These designs were then reformatted, for ease of comprehension. Additionally, once the morph matrix was developed the team choose subsystem designs or a combination of subsystem designs from each category to generate complete system designs. The team decided that they would be more focus on the designing of the subsystems and would only generate four final designs. This was due to the amount of systems which had to go into the ventilation system to meet the customer's requirements. Moreover, using a Morph Matrix allows for the team to easy replace a main component of the system by referring to a category of the matrix. Lastly, all the ventilation systems designed are assumed to have temperature and humidity sensors for inside and outside air which will be used to calculate the appropriate actuation needed for ventilation. Along with the sensors, each design will have a solar panel.

Design one, seen in Appendix C: Figure C.2, is the first complete system design the team developed. This design utilizes the first design for vents, first design for actuation, third design for instillation, and fourth design for economizer and/or ventilation from the Morph Matrix. This design uses a panel vent which would change its angle of attack by use of a motor and actuator arm. This would then increase or decrease the surface area of which air is being taken in or expelled. If outside air is being taken in, it will then mix the outside and inside air before going through a single economizer to damp and filter the air mixture. The air is drawn using fans and will then be distributed to either the HVAC system or the building. Additionally, the design system uses a dome to direct the solar radiation from the sun to the solar panel. This is hypothesized to increase the amount of energy the solar panel will produce.

Appendix C: Figure C.3 shows the second design the team generated using the Morph Matrix. This design uses the second design for vents, the third design for actuation, the first design for implementation, and the first design for economizer and/or filter. The design utilizes dampers and economizers placed on the perimeter of the panel and is actuated by a hydraulic arm. Like the first design developed, this design will actuate, increasing the intake of outside air based of the temperature and humidity of the air both inside and outside. This air is then directed by use of a fan to the mix with the inside air. The inside air will have gone through a damper and filter before mixing with the ambient air. Finally, utilizing fans the mixed air is then directed to the HVAC system or the building.

The third design can be seen in Appendix C: Figure C.4. This design utilizes the third design for vents, second design for actuation, fourth design for implementation, and second design for economizer and/or filter. The design has the panel sitting flush with the roof of the building and is actuated using a gear train. The gear train moves along a slotted portion to lift the panel up and it is then slid along the top of the roof providing ventilation. Depending on the desired ventilation, based on outside and inside humidity and temperature, the design dictates the amount in which the panel will be displaced. The outside air is then forced through an economizer using a fan which will then mix with the inside air. In this design, the mixed air is free to move in the open space below the roof. This air would then be sucked out near the walls of the open area to be directed into the HVAC or into the building.

In Appendix C: Figure C.5 depicts the last design developed using the Morph Matrix. This design is a combination of subsystem designs. The design utilizes both the first and second design for the vents, both the first and forth design for the actuation, the first design for implementation, and the first design for the economizer and/or filter. This design is offset on the roof and contains vents on the side. These vents are actuated by using a smart material which expands, and contracts based on temperature and/or humidity. If more ventilation is needed, in addition to the vents actuated by the smart material. The panel itself will be raised to provide a larger surface area for the outside air to be taken in. This outside air is then directed through a fan which displaces the are through a damper and filter. This filtered outside air is then mixed with filtered inside air which is then disturbed to the HVAC system or the building. Additionally, the use of an hydraulic actuator rather than arms controlled by motors was discussed as alternative actuation. This design is similar to the second complete system design the team generated. However, this design combines aspects and uses ventilation on the sides rather than dampers.

These complete subsystem designs and complete system designs were analyzed using rationale design selection techniques. The selection process used is discussed in the next section “Design Selected” and “Rationale for Design Selection”.

5 DESIGN SELECTED - First Semester

The design which was originally selected was the fourth design generated using the Morph Matrix, Appendix C: Figure C.1. The design was selected using a rational selection process which compared the subsystem and system designs generated by the team to customer needs. This was done to ensure the selected design meets the requirements given by the client. The design was then redesigned to fit the building implementation and to account for the analytical analysis completed by the team.

5.1 Rationale for Design Selection

Based on the multiple designs that were generated, a final design had to be chosen. This was done by using a decision matrix. A decision matrix takes the customer needs and gives a score of the design based on the customer needs. The weight is a percentage that is based on the importance of the customer needs. The higher the weight was, the more important the customer need is. In figures 12 the two highest weights given to the customer needs was that the design must be bio-inspired, and the design must increase the overall energy efficiency of the building. These two customer needs both has a weight of 0.25. The next two highest weights of the customer needs were that the system must have a short payoff and that the system must be safe. The rest of the customer needs all have the lowest weight of 0.05, which indicates that they are not as important as the other customer needs. After the weight of the customer needs was indicated, the design gets scored based on how well it correlates to the customer needs. The score was based on a scale of 0-100 with 100 having the most correlation. Lastly, the weighted score is the weight multiplied by the score the design received. The weighted score was then summed up to give a total score for the design. Based on figures D.1 (in Appendix D) and 9, CONCEPT 12 had the highest score of 186.25 and CONCEPT 6 had the lowest score of 151.25.

		Figure 3	
Customer Needs	**Weight (%)**	Score	Weighted Score
Must be bio-inspired	0.25	100	25
Must increase energy efficiency	0.25	95	23.75
Must have a short pay-off	0.12	20	5
Must provide the same sevices as current system	0.05	50	12.5
Must be easy to maintain	0.08	85	21.25
Must be space efficient	0.05	90	22.5
Must bring building up to code	0.05	95	23.75
Must have adjustable times	0.05	30	7.5
Must be safe	0.1	90	22.5
Total	1	655	**163.75**

Figure 12: Decision Matrix for Concept 9

Based on the decision matrix, since concept 9 scored the highest, it became the final design. This design included an elevated solar panel that is attached to the roof of a building. The solar panel is placed in a metal case where vents are installed on the sides. These vents can be actuated by a smart material that expands when the outside temperature increases and contracts when the temperature decreases. The solar panel and metal case can also be actuated by a motorized arm that is controlled by the temperature of the outside. Once vents and/or panel is open, the building will have a fan and dampers that can help bring the outside air into the building while filtering that air. After the air gets filtered, the air gets mixed with the inside air and gets distributed throughout the building through fans. This can be seen in Appendix C: Figure C.5.

The final design scored a total of 100 points for being bio-inspired. The bio-inspired components in the design were the vents. The vents were inspired by how a pine cone can open and close its shape depending on the temperature and humidity. If the temperature and humidity increase, then the pine cone will open [14]. However, when the temperature and humidity decreases, then the pine cone will close its shape. The other bio-inspired components are the smart material. The smart material can actuate based on the outside temperature like the pine cone. The team scored the design a 90 for increasing the energy efficiency of the building. This is because the vents will allow for cooling of the building and the solar panels will generate energy for the fans to distribute the filtered air entering the building throughout the building. However, the customer need for having a short payoff was scored the lowest. This customer need scored a 65 because there were no proper calculations of how much energy the solar panels will generate and how much money it can save. A score of 90 was given to the customer need of having adjustable times because the design would provide ventilation depending on the temperature of the building and the demands of ventilation. If the building reaches a certain temperature, then the vents will start to actuate. Once the building reaches a lower temperature, then some vents will close to bring the temperature of the building back up to a specified temperature. A score of 85 was given to the customer needs of not generating excess noise pollution because the system will not make much noise when vents are open but will produce some noise when the motors of the panel are actuating the panel. Summing all the weighted scores from all customer requirements gave the design a total score of 186.25, which was the highest score out of all designs.

Once the design was chosen, a structural and ventilation analysis was performed. Based on these findings along with the insight provided from a physical walkthrough of the building, the selected design was redesigned for better implementation of the system. All the main criteria were kept, but the physical geometry of the structure was changed.

5.2 Design Description

The final design being presented was a rooftop ventilation housing that would be placed on the main ridge of SBS West. Its function would be to replace the current venting intake and exhaust/relief system that is currently designed into the ridge of the roof. Effectively the housing would sit on the ridgeline of the roof where it would be ducted down to the current relief and intake air ducts underneath the ridgeline, this can be seen above in figure 3. One housing unit would be ducted to three current ducts, these current ducts can be seen in figure 4 above. The proposed idea were the set up 14 new units (42 ducts in SBS main ridge) that would replace the function of venting air to the building.

The proposed design can be seen in a isometric views in Figure E1 and E2 in Appendix E. Each unit was designed with two 5ft x 3ft solar panels oriented next to one another at the roof of the vent facing the south side of the building. Each panel is rated at 330 kWh. The intake vent is located on the south side and exhaust venting is on the north side of the ridge as seen in figure 12. The vents are located on the north and south faces of the housing underneath roof structures to prevent any snow or weather to come into the ventilation ducting. The vents would be actuated using a smart material which was proposed to be nitinol. Each housing structure would be built out of square steel tubing and sheeting to cover the frame. This structure was designed to handle the weight of 6ft of snow due to flagstaff receiving storms that have produce up to 8ft of snowfall [15]. The structural analysis of the housing can be seen in Figure E3. The design was governed by the four main factors; solar panel size, current ducting placement, roof-ridge geometry, and venting area. The two solar panels need to be supported and facing south at approximately a 30-degree angle off horizontal. The vent area of the housing needed to be the same as that of three ducts. Finally, the overall length of the housing need to cover that of three ducts. By placing the solar panels side by side creating a length of 6 ft, the housing will include three current ducts in its footprint. The vent area is required to vent three ducts was calculated to be 5.5 square foot or 14 in x 60 in. The base of the housing needed to sit flush on the roof of the building so the base was designed to match the pitch of the ridge. Up to this point only the ventilation structure and geometry was completed. Drawing detailing the exact dimensions of the housing can be seen in figure E4. In the future, more specifications on actuating the vents with a smart material would be analyzed and implemented into the current design.

6 PROPOSED DESIGN - First Semester

The proposed design was a replacement to the current ventilation system attached to the roof's ridge of SBS West which can be seen in Appendix E Figure 1 and 2.The housing was to be constructed out of a steel tubing frame and then covered by sheet metal creating the housing. The south facing roof was to be constructed of two 5 ft x 3 ft solar panels side by side. The north facing roof was to be constructed out of a steel tubing frame and covered with sheet metal as well. The vents themselves were to be created out of steel sheeting. The actuation of the vents would be controlled by a air temperature sensitive spring made out of Nitinol. To accomplish this, the materials that would be used for one housing unit can be seen in Appendix F, Table F1.

7 IMPLEMENTATION - Second Semester

After numerous hours spent on analyzing the mechanical HVAC system in SBS west and developing a possible ventilation design, the team planned to prototype their proposed final design. Due to the uncertainty of funding, the team was unsure of how this prototyping phase would take place. After speaking with the professor and teaching assistant for the course, the team was able to secure $700 of funding from the mechanical engineering department. Although this is not enough funding to create a full scaled prototype, as the team had planned, it was enough to physically test aspects of a design with a possible scaled prototype.

The team decided, after some deliberation, the best course of action is to focus on the bio-inspired aspect of the design and the effect this has on ventilation of a controlled volume. The main control volume that handles the air and pressurization within the building is the plenum. The team chose to conduct a design of experiments (DoE) around the plenums in order for the team's results to reflect the building's needs. To efficiently analyze the bio-inspired aspect of the design. The team decided a DoE will allow for multiple bio-inspired vents to be generated and tested, along with other variables which contribute to the efficiency of ventilation.

7.1 Manufacturing

With the team now focusing on developing a DoE to test and analyze which bio-inspired ventilation method will best fit the design, the DoE was split into three categories of experiments: analyzing the pressure relief based on a set pressure, analyzing the pressure relief based on a constant flow of air, and analyzing the change in temperature from each vent. All experiments will use a one cubic foot plexiglass chamber constructed from 12" by 12", ⅛ inch thick pieces of plexiglass which will be epoxy together. This chamber will have pressure, humidity and temperature sensors which allows for data to be collected and extrapolated to analyze, with the use of Arduino. A computer aided design (CAD) model of the experimental setup can be seen below in figure 13.

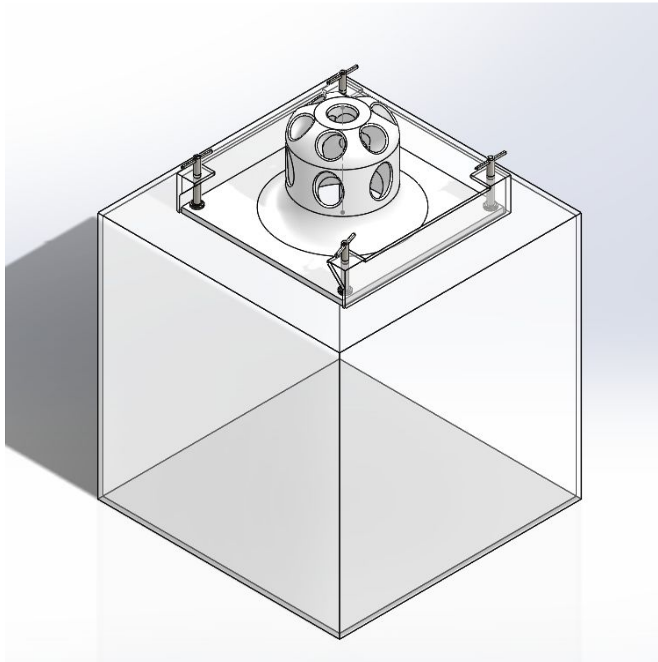


Figure 13: Experimental Chamber CAD Model

Figure 13 is the CAD model of the experimental chamber CAD model. Holes have been added to the model to represent where the sensors would sit or other components needed. The chamber will have a slit cut in the top measuring at 36 square inches to allow for the air to escape into the designed vents. The vents will be attached using a clamping system, CAD model seen in figure 13, and will use gasket tape or O-rings to ensure a tight seal.

Since these experiments will be to relieve/equalize pressure, the team will have a valve stem attached to the chamber which will allow for the team to pressurize the chamber. To allow for this pressurization of the chamber, the team must design a mechanism which traps the air and can allow for an instant release into the designed vents.

7.1.1 Design of Experiments

With the chamber manufacturing being set up and planned. The team is able focus on the DoEs themselves and how they are to be conducted. As stated previously there are three categories of DoEs the team would like to conduct, but are ordered in a way which addresses how likely they are to be completed. The team first aims to test pressure relief vs time of each vent after actuation. The second test aims to test pressure vs time but the vent was not open with a constant pressure coming into the vent. The final test aims to test temperature removal over time by each vent. With each of these tests completed the team was able to choose the best vent. The entire Design of Experiments document can be seen in Appendix G.

The only thing left to finish the setup of the DoE process is setting up the Grove-Barometer Sensor (BMP280), which measures pressure, temperature, and altitude, and the Arduino program which will be used to analyze the data collected [16]. Since the team has no previous experience coding Arduino, the team plans to read up on to code Arduino to analyze pressures and temperature. The team then plans to come together to generate the placement of the sensor(s) along with the code needed to collect and analyze the data.

7.1.2 Bio-Inspired Ventilation Designs

Following the setup of the DoEs the bio-inspired vents which will be analyzed were created on SOLIDWORKS and are planned to be 3D printed with the help of 3D Systems out of Portland, Oregon. Each member was tasked with finding an aspect of nature and generating a design to be tested. The aspects of nature which were chosen to create these vents are Fibonacci's Sequence, flower's ventilation, termite mound ventilation, and pinecone ventilation.

Fibonacci's sequence is a naturally occurring sequence seen in sea shells and all over nature. This sequence was taken and used to generate a fan/ turbine blade to pull the air out of the chamber. The Fibonacci vent design scheduled to be printed can be seen in figure 14 below.

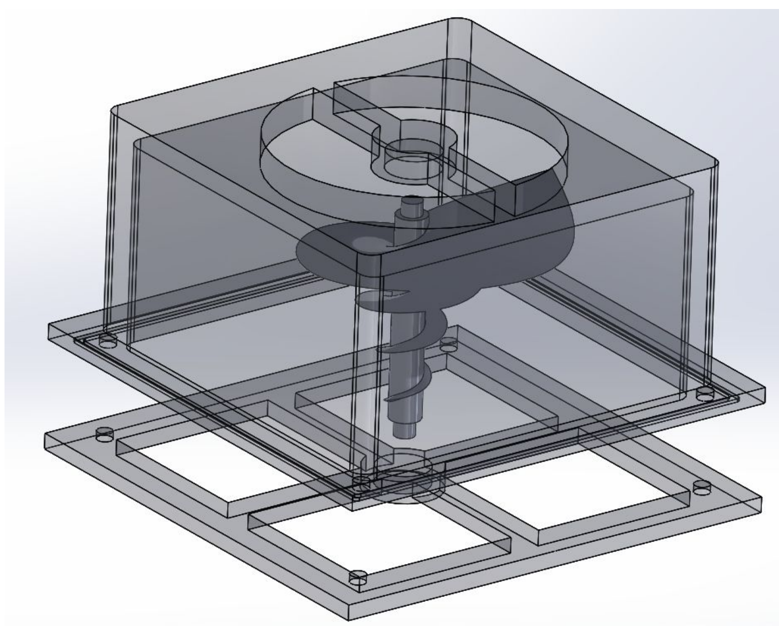


Figure 14: Fibonacci Vent Design to be Printed

The flower vent design is one which is based on how flowers blossom. When flowers are ready to blossom, pedals open from the bud of the flower. The flower vent design incorporates how a flower blossom by having pedals attached to a shaft that can rotate up and down depending on the airflow and pressure coming out of the vent. The design which will be printed can be seen below in figure 15 and 16 below.

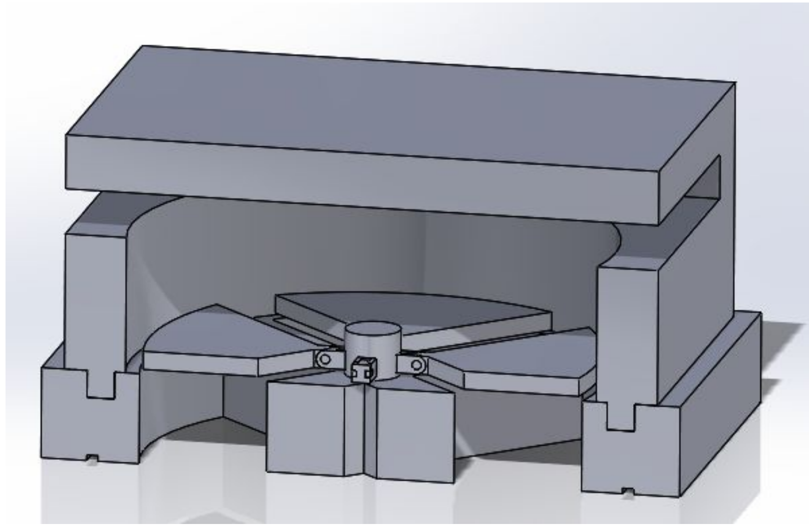


Figure 15: Flower Vent Design

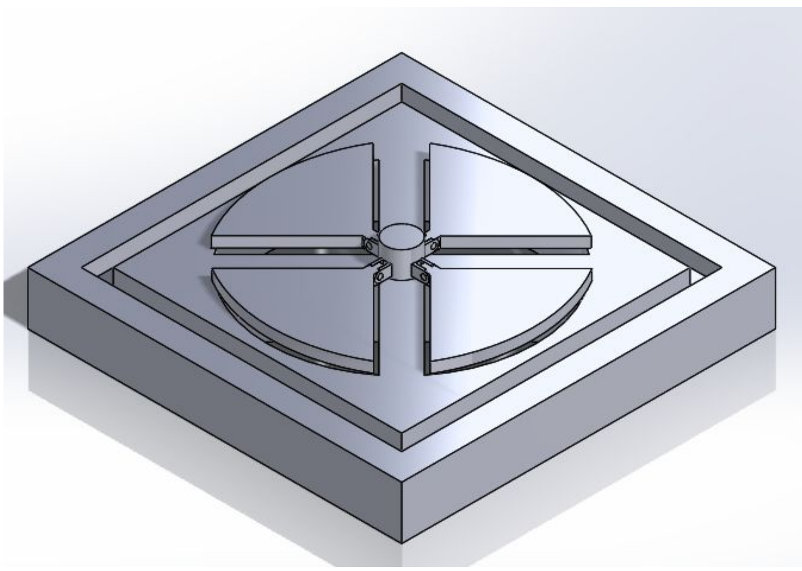


Figure 16: View of Pedals

The termite mound vent design is based on how termites ventilate their mounds. The basic idea is that air flows into a large area at the bottom of the mound and then uses a series of smaller ports or tunnels to the surface of the mound to circulate the air inside the mound. The termite mound vent design to be printed can be seen below in figure 17.

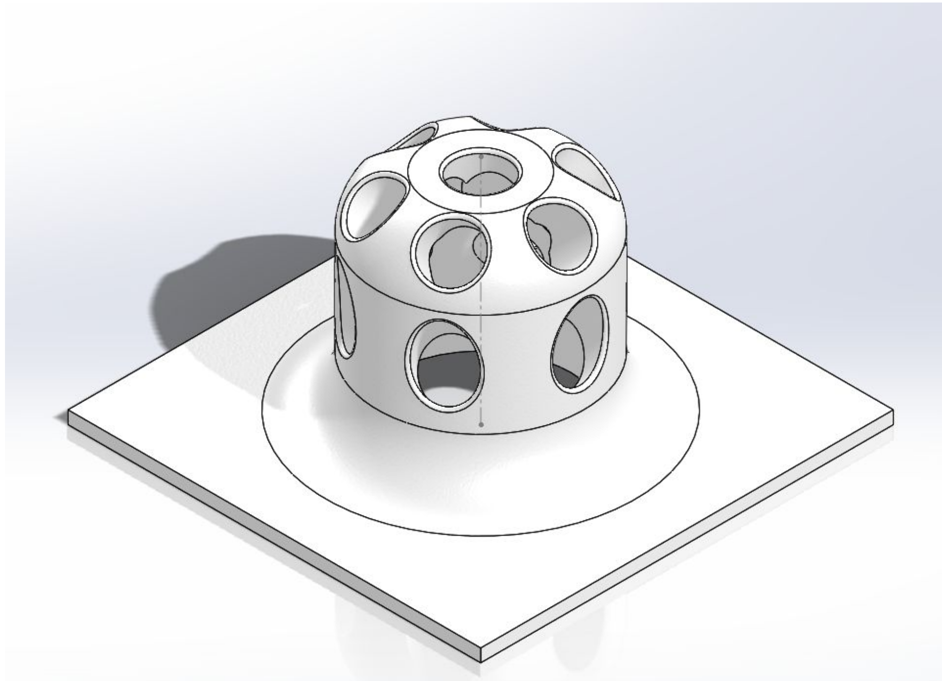


Figure 17: Termite Mound Vent Design to be Printed

The final design which is scheduled to be printed in the vent based on pinecones. This design is based on how pinecones can open and close based on the pressure outside and inside of the pinecone (also uses humidity). The pinecone design to be printed can be seen in figure 18.

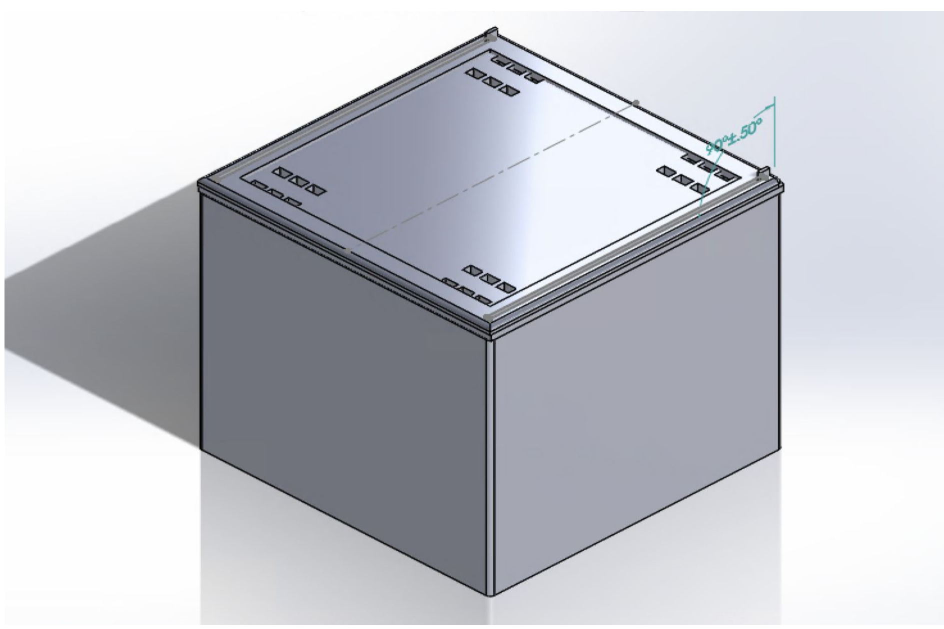


Figure 18: Pinecone Vent Design to be Printed.

7.1.4 Materials and Budget

With all aspects of the DoE and manufacturing laid out, the team has begun purchasing and organizing their materials to manufacture. A complete set list of the materials purchased (and still need to be purchased) can be seen in the Bill of Materials (BoM), Appendix F figure F1. The BoM shows that under $200 dollars out of the $700 original budget has been spent which leaves the team approximately over $500. The expenses, including anticipated expenses can be better visualize by looking at table 3 below.

Table 3: Budget and Expenses

Part Name	Quantity	Individual Cost
Plexiglass	8	$8.99
Epoxy	2	$9.49
Valve Stem	1	$8.75
Plexiglass cutter	1	$4.95
Arduino Set	1	$59.99
Barometer	1	$9.50
Budget		$700
Total Cost		$174.09
Remaining Budget		$525.91

The money remaining will be spent on parts which may have been forgotten when setting up the manufacturing of the chamber and Arduino. Additionally, the excess money will be used to help create a scaled model of a final ventilation design for SBS west, which will utilize the main component of the best bio-inspired vent design analyzed. A schedule of the timeline of manufacturing and who is responsible can be seen in figure H1, Appendix H.

7.2 Design Changes

From the first semester to the second semester, there have been changes as the project progressed. The first change implemented was deciding not to use a smart material as the bio-inspired part of the design. Rather, each member was tasked to create a prototype design that will be tested. Each of these vents will be tested in the pressure chamber and analyzed for their ability to vent pressure.

During the beginning of the implementation stage a few issues arose. The first issue was the team did not have adequate time to brainstorm, design, order materials, and build. This is due to having no funding the first semester and a change in the project requirements between semesters. The second issue the team faced, was the parts which were ordered to begin the construction of the chamber arrived, except for the main component needed, the pressure transducer. This was not scheduled to arrive till the end of March or the beginning of April. In order not to delay the process any further the team has ordered a new pressure transducer (which also measures temperature and altitude) and expedited the process. Additionally, although the plexiglass pieces could be epoxied together, the team decided they should wait till the arrival of the new pressure transducer. This was decided upon because the team believed it would be easier to orientate the pieces of Arduino and pressure transducer, if they did it before assembly of the chamber. Furthermore, with a limited budget the team did not want to risk having to order new parts.

With the delay of the construction of the chamber, the team decided it would be best to finalize their bio-inspired vents and have them printed. However, when the team went to print the vent designs at the Maker Lab at Cline library, the manufacturing was declined due to the vents being to larger for the smaller 3D printers and the larger 3D printers being out of service. Therefore, the team decided the best course of action is to outsource the printing to 3D Systems, which the team was fortunate enough to have this done for free. This brought forward another issue. The issue is the size of some of the components designs (printing will still be attempted) and one designs has walls which are too thin to be printed and will have to be redone.

Finally, the largest issue with the DoE and testing each vent, is the room for error in the experiments. This is due to the speed of the air leaving the vent and the time associated with the equalization of the pressure. Which may cause some, if not all, data collected to be inconclusive. However, the team believes they will be able to deviate this issue by varying the surface area of the outlet of the chamber into the vent. The surface area change will allow for a the time for the pressure to equalize to lengthen and for data to be easier to collect. Once all of these issues are resolved, the vent design that performs the best in the DoE will be chosen to be scaled and implemented into the design originally propose by the team. This will allow for the ventilation needs of the system and plenum to be met and for an efficient design.

REFERENCES

[1] Garlick, M. (2018). Retro-Commissioning Findings Report Social and Behavioral Science West Building. [ebook] Available at: http://file:///C:/Users/kmats/Downloads/SBS%20West%20Recommissioning%20Study%20Findings%20Report_Revised%20(1).pdf [Accessed 30 Nov. 2018].

[2] E. Ackerman, "Heat Your House with Someone Else's Computers", I*EEE Spectrum: Technology, Engineering, and Science News*, 2014. [Online]. Available: https://spectrum.ieee.org/energywise/energy/the-smarter-grid/heat-your-house-with-someoneelses-computers. [Accessed: 13- Feb- 2018].

[3] P. Patel, "Efficient Air-Conditioning Beams Heat Into Space", *IEEE Spectrum*, 2017.

[4] Babiak, J., Olesen, B. W., & Petráš, D. (2009). *Low temperature heating and high temperature cooling. Brussels: REHVA - Federation of European Heating, Ventilation and Air Conditioning*

[5] J. Kinnear, "What's Better, Solar Thermal or Solar PV? | Solar Power Authority", *Solar Power Authority*, 2018. [Online].

[6] Office, J. (2018). *Researchers design moisture-responsive workout suit*. [online] MIT News. Available at: http://news.mit.edu/2017/moisture-responsive-workout-suit-0519 [Accessed 26 Oct. 2018].

[7] "Commercial Ventilation | The Building Codes Assistance Project", Bcapcodes.org, 2018. [Online]. Available: https://bcapcodes.org/tools/code-builder/commercial/ventilation/. [Accessed: 26- Oct- 2018].

[8] A. Blumenfeld, Cdn.ymaws.com, 2014. [Online]. Available: https://cdn.ymaws.com/www.nibs.org/resource/resmgr/Conference2014/BI20140109_BETEC_Thumm_Blume.pdf. [Accessed: 26- Oct- 2018].

[9] Facilitiesnet. (2018). *The Three Types of Air Filters - Facilities Management Insights*. [online] Available at :https://www.facilitiesnet.com/iaq/article/The-Three-Types-of-Air-Filters-Facility-Management-IAQ-Feature--11235

[10] Sparrow Exteriors. (2018). What Types and Styles of Roof Vents Are There? - Sparrow Exteriors. [online] Available at: https://sparrowexteriors.com/2013/08/16/what-types-and-styles-of-roof-vents-are-there/ [Accessed 26 Oct. 2018].

[11] C. Woodford, "How hydraulics works | Science of hydraulics," *Explain that Stuff*, 26-Apr-2019. [Online]. Available: https://www.explainthatstuff.com/hydraulics.html. [Accessed: 26-Oct-2018].

[12] Suvo, "What are Gear Trains? Variable Gear Train," *Bright Hub Engineering*, 12-Nov-2018. [Online]. Available:

https://www.brighthubengineering.com/machine-design/66020-learn-about-gear-train-and-variable-gear-train/. [Accessed: 14-Mar-2019].

[13] “Shape Memory Alloys,” *NASA*, 2019. [Online]. Available: https://technology.nasa.gov/patent/TOP3-407. [Accessed: 14-Mar-2019].

[14] Vanstone, E. (2018). *Pine cone Weather Station*. [online] Science Sparks. Available at: https://www.science-sparks.com/pine-cone-weather-station/ [Accessed 26 Oct. 2018]. https://www.facilitiesnet.com/iaq/article/The-Three-Types-of-Air-Filters--11235 [Accessed 26 Oct. 2018].

[15] B. Bruner, “Flagstaff's Storm of the Century remembered 50 years later,” *Arizona Daily Sun*, 13-Dec-2017. [Online]. Available: https://azdailysun.com/opinion/columnists/flagstaff-s-storm-of-the-century-remembered-years-later/article_725a8071-7688-57d4-b15d-86381fa3e3db.html. [Accessed: 05-Nov-2018].

[16] *Grove - Barometer Sensor (BMP280)*, 2019. [Online]. Available: https://store.arduino.cc/usa/grove-barometer-sensor-bmp280. [Accessed: 15-Mar-2019].

APPENDIX A

System QFD

Date: 02/14/2018

Input areas are in yellow

		1	2	3	4	5	6	7	8	9	10
1	4 Year Pay Off										
2	New - Old Thermal Output										
3	Energy Efficient	++									
4	Building Compatable/ Space Efficient	+		-							
5	Ease in Repair and System Checks	++		+	+						
6	Temperature Management	+	+	++		+					
7	Selective Heating/ Cooling	++	-	++	-	--	++				
8	Display Usage (Energy, Hours, etc.)			++	-	++	++	+			
9	Mechanical System			-	+	+	-	+	-		
10	Noise Pollution					+				-	

Legend

A	SolarDuct
B	Model Buderus SB625WS
C	RQNL-B

	Customer Requirement	Customer Weights	4 Year Pay Off	New = Old Thermal Output	Energy Efficient	Building Compatable/ Space Efficient	Ease in Repair and System Checks	Temperature Management	Selective Heating/ Cooling	Display Usage (Energy, Hours, etc.)	Mechanical System	Noise Pollution	1 Poor	2	3 Acceptable	4	5 Excellent
			Engineering Characteristics										**Customer Opinion Survey**				
1	System Pays for Itself	3	9		3		9	3	1	3	3				C		AB
2	Same Heating and Cooling as Current System	4		9	3		9	3	9	3	9				BC	A	
3	Reduce energy Usage	5	3	3	9			3	3	9	3					BC	A
4	Easy to Fix System Problems	3	1	1	1	3				1	3	3		A	B		C
5	Uses the Same Space	2				9	3		1		1					AB	C
6	Less Noise	1			1		1				1	9			B		AC
7	Adjustable Timer	2		3	9			9	1	1	3			ABC			
	Technical Requirement Units		$/year	KJ	KJ/hr	m^3	N/A	° C	m^3	All	N/A	dB					
	Improvement direction		<	=	<	=	>	>	N/A	>	N/A	<					
	Relative Technical Importance		8	8	2	5	4	7	5	3	1	8					

Figure A.1: Simple QFD

APPENDIX B

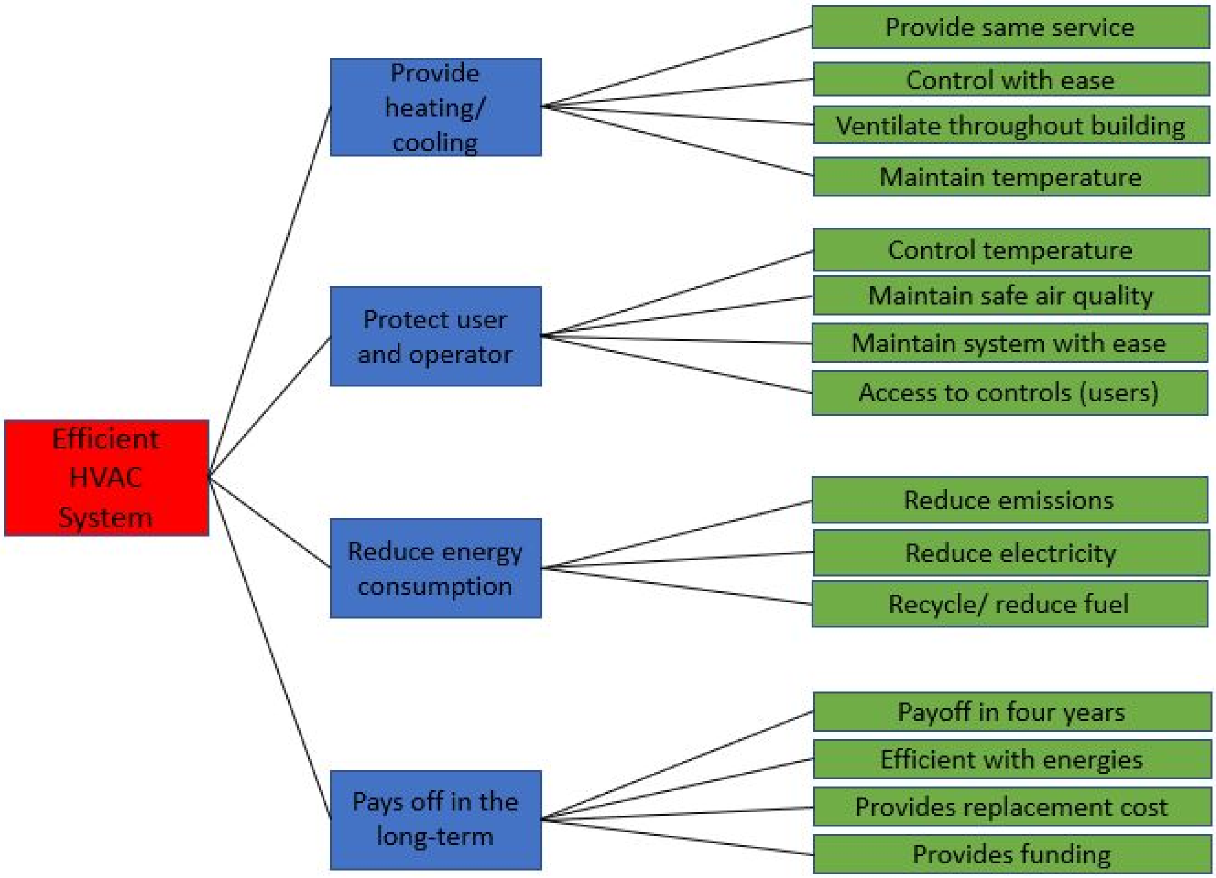


Figure B.1: Problem Decomposition

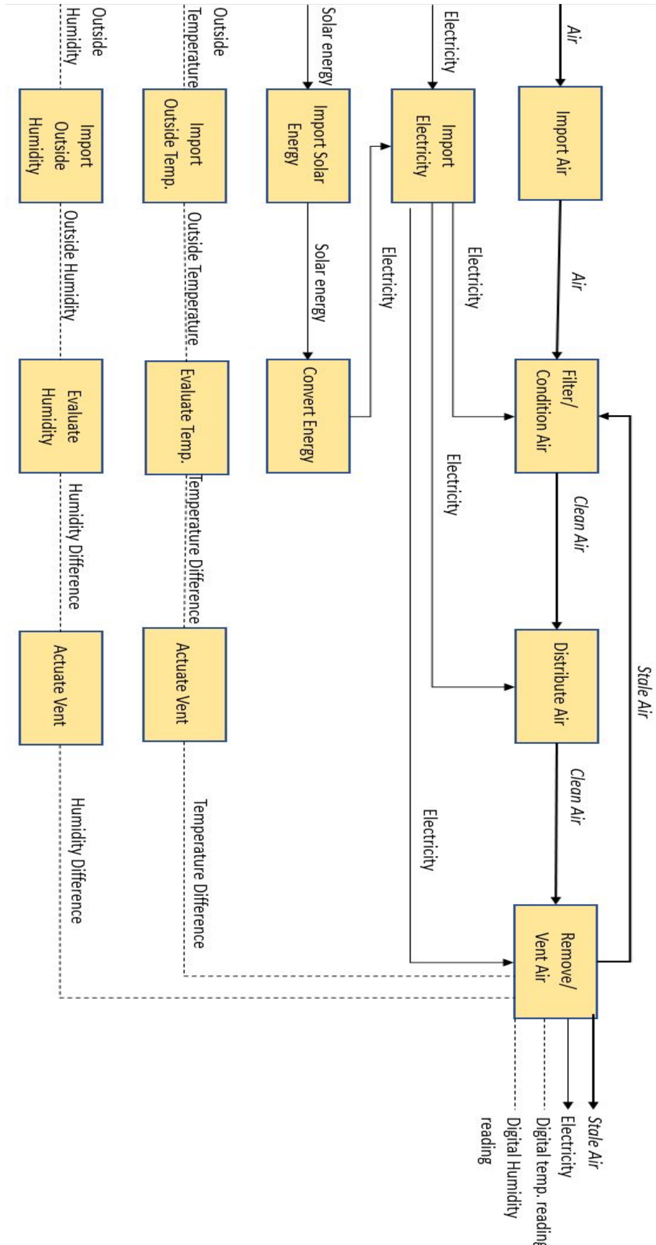


Figure B.2: Hypothesized Functional Model of a Ventilation System

APPENDIX C

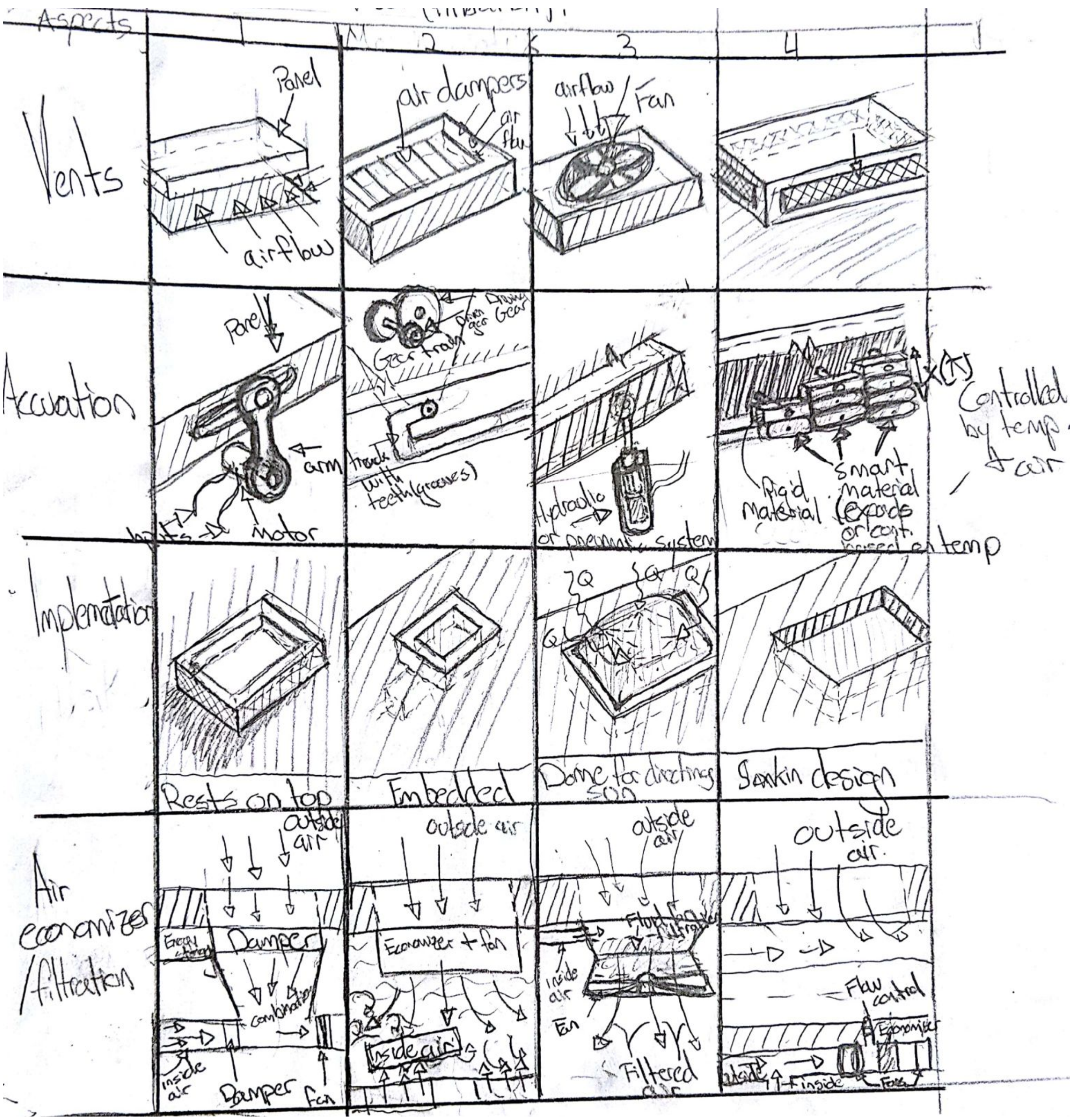


Figure C.1: Morph Matrix of Subsystems

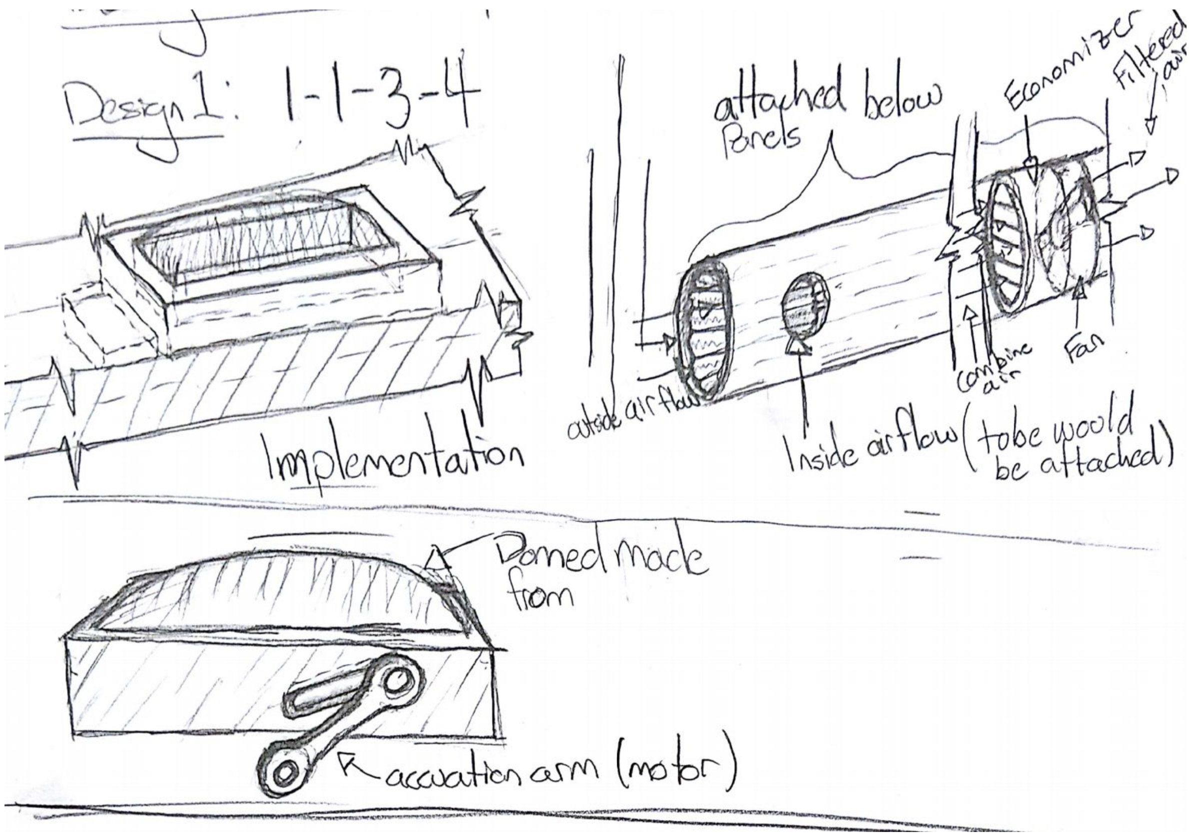


Figure C.2: Design One Generated via Morph Matrix

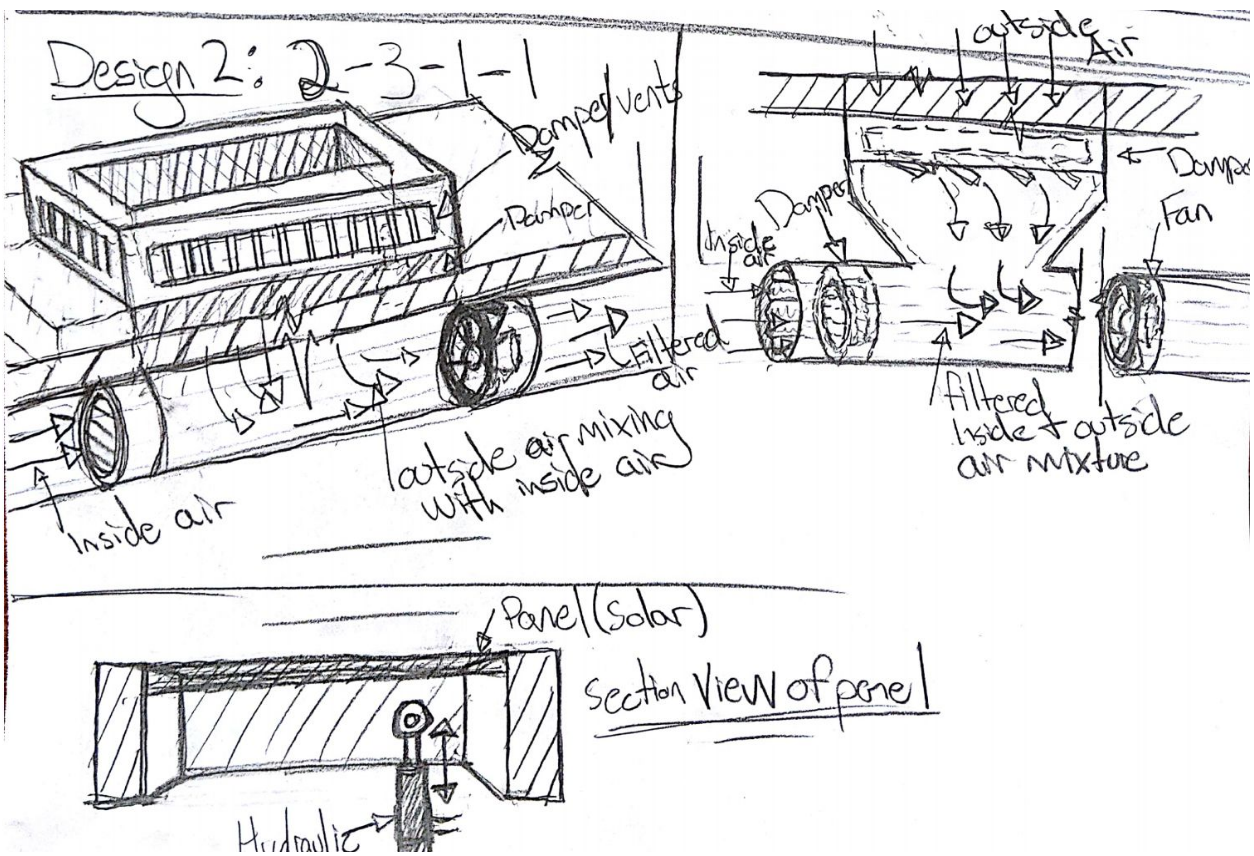


Figure C.3: Design Two Generated via Morph Matrix

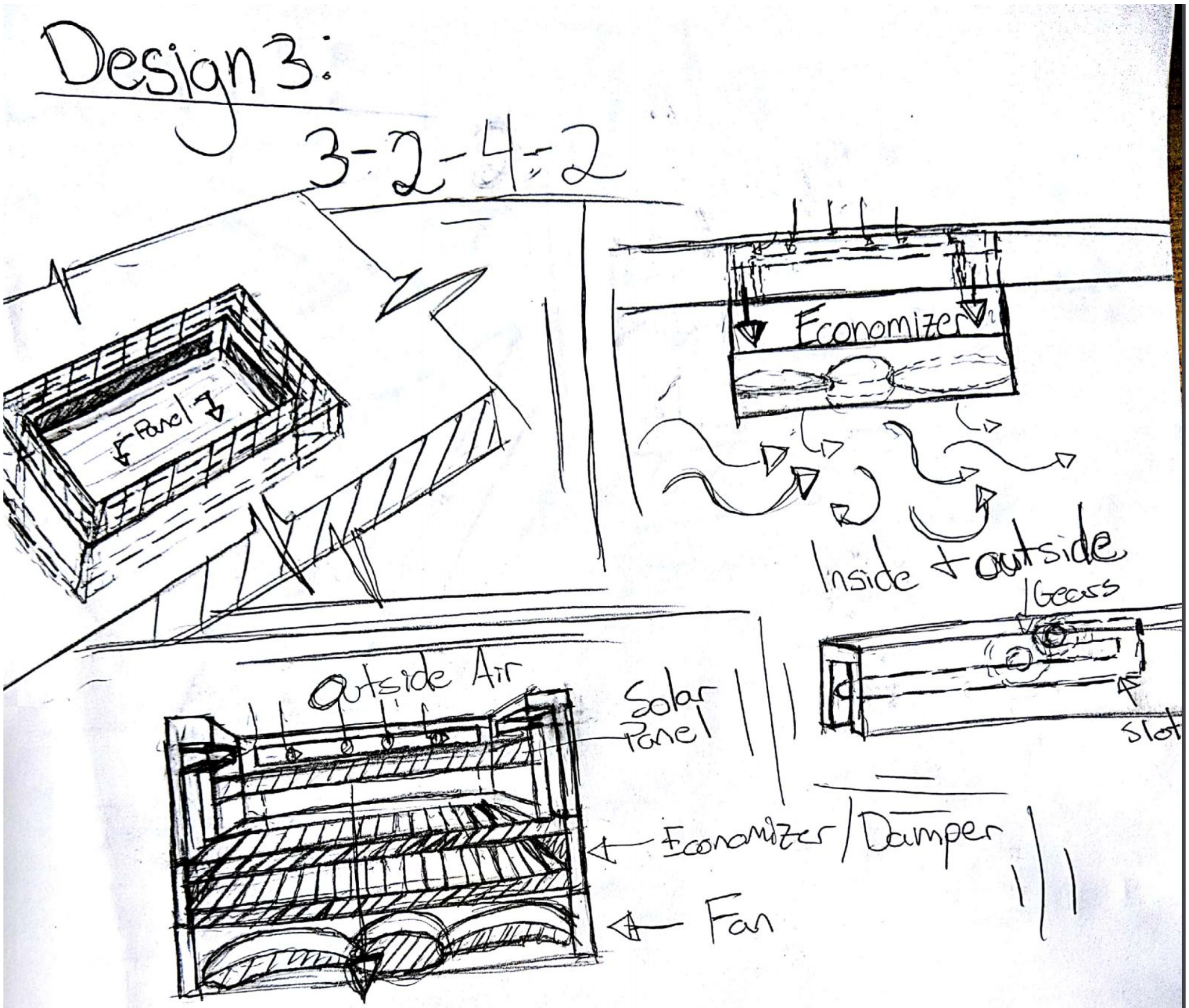


Figure C.4: Design Three Generated via Morph Matrix

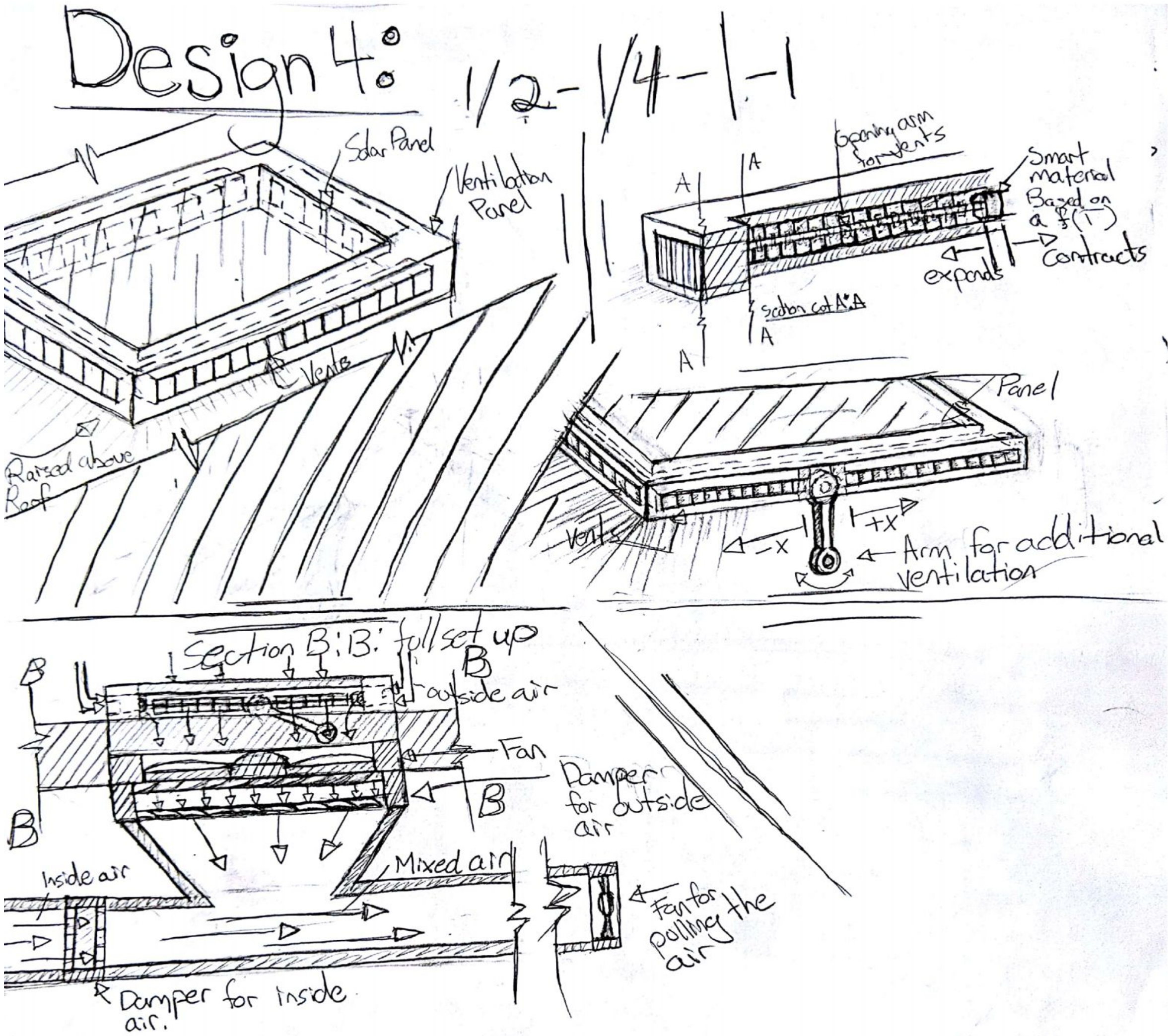


Figure C.5: Design Four Generated via Morph Matrix

Table C.6: Advantages and Disadvantages of Systems

System	Advantages	Disadvantages
Figure C.2	• Bio-inspired • Provides same services as current system • Can regulate intake of air	• Might generate lots of noise with motors • Does not generate solar energy
Figure C.3	• Bio-inspired • Provides same services as current system • Can regulate intake of air • Generates solar energy	• Might generate lots of noise with motors
Figure C.4	• Bio-inspired • Provides same services as current system • Can regulate intake of air • Generates solar energy	• Might generate lots of noise with motors • Complicated to implement gear trains • High maintenance
Figure C.5	• Bio-inspired • Provides same services as current system • Provides adequate ventilation • Can regulate intake of air • Generates solar energy	• Might generate lots of noise with motors

APPENDIX D

		Figure 3		Figure 4		Figure 5		Figure 6	
Customer Needs	**Weight (%)**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Must be bio-inspired	0.25	100	25	85	21.25	100	25	100	25
Must increase energy efficiency	0.25	95	23.75	90	22.5	90	22.5	70	17.5
Must have a short pay-off	0.12	20	5	70	17.5	70	17.5	60	15
Must provide the same sevices as current system	0.05	50	12.5	30	7.5	70	17.5	50	12.5
Must be easy to maintain	0.08	85	21.25	80	20	85	21.25	50	12.5
Must be space efficient	0.05	90	22.5	95	23.75	85	21.25	90	22.5
Must not generate excess noise pollution	0.05	95	23.75	100	25	80	20	70	17.5
Must have adjustable times	0.05	30	7.5	0	0	0	0	30	7.5
Must be safe	0.1	90	22.5	90	22.5	90	22.5	85	21.25
Total	1	655	**163.75**	640	**160**	670	**167.5**	605	**151.25**

		Figure 7		Figure 9		Figure 10		Figure 11	
Customer Needs	**Weight (%)**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Must be bio-inspired	0.25	100	25	80	20	100	25	95	23.75
Must increase energy efficiency	0.25	90	22.5	90	22.5	85	21.25	90	22.5
Must have a short pay-off	0.12	70	17.5	50	12.5	50	12.5	50	12.5
Must provide the same sevices as current system	0.05	70	17.5	60	15	65	16.25	60	15
Must be easy to maintain	0.08	85	21.25	75	18.75	80	20	50	12.5
Must be space efficient	0.05	80	20	80	20	85	21.25	85	21.25
Must not generate excess noise pollution	0.05	90	22.5	80	20	75	18.75	60	15
Must have adjustable times	0.05	0	0	90	22.5	90	22.5	60	15
Must be safe	0.1	95	23.75	85	21.25	85	21.25	85	21.25
Total	1	680	**170**	690	**172.5**	715	**178.75**	635	**158.75**

Figure D.1: Decision Matrix for Concepts 1-8

APPENDIX E

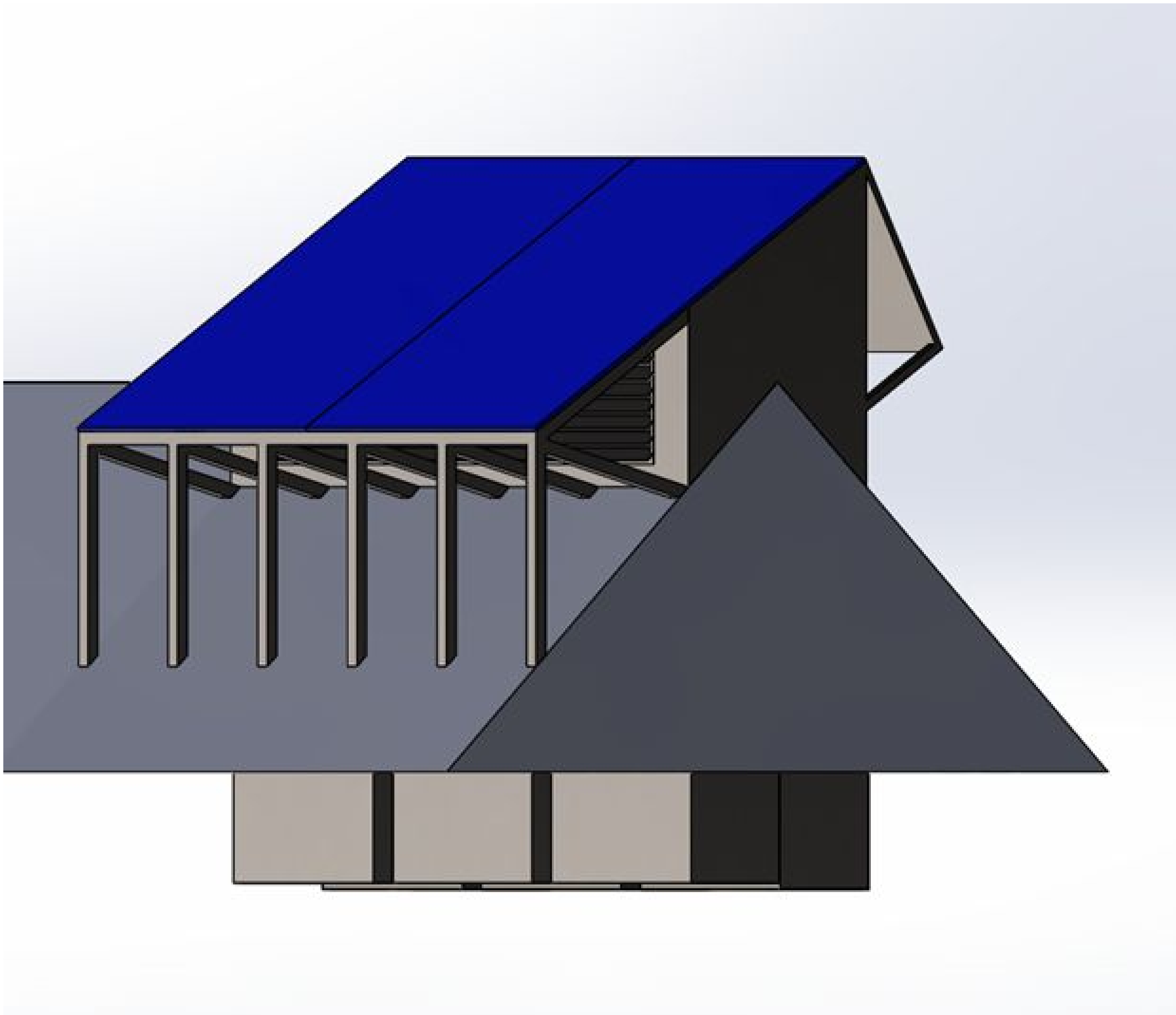


Figure E1: Quartering South Face with solar panels attached. On roof structure attached to 3 intake ducts.

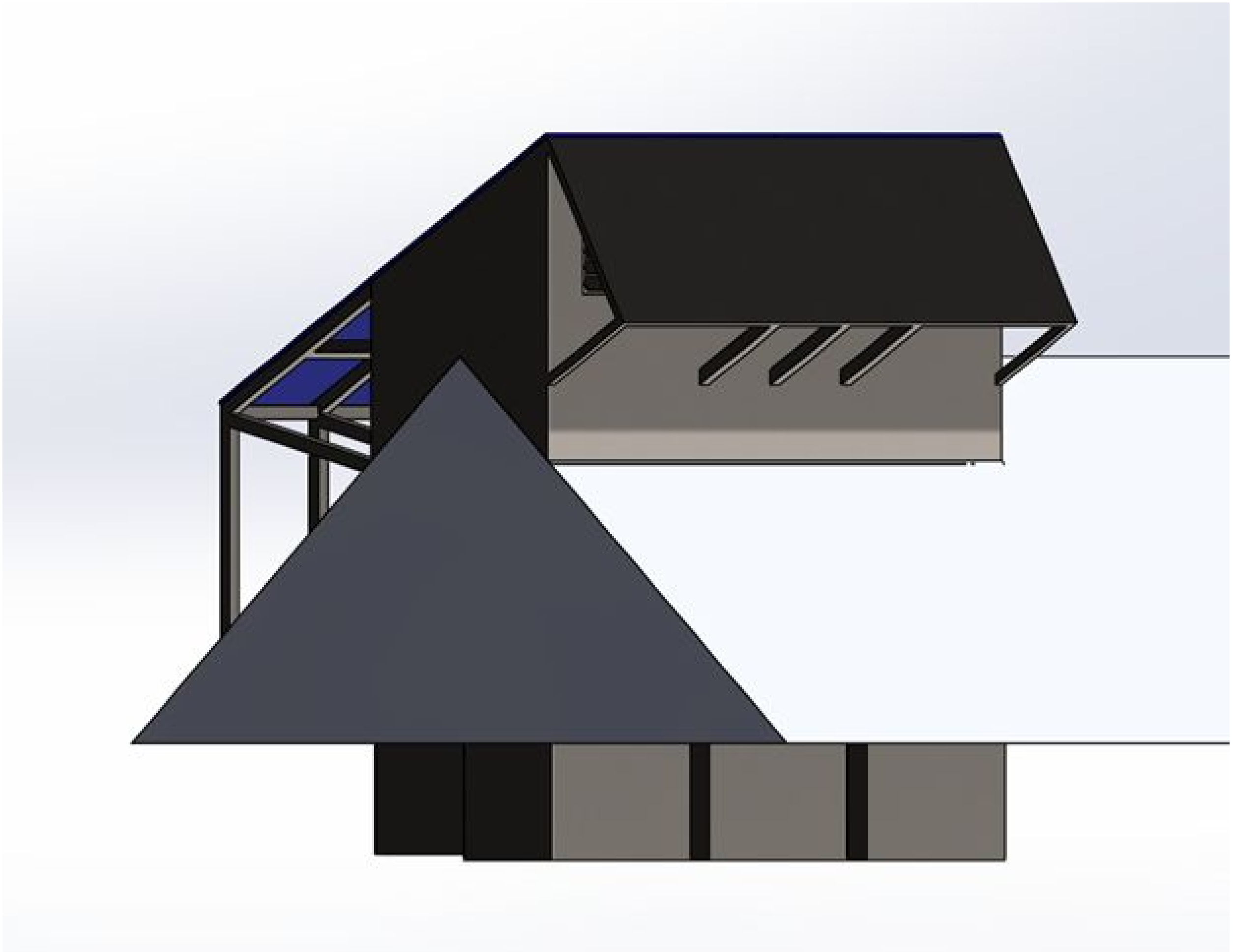
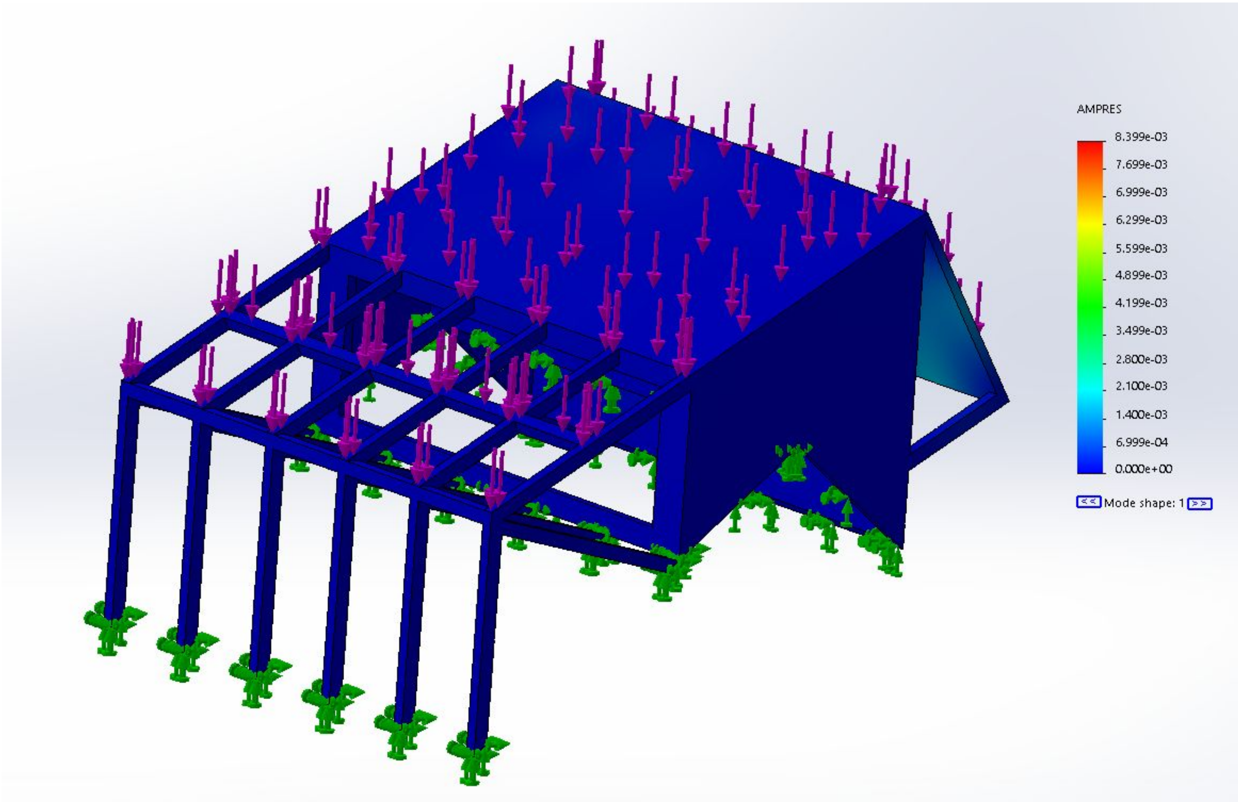


Figure E2: Quartering North Face of final design sitting on roof attached to 3 exhaust ducts



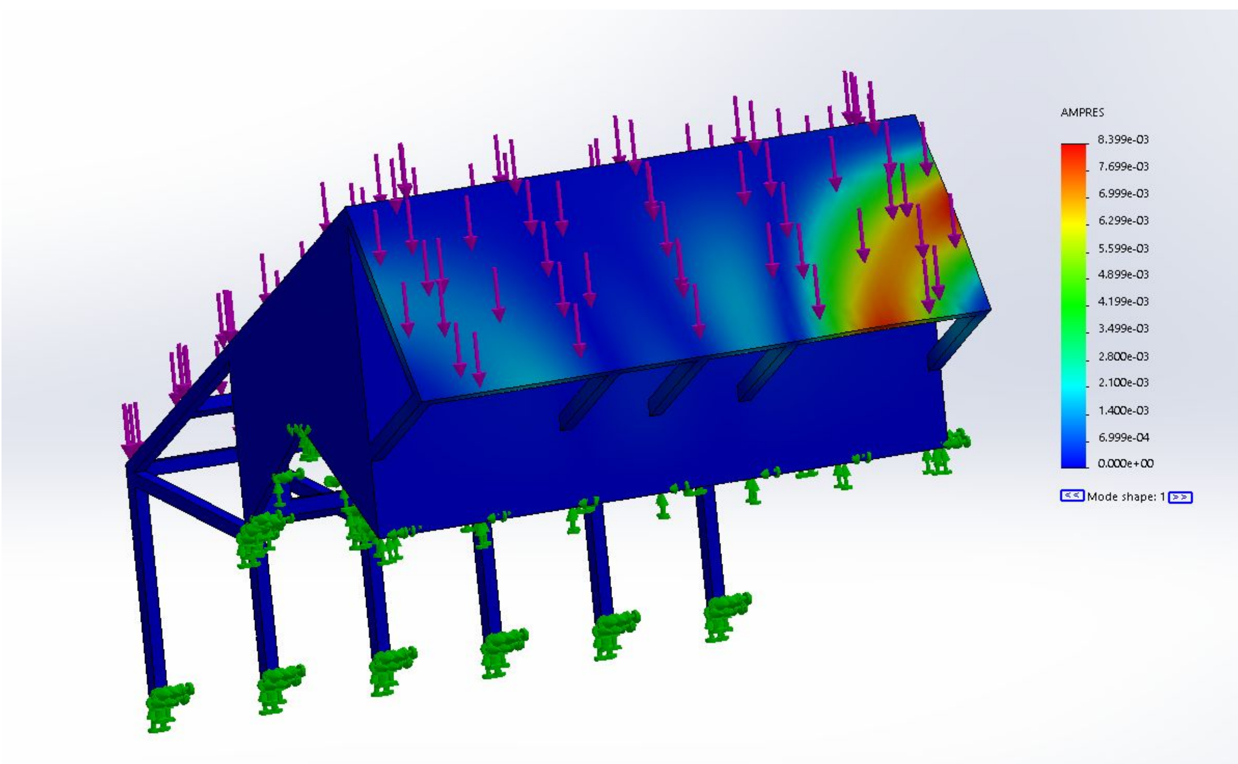


Figure E3: Stress analysis of 6ft snow load on structure.

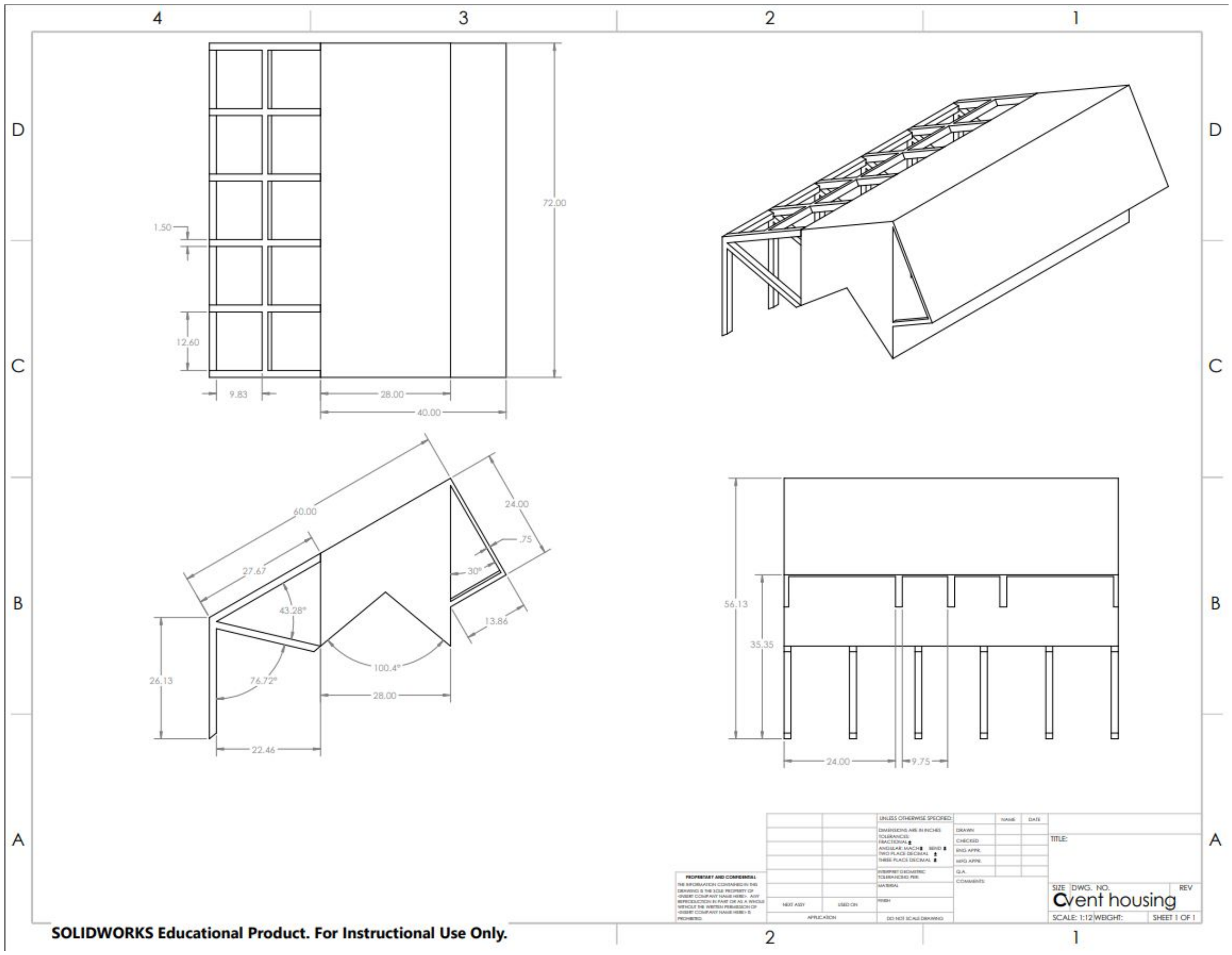


Figure E4: Drawing of vent housing

APPENDIX F

Bill of Materials								
Team				Bio-Inspired Design for Energy Efficiency				
Part #	**Part Name**	**Qty**	**Description**	**Functions**	**Material**	**Dimensions**	**Cost**	**Link to Cost estimate**
1	Plexiglass	8	Clear Acrylic Plexiglass	Walls for pressure chamber	Acrylic Plexiglass	12" x 12 " x 1/8"	$8.99	https://www.amazon.com/Plexiglass-12-Clear-Acrylic-Sheet/dp/B01NBVKDPD
2	Epoxy	2	Gorilla Glue Epoxy	Attach and seal the walls of the	Epoxy		$9.49	https://www.amazon.com/Gorilla-Epoxy-Minute-ounce-Syringe/dp/B01M7VD07W/
3	Valve Stem	1	VVTR TR-416-S Valve Stem	Pressurize the pressure chamber	Metal valve with nickel finish		$8.75	https://www.amazon.com/VTR-TR-416-S-Outer-Mount-Metal/dp/B01BRVCQ7K/ref
4	Plexiglass Cutter	1	Red Devil 1170 Plexiglass Cutting Tool	Cut vent opening in the pressure chamber			$4.95	https://www.amazon.com/Red-Devil-1170-Plexiglass-Cutting/dp/B000BZZ1D0/ref=sr_1_9?hvadid=323168400638&hvdev=c&hvlocphy=9060078&hvnetw=g&hvpos=1t1&hvqmt=b&hvrand=13012760874514944019&hvtargid=kwd-402330189991&keywords=sheet+glass+cutter&qid=1551297109&s=gateway&sr=8-9&tag=googhydr-20
5	Arduino Set	1	ELEGOO Mega 2560 Arduino Set	Code Arduino to analyze temperature and pressure measurements			$59.99	https://www.amazon.com/EL-KIT-008-Project-Complete-Ultimate-TUTORIAL/dp/B01EWNUUUA/ref=sr_1_4?keywords=arduino+kit&qid=1551297142&s=gateway&sr=8-4
6	Barometer	1	Barometer Sensor (BMP280)	Measure barometric pressure, temperature, and altitude with ihg accuracy			$9.50	https://www.amazon.com/EL-KIT-008-Project-Complete-Ultimate-TUTORIAL/dp/B01EWNUUUA/ref=sr_1_4?keywords=arduino+kit&qid=1551297142&s=gateway&sr=8-4
Total Cost Estimate:							$174.09	

Figure F1: Bill of Materials

APPENDIX G

To: Dr. Oman
From: Bio-Inspired Design team
Date: February 22, 2019
Subject: Design of Experiments for Testing Pressure Relief of Bio-Inspired Vents

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The Bio-Inspired Energy Efficiency team has been working diligently on developing designs to improve the ventilation of the Social Behavioral Sciences west (SBS west) building at Northern Arizona University. Rather than continuing the analytical analysis on the building the team has decided to analyze ventilation via prototyping and a Design of Experiments (DoE). The team will use four Bio-Inspired vent designs to be tested in the DoE. The team will be focusing on the pressure relief of each vent when conducting the experiments. Pressure will be the main focus because within SBS west the relief plenums of the Heating Ventilation and Air Conditioning (HVAC) system are over pressurized, to approximately. This pressure needs to be reduced to 1 atm or reach equilibrium between the atmospheric air and the plenum air. With the current ventilation not adequately depressurizing the plenum, the team plans to use the collected data of the DoE to generate a design which will.

DoE Overview

The DoE will contain three categories; Will be Analyzed, Should be Analyzed, and Hope to Analyze. The DoE is split into these three categories because with the time left to complete this project, the team is unsure what they complete (quality work wise). The first category being, Will be Analyzed, refers to the first DoE which will be conducted before the semesters end. This DoE will be to analyze the depressurization of a system which was closed when pressurization. The second category being, Should be Analyzed, refers to the DoE the team believes they will be able to conduct in addition to the first. This analysis takes the analysis of pressure a step further by having a open system which will have continuous flow rate of air inserted into the system while being continuously vented. Finally, the last category being, Hope to Analyze, which refers to an additional DoE the team would like to conduct. This DoE does not deal with pressure like the previous DoEs stated. Rather this DoE analyzes how well the vent designs regulate temperature. This DoE is listed last because it is not as important analyzing pressure, according to the client.

Setup

This section will describe the setup (hypothesized) needed to conduct each DoE in each category. This will provide what is needed to conduct each of these experiments. For all DoEs the testing fixture that is proposed is a plexiglass box which has a volume of approximately one foot squared.

Setup - Category One
For the first DoE there are a number of things needed which need to be setup in a specific way. First the team will use a pressure tight chamber (created by the team) which will have a inlet, allowing for the chambers internal pressure to be increased. At this inlet a manometer or a pressure gauge will be incorporated to allow them team to get a pressure reading of the air inside the chamber. Additionally, there will be a manometer or pressure gauge on the outside of the chamber as well, to record the ambient air pressure. The pressure gauges the team hopes to use will provide a pressure reading over an interval of time. The top of the chamber will have the ability to attach and detach each of the vents generated by the team, being sure a proper seal is in place. The area in which the vent will attach will have the ability to be blocked off, to allow for pressurization to occur. Furthermore, a way to release the pressurized air into the vent being tested will be implemented into the chamber design. Along with the experimentation setup listed the team will use some method to time the depressurization (depending on parts able to be obtained) and the team will use a computer to help with data analysis.

Setup - Category Two
For the second DoE the team will use a similar setup to the first DoE. However, this setup will be open to the vent, rather than being sealed to start. Additionally, this setup will have a inlet, which is airtight, which will provide a constant flow rate of air into the chamber. Simply, this setup is almost identical to the first DoE but is a open system with a constant air flow, rather than a closed system with interval pressure like the first DoE.

Setup - Category Three
The setup of this final DoE is not as detailed as the previous DoEs because of the uncertainty to if this will be completed. This DoE will be to analyze how effective the vent designs are in equalizing the temperature between the inside and outside temperatures. This will be done by having a device which could heat up the air being inserted into the chamber. Vents will be kept open while hot air is introduced. A fan and tubing will be used to circulate the flow while venting is occuring. This will require additional piping and fans to be setup. The orientation of this piping and the fans are not yet determined. The rest of the set up is the same as the setup for the DoE in category one.

Constants and Assumptions
In order for these DoEs to be conducted a number of aspects must be held constant and assumptions must be made.

Provided below is a list of the aspects of the DoE which must be held constant or assumed:
- Constant surface area of the outlet of each vent
- Constant volume of air in chamber - One cubic ft
- Measuring devices for each experiment are the same
- Constant pressure for each test (category one)
- Constant flow rate of air introduced (category two)
- Constant temperature (Both category one and two)

- Constant temperature and flowrate of air being introduced (category three)

This only addresses some of the constants and assumptions to be made. More will be defined when the experiment is conducted. The team knows more will need to be made but they are unsure as to what they are at this time.

Testing Procedure

The testing procedures (some hypothetical) of each DoE to be conducted are listed below. These testing procedures are subject to change as the prototyping of the vents continues because forced changes may occur throughout the process. Due to this being a DoE each vent measured will have additional variable changes, forced vs. free ventilation and actuation or surface area of vent.

Category One Testing Procedure

Provided below is the testing procedure which will occur for the DoE to test how fast and efficiently each vent equalizes the pressure for a closed system.

1. Take measurements of the ambient temperature and atmospheric pressure. Record these values.
2. Decide whether forced or free ventilation and what actuation or surface area will be used first.
3. Convert pressure readings to pounds per square inch (psi) to relate pressure to the gauge readings. Equation (1) provides the equation to convert atm to psi.

$$P(psi) = x / 14.696 \tag{1}$$

$$x = P \text{ in atm}$$

4. Fix the prototype to testing fixture and make sure it is sealed. To do this, seal the vents off from the chamber. Then inspect the pressure gauge to ensure it is holding pressure.
5. Pressurize the chamber using the pressurization apparatus (possibly a bike pump) up 0.5 atm (convert to psi). Only use 0.5 atm because the gauge is reading in gauged pressure.
6. Start video recording of pressure gauge and/ or data collection software
7. Start timer, manually or on software, before freeing the air to the vent.
8. After about 30 seconds, open the vent
9. Stop recording data a few seconds after the pressure gauge reads 0 psi (again because of gauge)
10. Extract data from the experiment; time lapsed, pressure change, etc.
11. Repeat steps 3-7 two more times with the same variable set up to understand accuracy of data.
12. Repeat these steps for every variation of variables.

Category Two Testing Procedure

Provided below is the testing procedure which will occur for the DoE to test how well and efficiently each vent equalizes the pressure for an open system.

1. Repeat steps 1-4 from the category one testing procedure.
2. Attach the desired vent to be tested. No need to seal the chamber before attaching.
3. Begin recording of pressure reading of the pressure gauge (if digital)
4. Initiate the blower (or apparatus to deliver air) and set to desired flow rate. Flow rate is still to be determined.
5. Record the pressure change within the chamber for a set time (for preliminary DoE, time will be 60 seconds).
6. Extract data and generate graphs for a visual comparison (or simultaneously generate graphs)
7. Repeat steps 3-7 two more times with the same variable set up to understand accuracy of data.
8. Repeat these steps for every variation of variables.

Category Three Testing Procedure

Provided below is the testing procedure which will occur for the DoE to test how well and efficiently each vent equalizes the temperature of the air being circulated in the chamber.

1. Repeat steps 1-4 from the category one testing procedure.
2. Attach the desired vent to be tested. No need to seal the chamber before attaching.
3. Begin recording the temperature of the inside of the chamber.
4. Actuate fans and blowers to heat and cycle air within chamber
5. Reduce heat of the air being inserted to ambient air temperature.
6. Record the temperature and time as the inside of the chamber equalizes to initial conditions.
7. Extract data and generate graphs for a visual comparison (or simultaneously generate graphs)
8. Repeat steps 3-7 two more times with the same variable set up to understand accuracy of data.
9. Repeat these steps for every variation of variables.

The steps explained in the testing procedures will change as these experiments are conducted. There are currently aspects the team can not account for at this time. Many things are subject to change but this is how the team plans to proceed with these DoEs.

Data Analysis

This section will provide a brief description of how the team believes they can best collect and analyze the data. The team hopes to collect all data relating to the DoEs simultaneously while they are happening. This means, the team hopes to use apparatuses which can record time, pressure, and temperature all at once and contrast tema to one another. Additionally, the team plans to use the standard DoE analysis to better understand their designs and what variables have an impact on its vents venting capability.

For the DoEs variables will be assigned either -1 or +1 (besides the actual vent). This is done to denote what aspect of the experiment is being used for each experiment and to provide explanation of the orientation of the variables being tested. For all experiments conducted three main variables will be analyzed using this DoE method. The first is the vent design, each design being assigned a value of one to four. The next variable is forced vs. free ventilation which will be changed for each vent in the same orientation. Forced ventilation will be assigned a -1 and free ventilation will be assigned a +1. The last variable to be analyzed is either actuation method or surface area (both could be done as well). To keep things simple, for now, two different actuations and/ or surface areas will be analyzed. This allows the team to assign a -1 or +1 to variable change, which makes it easier to compare to forced vs. free ventilation. This also drastically minimizes the number of combinations possible with these variables. If a larger surface area is used it will be given a +1 and if a smaller surface area is used it will be given a -1. Actuation could be assigned either way, but can not be determined at this point because actuation methods are unclear. For a visual representation of how these combinations will be tested, refer to figure 1 below.

Bio_Inspired	Free Vs. Forced	Surface Area
1	1	1
	1	-1
	-1	1
	-1	1
2	1	1
	1	-1
	-1	1
	-1	1
3	1	1
	1	-1
	-1	1
	-1	1
4	1	1
	1	-1
	-1	1
	-1	1

Bio_Inspired Vents:	Termite =	1
	Fibonacci	2
	Flower =	3
	Pinecone	4
Free Vs. Forced:	Free =	1
	Forced =	-1
Surface Area:	Large =	1
	Small =	-1

Figure 1: Combination of Variables Using DoE Format.

Figure 1 is to represent the combinations of variables. This is not to represent how the DoE tables which will be properly populated. When the DoEs are conducted these combinations of variables will be repeated for each DoE done, and may include additional variables. When the proper DoE is written up this will include time for category one, pressure for category two, and temperature and/ or time for category three. Additionally, the changing variables which are be analyzed will be given variable names such as x1, x2, x3,... and xn (n being number of variables) . Then those aspects which are being found each time a variable is changed (ie. time) will be assigned y1, y2, y3,....and ym (m being the number of aspects being found).

Once all the data is collected and extrapolated properly, the team will create response graphs for each of the variables to help visualize and analyze these different variable orientations. From there the effects of will be calculated, along with any expected error. Although the expected error will most likely not analyze all the errors needing to be addressed within these DoEs. More advanced analyses will be done on the data. However, these analyses can not yet be determined until we have further laid out the experiments to be conducted.

Conclusion

The Design of Experiments which are to be conducted are all subject to change. These are subject to change because without having any of the components manufactured it is difficult to tell what will work and what will not. However, the categories of the different DoEs are oriented in such a way that first category has the most detailed description of how the DoE will be done. Were as the last category represents the DoE with the least detailed description of how the DoE will be conducted. Moving forward the team plans to conduct the first round of experiments within two weeks.

APPENDIX H

WBS	Task description	Responsible	Start date	Finish date	Progress
1	Construction of the pressure chamber	Kyle	3/16/19	3/24/2019	0%
2	Attatch all measurement readings to pressure chamber	Team	3/24/2019	3/28/2019	0%
3	3D print Fibonacci vent	3D Systems	3/14/2019	3/22/2019	100%
4	3D print Pine Cone vent	3D Systems	3/14/2019	3/22/2019	0%
5	3D print Termite Mound vent	3D Systems	3/14/2019	3/22/2019	100%
6	3D print Flower vent	3D Systems	3/14/2019	3/22/2019	0%
7	Construct sealing method of vents	Team	3/16/2019	3/28/2019	0%

Figure H1: Manufacturing Schedule