Solar Ventilation System Design for SBS West

Northern Arizona University

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BIO-INSPIRED Energy Efficiency

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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 dependant 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.

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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 has been tasked with making Northern Arizona University (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 main focus of this design project. Currently this project has no outside sponsorship, besides the client and the Mechanical Engineering Department at NAU. Efforts to receive additional sponsorship are still being taken and are expected to continue throughout the entirety of the 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.

1.1.1 Background Information

Background information regarding the inefficiencies of building and HVAC systems was done to provide the BEE team with a better understanding.

Many HVAC (Heating, Ventilation, and Air Conditioning) systems contained in buildings are energy inefficient. Buildings in the United States (U.S) are responsible for over 70% of electricity consumption and approximately 40% of carbon emissions, with HVAC systems being the main contributor [1]. A boiler is a common HVAC system, which wastes fuel (diesel or oil) and at low temperatures, wastes productive energy (exergy) [2]. This waste results in a loss of money and produces harmful emissions. Although some buildings have been using natural gas as a fuel source, natural gas still emits significant amounts of carbon dioxide (CO2), which is a greenhouse gas, and energy (exergy) is also lost [2]. These inefficiencies create the need for the redesign and optimization of HVAC systems in buildings. Additionally, if a building reaches a certain age they are grandfathered in. However, most building should be brought up to the proper codes to avoid problems in the future.

1.1.2 Motivation

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 problem statement can be divided up into three sections: needs statement, problem definition, and constraints.

1.2.1 Needs Statement

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.

1.2.2 Problem Definition

The problem definition can be split up into three different sections: the goal statement, objectives and constraints. The goal statement is a response to how the team will solve the problem given. The objectives are the expectations and conditions from the client. Lastly, the constraints are certain conditions that the team must satisfy for the design of the system.

1.2.3 Goal Statement

As a team we started with a broad scope that fit the problem definition and then kept narrowing it down until we got we got a final statement that is more specific and was selected by Jon Hitzinger.

1. Improve the energy efficiency of SBS West.
2. Reduce the amount of energy consumed in SBS West through heating.
3. Design a system to improve the energy efficiency and ventilation for SBS West.
4. Bring the SBS West building up to proper ventilation code while providing energy efficiency for the current HVAC system.

Although it is not mentioned in the needs statement the team will be utilizing bio-inspired design to create a design solution.

1.2.4 Objectives

The table below (Table 1) displays the overall objectives of the project with the measurements, criteria, and the units of measurement to quantify the objectives.

Table 1: Objectives

Objective	Basis for Measurement	Criteria	Units
1. Cost effective	Annual cost savings	Cost	US dollars
2. Reduce amount of energy used	Annual kWh	Energy	kWh
3. Safety for users	Electrical current	System shutdown	Amps
4. Provide same service as current heating system	Building temperature	Temperature	℉
5. System savings pay-off	System pays itself off in 5 years	Cost/efficiency	US dollars/annual kWh
6. Bring building up to proper codes	Ventilation	Temperature	℉

Objectives 2-4 should comply with the 2014 NEC (National Electric Code) and the NFPA code 1 (National Fire Protection Association) [3].

1.2.6 Constraints

A list of constraints was collected to give a clear understanding what the system must or must not be able to do.

1. Must provide the proper ventilation to meet codes for commercial building.
2. All services that are provided now must be provided in the solution.
3. The system must pay for itself in 5 years and/or cost effective.
4. Size of system must fit in the space provided.
5. Must be able to increase or decrease the temperature of the building.
6. The system must not increase NAU's carbon footprint.

1.3 Original System

The final design previously developed by members of the BEE team was a Solar Radiation and Ventilation. This system met the desired criteria to be effective and successful for the previous client. This can be seen in figure 1. The Solar Radiation and Ventilation system works by using solar to generate electricity and the sun to radiate heat. This system also allows for different levels of ventilation depending on the outside climate. The ventilation is controlled by a set of arms that is controlled by motors, and they will extend or contract depending on user defined temperature of building. This system excels in the two main criteria, which are reduce energy usage and system pays for itself.

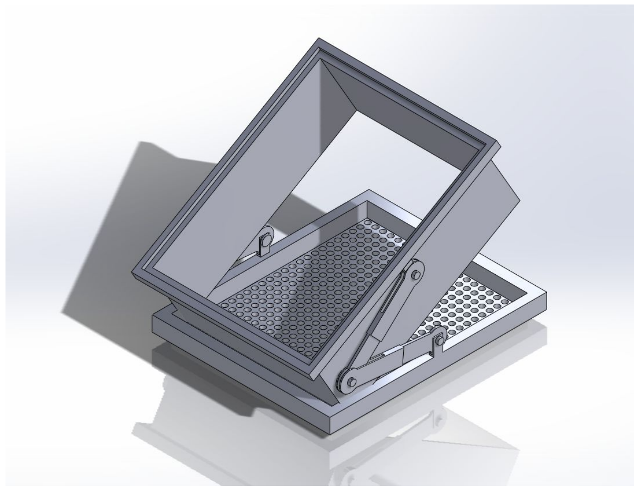

Figure 1: Original Design

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 and contrast the requirements. Additionally, design solutions for HVAC systems were found and benched marked versus the customer requirements.

2.1 CRs

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 have a short pay-off:** The system must generate enough energy so that the system can help the building save enough money to pay itself off in a certain number of years depending on the total cost of the system. If the system cost is under $500,000, then the system must pay itself off in less than five years. If the system cost is over $500,000, then the system must pay itself off in less than ten years. Additionally, as depicted by the client, cost of some aspects may be neglected because bringing the building up to code trumps the costs.
4. **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.

5. **Must be easy to maintain:** The system must be easy to perform maintenance and repairs when needed.
6. **Must be space efficient:** The system must not take up more space than the current system.
7. **Must not generate excess noise pollution:** The system must not generate a lot of noise. This is to provide faculty and students an appropriate work environment.
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.

2.2 Engineering Requirements

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

1. 5-year payoff estimate: 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: 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: The system must increase the energy efficiency of the building by reducing the amount of energy being used.
4. Size <= Current size: 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: 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. Selective heating/cooling: The system must be able to heat and cool the building depending on the demands. If no one is in the building, then the system shuts off.
9. Display usage: The system can display how much energy is being generated and used while also displaying the temperature of the building.
10. Mechanical system: The system must be mechanically engineered with bio-inspired design incorporated into the design
11. Noise pollution (Reduce): The system must not produce excess noise pollution. This is to provide faculty and students a comfortable working environment.

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.

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 SOTA designs have been done and conveyed through this section.

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 [4]. 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 [4]. This concept has been interpreted in many ways, from single-room heating to building heating [4]. 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 2), which are panels that collects and amplifies solar energy to heat and pump fluid (e.g. water) throughout the building [5]. 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 [5]. 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 [6]. 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.

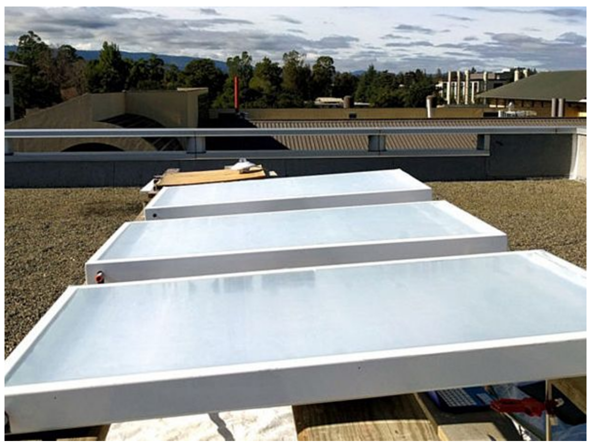

Figure 2: Radiative Panel with Ventilation Example [4]

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 [7].

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 [8]. 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 considered to be 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 systems, the filtration, the conditioning, and the distribution, and the removal of air [9]. 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 [9]. 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 [10]. 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 you decompose 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 of. 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 as a result 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 4.

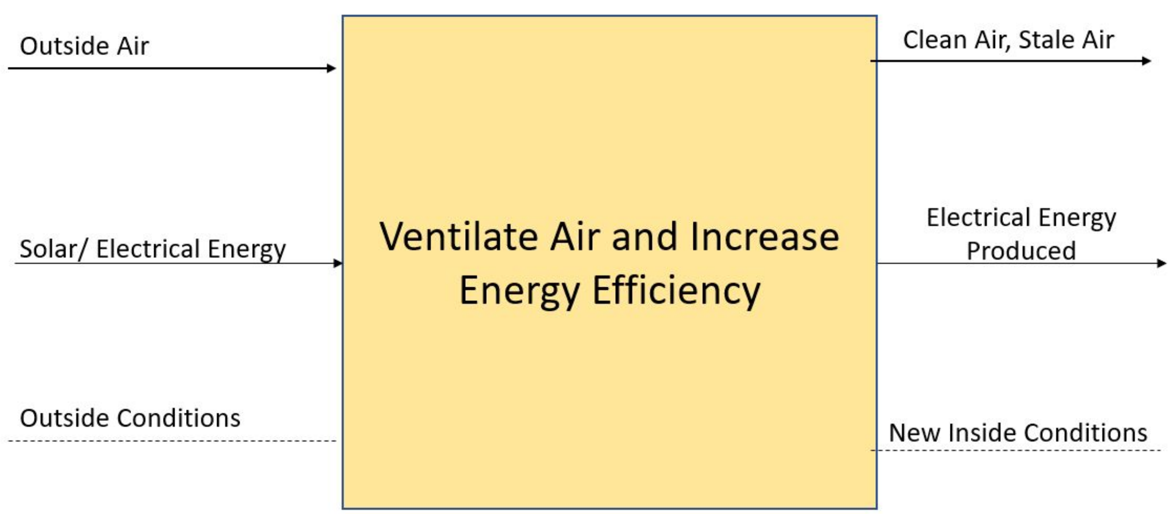

Figure 3: Black Box model of a ventilation system

3.3.3 Hypothesized Functional Model

Once the black box model is 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 have decided to consider, and they are fiberglass air filter, polyester and pleated filters, and high efficiency particulate arrestance (HEPA) filters.

3.4.1.a Fiberglass Air Filter

A fiberglass air filter is made of fiberglass material. It is designed with small fibers which restricts dust from going through the filter [11]. 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 suggest that the filters should be replaced after 30 days.

3.4.1.b Polyester and Pleated Filters

Polyester and pleated filters are made up from cotton, synthetic, and Polyester [11]. 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.c 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 [11]. 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 type 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.a Box Vent

The box vent, which is also known as low profit vents, is designed for an open hole in the roof in order 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 [12]. Also, the box vent is static vents which implies it has no moving part in the design.

3.4.2.b Wind Turbines

Wind turbines are designed to have circular movement relying only on the wind power. This movement helps the the wind turbines to produce cool air to the building and exits the heat from it [12]. Thus, this vent style does not have motors because it is only relies on the wind to move. Moreover, wind turbines is considered as a dynamic vents 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 in order to satisfy different customer needs.

3.4.2.c 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 [12]. 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 does 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.a 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 [13]. 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.b 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. This system like the hydraulics is very accurate in providing the right ventilation area and is simpler than the hydraulics which is in need of a 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.c 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. 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 to generate designs for the subsystems. The team then narrowed down, using methods mentions in Appendix C: figure C.1, the designs done independently to 16 complete subsystem designs. The designs were then categorized and used to create four complete system designs. This was done using a Morph matrix.

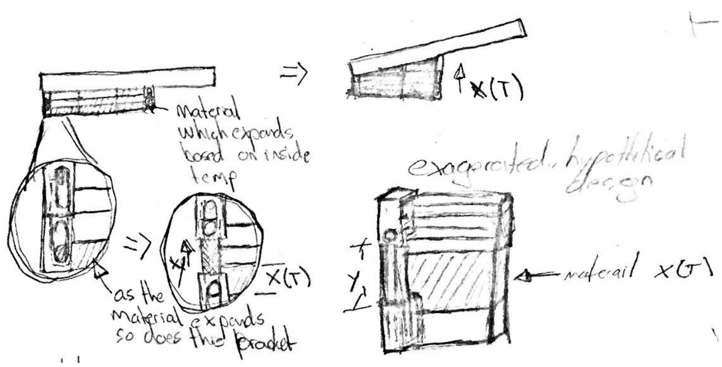

Figure 4: Actuation Using Thermal Smart Material

Figure 4 is a subsystem design drawn up by a member of the team. 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.

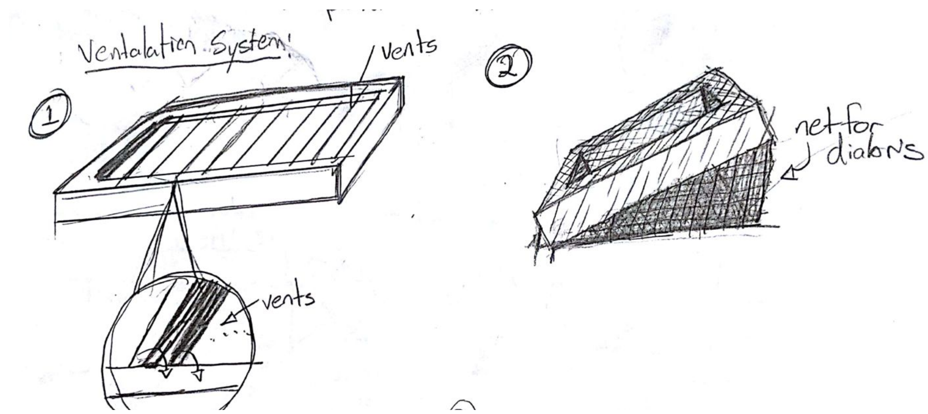

Figure 5: Sample of Vent Design

Figure 5 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.

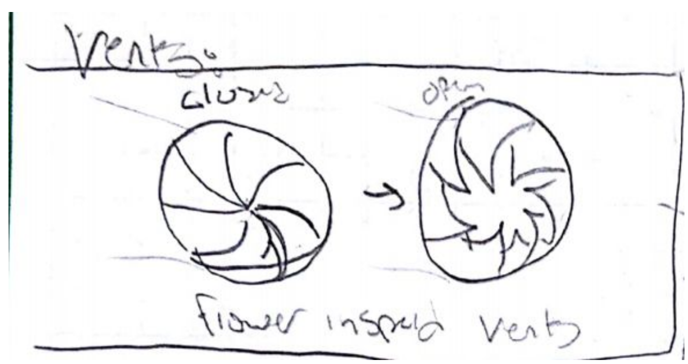

Figure 6: Vents Based on Flowers

In figure 6 a design for vents for the ventilation system were 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.

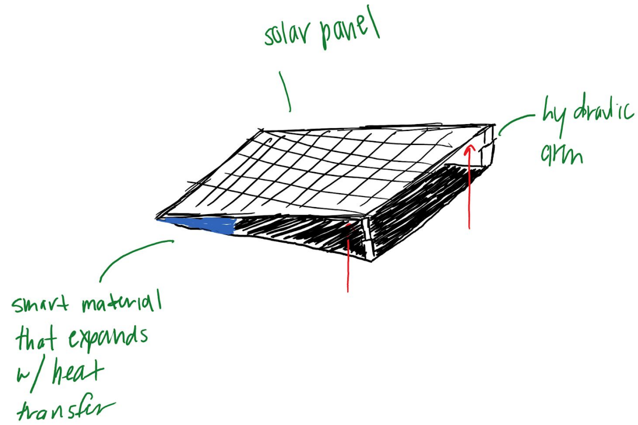

Figure 7: Panel Actuated by a Smart Material and Hydraulic Arm

Figure 7 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: Fan Based on Whale Fins

In figure 8, 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.

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.

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. One last thing to take into consideration, is that 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 Mortph 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.

In Appendix C: Figure C.3, is 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, 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

The design which was 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.

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 is, the more important the customer need is. In figures 15 and 16 the two highest weights given to the customer needs is 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 are 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 is indicated, the design gets scored based on how well it correlates to the customer needs. The score is 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 is 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 12	
Customer Needs	**Weight (%)**	Score	Weighted Score
Must be bio-inspired	0.25	100	25
Must increase energy efficiency	0.25	90	22.5
Must have a short pay-off	0.12	65	16.25
Must provide the same sevices as current system	0.05	70	17.5
Must be easy to maintain	0.08	75	18.75
Must be space efficient	0.05	85	21.25
Must not generate excess noise pollution	0.05	85	21.25
Must have adjustable times	0.05	90	22.5
Must be safe	0.1	85	21.25
Total	1	745	**186.25**

Figure 9: Decision Matrix for Concept 9

Based on the decision matrix, since concept 9 scored the highest, it became the final design. This design includes 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 are the vents. The vents are inspired by how a pine cone can open and close its shape depending on the temperature and humidity. If the temperature and humidity increases, 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 are 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 will 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.

6 CONCLUSION AND FUTURE WORK

The work that has been done was to generate a design that would bring SBS West, at NAU, to the proper ventilation codes while providing energy efficiency. Additionally, this design incorporates aspect which were inspired by nature.

The team has a better understanding of what is needed from their design, pre-existing designs which meet some of the required aspects, and the function of the system being developed. With these insites the team was able to generate concepts which satisfied the need for a subsystem and/or system as a whole. Subsystem designs were then selected to develop complete designs. These complete designs were then analyzed to generate a final design.

With a final design generated, the team will confirm with the client that they are able to move forward with the proposed design. After confirming the design, the team will be able to complete a series of analyses in which they have been working on. These analyses are split among the team members with Taylor focusing on ventilation, Talon focusing on structural and actuation analysis, Hani focusing on heat exchangers, and Kyle focusing on solar analysis. These analyses will then be signed off by their professor and client. These will then be compiled into this document along with any additional content regarding the project. A final proposal and/or report will be compiled, which will include basic prototyping, to be evaluated. This project will continue in the spring of 2019. The content that will be incorporated during this time is still to be determined. However, it will end with a presentation at NAU’s undergraduate symposium.

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APPENDIX A

System QFD

Date: 02/14/2018

Input areas are in yellow

#	Correlation	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
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		v	=	v	=	^	^	N/A	^	N/A	v					
	Relative Technical Importance		8	9	2	5	4	7	6	3	1	9					

Figure A.1: Simple QFD

APPENDIX B

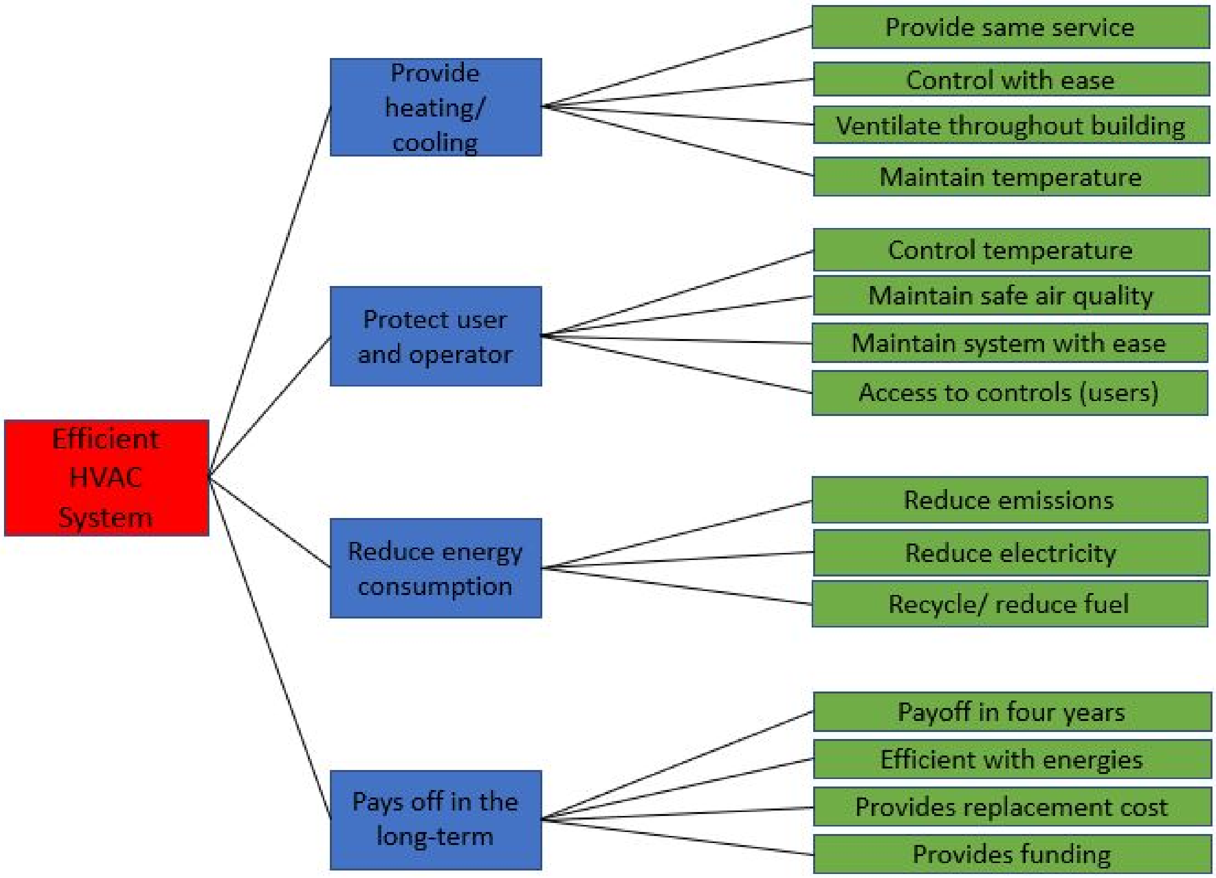

Figure B.1: Problem Decomposition

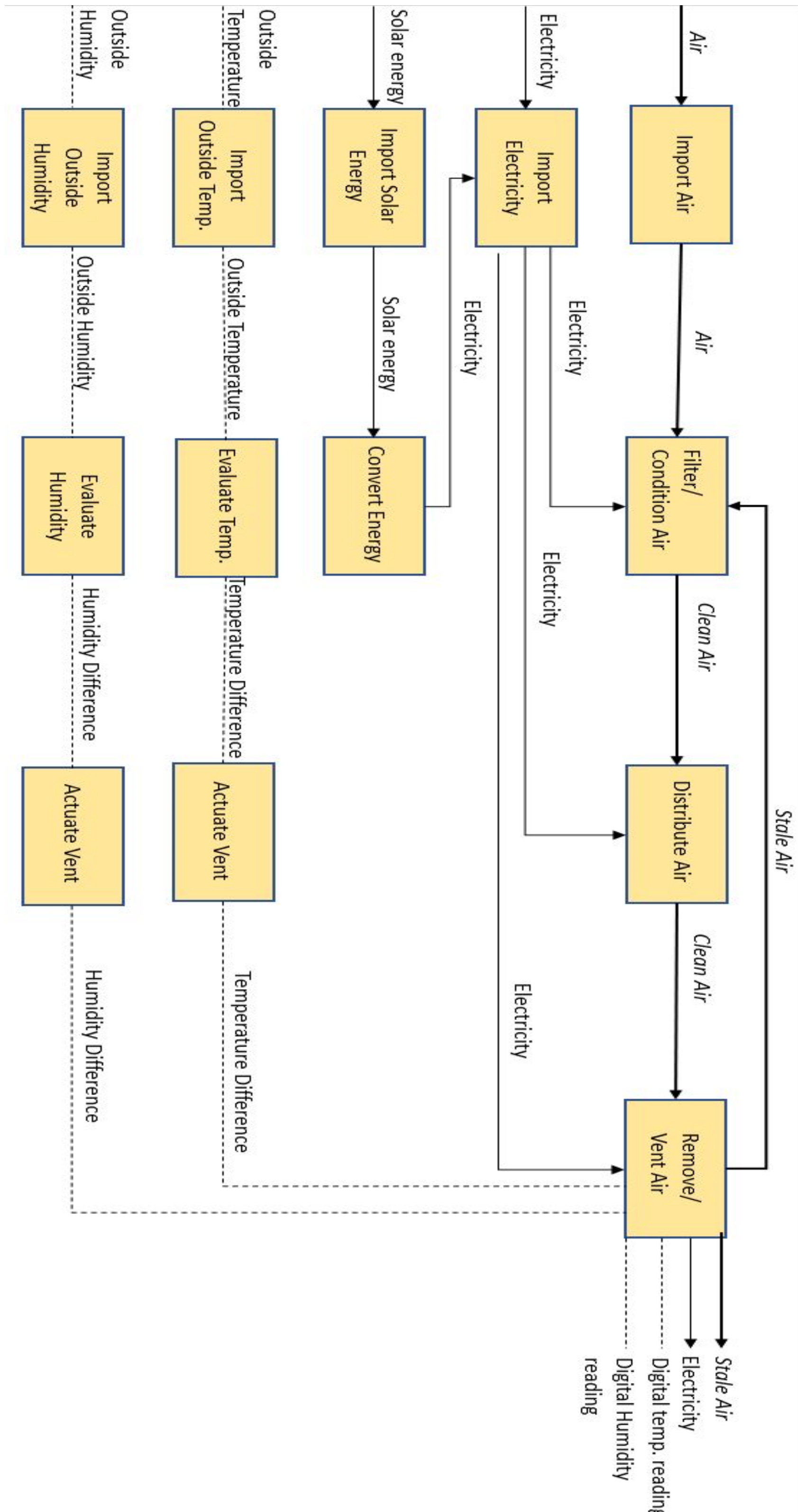

Figure B.2: Hypothesized Functional Model of a Ventilation System

APPENDIX C

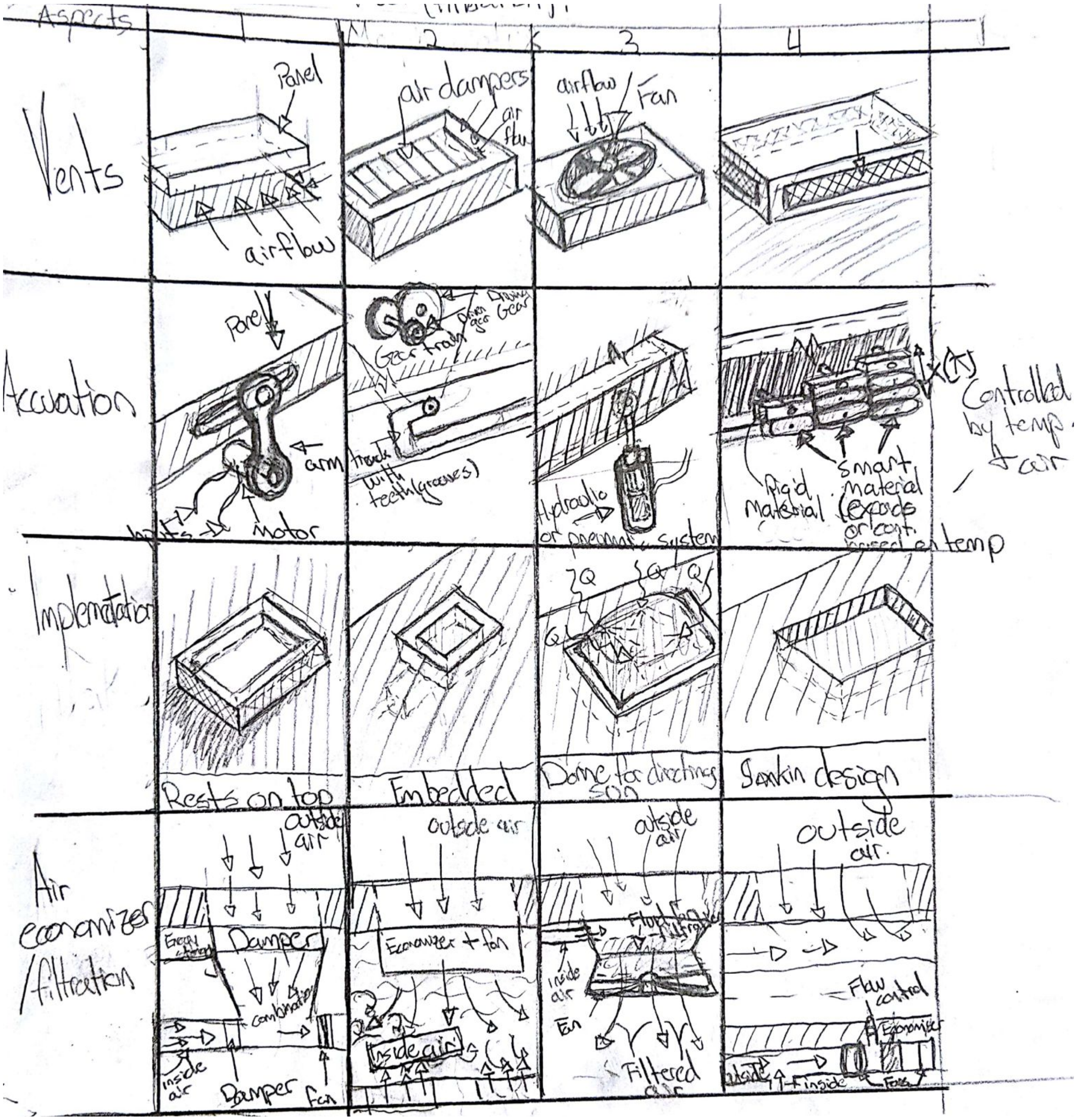

Figure C.1: Morph Matrix of Subsystems

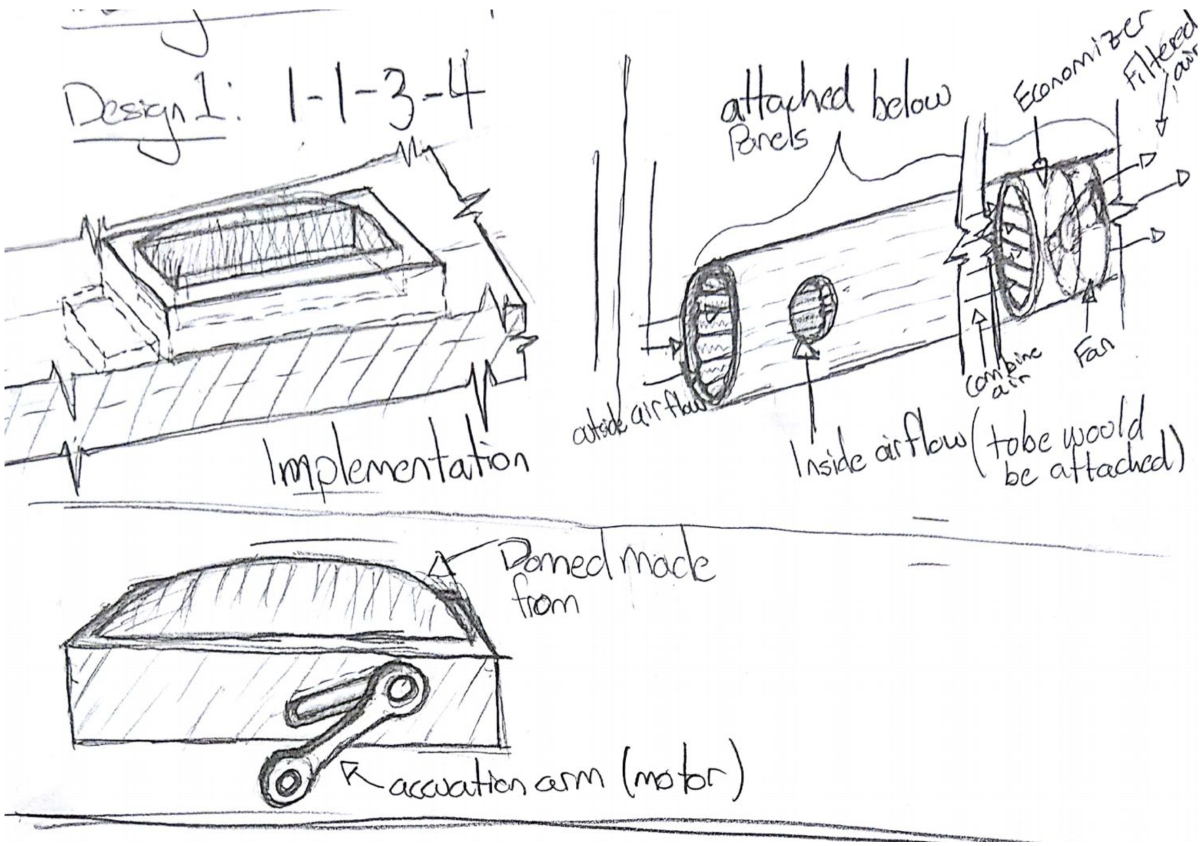

Figure C.2: Design One Generated via Morph Matrix

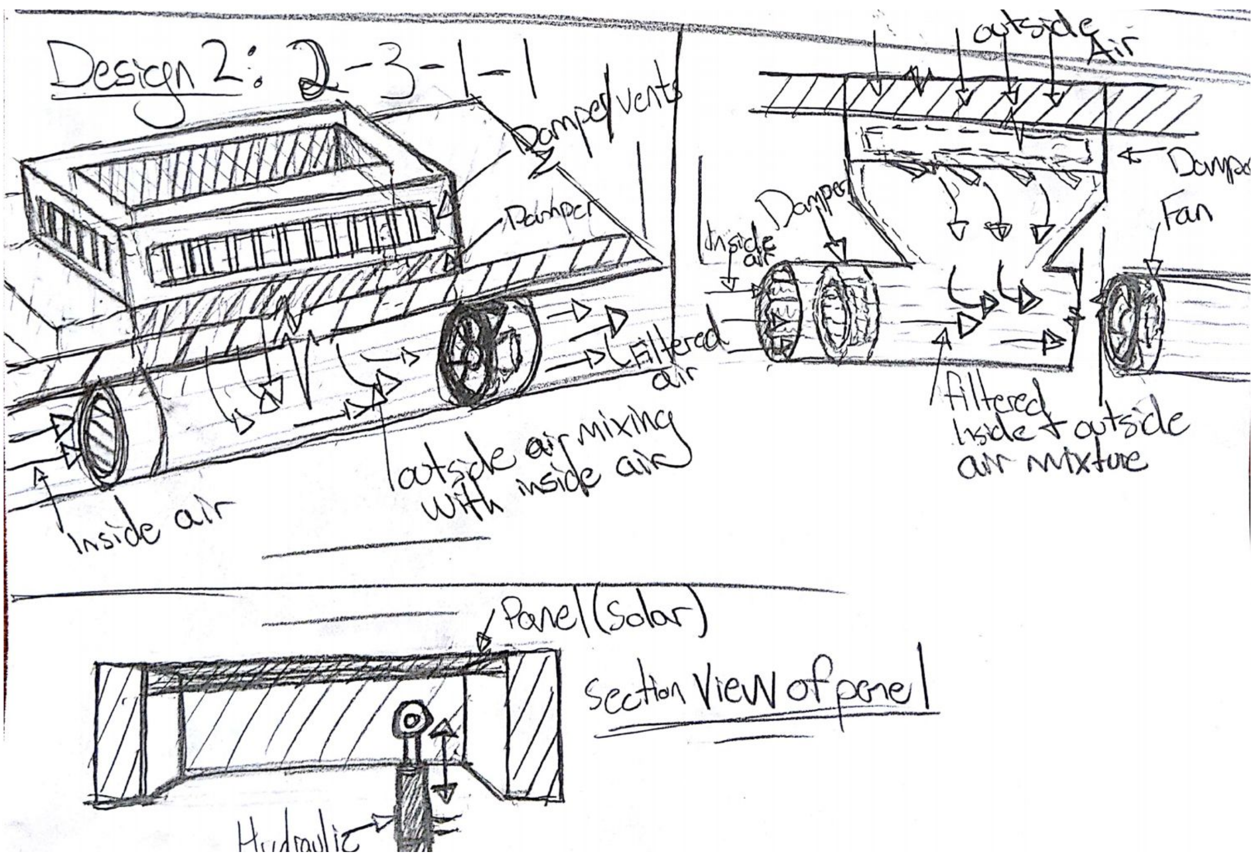

Figure C.3: Design Two Generated via Morph Matrix

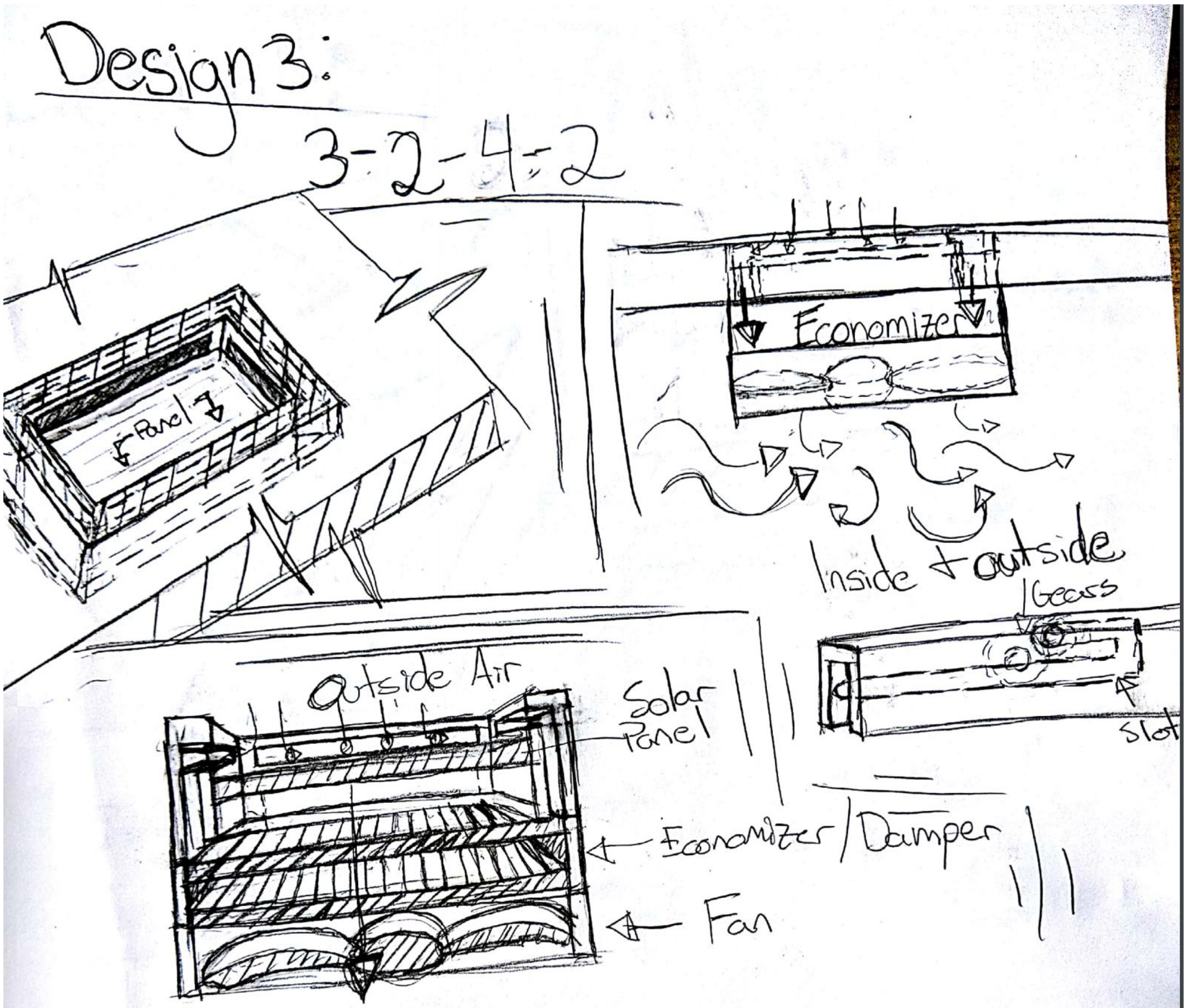

Figure C.4: Design Three Generated via Morph Matrix

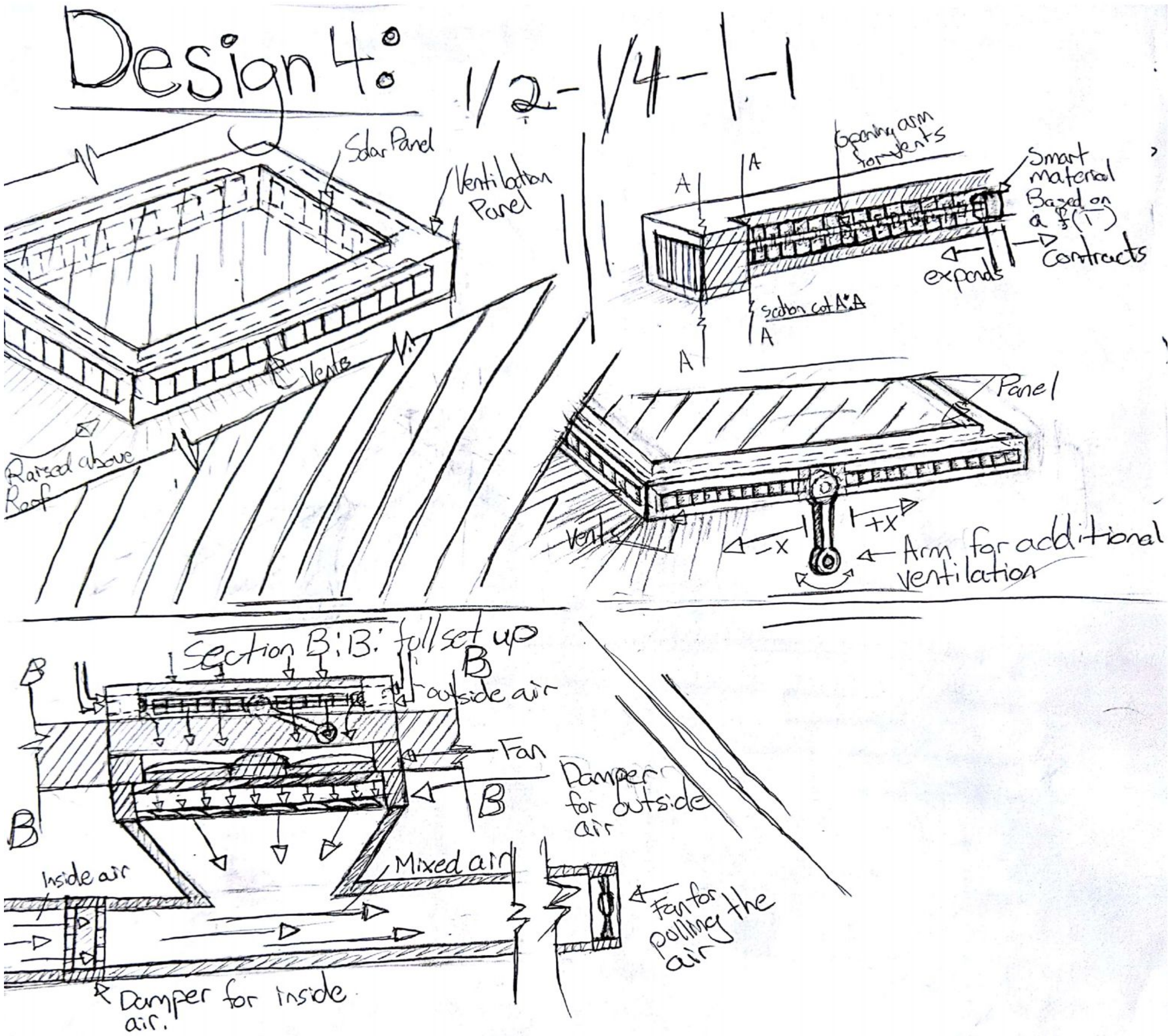

Figure C.5: Design Four Generated via Morph Matrix

APPENDIX D

Customer Needs	Weight (%)	Figure 3 Score	Figure 3 Weighted Score	Figure 4 Score	Figure 4 Weighted Score	Figure 5 Score	Figure 5 Weighted Score	Figure 6 Score	Figure 6 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**

Customer Needs	Weight (%)	Figure 7 Score	Figure 7 Weighted Score	Figure 9 Score	Figure 9 Weighted Score	Figure 10 Score	Figure 10 Weighted Score	Figure 11 Score	Figure 11 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