SolarFocus

A Solar Tracking and Reflecting System

April 21, 2009

ME 450, Winter 2009

Professor Steven Skerlos

Team 25

Katie Caruso

Patrick Hughes

Justin Koehn

Kelley Maynard

1. Abstract

This project aims to develop a simple, scalable, and low-cost motorized mirror system for the G.G. Brown building renovations at the University of Michigan. The mirrors will be directed by a light-sensing control system to track and reflect solar energy. The sunlight will be reflected into the North-facing windows of G.G. Brown – windows that do not normally receive direct sunlight. Each square meter of mirror can provide up to 1000 watts of energy, thereby displacing the equivalent fossil fuel usage and emissions. After piloting this technology in new G.G. Brown building, it can be generalized to residential and commercial applications.

2. Executive Summary

The purpose of SolarFocus is to design a simple, cost-effective sun reflecting system that re-directs solar energy to areas that would not naturally receive direct sunlight. This project was inspired by University of Michigan chemical engineering professor Peter Woolf, who recognized the potential to harness and deliver the sun's abundant energy to rooms on the north side of buildings, thereby offsetting heating and lighting costs. The pilot version of SolarFocus was designed to be implemented on the renovated G.G. Brown atrium at the University of Michigan.

SolarFocus joins a small market of technologies that aim to harness the sun's energy for practical purposes. However, unlike current sun-tracking technologies, SolarFocus is innovative in that it combines a brainless control system with solar mirrors to reflect sunlight into buildings. From analyzing the current solar technologies, it was determined that there is a lack of available brainless technology; current industry standards all include memory or programming for precise solar tracking. This reliance on "brains" has inflated the cost and accuracy needed for harnessing solar energy.

The design process was motivated by brainstorming design solutions based on a functional decomposition, determined customer requirements, and corresponding engineering specifications. The four most promising solutions were analyzed and compared by energy transfer efficiency and cost. A hybrid of these concepts was selected as the alpha design for the G.G. Brown atrium. The key components of the system are the mirror, two motors, a control system, and a photosensor grid. The photosensors will provide feedback through the control loop and consequently orient the mirrors to maximize solar energy intake.

The testing and validation of the initial design included a proof-of-concept, physical testing, a thorough lighting simulation, and several thought experiments. These tests and validations yielded a final design that includes the use of apertures to minimize external noise impact, an outdoor grid placement to eliminate indoor noise, an on-the-mirror sensor array to determine availability of sunlight, and a validated control strategy. The lighting simulation also refined the energy transfer predictions for G.G. Brown and updated cost estimates were combined with these predictions to give a final cost-benefit analysis. The final design of SolarFocus was compared to the original engineering specifications. Following this evaluation, recommendations were made to optimize future design iterations.

The impact of implementing SolarFocus on the G.G. Brown atrium will include \$240 annual energy savings, or approximately 5.3% of annual atrium energy costs, 1.6 metric tons of annual CO_2 offsets, an investment in the forefront of solar energy harnessing technology, and close to a 400% cost reduction from industry benchmarks. With these projected outcomes, we recommend continuing the developments to implement SolarFocus on G.G. Brown as well as further developments to expand the design to other residential and commercial applications. The SolarFocus design has great potential to impact solar technology both locally and globally and provides the opportunity for current mechanical engineers to contribute to the Michigan Difference.

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3. Problem Description

This project will use solar mirrors and feedback control to track sunlight and deliver it to the north-facing windows for the new G.G. Brown atrium. The project originated from the ponderings of a chemical engineering professor and has been narrowed and developed into a specific application for a specific building.

3.1 Project Background

The project sponsor is chemical engineering professor Peter Woolf from the University of Michigan. This project was conceived as Professor Woolf noticed the lack of sunlight delivered to the north side of buildings. In his north-facing G.G. Brown office, Professor Woolf, a feedback control expert, envisioned a photosensor-based system that provides feedback control to orient a mirror to maximize solar energy capture. This concept was then presented to the team as a project with potential for entrepreneurial ventures, positive environmental impact, and energy cost reduction.

In the broadest sense, the central motivation of this project is that the sun is an abundant and under-used power source that is available to help offset energy costs and human environmental impact. More solar energy strikes the surface of the earth in one hour than is provided by all of the fossil energy consumed globally in a year [1]. This project joins in the efforts of harnessing this energy in order to reduce the global environmental impact.

3.2 Focusing the Project

Although the motivation of this project was strongly defined, the specific application and further details of the project were relatively vague. One initial task for the team was to narrow the project focus and goals to effectively apply the defined concepts. We decided to choose a specific building in which to pilot the design so that we could have concrete dimensions, occupants, and climate in which to base the strategies and decisions. The technology established from this phase can be generalized to several locations and applications.

Figure 1: G.G. Brown Renovation Plan

Source: Perkins & Will, Integrated Design Solutions.

The team chose the G.G. Brown building as the pilot venue for the solar mirror system. The G.G. Brown building is set to undergo renovations in the near future; this provides an excellent opportunity for design and implementation of the new solar building technology. We will design the system around the architectural and operational plans for the new G.G. Brown building (Figure 1). Specifically, the system will be designed to reflect sunlight into the north-facing atrium of the G.G. Brown renovation. The atrium is a very visible and centralized space in the new building that will help showcase the new technology. Additionally, the size of the atrium allows for a larger reflective surface and therefore greater energy transfer, making the investment more cost-effective. Further discussion of the decision to apply SolarFocus to the atrium is in Section 7.3 below. The potential to implement a mechanical engineering design project into the mechanical engineering building is unique, exciting, and fitting.

3.3 Project Outcome and Goals

The overall goal of this project is to design a simple, cost-effective system that provides solar heat and light to areas lacking access to direct sunlight. The design will be validated through a physical proof-of-concept and a lighting simulation presented at the Design Exposition. An additional goal of this project is to develop detailed plans and concrete savings data for the project implementation and present them to the G.G. Brown Renovation Committee. The group's work this semester may therefore lead to the implementation of the technology for the new G.G. Brown building. Long-term outcomes may also include an entrepreneurial venture associated with this technology and further generalization and application of the design. This project therefore has the potential to significantly impact solar technology and consequently worldwide renewable energy efforts.

4. Background Information

There have been recent significant advances in creating usable energy from solar power in a cost-effective and environmentally friendly way. To reach the goal of designing a simple system that harnesses solar energy, we began by improving the understanding of the underlying need for sustainable design, and current techniques, practices and products for turning solar power into usable energy. While the practice of sustainable design utilizes many forms of renewable energy, we were particularly interested in architectural use of solar technologies. We also researched areas that will be instrumental in the physical design and validation. These areas include several forms of actuation for the mirror, control theory, and solar energy quantities. The background information most relevant to the final design is given below; additional background information is in Appendix D. With all of this information as a basis, we propose that SolarFocus has the ability to fulfill a market need for solar energy.

4.1 An Introduction to Sustainable Design and Green Architecture

Practicing green architecture and sustainable design started long before the recent movement of making "green the new black," but continuing its advancement is as important now as ever before. An increasing global demand for energy is predominantly being met by increasing the combustion of fossil fuels as shown in Figure 2. This solution is not only negatively impacting the environment, but is also relying on a rapidly depleting resource. Using solar energy to offset some of these emissions will shift this reliance to

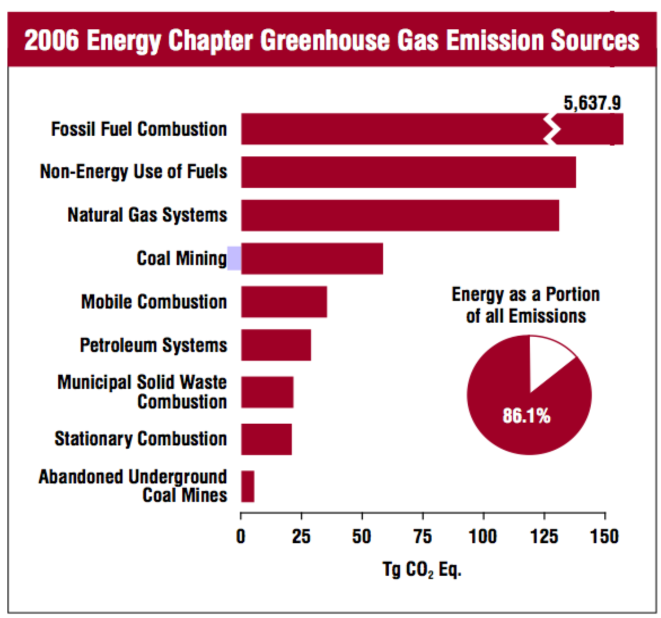


Figure 2: Emissions Sources of Greenhouse Gases

Source: EPA 2006 Inventory of Greenhouse Gas Emissions and Sinks
http://www.epa.gov/climatechange/emissions/index.html

an abundant and daily renewing energy source.

Green architecture aims to increase resource efficiency; particularly, the efficient use of energy, water, and building materials. This practice aims to minimize the impact of a structure on the environment and on human health throughout the entire building lifetime - including design, construction, operation, maintenance, and removal. Often, the goal will include improving the balance and connection between building occupants and the outside environment [2]. This is a rapid growth industry for residential and industrial buildings, and has spread even to entire communities. Figure 3 shows the Drake Landing Community in Alberta, Canada. The community harnesses enough solar energy to meet 90% of their demands, and remarkably, this includes generating sufficient electricity to meet winter heating needs, even in Northern America [23]. Though it maintains the appearance of a common sub-division development, enough solar energy was harnessed to heat and power the community throughout the year by storing abundant summer solar energy for year-round use. Most recent projects on the University of Michigan campus have been designed with sustainability in mind, often meeting LEED silver standards, as discussed in Section 4.3 below. The American Institute of Architects publishes a yearly Top Ten list of completed “Green” projects - a testament to the movement’s growing industry support [3].

Figure 3: Drake Landing Solar Community; Alberta, Canada

Source: Drake Landing Solar Community, Photo Albums. http://www.dlsc.ca/

4.2 Solar Technology Benchmarking

Solar technology is an important aspect of green architecture because it can harness solar energy to help offset the high-energy demands of buildings. The current solar technology associated with green architecture and most comparable to SolarFocus will be discussed below. Additional information on solar technology in green architecture is provided in Appendix D.

4.2.1 Sun Tracking

Sun tracking is a prevalent technique used to several types of solar collectors and reflectors. This orientation can result from passive, active or chronological tracking as determined by the mathematically predictable movement of the sun throughout the day. This often requires a level of accuracy that can be prohibitively complicated for residential or small-scale industrial use.

The most common solar tracker is the heliostat, which is typically used to track the sun in order to maximize the efficiency of reflective surfaces and photovoltaic cells. Heliostats are used in solar telescopes and can be as simple as an equatorial mount chronologically tracking the sun to as complicated as computer controlled precise movement [11].

4.2.2 Photovoltaic Cells

One of the more recent advents of solar technology has been the development of solar photovoltaic cells which provide a clean and reliable source of energy through semi-conductors generating electricity from sunlight. The photons from the sunlight collide with electrons on the solar cell causing the electrons to jump into a higher energy state and creating electricity. The photovoltaic (PV) industry is consistently high-growth, averaging a growth rate of 30% in the past decade [8]. Though PVs have a relatively low payback time (between one and three years), the initial investment is larger than current residential electricity costs in Michigan and can be prohibitively costly for residential or small-scale use [9]. Solar energy has been used to not only heat and ventilate, but also to air-condition homes. For example, the Sun Lizard product harnesses energy with PV cells and a complete climate control system for residential use [10].

Figure 6: Practical Solar Heliostat and Reflector
Source: Practical Solar. http://www.practicalsolar.com/

4.2.3 Solar Reflectors

Solar reflectors differ in purpose from PV cells in that they aim to use their reflective surfaces to redirect and/or concentrate sunlight instead of converting the energy to electricity. Solar reflectors, can, however, be used in conjunction with PV cells by using a parabolic solar reflector to concentrate sunlight onto a PV cell. Non-concentrating solar reflectors are typically used to redirect sunlight. This redirection of sunlight is the basic concept behind SolarFocus. The only device on the market found with a similar purpose is Practical Solar (Figure 6). Practical Solar devices have the same goal and concepts as SolarFocus: using simple mirrors that follow the sun's movement and reflect solar energy into the north sides of buildings. The main difference between Practical Solar and SolarFocus products is that Practical Solar uses open-loop heliostat programming to track the sun throughout the day while SolarFocus uses no-memory, closed-loop feedback control. Practical Solar's open loop control system for solar tracking, if correctly calibrated, can be highly effective [12]. The problem associated with an open control loop is that there is, by definition, no feedback so there is no monitoring of actual sun location in comparison to predicted. Additionally, the technology required to program the mirror's movement throughout the day is a significant portion of the cost of a sun-tracking and reflecting device. Cost comparisons between Practical Solar and SolarFocus technologies will be given in Section 11.1.3 below.

4.3 Programs and Standards

Existing standards will directly impact and indirectly guide the details of this project. On the University of Michigan campus, Planet Blue maintains well-developed operational guidelines out of both environmental and cost concerns. On a larger scale there are governmental standards and programs that will be considered in the development and design of this project. Of particular importance to the G.G. Brown Renovation Committee is meeting the Silver standing for the LEED program. The **L**eadership in **E**nergy and **E**nvironmental **D**esign is a rating system designed by the United States Green Building Council (USGBC) to provide benchmarks for the design, construction and operation of highly performing green energy buildings [13]. The University of Michigan aims to meet at least the Silver level of certification in this program on all new building endeavors. There has been significant advancement in developing international programs as well, which will help advance solar technology standards world-wide. Additional standards reviewed were in regards to available lighting in buildings as determined by IESNA [20].

4.4 Additional Cost Saving Benefits

Beyond the cost savings presented by offsetting the energy demand of a building with the comparatively free solar energy, additional savings are also present through free market and governmental incentives. There are compliance and voluntary markets for renewable energy credits and carbon offsets that allow producers of renewable energy the option to make immediate return on their investment. Compliance markets arose out of the need for businesses to meet emission standards by buying back energy expenditures in the form of renewables. Voluntary markets are available for individuals or companies to “use” renewable energy sources even if there are only traditional electrical and gas supplies in their immediate area [14]. As such, these markets are usually geographically constrained, and supply and demand are determined by region. An influx of financial and governmental support is expected with the new U.S. Presidential administration. Dr. Steven Chu, the Secretary of Energy (2009) is already looking to increase research in electric batteries, solar power, and bio-fuel. This shift in priority from previous administrations will likely result in a more developed carbon tax, or cap-and-trade system, greatly benefiting industrial buildings with renewable energy sources. The cap-and-trade system sets a “cap” at the allowable amount of carbon emissions. Countries, industries, or companies can then “trade” permits indicating any change from that amount. For instance, if Company A and B are both allowed 100 units of carbon emissions and Company A only emits 80, A can sell the permit to emit the remaining 20 units. This then allows Company B to emit up to 120 units [24, 25, 26]. Trading carbon offsets (the representation of one metric ton of carbon dioxide reduction) and renewable energy credits (proof of one megawatt-hour of electricity generated from renewables), allows for those who are highly dependent on traditional energy sources to encourage the development and production of sources that are more sustainable and environmentally neutral. This market will also provide the G.G. Brown Building Committee increased financial incentive for implementing experimental technologies such as SolarFocus. Prone to market variability, the price of these commodities can fluctuate greatly; in 2006 the price rose from \$5 to \$90 per credit with a \$20 median [15]. A more reliable source of cost savings is tax incentives as dictated by federal and state governments. The Emergency Economic Stabilization Act of 2008 increased tax credits for energy- efficient products; a user can redeem up to 30% of the original investment or \$1.80 per sq ft of building floor if through renewable resources they achieve 50% energy savings [16]. To further encourage the development of energy-efficient products, the government provides direct subsidies to renewable energy products. This includes not only the production of electricity, but also any Research and Development (R&D) costs, purchasing or installing renewable products (such as Solar or Fuel Cells), and crediting the construction of energy-efficient buildings [27]. These cost saving incentives are discussed further in the 9.9 Final Concept Cost Benefit section below.

4.5 Solar Energy Availability

Before beginning design of the SolarFocus, it was important that we knew the amount, type, and timing of energy that it will be reflecting from the sun. These factors will have a significant effect on the design and its effectiveness, which is the overarching factor that will influence the design. The sun emits energy from the fusion of hydrogen and helium atoms. The emissive power of the sun is on the order of 10^{23} kW, but only a small portion of this energy is intercepted by the earth because of the size of the earth and its distance from the sun [28]. The sun's energy is transferred to earth by electromagnetic radiation in discrete packets of energy called photons. The radiation emitted by the sun is 50% infrared spectrum, 41% visible spectrum, and 9% ultraviolet spectrum [28]. If the earth were modeled as a stationary thin disk perpendicular to the sun, the solar irradiance (radiation power incident on a surface) top of the earth's atmosphere is approximated to be 1370 W/m^2 [28], a value known as the solar constant.

The actual amount of solar irradiance on the earth's surface at a particular location and time is not 1370 W/m^2 because the earth is not a stationary disk but a rotating sphere and because the earth's atmosphere reduces the solar radiation. This reduction occurs by the clouds and particles in the atmosphere either absorbing the radiation or reflecting it back out of the atmosphere. The radiation that reaches the surface of the earth arrives in the form of direct radiation or diffuse radiation – radiation that is scattered as it passes through the atmosphere. Additionally, objects on the surface of the earth can receive the sun's radiation after it is reflected off of the earth. The amount of radiation that is reflected, absorbed, and scattered by the atmosphere varies with the humidity and cloud cover of an area [28].

The curvature and rotation of the earth also greatly influence the irradiance at a particular location on the earth. The earth is rotating about its own tilted axis and is also rotating about the sun, creating hourly and seasonal variations (respectively) in the angle of incidence of the sun's rays on the earth. The curvature of the earth's surface also causes variations of this angle with latitude. A direct ray yields more irradiance per unit area than an oblique ray because 1) the irradiance is spread over a smaller area, 2) an oblique ray must pass through more atmosphere in order to reach the earth, and 3) the albedo, or reflectivity, over the atmosphere is greater for oblique rays [28]. The first reason for reduction in irradiance is eliminated if the surface is always oriented normal to the sun's rays, such as in a 2-axis tracking solar panel. The amount of daylight also varies with latitude and therefore affects the total radiation received per day.

Because of the temporal and spatial variations in solar irradiance, determining the total amount of solar radiation available to be harnessed at a specific location and time is a science in and of itself. Radiation at specific locations on the surface of the earth can be measured directly using a pyrometer or a pyroheliometer or can be derived from satellite measurements. The NASA Atmospheric Science Data Center derived solar radiation and other meteorological parameters for each latitude-longitude quadrant from satellite observations over a 22-year period (Jul 1983 - Jun 2005) in a project called Surface meteorology and Solar Energy (SSE) [29]. The principal data categories used to calculate earth-surface radiation included top-of-atmosphere (TOA) radiance, cloud cover, and surface parameters [29]. Direct normal radiation is defined by SSE as the "amount of electromagnetic energy (solar radiation) at the Earth's surface on a flat surface perpendicular to the Sun's beam with surrounding sky radiation blocked" and is a key parameter for solar energy capture [29]. SSE's 22-year monthly averaged direct normal radiation for the latitude-longitude quadrant of 42-43 N and 83-84 W (Ann Arbor, MI) is in Table 1 below. The data is in kWh/m^2/day, meaning the number of kWh arriving on a 1 m^2 surface perpendicular to the sun over the course of an entire day.

Table 1: Monthly Averaged Direct Normal Radiation for Ann Arbor, MI [30]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Radiation (kWh/m^2/day)	2.70	3.20	3.74	4.30	4.69	5.53	5.67	4.91	4.88	3.73	2.52	2.24	4.01

Heating-degree days (HDD) and cooling-degree days (CDD) are a common way to measure the heating and cooling energy requirements for a specific climate. A degree day is defined as the difference between the average daily temperature at a specific location and a base temperature of 65 ° F [31]. A negative value yields cooling degree days and a positive value yields heating degree days. The more heating or cooling degree days there are a month, the more energy is required to heat or cool a building. Table 2 gives the monthly average heating and cooling degree days for Detroit, MI from 1961-1990 [31].

Table 2: Heating and Cooling Degree Days in Detroit, MI

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
HDD	725	616	504	295	135	21	0	9	57	242	413	632	3649
CDD	0	0	0	0	21	64	128	103	27	4	0	0	348

4.6 Stepper Motor Actuation

After gaining sufficient knowledge about sustainable design and external factors that will influence the effectiveness of SolarFocus, our attention shifted to potential mechanisms of motion for the system. Actuation is defined as the conversion of energy to mechanical power and can be accomplished through a variety of methods [32]. Actuation can be supplied in rotational or linear form. Common types of actuation include electric, hydraulic, and pneumatic. Smart materials can also provide actuation. The final choice for the actuation of SolarFocus was a stepper motor; a description of how a stepper motor works is given below, while the descriptions of alternate forms of actuation considered are in Appendix D.

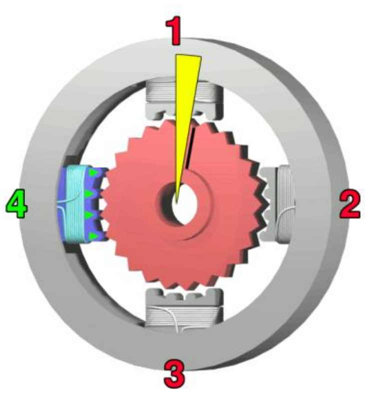


Figure 7: Stepper Motor Rotates in Precise Increments

Source: http://www.societyofrobots.com/member_tutorials/node/28

Electric motors provide actuation with electric current that induces motion through electromagnetic forces. The electric current can be supplied in alternating (AC) or direct (DC) form. A stepper motor is a specific type of DC electric motor that can create rotational actuation. A stepper motor rotates at discrete increments as it is supplied with electric pulses from an external controller [32]. As seen in Figure 7, the electromagnets (labeled 1-4) are slightly misaligned and are magnetized in sequence. As each electromagnet is magnetized, the center gear rotates to align with it. As the next electromagnet is activated, the gear rotates to align instead with it, creating discrete steps of rotation. A stepper motor is useful for precise position control but does not inherently provide position feedback.

4.7 Control Theory

There are two basic forms of control, open and closed loop. Open loop control does not include feedback mechanisms, while closed loop does. Current solar tracking technologies all use heliostats, which are a form of open loop control that predict the sun's position based upon a formula for the position of the sun throughout the year. Because this system predicts where the sun will be and bases controls off of this, it is referred to as a "brained system". This type of system requires a microprocessor which is capable of calculating the sun's position for all times of all days throughout the year. Another option is to avoid feedback altogether, and to have a stationary mirror. This presents a very cheap solution, but with its low cost comes extremely low efficiency. This type of system cannot track the sun throughout the day. A third type of feedback which is not yet employed in solar technology is closed loop feedback. This type of feedback detects the positioning of the sun through sensors, and guides motion based upon the location of redirected energy relative to the desired direction [43]. Because this system is not capable of predicting the sun's position, but rather reacts to where it is measured to be, this will be referred to as a "brainless system."

4.8 SolarFocus: A Simple Alternative

Although the market for harnessing solar energy is a rapidly developing industry, there is still an absence of low-tech, low-cost products for reliably tracking the sun. Given the reliability of the rising sun, and the relatively low maintenance required to use its energy when compared to geothermal, wind, or hydro solutions, solar energy solutions have incredible potential. Open loop systems are prohibitively expensive for the average user, and stationary systems lack the efficiency necessary to validate their use. Most research and industry products are highly effective at gathering, storing and distributing solar energy given correct orientation with the sun. Using programming to provide this orientation is unnecessarily costly while orienting the technology passively can allow for excessive energy losses. For these reasons, neither of these choices are viable solutions to reducing energy emissions. Closed loop feedback, however, provides a means to reduce the cost of open loop systems, while improving efficiency over stationary systems. The goal for this project is to create a closed loop feedback design which synthesizes low cost and high precision in order to create a solar reflector which is environmentally and financially sustainable.

The team feels confident that SolarFocus will be able to bridge the gap between well-developed control theory and available solar technology. Photosensor grids on the outer north-facing windows will give input to the control-loop, which, in turn, will orient the solar mirrors to maximize the room's sunlight exposure. By using a feedback loop system, the device will be self-correcting and very precise without the use of programming, memory, or extensive solar tracking.

5. Creation of Engineering Specifications

With a more thorough understanding of background information and a clear direction for the project, the next step was to create engineering specifications for the solar reflector. This process began with the identification of clients, which helped us to consider every angle of the project. After determining the five main customers, we created a weighted list of their requirements, based upon how important each requirement was to each customer. From this list, we generated the engineering specifications which will be the guide and evaluation metric for the development process. These were weighted according to their relation to each of the customer requirements in order to discern those that are most crucial to the design. The final steps were to develop target values for each spec and to evaluate their correlations. These correlations help evaluate tradeoffs between specs and, along with rankings, help to determine when and in what manner compromises will have to be made. The overall result of engineering specification generation was to give the team a basis for what the solution must include.

5.1 Customers

The first step in the engineering specification generation was to define all customers of the product. It was important to look at it from many different perspectives, since each user will have different requirements. We decided that there are five main users of the reflector. These five customers, in ranked order according to their importance to the design, are: nature, building occupants, G.G. Brown planners and architects, G.G. Brown operations personnel, and construction staff.

5.1.1. The Environment

It is important that nature be considered in the final design since it will, in effect, be the main user of the product. The project goal is to harness the sun's energy to replace fossil fuel consumption. It is also very important to take "nature's opinion" into account because it is a customer unable to voice its own opinion and therefore cannot evaluate any flaws in the design. The environment will be most concerned with the reduction of emissions, but will also have a stake in anything that could be potentially damaging, such as input carbon costs and the environmental impacts over time of the materials used to make the system.

5.1.2 The Occupant

The next most important customers are the occupants of any building that uses the reflector system. Their comfort and enjoyment of the heat and light brought into their office will, in large part, determine whether the product makes it past a prototype. These customers will be concerned mainly with the ease of use of the system, and how much it improves their daily experience. It is also important that the system be aesthetically pleasing. Even if it is extremely functional, building occupants won't like it if it isn't visually appealing.

5.1.3 Planners and Architects

The planners and architects of G.G. Brown will also be critically important to consider in the design process. All financial decisions will be made by the project's financial team, and they will only adopt this solution if it isn't highly fiscally risky. Therefore, it is critical that we present a viable solution that can produce measureable savings over a short period of time with low initial costs. It is important to design with architects in mind since they will be key in incorporating our ideas into the renovation project. They will be highly concerned with how many changes will have to be made to existing plans and how well the system integrates into the building.

5.1.4 Operation and Construction

Building operators and construction team constitute the final groups of clients. The building operators will be concerned with the maintenance of the system, as well as its reliability. They will receive all feedback from occupants about the product performance, so they will provide key feedback on its strengths and weaknesses. They also pose a potentially large continuing cost to the system as they will need to be paid to fix all problems and breakdowns. A large part of designing for building operators will be designing the system to be reliable. The construction team will be in charge of installing the system, and will primarily be concerned with issues such as overall size and weight.

Each of these five groups was considered when creating customer specifications and each add a different perspective from which to look at the project. During design, it is of critical importance that we keep all of these customers in mind.

5.2 Customer Requirements

With these customers in mind, we brainstormed the concerns of each. These concerns were based on the priorities and dealings of each customer, and were evaluated as such. Once the full list of customer requirements was generated, their importance to each customer was ranked. We used a ranking system that assigned 0, 1, 3, or 9 points to each requirement for each user, depending on the requirement's importance to that user (see Appendix E). The total client importance was summed for each requirement and ordered, with a weight given relative to the highest total importance (Table 3).

Table 3: Ranked Customer Requirements Show Areas about which Customers Care Most

CUSTOMER REQUIREMENT	*WEIGHT*
Reduces building energy required	1.00
Cost effective	0.89
Can be added to existing plans or building	0.84
Meets common practice building light standards	0.84
Maintains efficiency over lifespan	0.84
Interface well with current systems	0.84
LEED certified	0.84
Reduces emissions	0.84
Doesn’t require manual adjustment	0.68
Space effective	0.68
Usable in summer	0.68
No harm if walking in line of light	0.63
Low initial investment	0.58
Easy to use	0.53
Adjustable to various buildings	0.53
Durable	0.53
Self- powered	0.53
Easy to maintain	0.53
Long Lifetime	0.53
Not eye sore	0.47
Light not too bright in room	0.47
Easy to install	0.47
Uses environmentally friendly materials and production/manufacturing	0.47

It is unnecessary to discuss each of these customer requirements individually, but it is worth pointing out the general themes into which they fall. One common theme in the requirements was environmental standards. These are expressed through emissions reduction, adherence to green building standards, and a general regard for nature. Another area of importance was cost. This area takes into account overall lifetime, efficiency, power generated, and upfront cost. A third area of focus was safety. If designed well, the system should create no safety concerns, but there are the possibilities of retinal damage, damage to the environment, and possibly even burns resulting from a poor design. In addition to this, another area of interest was ease of use. Considering the ease of ‘use’ of all potential customers, this area covers installation, frequency of system adjustment, and maintenance concerns. A final area of consideration was comfort, dealing with the adjustability of the system and accuracy of heat and temperature control. Each individual customer requirement was used to generate engineering specifications, the most crucial part of the initial design phase.

5.3 Engineering Specifications and Targets

With the knowledge gained from the customer requirements, we created engineering specifications in order to provide the team with a concrete way to evaluate how well it operates and reduces emissions, as well as how well it fulfills customer wishes are being fulfilled throughout the design process. These specifications will be used to evaluate all potential and trial designs, so a thorough generation and understanding of them will provide invaluable insight about the quality of the designs and will also guide the design generation process.

A total of 28 design specifications were created in response to the customer requirements list. These specifications are all quantifiable and/or testable through benchmarking in order to allow us to evaluate the designs quantitatively. Each of these specifications was benchmarked against standards, current devices, and other constraints in order to create target values for a robust design. An ordered list was created in order to help us discern the importance of each specification and is shown in Table 4 below. They were ranked in a similar manner to customer specifications; however, this time, the correlation between engineering specifications and design requirements was measured (see Appendix F).

Table 4: Ordering Engineering Specifications by Importance Shows Six that Stand Out

WEIGHT	SPECIFICATION	TARGET (units)
41	Lifetime	> 30 (years)
39	Minimum Energy Production	> 1100 (kWh electricity and natural gas) per m^2
37	Maximum Temperature	< 72 (°F) winter, < 78 (° F) summer
35	Reduction of Building Energy Cost	> 2.5 %
34	Payback Time	< 4 (years)
34	Reduction of Building Emissions	> 2.5 %
30	Motion	2 (axis)
30	Maximum Light Intensity	< 850 (lux)
29	Light Adjustability	± 50 (lux)
29	Automatic Control	± 5 (°F) and ± 50 (lux)
27	Efficiency Loss Over Lifetime	< 20 %
27	Peak Efficiency	> 40 %
23	Unit Weight	< 100 (lb)
22	Window Characteristics	> 40 % (light transmittance) and (Solar Heat Gain)
22	Operational Carbon Emissions	0
21	Seasonal Maintenance	≤ 2 (per year)
21	Range of Motion	$60 < \theta_{alt} < 60$, $90 < \theta_{az} < 130$ (°)
17	Necessary Additional Power	0
16	Mounting Area	< mirror area
15	Operating Temperature Range	-25° F < Temp < 115° F
15	Operating Wind Range	> 80 mph
15	Operating Snow Build	> 50 lb.
14	Created Energy Costs (cooling)	0
14	Carbon Footprint	< 150 (kg carbon)
14	Install Time	< 8 (hours)
13	Unit Investment	< 400 ($\$/m^2$)
11	Additional Tools/Skills for	0
11	Distance from Building	5.6 (ft per ft building height)

This above ranked list of engineering specifications will help to make choices between two negatively correlated factors as we start concept generation, with the more important specification taking precedence over the less important specification.

It is important to touch on the source and reasoning for each of these design specifications, since they will all influence the final design. It is critical to note, however, that not all specifications should be treated equally and that the top six specifications in Table 4 should be given great priority over all other specifications. These specifications scored significantly higher than all other specifications, highlighting them as particularly important. This discussion will reflect this relative importance, giving more detail about these top six specifications and briefly explaining the remaining 22 specifications.

5.3.1 Product Lifetime

The analysis showed that the most important design specification is the product lifetime. This will directly affect total lifetime savings, both in form of reduced cost and reduced emissions. It also directly affects the general cost effectiveness of the product, since a longer lifetime will help to spread the initial investment over a longer period and more energy will be saved. The 30-year target was benchmarked off of current solar cell technology, which states a lifetime of 30 years at no more than 20% efficiency loss [17]. Since the product will augment or replace solar cells in many applications, the lifetime should match, if not exceed, this current technology.

5.3.2 Minimum Energy Production

The second most important specification is reflector's minimum energy production. This also directly relates to savings both in energy costs and emissions. It is important that the product be able to produce an amount of energy that will be at least minimally useful, since a product that doesn't provide tangible benefits, even if it is low-cost, is unacceptable. We set a target of producing 1100 kWh electricity, or an equivalent combination of electricity and natural gas. In order to create this specification, we calculated the amount of energy (at current prices) must be offset each year to have a payback time of 4 years and an initial investment of no more than $400 per square meter.

5.3.3 Temperature Control

The third specification is that to have a way to control the high temperature of the system. This is important because it greatly affects the comfort of building occupants. Additionally, with lack of proper temperature control, especially in the summer, the reflector has the possibility of raising emissions and costs through overheating rooms that will then need to be cooled. It is, therefore, quite important that we control temperatures to stay below the range of discomfort and additional cooling costs. ASHRAE defines a maximum comfortable temperature of roughly 72° F in the winter and roughly 78° F in the summer [19]; we took these levels to be the seasonal maximum allowable temperatures.

5.3.4 Emission and Cost Reduction

The two specifications are the reduction of emissions and the reduction of cost are very closely related and therefore worth talking about together. They are closely correlated because they both have the amount of energy savings as their determinant. They differ slightly in their clients, since nature cares more about emissions while planners care more about cost. The target value for these was set at 2.5% for a very simple reason. Reduction of building energy costs by this amount grants one LEED certification point [13]. All U of M buildings strive for this certification, so it was a natural choice. It is also important that we aim to produce no emissions during daily operation of the system. While there will be an amount of carbon emissions necessary to create it, we expect that this amount will be negligible as compared to the amount of emissions savings that it will produce over the course of its lifetime. We plan to prove this through a Life Cycle Analysis, as described in Section 11.4.

5.3.5 Product Payback Time

One final specification that is worth describing in detail is product payback time. As discussed in the energy production section, this will be based upon the present value of savings of the system at a potential investment rate of 5%, the amount of energy cost reduction that it can produce, and its upfront cost. This value is closely correlated to cost (and therefore emissions) reduction, initial investment, and product savings. It will provide a good way to quantify the system's overall cost-effectiveness. To meet University of Michigan Planet Blue standards, the payback time was specified as 4 years. With this held constant, and increase in price can only be justified by a greater increase in energy savings. As mentioned above, this spec, along with minimum cost savings, determines how much energy per dollar the product must save. This is an extremely important specification when dealing with planners and architects, who are often predominantly concerned with the cost savings of any proposed project.

5.3.6 Additional Specifications

While the preceding specifications are of highest importance, this by no means suggests that the rest of the developed specifications are unimportant. It merely suggests that, in the case of a negative correlation between two specs, one of these first six will be given priority. The remaining 22 specifications will each be briefly explained.

The motion of the reflector will be critical to its efficiency, with two-axis motion shown to give a 40% increase in energy production over a passive design. It is important that this technology be cheap, since we must make it more cost effective than a passive system.

The maximum light intensity that the system can produce is highly important to prevent discomfort occupants. We set this value at 850 lux as suggested by IESNA [20] in order to avoid any possible discomfort. It is important that the system has a way to control the maximum amount of light that it delivers into a room.

At first glance, adjustability and automatic control would seem to be similar to the maximum light intensity measurement. However, this specification reflects how sensitive the system will be to user input. Light adjustability will control whether the system is a binary on/off or has a continuum of different settings. The automatic control of the system will determine how much variation from user inputs will be accepted. We determined that the system should have a resolution and accuracy of ± 50 lux and a resolution of ± 5° F. We cannot determine the temperature settings beyond setting a maximum temperature because we cannot control the building's main heating system that will provide any heat that the system does not.

It is important that the reflector has high efficiency and maintains its efficiency over time, since effectiveness will decrease as efficiency decreases. This will require that the lifetime of all parts and materials must be chosen for their effectiveness over their entire lifetime. We set 40% as the minimal peak efficiency with 20% as the maximum efficiency decrease, which matches current solar panel technology [17].

The weight and size of the reflector system will determine how easily it can be installed and maintained. Therefore, we set targets that the mirror's base structure cannot have a larger cross-sectional area than the surface area of the mirrors, and it cannot weigh more than 100 lb, corresponding to an amount that two people could easily move together.

We must consider the characteristics of building windows as we progress through the design process, since they have the potential to greatly decrease the efficiency of the reflector. The amount of light transmittance will put a limit on the efficiency of light transfer, while the amount of solar heat gain will limit the heating efficiency. We set both of these values to be greater than 40%, in accordance with the minimum efficiency standards.

In order to keep emissions low, we set targets of operation without any external powering, no carbon emissions during operation, and a carbon footprint less than 150 kg carbon. This final value is benchmarked from the current amount of carbon output used to create solar panels.

Several engineering specifications also considered the environment in which the reflector will be operating and its interaction with its environment. Michigan faces both harsh winters and the occasional hot summer. For this reason, we set engineering specifications for temperature, snowfall, and wind. We considered other factors such as rain, but decided that they will be covered by these three. The target temperature operating ranges for these are anywhere between -25° F and 115° F for temperature, at least up to 80 mph winds, and a snow accumulation of at least 50 lb/m^2, a value which corresponds to 28" of snow.

The two specifications dealing with operational issues are the seasonal maintenance adjustments and additional tools and knowledge required to maintain the systems. These were developed with the goal of keeping the systems easy use from a maintenance perspective. We decided that seasonal adjustment shouldn't be required more than twice per year, once for the winter season and once for the summer season. We also decided that maintenance personnel should be able to operate and maintain the system without any special knowledge or tools, but nothing more than a simple instruction manual.

The range of motion will directly affect the maximum efficiency of the system. We can move the mirrors in an altitudinal or azimuth direction in order to follow the sun. Using input angles from the sun over the course of the year [21], we decided upon the following range: $60 < \theta_{alt} < 60$, $90 < \theta_{az} < 130$ (°). These angles are further described in Section 7, Figure 13 below.

A specification which will be directly correlated to the maximum room temperature is created cooling costs. We realize that, if not properly utilized, the reflectors have the potential to heat rooms in the summer, resulting in an increase in cooling costs and emissions. Therefore, the target is zero additional cooling energy required during the summer. This may require us to come up with a novel way to redirect or use the heat.

The initial investment is an important specification since it will in large part determine how likely the G.G. Brown planning committee is to adopt our idea. We initially decided that $400, the working capital, would be an adequate per unit cost goal for the system. However, once we selected to use SolarFocus on the G.G. Brown atrium, we decided that it is not reasonable to create a system large enough to have non-negligible impacts for less than $400. For this reason, we feel that it is more appropriate to judge the design as a cost per m^2 of mirror. This will allow us to compare designs of different sizes, and it will also allow us to predict the cost of scaling up/down the design for future applications. This specification will be secondary to product payback time.

The two final engineering specifications relate to the installation of the system. First, we feel the install time should be kept low, which will keep the design simple and easy to use. Second, the reflector should be at no greater than a 10° angle with the top of the building. This will prevent the building from creating excessive shading on the reflector. This concern led us to develop a specification for the distance away from the building. We decided that install times should be kept less than 8 hours, and that the distance from the building should be at least 5.6 feet per foot of building height.

With all of the presented specifications, it may be easy to lose sight of their overall meaning and purpose. These specifications provide a guideline for future designs, and their purpose is to help us critically and quantitatively evaluate any concept we consider.

5.4 Correlations

There are some negative correlations between the design specifications. Many of the specifications deal with the initial cost of the system, but some of the specifications will contradict this and add cost, but also add efficiency. Another negative relationship is between lifetime and a 2-axis tracking system. We want the lifetime to be 30 years, but a more complex sun tracking system means more moving parts. The increase in moving parts could decrease the lifetime of the design. The major tradeoffs in the project are efficiency versus cost and simplicity.

6. Concept Generation

To confidently proceed with an alpha design, the team generated a variety of concepts and then systematically determined the best design for the desired product function. The broad design goal and customer requirements were kept at the forefront of our minds during this crucial process.

6.1 Functional Decomposition

The first step in the concept generation process was to define the product goal and the corresponding required product functions. The end goal of the product is to redirect sunlight into north-facing windows to provide heat and light. The product needs to perform several functions in order to accomplish this goal. These sub-functions were determined by a broad-range functional decomposition in block diagram format (see Appendix H). This decomposition helped us to better understand the flow of energy and information through the product and the sub-functions that the product needs to perform in order to transfer and convert this energy and information.

6.2 Brainstorming

Using the functional decomposition and other product requirements, the team brainstormed solutions for five sub-problem categories of the product:

- Reflect and direct sunlight
- Control and power movement
- Self-protect from elements
- Control quantity of heat and light directed into room
- Utilize heat and light once it enters the room

The initial main brainstorm session took place in a relaxed environment with the intent of encouraging creativity and generating a variety of ideas. We went through each category and generated as many ideas as possible to solve the sub-problems. The list of solutions and options for each sub-problem is in Appendix E. During this brainstorming session, ideas also came up for the 'broad concept' of the design, as opposed to a specific sub-problem:

- Light shelves with mirror on corner of roof
- Mirrors on corner of roof
- Giant moving light shelf
- Many small mirrors across the road
- One Flat mirror across the road
- Telephone poles/ light poles
- Prisms
- Light tubes

These concepts were the results of 'big picture' creativity as opposed to solving the individual sub-problems. They were not, however, complete solutions to the overall design problem because as initial ideas they do not address all of the required functions of the design.

6.3 Concept Generation Considerations

With the lists of sub-problem solutions and big picture ideas, we needed to organize and evaluate our many ideas. We initially narrowed down the brainstormed ideas by discarding options on the basis of feasibility, cost, practicality, and the satisfaction of customer requirements. We still had several decisions to make for all the aspects of the product, but we split them into categories of decisions crucial for the initial concepts and future decisions, summarized in Appendix I and J respectively. The decisions that were put off for future consideration were those regarding how the device will self-protect from the elements, how the quantity of heat and light entering the room will be controlled, and how we will utilize the heat and light that enters the room. These decisions seemed suitable to delay because their associated structure and function will be more of an accessory to the system and will not affect the basic design of the system. With those tasks delayed, we focused our efforts on the ideas and decisions that we thought were crucial to this initial concept selection, which can be divided into the control system, the actuation system, and the reflection system. We first determined preliminary plans for the control and actuation systems, and then explored the options for the reflection system.

6.3.1 Control System

Unlike other portions of the design, there were not many options to compare for the overall control strategy. There will be a photosensor, a control board, a room control loop, a transmitter and receiver, and a way in which to control the motor. Most of the selection process is between different parts, rather than different ideas.

We looked into both photodiodes and photovoltaics for use as sensors, and decided to use photovoltaics. This is a clear choice, since it is a design spec that the prototype must be self-powered. Using solar cells to sense light in a room will allow the dual function of also powering the indoor control circuit. The control board must consist of voltage adders and subtractors, so that we may compare the amount of light hitting different parts of the room and control the in-room lighting system.

We are planning to modify an off-the-shelf control system for the indoor room lighting. There are already systems that are set up to do this, so the only modification that we will need to make is integration of the sensing loop to replace the normal physical control.

The transmitter and receiver selection will be based upon compatibility with other system elements. They must have the proper range, take proper input voltages, and they must run on relatively low power. None of these requirements will be difficult to satisfy, so we will choose this component after all others.

6.3.2 Actuation System

Several factors contributed to the selection of an actuator for the mirror movement. A DC electric motor was determined to be most easily compatible with the photovoltaic energy source. It is cheaper than either the hydraulic or pneumatic motors, and the simple rotary motion it provides would require the least additional design and structure in order to use it to rotate the mirror. A piezoelectric motor is precise and efficient, but is expensive and more suitable for smaller-scale applications. The two types of DC motors considered were a servomotor and a stepper motor. Both options would have ample accuracy and are relatively cheap. The main difference between a stepper motor and a servomotor is that a stepper motor has open-loop control whereas a servomotor provides closed-loop feedback. However, if we can prove that the system does not need position feedback through feasibility testing of an open loop system, we will not need closed loop feedback. A main advantage of using an open loop system is that it will keep costs to a minimum. Tachometers, which are necessary for the operation of servomotors, are quite expensive and would raise the price of the system a great deal. They are not necessary because it is not the actual position of the mirror that really matters, but rather the light received in the room, which is already monitored by the photo sensors. Therefore the team decided to use a stepper motor to actuate the mirror rotation. One concern in choosing the stepper motor was whether its step resolution would be small (or precise) enough for use in the design. Proper stepper motor selection confirmed that there do exist motors that meet design requirements. Although at this point we are planning to use two stepper motors to rotate the two axes of the mirror, future design iterations could look to use an SMA or other thermal expansion material to provide the necessary yearly rotation about the east-west axis. The material placement would be calibrated with the mirror position in such a way that the expansion or "remembering" of shape by the material as heat increases in the summer would cause the mirror to rotate at the appropriate rate with the seasonal variation in the sun's incident angle. This option will likely be cheaper than using one stepper motor per axis.

6.3.3 Reflection System

Several factors needed to be considered in designing the reflection system including: the mirror orientation, mirror location, mirror material and number of reflections in the system. In general, the mirrors of the system can either be directed toward the ceiling of a room or toward the floor of a room. Directing the mirror down into the room is advantageous because it mimics how the natural sunlight enters a room. This orientation will be correlated to the efficiency of solar energy transfer. Considering the building dimensions and the solar angles, the mirrors can be placed on the ground farther away from the building, raised on poles and closer to the building, or attached to the corner of the north-side roof. This decision greatly affects the structure of the system. In addition to the orientation and location of the mirrors, the number of mirrors and reflections in the system will affect the efficiency and the structure of the design. Having a single reflection angle would consist of a single mirror reflecting into the building. Having multiple reflection angles could consist of multiple mirrors directing in multiple directions (into different areas of the building/room) or having a mirror direct onto a light shelf that directs into the building.

6.4 Initial Four Concepts

Considering these options in depth, we narrowed the focus to four concepts that could then be evaluated on the basis of energy efficiency and cost, which are two of the primary customer demands. As mentioned above, in section 6.3, the tentative plan for all four concepts was to have the described control system with a stepper motor actuation system.

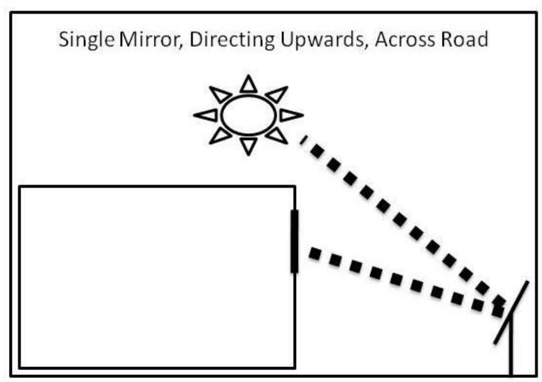


Figure 9: Concept 1

6.4.1. First Concept: Ground Level Mirror Placement

The first concept stems from the original idea of Professor Woolf of having a mirror on the ground reflecting up into a window (Figure 9). This is physically the simplest concept, and therefore would likely be easiest to design and manufacture. One potential concern with this design is that it would be located across the road from G.G. Brown, which would detract from the unity of the system and make it more susceptible to vandalism. Another concern is that the sunlight reflecting upwards into the building could shine into occupants' eyes.

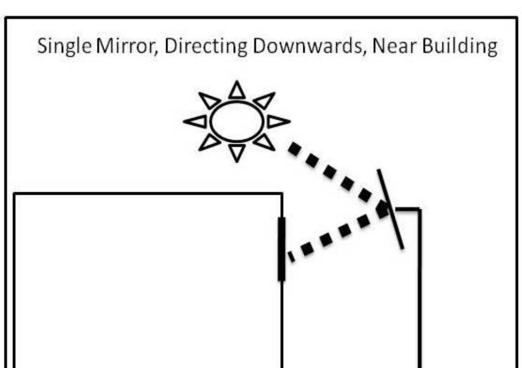


Figure 10: Concept 2

6.4.2. Second Concept: Mid-Level Mirror Placement

The second concept involves moving the system closer to G.G. Brown and raising it into the air so that the light shines down into the rooms (Figure 10). Ideally, this system would be placed on an existing structure near G.G. Brown, such as the lamps in the parking lot. This concept greatly reduces the vandalism concern and makes the entrance angle of the sunlight more accurately representative of the direct sun. One concern with this concept is that the elevated system could be unstable in windy conditions.

6.4.3 Third Concept: Roof Mirrors Reflected to Indoor Space

The third concept is placing the reflection system on the north corner of the roof of G.G. Brown (Figure 11). This concept makes the system much more self-contained and would not require a transmitter and receiver to control the mirrors. The mirror would reflect sunlight directly down into the building. The biggest concern with this concept is the structure necessary in order for the system to be attached to G.G. Brown and maintain the appropriate angles to reflect the sunlight into the building.

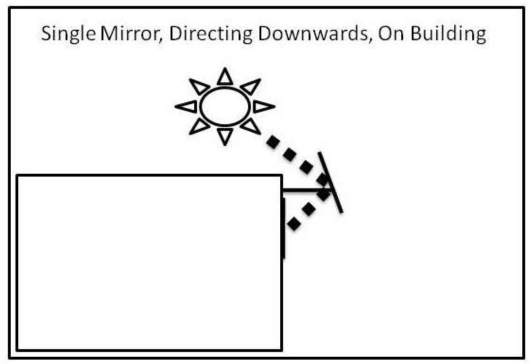


Figure 11: Concept 3

6.4.4 Fourth Concept: Roof Mirrors Reflected to Light Shelves

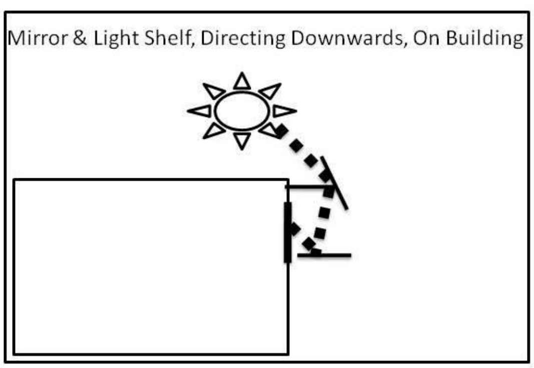


Figure 12: Concept 4

The fourth concept has a similar structure to the third concept with an additional reflection onto a light shelf at the base of the windows (Figure 12). The mirror structure on the corner of the roof will reflect down onto light shelves, which will in turn reflect the light up into the room. Because light shelves are usually only used in south-facing rooms, the benefits of adding light shelves to the reflection system are uncertain. This design will explore these benefits (and potential concerns) of such a design.

6.5 Indoor Space Target

Another area of distinction between the concepts is the indoor space into which the sunlight will be reflected. It was decided that the sunlight should be reflected into the renovated G.G. Brown building, but it had not decided exactly where. In reviewing the plans of the G.G. Brown renovation during this concept generation phase, there seem to be fourteen north-facing office rooms that could potentially receive sunlight from a SolarFocus system. Initially, the plan was to design the system to be implemented to reflect into one of these north-facing office rooms. However, the renovated G.G. Brown will also have an atrium with its north wall entirely glass. As the design process continued, the possibility of increasing the scale of the product and designing it to reflect into this north-facing atrium was identified. Finally, review of the G.G. Brown plans showed that there is an addition of a "mechanical penthouse" above the fourteen office rooms. This fact will make it difficult to implement an on-the-roof design (Concepts 3 or 4) for the office rooms. In moving forward in the concept selection, a key step was to decide between focusing providing sunlight to the atrium or to the fourteen office rooms.

7. Concept Selection

With four basic concepts developed, there was a need for a quantitative means to evaluate them. The efficiency of each concept was analyzed on the basis of energy transfer capabilities. Each concept was then compared by estimated costs. Another crucial decision was the number of systems to implement, and in which type of room or area of G.G. Brown. These systematic decisions helped to confidently select the alpha design.

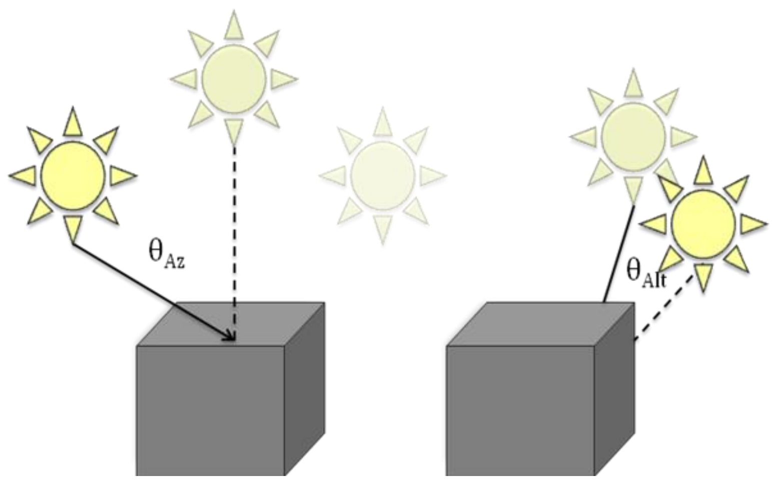


Figure 13: Azimuth and Altitude Solar Angles

7.1 Preliminary Concept Engineering Analysis

To effectively compare the four preliminary designs, we determined the respective costs and benefits of each mirror placement. The benefits were calculated by determining the efficiency of the energy transfer of the mirror at different times of day throughout the year. To begin, we calculated the energy transfer to the indoor space from the mirror at 9am, 12pm, and 3pm during the Winter and Summer Solstices. This served to give us a basic tool of comparison and further our understanding of energy transfer by the mirrors. We performed a more detailed analysis on the final concept selection, discussed in Section 8 below; however, this was sufficient for preliminary comparison.

The efficiencies of the mirrors were determined using the incoming sun energy and placement with respect to the target indoor space. The sun's position is determined by altitude and azimuth angles, shown in Figure 13 below. The altitude angle indicates the sun location with respect to the horizon in a north-south direction.

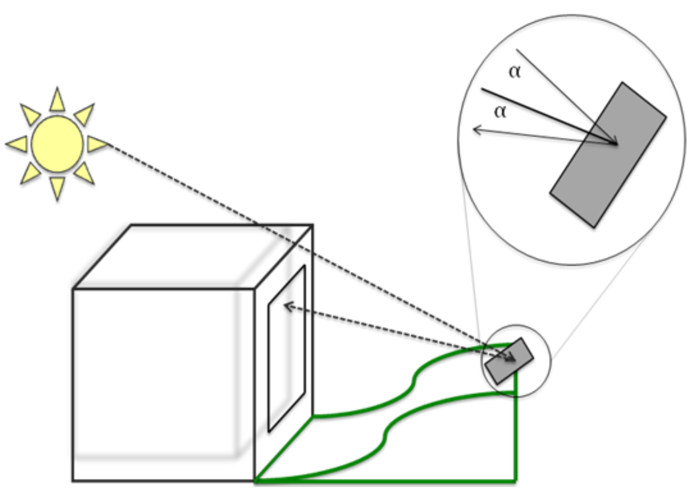


Figure 14: Optical Reflection Axis

While this will vary slightly throughout the day, it has a greater impact during the change of seasons. On the Winter Solstice, the altitude angle with change from 0° to 20° while on the Summer Solstice, this angle will change from 0° to 70°. The azimuth angle is determined by the sun's progress throughout the day in the East-West direction. Unlike the altitude angle, the azimuth varies predominately throughout the day, with much smaller changes during seasonal progression. On the Winter Solstice at 42˚ N latitude, the azimuth angle varies from -55° to 55°, during Summer Solstice it will progress from -122° to 122° [21].

Given the sun placement, we were able to calculate the amount of energy being reflected by the mirror. Optical Law holds that the angle of reflection will be halfway between the incoming angle and the outgoing angle, shown in Figure 14 [40].From this we determined the necessary mirror angle needed to reflect the incoming sun to the indoor space. Determining the needed mirror placement also allowed us to calculate the efficiency of the solar energy hitting the mirror. Because the mirror will not be placed perpendicular to the sun (but rather perpendicular to halfway between the two tracking targets), there will not be a 100% energy transfer and some solar energy will be lost. Only the perpendicular energy component of the sun will be reflected into the indoor target; the parallel component of the solar energy will be lost in this application. Furthermore, there will be some energy loss due to the reflectivity of the mirror. In this initial analysis we assumed the reflective surface to be polished aluminum, which has a reflectivity of .96 [41]. The energy not reflected from the surface (the remaining 4%) will be either absorbed or transmitted and would not impact the amount of energy received by the indoor space. The amount of energy reflected from the surface is assumed to transfer 100% to the outside of the building. Because the energy transfer is done solely by reflection (and not emission), there should be no energy loss unless an external force disrupts the reflection. For these comparisons we did not consider the energy loss due to the window transmissivity as it will be constant across all of the concepts. Given these assumptions we were able to compare the efficiency of the initial concepts in the following sections.

7.1.1 First Concept: Ground Level Mirror Placement

In the first concept, the mirrors are placed on ground level approximately 150 ft away from the building. In this initial analysis, the mirror is assumed to be 0 feet from the ground, each story of the office building is 12 ft tall, and each office is 12 feet by 12 feet by 9 feet (12ft x 12ft x 9ft). These assumptions then lead to a 1 m^2 mirror having a target reflection of a 12ft x 9ft window 16.5 ft from the ground, or to a second story office. Given these assumptions we determined that the window is 6.3° from the horizontal. We used the Winter Solstice and Summer Solstice angles to determine the necessary axis of reflection such that:

$$\theta_{Normal} = \theta_{Room} + \frac{\theta_{Sun,Alt} - \theta_{Room}}{2} \quad \text{(Eq. 1)}$$

Using θ_{Normal} we could find the necessary angle of the mirror such that the mirror would be perpendicular to the axis of reflection:

$$\theta_{Mirror} = 90 - \theta_{Normal} \text{ (Eq. 2)}$$

Using Eq.1 and 2, and the efficiency calculations discussed previously we determined that Concept 1 had a maximum efficiency of 95.3% and a minimum of 81.5% for energy transfer from the sun to the window. These results are summarized in Table 5 below.

7.1.2 Second Concept: Mid-Level Mirror Placement

The second preliminary concept is comparable to Concept 1, however the mirror is closer to the building and elevated from the ground, simulating the effect of mirrors placed on parking lot light posts. In these efficiency calculations, the dimensions of the mirrors and target building area remained constant; however, the mirrors were designed to be placed 56ft from the building (in the parking lot), and at 20 ft above the ground (on a light post). Using the same method of calculation, the maximum efficiency was 94% and the minimum was 76.7%. There was a drop in efficiency from Concept 1, though the designs are similar. This is due to the orientation of the mirror; at 150ft away, the mirrors will always have an angle of less than 90° to the horizontal, while at 56ft away and 20ft high the mirrors had an angle of greater than 90° as shown in Figure 15. This results in a loss of energy transfer because of a diminished reflective space.

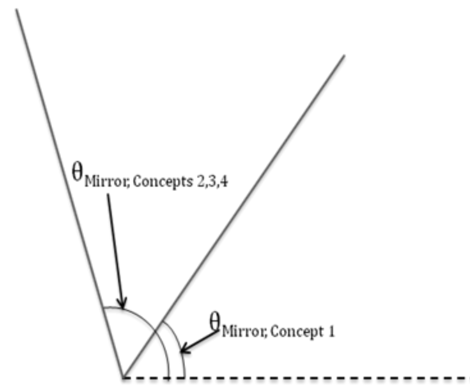


Figure 15: Mirror Angle is Optimal when Below 90°

7.1.3 Third Concept: Roof Mirrors Reflected to Indoor Space

One of the primary concerns with Concepts 1 and 2 was that they were so far from the windows so they weren't constrained to the building footprint. In Concept 3 this was remedied by cantilevering the mirrors from the corner of the roof. It was assumed that the mirrors would hang 3 ft from the side of the building and would need to reflect into the same second story office space. The maximum efficiency of this design was 91.2% and the minimum was 69.9%. Like Concept 2, energy transfer was diminished because the angle of the mirror was greater than 90°. After initial calculations we determined that this concept would be particularly difficult to integrate on G.G. Brown due to the mechanical suite located on the top of the building. Because of the building's exterior shape, a mirror 3 ft from the edge would not receive consistent sunlight. For the mirror to be in direct sunlight it would require extensive supports to cantilever the system further away from the building, this is discussed in greater detail in Section 7.2 below.

7.1.4 Fourth Concept: Roof Mirrors Reflected to Light Shelves

The final preliminary concept used Concept 3 to reflect light onto light shelves instead of directly into the building. We again assumed that the mirrors would be 3ft from the corner of the building, reflecting onto light shelves 6ft down from the roof. In this case, there were two reflections instead of one causing further energy loss. Even assuming that the light shelves were made of polished aluminum and had a reflectivity of .96, this concept had significantly lower efficiencies. The maximum energy transfer would be 67.2% efficient and the minimum a mere 31.9% efficient. This concept combined the energy loss of a θ_{Mirror} greater than 90° and the necessary loss accompanying each of the multiple reflections.

7.1.5 Indoor Space Target

All of the preliminary concepts could be applied to either the G.G. Brown Atrium, or a second story south-facing office. The calculated efficiencies for the four concepts in Table 5 below will remain constant for either application as will the energy reflected per mirror. The significant difference will lie in the increased number of mirrors used to reflect solar energy to the atrium.

Table 5: Efficiencies for Preliminary Concepts

Concept	Winter Solstice Max	Winter Solstice Min	Summer Solstice Max	Summer Solstice Min
1	95.3%	85.2%	83.0%	81.5%
2	94.0%	85.1%	82.3%	76.7%
3	91.2%	84.3%	80.9%	69.9%
4	67.2%	65.5%	61.4%	31.9%

7.2 Preliminary Concept Cost Benefit Analysis

Beyond comparing the efficiencies of the four concepts, it was also necessary to compare the costs required to achieve these benefits. For the preliminary analysis, these included rough estimates of costs associated with the installation, structural requirements, mirrors, photo sensors, photovoltaic cells, motors, and control system requirements. All of the concepts will use the same motor and used same assumptions for estimates. To estimate labor we assumed that it would cost $30/hour to employ a skilled worker. In order to minimize disruptive impact during installation we want to minimize total installation time by employing at least 3 workers simultaneously. Installation time differed for each concept, discussed below, which varied total installation cost. Cost for structural support was estimated using the cost of steel and required strength for each concept. Cost for mirrors, photo sensors, and motors was constant for each concept during this preliminary analysis since each concept is similar in size. Concept 1 and 2 had higher costs associated with the transmitter, receiver, wires and controller as related to the proximity to the building (discussed in detail below).

7.2.1 First Concept: Ground Level Mirror Placement

We estimated that Concept 1 would take approximately 4 hours to install. This was lower than the other three because of the placement of the mirrors. Because they will be installed on the ground, installation would be simpler and take less time. This placement will also have lower maintenance costs than mirrors cantilevered from the roof. The cost estimation is summarized in Table 6 below.

7.2.2 Second Concept: Mid-Level Mirror Placement

Concept 2 had very similar costs compared to Concept 1; however, the installation was significantly higher due to mirror placement. We estimated that it would take 3 laborers 6 hours to safely install the mirrors on a raised pole. Also like Concept 1, the control system costs are slightly higher from the need for a transmitter and receiver. Other costs are summarized in Table 6 below.

7.2.3 Third Concept: Roof Mirrors Reflected to Indoor Space

Unlike Concepts 1 or 2, Concept 3 is cantilevered from the roof of the building. This should take approximately 18 hours to install, or 3 laborers 6 hours. It will require additional structural support to maintain integrity of the overhang. We expect that the control system cost will decrease, as the mirror systems will not require a transmitter or receiver due to their proximity to the building.

7.2.4 Fourth Concept: Roof Mirrors Reflected to Light Shelves

Installation costs for Concept 4 are much higher than the previously discussed concepts because of the added component of a light shelf. We estimated that it would take 3 workers 8 hours to install. The light shelves also caused structural costs to increase as well as expected maintenance. The only function that was less expensive was the control system, which, like Concept 3, would not require a transmitter or receiver.

Table 6: Concept Cost Estimation

Characteristic	Concept 1 Costs	Concept 2 Costs	Concept 3 Costs	Concept 4 Costs
Installation	$ 360	$ 540	$ 540	$ 720
Structural	$ 50	$ 30	$ 50	$ 80
Mirrors	$ 90	$ 90	$ 90	$ 90
Photo Sensors	$ 48	$ 48	$ 48	$ 48
Stepper Motor	$ 50	$ 50	$ 50	$ 50
Control System	$ 50	$ 50	$ 20	$ 20
Total	***$ 648***	***$ 808***	***$ 798***	***$ 1008***

7.2.5 Indoor Space Target

The final conceptual distinction to make is application of SolarFocus to an office room or to the G.G. Brown Atrium. The north side of G.G. Brown has 14 offices, and cost associated with the application to offices will be 14 times that of an individual room; for the preliminary analysis we assumed this could be done with 14 replicate mirrored systems. Using comparable assumptions for the atrium, the costs associated with atrium application were calculated by total available window area. With that said, there will be some economies of scale and overall cost will be less than the equivalent size in office space. This is due largely to a significant reduction in installation and structural costs, as summarized in Table 7 below.

Table 7: SolarFocus in Atrium Cost Estimation

Characteristic	Concept 1 Costs ($)	Concept 2 Costs ($)	Concept 3 Costs ($)	Concept 4 Costs ($)
Installation	360	540	540	720
Structural	50	30	50	80
Mirrors	90	90	90	90
PVs	48	48	48	48
Motor	50	50	50	50
Control	50	50	20	20
Total by Room	648	808	798	1008
Total for 14 Rooms	9072	11312	11172	14112
Total by Atrium	***6804***	***8484***	***8379***	***10584***

7.3 Final Concept Selection

The selection of the final concept is a hybrid of Concept 1 and Concept 2 based on the preliminary cost/benefit analyses. SolarFocus will be elevated in a similar manner to Concept 2; however, it will be placed further from G.G. Brown in order to have the sunlight direction aimed upwards and preserve the efficiencies of Concept 1 by maintaining a mirror angle of less than 90° which.

The G.G. Brown Atrium was chosen as the indoor space target for the design. As seen in Table 7, this option is more cost-efficient because of economies of scale associated with a large mirror reflection and a single control system for the atrium. Additionally, the single atrium system can conveniently be placed in the traffic circle directly north of the atrium and fulfill the geometry requirements for the concept 1-2 hybrid design. The single system of the atrium will achieve a higher scale of energy offsets and therefore a more significant impact on monetary savings and emissions offsets. Finally, the high visibility and central location of the atrium system can increase awareness and publicity of this new technology. With these factors combined, we are confident that piloting the design on the G.G. Brown atrium is the best available option for SolarFocus.

8. Alpha Design

The alpha design consists of the outcomes of all the combined decisions during the concept selection phase. This design requires validation and testing to prove the feasibility of such a system providing a significant amount of energy to the G.G. Brown atrium. This section describes the initial design for G.G. Brown and describes the steps taken for the initial energy transfer validation of the design.

8.1 SolarFocus on G.G. Brown

The design for the SolarFocus system will sit in the middle of a traffic circle in the G.G. Brown parking lot, and will reflect energy into the top of the new atrium. Figure 16 shows a stylized view of this system.

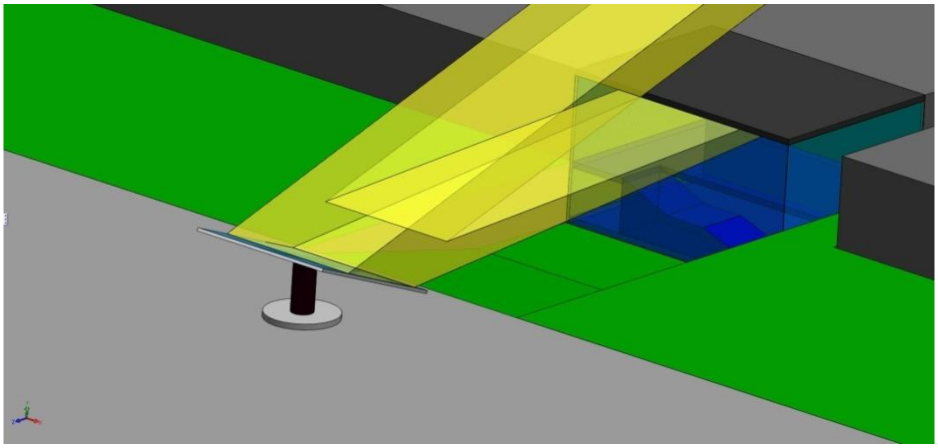


Figure 16: The SolarFocus System will Heat and Light the New G.G. Brown Atrium

There are several important design aspects and considerations that are included in this drawing. The first is that this design will not reflect into peoples' eyes. It will be placed on supports that will raise it above eye level, and will then reflect upwards onto the atrium ceiling. Since the atrium does not have a third floor, eye irritation will not be an issue. Also, since the energy will be directed toward the ceiling of the atrium, light will reflect off the ceiling and come down in a very natural manner. Some heat will be reflected off of the ceiling, while the rest will be absorbed by the ceiling and reradiated into the room.

We have chosen to put the SolarFocus in the middle of a traffic circle so that it will be a focal point of the new atrium. This positioning will put it in a position where it will be noticed by all users of the atrium and parking lot; showcasing the new building's practical, stylish, and environmentally friendly design. Since SolarFocus will be a major focus of the atrium, it will be necessary to make it aesthetically pleasing. Currently, we are concerned mostly with functionality, but we recognize that it will be important to consider aesthetics once we have proven the feasibility and benefits of installing this system.

To track maximum motion of the sun, the SolarFocus system will have to have a range capable of covering all positions of the sun. One final consideration is that the system must be able to track the sun's motion precisely enough to provide small, slow motions. The biggest constraints on this motion will be the step angle of the motor and the distance from the building of the system.

A more thorough description is included in Appendix L. Although some of the alpha design details carried through to the final design, many details changed. To further describe or analyze the alpha design at this stage would be premature; however, some details from the Appendix L will be referenced in the critique in the following section (Section 9. Critique of Alpha Design).

8.2 Alpha Design Engineering Analysis

The alpha design efficiencies were calculated using similar methods as described in the preliminary concepts' benefit analyses; however, for the alpha design these methods were applied more accurately and extensively and at higher frequency. Using sun-positioning data [21], we determined the angle of the sun at every hour, of every day, throughout the year. Given the dimensions of the G.G. Brown atrium, we were able to determine θ_{Window}= 5.7°. Using the angles of the sun location and the θ_{Window} we determined θ_{Normal} for the reflection axis at each location. In turn, we could then calculate the efficiencies on an hourly basis throughout the year. This data is summarized on a monthly basis in Table 8 below.

Table 8: Calculations of Predicted Energy Transmission

Month	**Predicted Average Efficiency**	**Average Solar Energy in Michigan ($kWh/m^2/day$) [30]**	**Predicted Energy Reflected to Window ($kWh/m^2/day$)**	**Predicted Energy Transmitted to Atrium ($kWh/m^2/day$)**
January	90.8%	2.7	2.5	2.2
February	89.0%	3.2	2.8	2.5
March	83.9%	3.7	3.1	2.8
April	74.0%	4.3	3.2	2.8
May	69.0%	4.7	3.2	2.9
June	*66.8%*	*5.5*	*3.7*	*3.3*
July	*67.9%*	*5.7*	*3.9*	*3.4*
August	*72.0%*	*4.9*	*3.5*	*3.1*
September	77.0%	4.9	3.8	3.3
October	87.6%	3.7	3.3	2.9
November	90.2%	2.5	2.3	2.0
December	91.2%	2.2	2.0	1.8

To quantify these efficiencies as energy benefits we used weather data determining the average solar energy received in Michigan throughout the year. This data included effects of cloud cover and stormy weather, which are significant during Michigan winters. Using this data combined with the efficiencies we calculated the average amount of energy the mirrors would reflect in $kWh/m^2/day$ throughout the year. We calculated the energy values on a monthly basis, an average yearly basis, and the average throughout the heating season (September through May) as shown in Table 9 below.

We further refined the predicted delivered energy by assuming 89% energy transmission through the window [42]. Though in preliminary analysis it was sufficient to compare merely how much energy was reflected from the mirrors, we determined how much of the G.G. Brown Atrium energy needs will actually be offset by SolarFocus. These calculations were used in conjunction with current energy prices for the Cost/Benefit Analysis in the following section.

Table 9: Energy Transmitted During Heating Season

Time Scale	Predicted Average Efficiency	Average Solar Energy in Michigan (kWh/m^2/day) [30]	Predicted Energy Reflected to Window (kWh/m^2/day)	Predicted Energy Transmitted to Atrium (kWh/m^2/day)	Predicted Energy Transmitted to Atrium Over Year (kWh/m^2)
Year	80.0%	4.0	3.2	2.9	1058.5
Heating Season (Sept -	83.6%	3.6	3.0	2.7	737.1

8.3 Final Concept Cost Benefit Analysis

The heating and cooling seasons for Ann Arbor were determined using the heating and cooling degree day data for Detroit (Table 2). The heating season was defined to be all months in which the number of heating degree days is greater than the number of cooling degree days, meaning a building needs more heating than cooling for that month. Using this criterion, the heating season for Ann Arbor was determined to be September through May. At this point, SolarFocus will only be in use during the heating season, so the cost-benefit analysis will be performed for these months.

The total cost of the design for the G.G. Brown atrium was determined from installation costs, structural material prices, mirror prices, cost of motors, labor, photosensors, and the cost other components of the control loop.

The major changes from the preliminary cost analyses for the office rooms to the final occur with the cost of the mirrors and installation. The total surface area of the reflector increased from 1 m^2 to about 10 m^2, making the cost of mirrors increase by a significant amount. Where SolarFocus saves money on this large-scale implementation is in its installation. Instead of installing the same system 14 times for all of the north-facing offices, the final design's installment cost will not be much greater than that of the concept 2, having SolarFocus on a light pole. The overall cost of the final concept design came out to be $2010. Since SolarFocus is a solar energy source, a federal tax incentive of 30% of the total cost will be available. This reduces the cost of the design to $1407.

The amount of kWh/m^2/day of radiation available for the mirrors in Ann Arbor, MI each month to be harnessed by the solar mirrors is given in Table 1, p.14. This data takes into account the all effects of Michigan's weather variations on the radiation available. As seen in Table 9 above, multiplying the average radiation available by the average efficiency of the mirrors per day will result in the amount of energy hitting the window. After taking into account the normal window transmission, we then could find the total energy in visible light and heat that enters through the window. Visible light makes up 41% of the radiated energy, while 50% consists of infrared radiation. Ultraviolet radiation makes up the final 9%, and the UV radiation not blocked by the windows can add additional heat. To find the total savings of the system, we converted the total energy delivered into respective proportions of visible light and infrared radiation. We then converted the kWh of infrared radiation into CCF of natural gas, because this is the unit of energy expenditures which the infrared radiation will be offsetting. The visible spectrum energy can stay in kWh because this is the unit of electricity costs for lighting. The UV energy transfer was not considered in the cost offsets but can provide additional heat to the atrium. The cost of energy is $0.085/kWh for electricity, and $0.958/CCF for natural gas. Since we found how much light and heat the mirrors are reflecting throughout the year, we initially found that the system will save $36.75/m^2 per year. Since SolarFocus will have about 10 m^2 of reflector area, the initial total cost savings is $367.50.

After finding the estimated savings per year, we wanted to determine the payback time of the final design concept. Using NPV for the payback time, we determined that the design on the atrium would pay itself back in 4.36 years. We used a 5% interest rate, the total energy savings, and the design cost after the 30% incentive. One of the engineering specifications from Design Review 1 was to have a payback time of 8 years. Having a short payback period will give SolarFocus a better chance of being installed on the G.G. Brown renovation.

This value is a conservative estimate because the available radiation used in these calculations does not include diffuse or earth-reflected radiation, which can also be harnessed by the solar mirrors. The albedo of snow is very high, meaning that the earth-reflected radiation available in the winter, SolarFocus' primary season, will be significant. Also, along with adding energy as heat, IR will add some energy as visible light. Finally, as mentioned above, the UV radiation can provide additional energy as heat. These two factors also contribute to the conservative nature of this estimate.

The yearly energy offsets and cost savings validated that the chosen concept has the potential to significantly impact the energy usage of G.G. Brown. These validated continuing this design. However, we recognized that the purely theoretical energy savings calculations do not take into account all of the factors that contribute to the efficiency of the system. For instance, we did not quantify how light would scatter as it traveled to the atrium and through the glass; instead, we assumed the light would not scatter. Additionally, ambient factors such as light shadowing and reflection from ambient buildings and reflection from snow cover were not taken into account. These shortcomings convinced us to pursue a lighting simulation software that could refine the efficiency and energy savings calculations. A description of this simulation is in Section 10.2.1. We also recognize that the cost of the system can be further refined as we move forward with the design. The final cost-benefit section, complete with the results of the lighting simulation, is in Section 11.1

9. Critique of Alpha Design

After moving forward with the alpha design, certain weak spots in the logic of the brainless tracking system were considered. These potential problems did not invalidate the alpha design, but rather were used as considerations for further developing certain aspects of the final design. The basic structure and location of the alpha design still proved to be optimal; however, the control logic of the system needed to be further specified.

The first concern with the brainless design was with the signal-to-noise ratio on the photovoltaic grid on the ceiling of the atrium. The goal of the grid is to measure and compare sunlight intake around the grid and therefore keep the mirror's reflection inside this grid. However, thought experiment showed that the sunlight would not be the only light input to the photosensors. Indoor artificial lighting or a reflective delivery van outside are just two examples of everyday "noise" that could give false inputs to the photosensor grid and therefore direct the mirror to reposition incorrectly. We therefore needed to determine whether this posed a real concern and provide a solution to prevent this incorrect repositioning from ambient lighting noise.

The other significant shortcoming of the alpha design was with regard to the photovoltaic grid's ability to track the sun during periods of no sunlight, such as at night or during a cloudy day. With the current alpha design, the photovoltaic grid would lose tracking ability as soon as the sun's reflection leaves the grid. Once this happens, there is no way in the current alpha design control system to redirect the sun's reflection back inside the grid. This poses a big threat to overall energy transfer quantities because the system will just have to "wait" until the sun's reflection comes back inside the grid in order to begin functioning properly again.

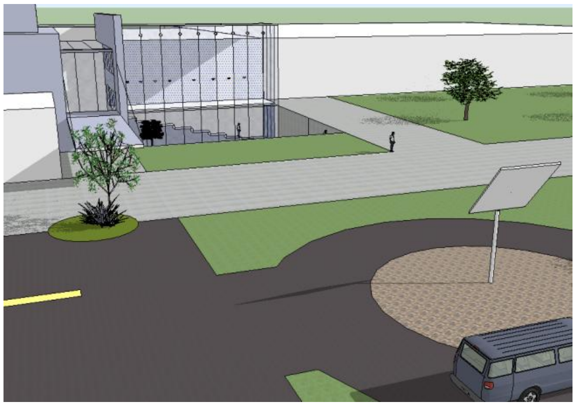
With these shortcomings, we realized that the design was not complete. We therefore moved forward to a design-refining process which consisted of several thought experiments and brainstorming sessions. By the end of this process we had arrived at a final design that addressed the identified weak spots of the alpha design. The final design and its justifications are described in the following section.

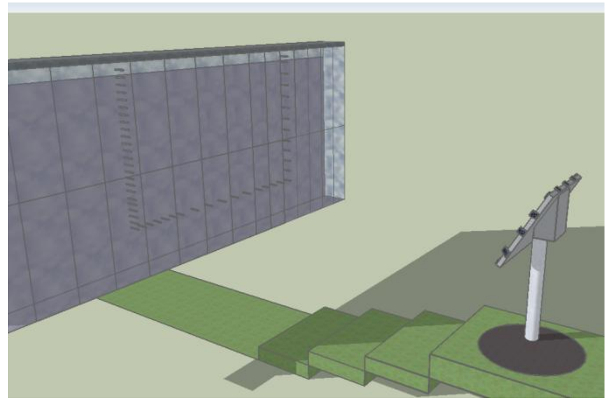
10. Final Design

The above concerns over the alpha design led the SolarFocus team to further refine the final design to address each operational issue. Through several design alterations, we eliminated the impact of indoor noise, reduced the impact of outdoor noise, and mitigated the potential of total tracking failure. Our final design, including these alterations, is described below. Aspects of our design which required further testing and validation are described in more detail in subsequent sections of this report.

10.1 Final Design: Overall Description

The final SolarFocus design is a 10m^2 polycarbonate mirror outside of the proposed G.G. Brown atrium. The G.G. Brown building is going to be renovated in the next few years, and the most recent drawings include a viewing atrium on the north side of the building. The atrium is 71 feet long (from east to west) and just over 19 feet deep (from north to south). Though technically three stories tall (approximately 46 feet), the atrium is laid out as a confined first story and bi-level "second" story. The first story faces a sloped grassy knoll, and the top of the hill marks the start of the bi-level. To the east, the atrium is connected to the rest of the G.G. Brown building, also expanded, and to the west it is neighboring the Dow building. The atrium has floor to ceiling windows across all 71 feet, and appears to have solid walls at the back. This can all be seen in Figure 17, which shows a 3D model of the proposed atrium.





Figures 17a and 17b: 3D Model of SolarFocus on G.G. Brown Atrium

The SolarFocus system has been designed to reflect only into the top bi-level story to reduce user irritation, but this reflection point could be altered. The system is designed to be placed at the top of the hill, at the same height as the start of the second story of the atrium, and approximately 150 feet away. This positioning allows it to be placed in a traffic circle which will be present in the new parking lot created with the building. To reflect into the building, the 10m^2 polycarbonate mirror will be anchored similarly to a street light-pole. It will be connected to a 15 feet tall, 8-inch diameter, steel beam, which will in turn be anchored to the ground with a cement casing.

The point of connection between the steel pole and the mirror will have a half-sphere cover, inside of which there will be the joint required for mirror-pole connection, and the motors powering the mirror rotation. The purpose of the half-sphere cover is to protect the electric components against the elements and to add aesthetic appeal to the design. In this design, there are two 24V stepper motors to allow for dual-axis rotation, both of which are connected to the control circuit. These are powered using photovoltaic cells placed on the top of the mirror. There will also be a solar powered battery for short-term energy storage. The connections between stepper motors and the mirror must be further developed in future design iterations, as must the exact power requirements of the battery and photocells. As the Earth rotates throughout the day, the mirror will need to track the movement of the sun. To do this, our system will track the reflection of the sun with a photosensor array placed on the outside of the atrium, Figure 18.

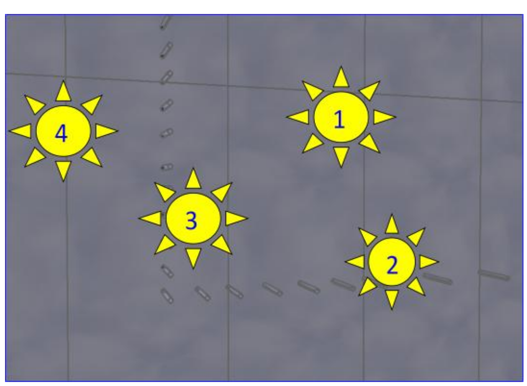


Figure 18: System Moves when Sun Moves Outside Sensor Grid

This is the same general concept of the photosensor grid in the alpha design. We have designed a control system which will constrain this reflection within the photosensor array. Ideally, all of the photosensors will output 0V, indicating that the reflection is properly constrained and there is no sunlight on the photosensor border of the grid. This corresponds to case 1 in Figure 18. However, if any of the photosensors receives a solar input, cases 2 and 3 in Figure 18, it will output a voltage to the control circuit. This means that the reflection is beginning to move off of the target photosensor grid. By comparing the output voltages of the photosensors throughout the array, the system will be able to determine where the mirror is reflecting and tell it to move back towards the middle of the array. A detailed description of the control logic of SolarFocus, as well as its validation, is given in Section 10.3.2.

The photosensor array is 26 ft long, 21 ft high, and is located on the exterior wall of the atrium. This size was optimized for energy reflection, but is placed to prevent reflection into user's eyes. It is on the north exterior window of the atrium to remove potential indoor noise acting as a sensor input. The sensors will be placed at a spacing of 8 ft. Further description of this array and the testing used to determine its size, location, and spacing are included in Section 10.3.1.

The other possible input for the control strategy is a set of photosensors on the mirror itself. This input was not included in the alpha design and was added to optimize SolarFocus' sun-tracking technique. These photosensors will be mounted on the sides of the mirror at angles of 45°, 90°, and 135° to the mirror side, discussed in Section 10.3.3.1 and seen in Figure 26. These sensors will alert the system if there is sunlight coming from a position which will not reflect onto the photosensor array given the current position of the mirror. This is shown as case 4 in Figure 18. If the voltage from these sensors becomes too large, indicating the sun has moved a great distance without being tracked, our control circuit will signal the mirror to rotate until it is back to a position which is reflecting on the photosensor array. This is a less-specific error correction than the previously described array, but will allow for correction of the system in response to large errors. This error correction is targeted to correct for tracking losses during periods of no sunlight. Even under normal operating conditions, the system will lose solar input during the night. Because there is no memory programmed into the system, it cannot be programmed to return to a set morning reflection position. This system also corrects errors caused by cloudy days, stormy days, or any other time in which signal from the sun has been lost for extended periods of time. Further description of logic of this error correction, as well as the validation of its ability to operate correctly, are included in Section 10.3.1.

These two control inputs will communicate with each other with a transmitter/receiver system. We recommend placing a transmitter on the atrium photosensor array to transmit the input signal to the mirror. The receiver should then be placed on the mirror controls, within the half-sphere cover described above. We recommend using a simple transmitter/receiver such as that used by RC cars or airplanes.

One concern with the alpha design was potential of exterior light noise on the photosensor array to negatively impact solar tracking. In cases where there was high reflection from outside operating conditions

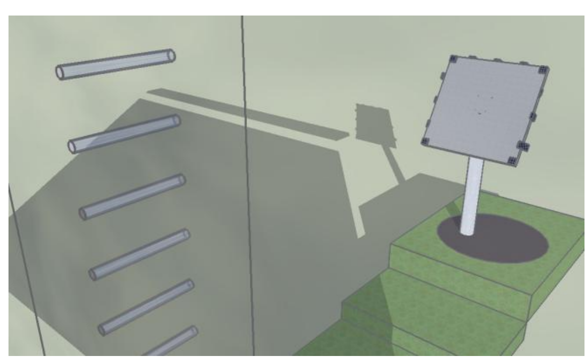


Figure 19: Apertures on Photosensor Grid

(delivery truck, snowy ground, icy roofs, etc.), it was unclear if the system would attempt to track an external input. This concern was mitigated by attaching apertures to the sensors, Figure 19.

At a 15:1 aperture length to sensor diameter ratio, the apertures remove uncontrolled inputs and only allow for the sensors to receive light from mirror reflections. For the photosensors used in testing, this requires 19” apertures on 1.25” photosensors. This design alteration not only prevents the aforementioned uncontrolled inputs, but also removes the exterior noise concern of any conditions we may not have considered. Further description of these apertures and the testing of their effectiveness in reducing external noise factors are included in Section 10.3.4.

10.2 Testing

The critique of the alpha design was performed using ‘thought experiments’ of what could cause our system to malfunction and ways to correct these issues; however, each of our recommendations needed to be tested in order to further develop validate them. In order to do this, we developed three separate test beds. The first test was an energy analysis using Radiance computer software, the second test analyzed apertures and their affect on signal and noise in our system, and the third test analyzed the feasibility of our control logic and ability of our system to operate under a variety of external conditions. This third test was designed and built and was used to validate our control system. However, it was not used to analyze external conditions, because the results of our aperture test showed that proper addition of apertures will effectively eliminate external noise. Each of these tests will be described in this section, and their role in testing and validating components of our final design will be included in following sections.

10.2.1 Light and Energy Simulation

A lighting simulation was desired to further investigate and quantify the energy transfer from the sun to the mirror to the atrium. This analysis allows us to take into account more variables than the physical test and gives us the opportunity to analyze different system setups without prohibitive monetary investment. The modeling and simulation stages resulted in a thorough model of G.G. Brown and surrounding buildings in Google Sketchup as well as a simplified model of the atrium in Ecotect with corresponding simulation performed with the Radiance analysis tool. The results of this simulation provided data for photosensor array size and positioning, energy and cost offsets, and viability of our control system logic. The modeling and analysis processes will be discussed below. The process which led to our final simulation, as well as validation of the simulation and discussion of its reliability, are included as Appendix M.

In order to simulate the energy transfer from the sun into the G.G. Brown atrium, we constructed a simplified model of the G.G. Brown atrium and SolarFocus using Rhinoceros 4.0. This model was then imported into Ecotect, a green architecture modeling and analysis program from Autodesk. Ecotect is compatible with an external lighting analysis tool called Radiance. This combination of programs allowed us to simulate the reflection of the sun off of SolarFocus and into the atrium.

Once the model was imported into Ecotect, materials, location, and time of day could be assigned. The materials of the surfaces both inside and outside of the atrium were inferred and assigned. A screenshot of the simplified 3D model in Ecotect is shown in Figure 20 below, with the SolarFocus mirror assigned as a solar reflector in order to visualize the reflection into the atrium. This model shows SolarFocus's optimal tilt and reflection at 9 am on January 15.

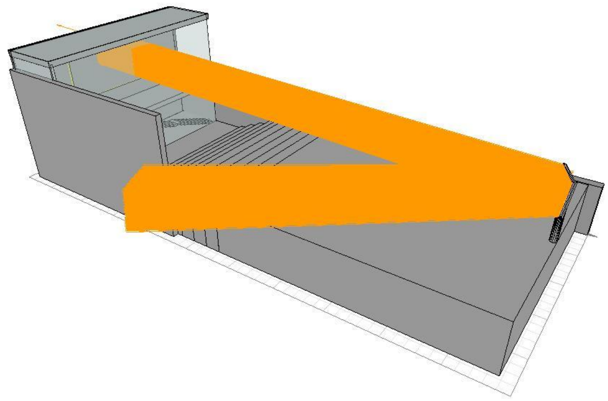


Figure 20: Model of SolarFocus and G.G. Brown Atrium in Ecotect

The convenient visualization of the solar rays in Ecotect allowed us to manually rotate the mirror to reflect the sunlight into a target area on the atrium. The time of year and day were varied throughout different parts of the analysis, and the mirror was rotated manually to realign the sunlight's reflection, just as the control system would command in the real life SolarFocus.

Although the mirror could be set as a solar reflector in Ecotect, the energy transfer requied using Ecotect's external analysis tools called Radiance. Therefore, once the necessary time, weather, and mirror angles were set in Ecotect, the model was exported to Radiance for lighting analysis. Radiance takes the inputs of materials, geometry, time, location, weather, and set views and outputs the set views with the lighting levels (in lux) available at any pixel on the picture, as seen in Figure 21. This process of modifying the model settings in Ecotect and measuring the lighting levels in Radiance was iterated throughout the analysis processes. These set views were the basis of all analysis performed using this simulation.

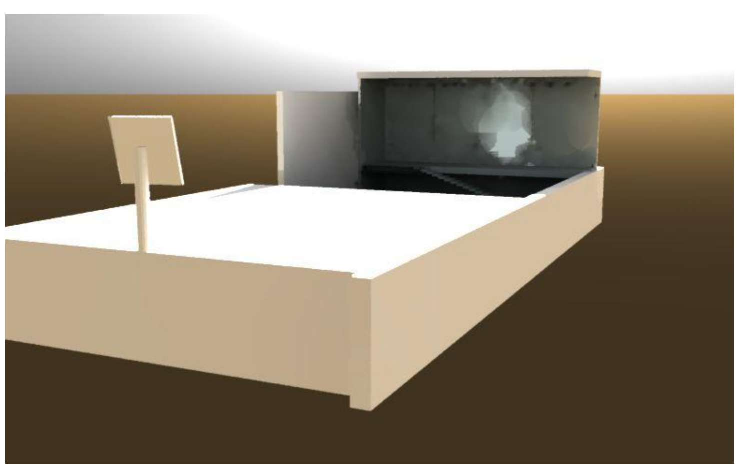


Figure 21: Radiance Simulates of Energy Transferred into G.G. Brown Atrium off of SolarFocus

10.2.2 Physical Testing

There were two separate aspects of our physical testing. The first was a test which analyzed the signal-to-noise ratio and looked at the impact of apertures on this ratio. It was found that adding apertures decreased ambient noise greatly, but did not greatly affect the amount of signal. This result suggests that adding apertures will improve the overall operation of our system. The second was a test which validated the control system which we designed and looked to determine acceptable signal-to-noise ratios for proper operation of our system. This test proved that our control system is capable of taking voltages from photosensors and creating signals necessary to drive stepper motors, demonstrating that our form of feedback is feasible. However, thorough experimentation using this test was not completed. This is mainly due to the results from our aperture test, which showed that adding apertures will effectively eliminate noise. With these results in mind, additional data from this second test would be rendered useless, since it was proved that apertures will effectively eliminate noise in our system. Further information on this test is available in Appendix N. The fabrication plan for this test can be seen in Appendix O. However, because the results of our aperture test made its results irrelevant, it will not be further discussed in this section.

Our experimental setup for the aperture test was quite simple. We anchored a Minolta Illuminance Meter light meter 3' away from a flashlight, which represented our signal input. We then placed a 16" long aperture around the sensor on the light meter. Starting from zero, we gradually increased the amount of ambient light using a combination of natural and artificial lighting, coming from all sides of the photosensor, which created a realistic testing scenario of various ambient lighting noise. We recorded lux values read by the light meter with and without the flashlight for each level of ambient lighting. We then removed the aperture and repeated the test. We defined ambient light to be noise, and defined signal to be the lux difference between having the flashlight on and only having ambient noise. This test procedure gave us four scenarios: apertures and only noise, apertures with signal and noise, no apertures with only noise, and no apertures with signal and noise. Results and implications of this test are discussed in Section 10.3.4.

10.3 Detailed Description and Testing/Validation of Components

As the team specified final design details, further validation was needed to defend the engineering changes. Testing was done to improve designs of photosensor array, control system strategy, and signal-to-noise reduction.

10.3.1 Photosensor Array

The primary input for the control system will come from the voltage output of photosensors on an array on the outside of the north window of the atrium. The size, shape, and location of the grid were optimized for energy reflection of the system. Using the Radiance light simulations, the average reflection area was determined under changing operating conditions. This was done by setting up distance markers on the back wall of the atrium and observing the reflection area in Radiance's generated images. To be able to direct the mirror, the reflection must be constrained to a size slightly greater than this average reflection area. The lighting simulation showed that the average reflection size was approximately 8m (26ft) wide and 6.5m (21ft) tall. From this, we decided to set our grid size to be 10m (33ft) by 6.5m (21ft) so as to maintain precision of reflection but leave some extra space on the right and left so that the mirror is not constantly adjusting to try and stay inside the array as the sun moves across the sky throughout the day. We did not add extra space to the top and bottom of the grid because we could not increase the size of the height any more before sunlight could possibly reflect into occupants' eyes. However, this is not nearly as big of a concern as adding the extra space on the sides of the grid because the vertical movement of the reflection roughly corresponds to seasonal changes whereas the horizontal movement corresponds to hourly changes. A sample image used for this calculation is shown in Figure 22 below.

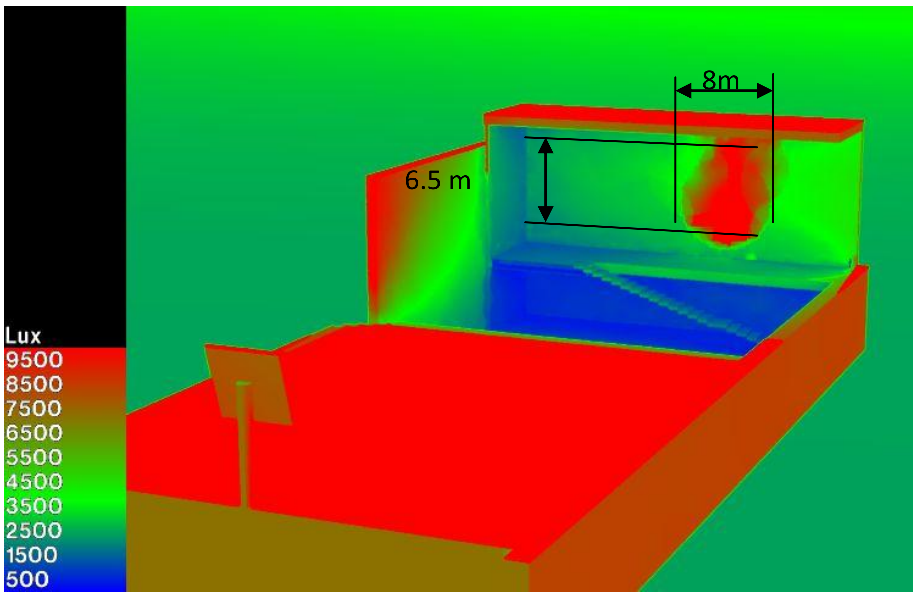


Figure 22: Sample Simulation Used for Array Size Optimization

The location of the grid was determined using previous engineering specifications in conjunction with basic geometry of the system. One of the specifications for SolarFocus was that it would not reflect sunlight into users' eyes. Because the mirror will be reflecting up into the atrium, reflected sunlight would be hitting users from "below the horizon" and it is currently unclear if this would act as an irritant. The bi-level atrium is only 30 feet tall, which is not much larger than the optimized array size. To reduce reflection impact, this grid will be placed starting at the roof. This will leave approximately 9 feet of operational room below the bottom of the grid, which should prevent nearly all direct interaction between the reflection and the people in the atrium. In the east-west direction, the 32ft wide array will be oriented at the midpoint of the 71ft wide atrium.

The spacing of the photosensors themselves was validated through the use of optics. Because the relative size of the mirror is infinitesimally small compared to the sun, the size reflection off of the mirror should be constant for a given sunlight condition. Given that the reflection only needs to be constrained within the array perimeter, but not to specific sensors, the perimeter should have sufficient sensors to prevent the reflection from "fitting" between them. Since the reflection will be approximately 8m by 6.5m, or 26ft by 21ft, placing the sensors every 8ft will provide more than sufficient input for tracking. With input every 8ft, it would be impossible for the reflection to go outside the perimeter of the array without hitting at least 2 of the sensors. This is shown in the diagram in Figure 23 below.

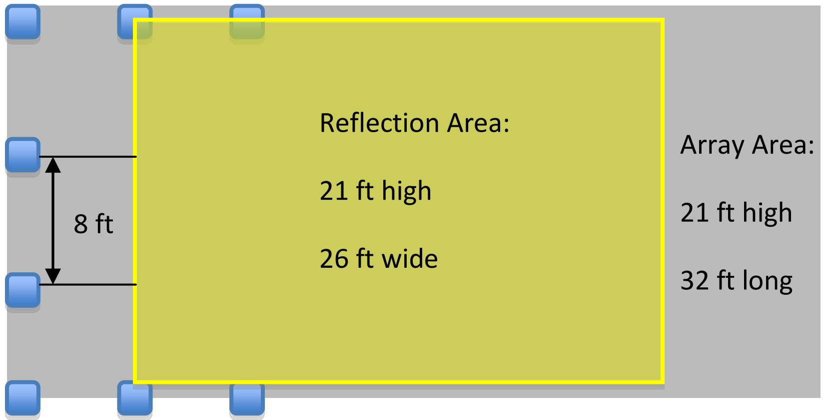


Figure 23: Sensor Spacing on Tracking Array

10.3.2 Control System

Our control circuit was designed to keep the sunlight reflection inside the photosensor array throughout the day. This control circuit is the principal part of the design of SolarFocus that replaces expensive heliostat technology that tracks the sun with "brains." The basic logic behind our brainless circuit is to "catch" the sunlight as starts to exit the grid and rotate the mirror so that the reflection is re-centered inside the grid. This is done by summing the voltages on the photosensors for each of the four sides of the grid. The left and right side voltages are compared to see if the reflection has shifted to one side of the grid. The top and bottom sides are also compared to see if the light has shifted up or down. The gain will be set such that the reading will still be between the desired input voltage ranges for the control system. If either comparison indicates that the reflection is higher on one side than the other and therefore moving out of the grid, the circuit will tell the stepper motor to rotate the mirror in the appropriate direction until the reflection is re-centered on the grid.

Figure 24 below diagrams a simplified version of our photosensor grid on the atrium windows. This is a diagram of the circuit that was built for our proof-of-concept, but uses the same control logic. While the diagrammed circuit takes in two voltages and creates outputs for a single axis of tracking, the full version will sum voltages from photosensors on each edge of the grid then perform the same comparisons and operations. This circuit will be replicated in order to provide the second axis of tracking necessary for G.G. Brown. For example, this circuit may represent one photosensor on the left side of the array and one on the right. In reality there will be several photosensors on each of these sides, and there will be another set of sensors and another control circuit for the top and bottom of the array.

10.3.2.1 Description of Circuit Diagram

The circuit diagram below shows the components and connections of the simplified control circuit. Again, besides the simplifications described above, this will be the exact control system SolarFocus will use to track the sun on G.G. Brown.

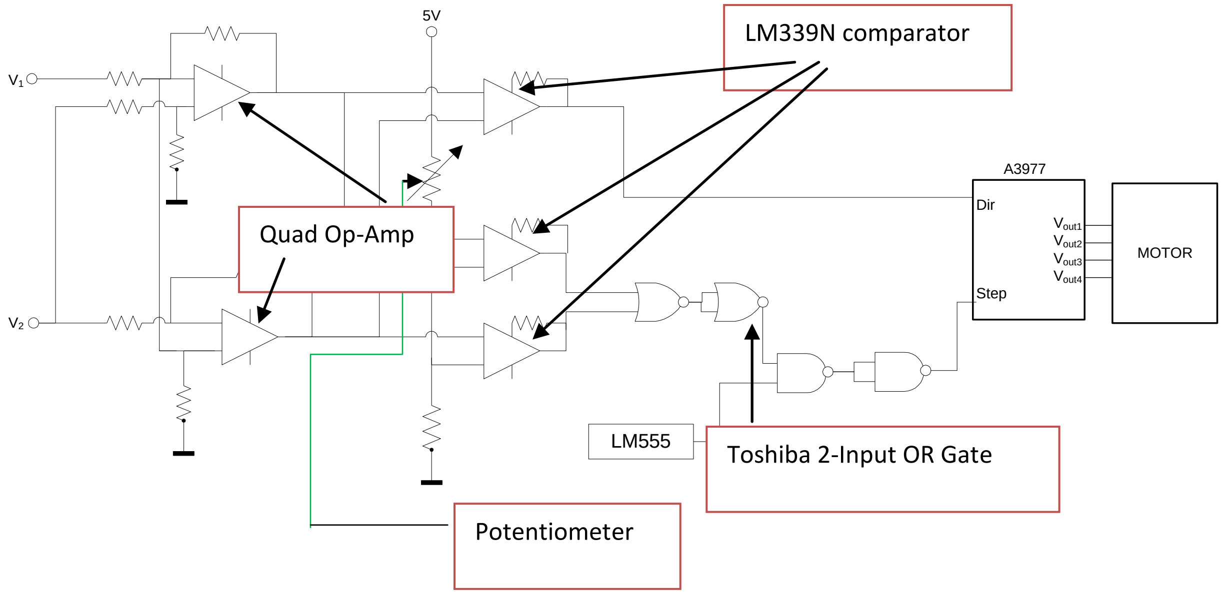


Figure 24: Control Circuit Turns voltage(s) into Motor Movement

The inputs to the system are based upon the voltages read by two Solarbotics RU 6716 6.7V photosensors. These voltages will be referred to V_1, for the right photosensor or set of photosensors, and V_2, for the left photosensor or set of photosensors, as seen in the diagram above. The basic idea of logic for the system is that if one voltage becomes much greater than the other, it indicates that the light is moving outside the acceptable range and the mirror must be rotated until the light is back in the target area.

The stepper motor will be controlled by an Allegro A3977 stepper motor control circuit chip. This chip needs two inputs of step and direction in order to move the stepper motor correctly. The step input must be in the form of a pulse, with the motor moving one step each time the step input goes high. The direction input is binary, with 1 representing motion to the right and 0 representing motion to the left. These inputs are made to be compatible with a PC controller, but we need them to work with only our sensor voltages as inputs. We therefore designed the control circuit to transform our sensor voltages into the step and direction inputs necessary for the A3977.

The first step of the circuit is subtracting V_1 and V_2. Subtracting these two measures a relative difference between the two, rather than the absolute voltages. This has the advantage of cancelling out any ambient light that may be coming into the photosensors, as long as it is coming into both of them equally. This subtraction is performed using two op-amps configured as differential amplifiers with no gain. To do this, we used four resistors of equal resistance around each op-amp. We need to use two sets of differential amplifiers in order to determine which voltage is greater; this is required because the DC circuit is not capable of producing negative voltages. With this setup, if V_1 is greater than V_2, the first differential amplifier will read the magnitude of this difference and the second will read 0 V. If V_1 is less than V_2, the first differential amplifier will read 0 V and the second will read the magnitude of the difference. Essentially, this portion of the circuit gives the absolute value of the difference between the two voltages.

The output from the first differential amplifiers is sent to an LM339N comparator. If the input from the first differential op-amp is greater than that of the second (meaning $V_1>V_2$), this comparator will read high. This high value will be fed into the direction terminal of the A3977 chip. This terminal, when high, tells the motor to move left and, when low, tells the motor to move right. If $V_2>V_1$, the comparator will be low and the circuit tells the motor to move right.

The two voltages coming out of the differential op-amps are fed into two more LM339N comparators. Each voltage is fed into the positive terminal of one of the comparators, while the negative terminal receives a reference voltage, V_{REF}. If the voltage in either of the positive terminals is greater than the reference voltage, it will signal that our signal must move in the direction specified by the direction input. We can set this reference voltage by adjusting the resistance, R_{POT}, of a potentiometer that is part of a voltage divider. This reference voltage is very important because it allows us to set the sensitivity of the system. It is important that the system is not overly sensitive, as this can lead to frequent motions of the mirror, resulting in a distraction to occupants and overuse of energy in the system. At the same time, it is important that the system has a high enough sensitivity to track the sun's motion. When compared to the reference voltage, our analog voltage will be turned into a digital voltage, either 5 V (high) if above the reference voltage or 0 V (low) if below the reference voltage. Since we are comparing both of the subtracted voltages to the same reference voltage, we will have a high output if the system needs to be rotated in either direction.

The step input for the A3977 is controlled using the output voltages from both comparators. These two outputs are fed into a Toshiba 2-input OR gate. If either of these is high, meaning the stepper motor needs to move in either direction, the output signal of the OR gate will be high. This signal is then fed into an AND gate, with the other input coming from an LM555 timer circuit. The LM555 circuit creates a pulsing signal at regular intervals. If this chip pulses at the same time as the control system signals a step is necessary, the output of the AND gate (and input to the step terminal) will be high, and the stepper motor will move one step. The chip is set to pulse every 10 minutes in order to keep track of the sun but not make the motor excessively active.

This description forms the basis of our brainless sun-tracking system. Given lighting inputs on the photosensor grid, it can track the sun and keep its reflection inside the target grid.

10.3.2.2 Validation of Control System

The simplified control system diagrammed in Figure 24 was built, with the help of CD Electronics, as a proof of concept. The final result is shown in Figure 25.

In this figure, LED lights are included to show the outputs which will go to the stepper motor. The DIR light shows the direction switch, left if high and right if low, and the STEP light pulses when stepping pulses are sent to the motor. We were unable to correctly configure the stepper motor driver due to a lack of electronics expertise, but we do not feel that this takes away from the proof of the system. When shining light on the right photosensor, the direction LED lit up, and the STEP LED pulsed as expected. This validated the system's ability to take light inputs and produce the STEP pulse. The left photosensor did not properly create these signals but we feel that this was also due to a lack of technical expertise rather than a flaw in design.

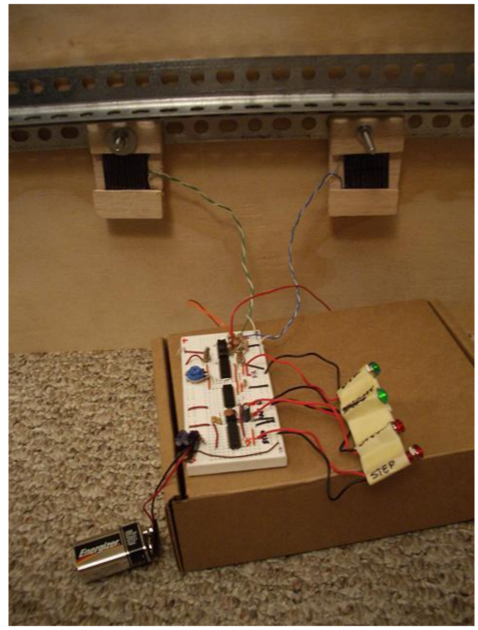


Figure 25: Constructed Control System

10.3.3 On-Mirror "Fly's Eye" Error Correction System

The main disadvantage to using a system without memory is that error correction is very difficult. Our proposed control system will eliminate a great deal of tracking errors as much as possible, but it is inevitable that we will lose tracking at some point. The most prevalent example of this is the motion that will be necessary to reset SolarFocus every morning, when the sun rises in a different location than was last tracked at dusk. This may also happen on extremely overcast days, when there is not enough light registered on the photosensors grid for an extended period of time. If the sun moves far enough without being tracked, it will reflect outside of the sensor array when it is no longer covered by clouds. This would happen anytime there is no sunlight reflected onto the grid as the reflection exits the grid through the photosensor border. Without any form of self-correction, our system will not know if it isn't reflecting onto the sensor array and could get stuck in a single position, with no step signal being produced. Therefore, we propose a simple form of error correction in which sun intensity levels are measured at angles different than that of the mirror. This section will give detail into the physical description of this component, describe the control logic which it will employ, and discuss the validity of using it as determined by the Radiance lighting simulation.

10.3.3.1 Physical Description

This system will measure the amount of light at different angles than the reflective mirror surface. If the mirror is tracking correctly, these light levels should be low because the light should be directed onto the mirror surface instead. If these light levels are too high, the mirror will be signaled to move. This is a very crude form of error correction, since signals of this nature will not be produced until tracking has been lost for a few hours. However, this is a satisfactory amount to keep SolarFocus tracking, and therefore effective, most of the time.

In order to perform this error correction, we will mount three sensors on each of the four edges of the mirror, 12 in total. One of these will be mounted perpendicular to the mirror, and the other two will be at 45° off of perpendicular in either direction, as is shown in Figure 26.

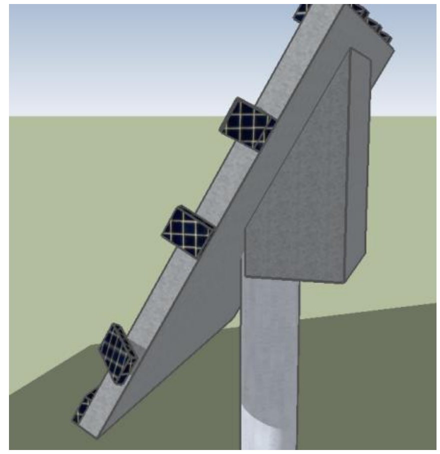


Figure 26: Fly's Eye Photosensors

These will all be facing outward from the mirror. When our mirror is properly positioned, it will be nearly perpendicular to the sun and, since these sensors are mounted at large angles to the mirror, they will not receive large amounts of light. However, if the system loses tracking, these sensors will receive increasing amounts of light as the sun moves and the mirror does not move with it. When the amount of light gets above a certain threshold, the control circuit will pulse to move the mirror several steps back toward the grid. We suggest that it move half of the number of total steps necessary to move the system from one limit to the other. We suggest this because we predict this amount of motion will bring the system back onto the photo sensor grid, without moving off of the other side.

10.3.3.2 Control Logic Description

The logic of this system is shown in Figure 27. For each of the four directions, the three voltages will be taken as input. Each will be compared to an adjustable reference voltage using comparators, in order to ensure the system is not falsely triggered to move. These signals will then be sent through OR gates, such that if any of them is high the output of the OR gates will be high. This output will then be fed into a flip-flop. This will turn high and will stay high until a reset signal is sent to it. This signal will be used to control the input to the step terminal of the A3977 chip. We will use a clock to count the number of steps that have been taken, and set it so that it signals the reset of the flip-flop gate at the specified number of steps, stopping the motion of the motor. The output from the controller can easily be changed upon the connection, which will allow any number of steps to be possible. However, by hooking up several output terminals and using AND gates, this could be configured to the desired step count.

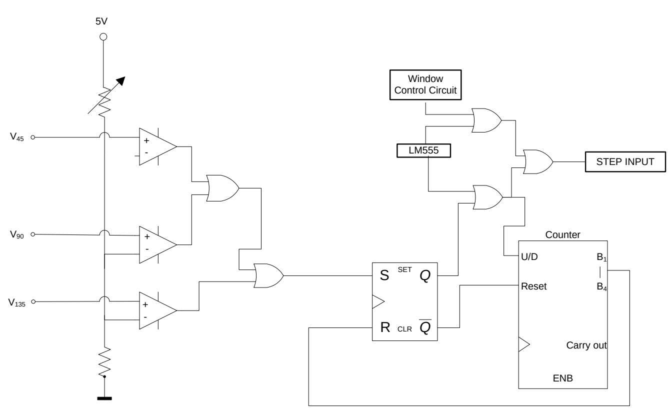


Figure 27: Fly's Eye Control Logic Remedies Large Errors in Tracking

The interface of this control system will also be quite simple. Rather than directly connecting the signal to the step input of the A3977, we will connect it to an OR gate with the signal from our sensor array control system. This will ensure that, if either signal is high, the motor will move as specified. It is important that the error control signal from one side of the mirror will be connected to the sensor array control signal from the opposite side of the mirror, since a high signal requires motion in opposite directions for these two.

10.3.3.3 Validation of Fly's Eye Error Correction

The lighting simulation in Radiance helped to prove the validity of the fly's eye error correction by comparing the amount of light hitting the edge of the mirror during correct tracking with the amount of light hitting the mirror during incorrect tracking. Appendix P explains in further detail this simulation process.The outputs of this portion of the simulation are summarized in Table 9 below.

Table 9: Simulation Validates On-Mirror Error Correction

Date and Time	Mirror Alignment	Lux level on Mirror Surface	Lux Level on Mirror Edge
April 15 at 10 am	Optimally aligned for 10 am	78700	14400
April 15 at 3 pm	Optimally aigned for 10 am (misaligned)	44500	70700

This single simulation simply aimed to investigate the order of magnitude of the lux level changes on the perpendicular edge of the mirror when it is "misaligned." A period of no sunlight from 10 am to 3 pm was modeled in this simulation and it showed that the increase of lux level when the mirror is misaligned at 3 pm is approximately 5-fold from when it was correctly aligned at 10 am. Because the mirror is misaligned, the photosensor grid on the windows will not be receiving sunlight and therefore the fly's eye can control the input. This 5-fold increase in lux levels proves that the increase is significant and thresholds can be set to use this increase as an error correction method. However, because the lighting levels on the edges of the mirror vary with timing, weather, and alignment of the mirror, an exact threshold of lux level to trigger mirror realignment is not finalized. A precise finalization is beyond the scope of this project; it would involve continuous simulation of lux levels on the edge of the mirror throughout variety of these conditions and determining the optimal lux level that triggered correction as soon as possible after sunlight was available but not on the grid. This simulation does, however, prove the validity of the fly's eye error correction and give this approximate range of a threshold for triggering correction. We suggest that this threshold be somewhere between 20,000 and 70,000 lux.

10.3.4 Aperture Description

After placing the sensor grid on the outside of the window to eliminate interior light noise, SolarFocus still had to deal with outside lighting noise. To solve this issue, directional apertures resulted from a thought experiment about how to eliminate noise but keep the sunlight input on the photosensors.

10.3.4.1 Physical Description

The apertures are a cylindrical shape and are placed over each sensor on the atrium window. The function of this component will be to greatly limit the amount exterior light noise that will hit any photosensor on the grid but still receive the light input from the mirror surface. The apertures were designed so that the apertures limit the photosensors to only be able to "see" see the mirror; all ambient noise will strike the outside of the aperture and not be seen by the photosensor (Figure 28). Given a photosensor diameter of 1.25 inches, the necessary length of the aperture to achieve this objective was calculated to be 19 inches. The apertures should be made of a light, absorptive material. Since the sensor grid is larger than the mirror, the apertures will need to be placed on an angle to the window, angling in toward the mirror depending on their specific position on the photosensor grid.

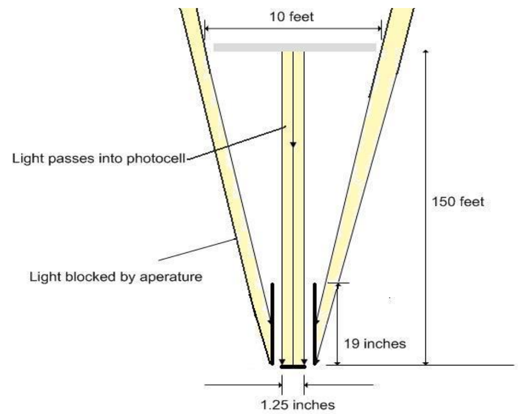


Figure 28: Aperture Dimensions

10.3.4.2 Aperture Validation

The aperture test which we ran proves that adding apertures to our photosensors will dramatically reduce noise without significantly decreasing signal. It was run as described in Appendix N. Our results, seen in Figure 29, show that noise increases with ambient lighting when apertures are not included, but does not change when apertures are included.

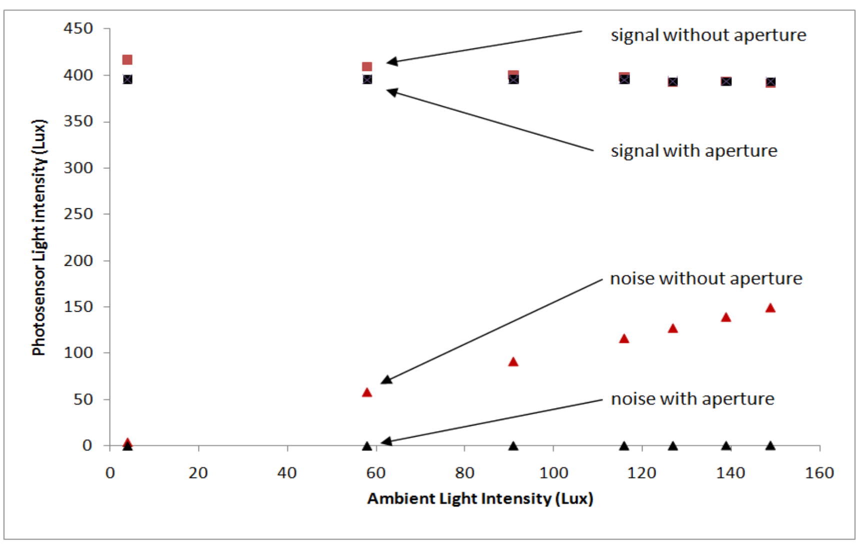


Figure 29: Adding Apertures Decreases Noise Significantly, has Small Affect on Signal

The value of the noise is also much smaller when apertures are included, with a maximum value of less than 1 lux corresponding to 149 lux without apertures. Our results also show that when apertures are included, the signal is slightly lower than when they are not, but that the signal does not change with ambient lighting conditions.

11. Discussion

The next step in the design process was to determine the financial and societal impact of SolarFocus. The following section includes the cost/benefit analysis of the system, a comparison to previously developed engineering specifications, and the environmental impact of installing on G.G. Brown.

11.1 Cost/Benefit Analysis

To determine the financial viability of the system, more accurate energy savings were calculated with the lighting simulation, and a more detailed cost analysis was completed.

11.1.1 Energy Savings

The light simulation allowed us to calculate the predicted energy delivered to the G.G. Brown atrium. By using yearly weather data specific to Ann Arbor and including specific dimensions of G.G. Brown and the surrounding buildings, the energy calculations are predicted to be more accurate than earlier estimates. The methods for calculating these annual savings from the simulation are described in detail in Appendix Q. If SolarFocus is implemented on the G.G. Brown atrium, it will deliver an average of 4,239 kWh of energy per year. This is separated into 1910 kWh of energy for light, and 2329 kWh of energy in the form of heat. The 2329 kWh of heat is the energy equivalent of approximately 80 ccf of natural gas delivered annually. These results combine to an annual offset 1.6 metric tons of CO_2 for the system, or 1.12 metric tons from electricity reductions, and .48 metric tons from heating reductions.

Using current costs in Michigan [48], these energy reductions yield an annual savings of $240. Implementing SolarFocus should result in a decrease in electrical expenditures by $163 and in natural gas expenditures by $77 each year. We expect that trading the carbon offsets as energy credits will result in an additional annual profit of $15 to $20 [14].Using current building energy costs, we estimated total yearly energy costs of the atrium at approximately $4500, so installing the SolarFocus system would offset about 5% annually[1]. This exceeds our engineering specification of 2.5% described in Section 5.3.

Additionally, under current DOE standards [16], SolarFocus should receive at least a 30% rebate for use of a renewable energy system. It would be eligible for additional funding from the DOE out of the [49] fund, and from the College of Engineering out of the Art Fund. The s energy savings of SolarFocus are summarized in Table 10 below.

[1] Cost offsets were calculated using the energy expenditures of the Computer Science and Engineering building on North Campus. According to Planet Blue, the CSE is 104,129 sq.ft. and annually spends close to $350,000. The proposed G.G. Brown atrium will likely be as open as CSE (including many windows), but is only 1350 sq.ft. [48].

Table 10: Annual Energy Savings in Application of SolarFocus on G.G. Brown Atrium

Item Description	Result
Energy Delivered	
Light Energy	1910 kWh
Heating Energy	2329 kWh
Total Energy	**4239 kWh**
Energy Savings	
Light Energy Savings	$ 163
Heat Energy Savings	$ 77
Total Savings	$ 240
Energy Offsets	
Electrical Offset	1.12 metric tons of CO_2
Natural Gas Offset	.48 metric tons of CO_2
Total Offset	**1.6 metric tons of CO_2**
Other Savings	
DOE Fund	30% + cost reduction

11.1.2 Total Costs

The costs associated with SolarFocus are grouped into manufacturing and materials, installation, and maintenance.

Manufacturing and Materials: Many of the material specifications were discussed in the design description and the majority of the costs came from the polycarbonate mirror and the structural support. The polycarbonate mirror was selected for its durability, high reflectivity and relative low cost compared to other large-scale reflective surfaces. The structural support used specifications of a street lamp pole, scaled to hold the increased weight of the system. The remaining costs are summarized in Table 11 below.

Table 11: Cost Associated with Materials and Manufacturing of SolarFocus

Category	***Item***	***Description***	***Cost per Unit***	***# of Units***	***Total Cost***
Manufacturing					
	Reflection	Mirror	74.47	25	1861.75
	Support	*Steel*	*627.09*	*1*	*627.09*
	Connections	Concrete Mount	100	1	100
		Nuts/Bolts/Etc	100		100
	Base	Cement: 70 lb bag	10	8	80
	Motor	2 stepper motors	100	2	200
	Battery	Solar Powered battery	40	1	40
	Reflect-Total				2981.75
	Control				
	Sensors	Photosensors/PV cells; 9 for feedback, 12 for 'flys eye', 1 for motor power	3	24	72
		Connections	1	16	16
		Wires	20	1	20
	Circuit Board	Blank board?	10	2	20
		wires(can use above)	20	0	0
		Components	50	2	100
Control-Total					228
Manuf-Total					3209.75

Installation: The basic costs associated with the installation of SolarFocus were estimated from typical costs with installing a parking light. These were compared against the cost in Michigan for renting appropriate installation machinery such as a crane, back-hoe, and boom lift. The majority of costs associated with the installation of the system were associated with the labor required, as shown in Table 12 below.

Table 12: Cost for Installation of SolarFocus

Category	*Item*	*Description*	*Cost per Unit*	*# of Units*	*Total Cost*
Installing	**Paper Work**				
		City Codes		0	
	Labor	x3 laborers	$/hr	hrs	
	Reflective Surf	Base	90	2	180
		Support	90	1	90
		Aluminum panel	90	2	180
		Motors	90	1	90
		Connecting	90	1	90
	Controls	Assembling Control	50	0	0
		Testing Control Board	50	0	0
		Installing Atrium	90	1	90
		Installing Surface	90	1	90
		Connecting Sensors to Controls	90	1	90
	Other	Attaching battery, etc	90	1	90
		Running/Testing	50	2	100
		Set up/ Clean up	90	3	270
	Equipment	Drills	40	0	0
		Ladder	40	0	0
		Crane/back hoe for	500	0	0
		boomlift/cherrypicker	300	0	0
		Cement Mixer	50	0	0
LIGHTPOLE	Install		1035	1	1035
Total-Install					1840

Maintenance: The final, long term, cost section associated with SolarFocus is the maintenance. It is expected that semi-annual calibrations will be needed, along with routine cleanings of both the reflective surface and the sensor array. The remaining maintenance costs are summarized in Table 13.

Table 13: Cost for Maintaining SolarFocus

Category	**Item**	**Description**	**Cost per Unit**	**# of Units**	**Total Cost**
Maintaining	Reflective Surf	Cleaning (both surface and joints)	30	1	30
		Adjusting/calibrating	30	1	30
	Control	Cleaning Sensors	30	1	30
		Replacing Wires	30	2	60
Maint-Total					150

Total Cost: The total cost for installing SolarFocus, before the DOE rebate is $5200. After the rebate and expected return, the present value of the system is $3600.

11.1.3 Cost Benefit Analysis

Given the benefits and costs discussed above, the present value of the system is $3600 with a payback time of 10.4 years. Though this payback time is longer than the original engineering specification, future design iterations may be able to reduce the cost of the system leading to shorter payback time. As energy costs continue to increase, this system will become more valuable as a renewable energy source, and has an expected lifetime of at least 30 years.

In comparison to industry benchmarking, this initial SolarFocus design offers close to a 400% decrease in initial costs, with comparable energy results [12]. Given this analysis, and the potential of this innovative technology, we are confident recommending that this is a long-term financially viable option.

11.2 Engineering Specification Evaluation

Throughout the design process, it was clear that the major impact of SolarFocus would be as an innovative alternative to current solar energy technology and that the most quantitative measurement of how well SolarFocus functions is its environmental impact. This analysis has focused on maximizing the energy transfer and subsequent cost and emissions reductions. In order to accomplish this end goal, the team chose to focus mainly on the engineering specifications dealing with cost and energy. Though the specifications developed in Section 5.3 should all be considered and implemented into the design, completion of all of them did not fall into the scope of a one-semester project. By meeting or exceeding the specifications for cost savings, the project has proven its potential for success and shown the benefits of being included in renovation plans. The exact specifications considered which deal with energy and costs specifications were: system lifetime, energy production, cost reduction, emission reduction, and energy intensity. The other main engineering specifications that were considered during this term were those dealing with system motion, efficiency, and system power. It was necessary that we met many of these secondary specifications in order to meet our main goals for system energy savings. Other specifications developed in Section 5.3 were outside the project scope, including exact maintenance calculations, implementing a dimming system, loss over lifetime, and weather durability.

11.2.1 Engineering Specifications Met by Current Design of SolarFocus

As mentioned, the current design of SolarFocus meets many of the engineering specifications developed at the start of this project. The design exceeds energy specifications, and fulfills goals for system motion, efficiency, and power requirements as discussed below.

11.2.1.1 Energy and Cost Specifications Met

The focus of the project has been on specifications dealing with energy consumption and reduction of the system. This includes the annual amount of energy produced by SolarFocus, the subsequent reduction of carbon emissions, the accompanying cost savings for G.G. Brown, the overall system lifetime, and the energy intensity (or user irritation) associated with system implementation.

11.2.1.1.1 Carbon Emission Reduction

To supplement claims of being a renewable energy source, SolarFocus should have negligible carbon emissions. The specification was to completely eliminate any emission, and as stated in Section 5.3, SolarFocus should have zero operational carbon emissions. The method of powering SolarFocus will be through the use of photovoltaic cells, a solar powered battered and transmitted voltages, so this specification was met.

The other aspect of carbon emission reduction is reducing the emissions of G.G. Brown itself. The goal was to reduce emissions by at least 2.5%. Using the energy production from above, SolarFocus can annually offset 1.6 metric tons of CO2. Planet Blue offers energy consumption of current on-campus buildings, and the SolarFocus offset was compared to emissions of similarly designed University buildings. In particular, the atrium was compared to the CSE building on North campus because it is likely that many similar materials will be used in the renovation of G.G. Brown. Energy requirements were scaled appropriately by square footage of the proposed atrium. These calculations yied a reduction of close to 5% and is therefore twice as much as the original specification.

11.2.1.1.2 Cost Savings

For potential installation on G.G. Brown, SolarFocus must offer measurable cost reduction. In recent years, the University of Michigan program, Planet Blue, has aimed to meet LEED standards on building renovations and re-designs. To meet minimum LEED points, SolarFocus must offset at least 2.5% of energy costs in a renewable manner. Based on the lighting simulation, SolarFocus can claim approximately 5% cost reduction for the atrium, which is a 200% improvement from specification. It is important to note, however, that SolarFocus is only capable of offsetting atrium energy requirements, not those of the entire building. In order to offset 2.5% of total building costs, SolarFocus would have to be employed on a larger scale with a method to distribute energy throughout the building. The energy offset of employing SolarFocus translates to an annual cost savings of $163 in electricity, $77 in natural gas, or a total of $240.

11.2.1.1.3 System Lifetime

To compete with industry standards, the system lifetime was specified as at least 30 years. These exact calculations should be refined, however, based on lifetimes of system components, the SolarFocus lifetime should exceed this specification.

11.2.1.1.4 Energy Intensity

There was some concern that excessive energy transfer could result in user irritation through either hot spots or painfully bright light. To meet current IESNA and University of Michigan lighting standards, we specified that the system should reflect less than 850 lux. Though the lighting simulation results show that SolarFocus will reflect significantly greater lux than this, we expect that the amount of lux measured within the atrium itself will meet this specification. The amount of light measured at the point of reflection will be higher than 850 lux; however, this should not be problematic in areas of use within the atrium since it is hitting the ceiling of the bi-level portion (about 30 feet above area of use) and will be at a much lower value when redirected towards building occupants.

11.2.1.1.5 Unit Cost

Although the high upfront investment leads to extended payback time (discussed in Section X below), the engineering specification of unit cost less than $400/m^2$ mirror was met. After the 30% DOE rebate, the cost of SolarFocus is $3600/10m^2$ or $360/m^2$ of mirror, which is approximately a 10% improvement from goal.

11.2.1.2 Other Specifications Met

Though the majority of the emphasis in meeting engineering specifications was on those dealing with energy and cost savings, the final design of SolarFocus also meets the specifications set forth regarding system motion, efficiency, and power requirements.

11.2.1.2.1 System Motion

The engineering specification for system motion was to have dual-axis rotational movement. This was needed so that the system could track the sun throughout the day, but also throughout the year (both in the altitudinal and azimuth directions, as discussed previously). To meet this specification, two stepper motors were used and will allow SolarFocus to have dual-axis motion.

Optimized system motion also requires that SolarFocus will be capable of rotating through the sufficient angles to reflect sunlight into the grid whenever the sun is out. This was specified as: $-60 < \theta_{alt} < 60$, $90 < \theta_{az} < 130$ (°). Using stepper motors to turn the reflecting surface allows for full rotation, and the stepper motors chosen have sufficiently small step size to produce precision of motion. As such, SolarFocus will be able to track the sun throughout the day and throughout the year and the specification was met.

11.2.1.2.2. System Efficiency

Early iterations of the design had predicted reflected efficiencies between 30% and 80%. The final design will reflect close to 90% available energy, which is significantly higher than the engineering specification of 40% peak efficiency.

11.2.1.2.3 System Power Requirements

The engineering specification is that the system would be self-powered, with no additional energy costs. As described in the Carbon Emission Reduction section above, this specification was met through the use of photovoltaic cells and a solar-powered battery which power through transmitted voltages.

11.2.2 Engineering Specifications to be Met by Future Design Iterations of SolarFocus

Although the scope of this project only allowed for SolarFocus to meet the specifications described above, there are still engineering specifications that were developed and should be met in future design iterations. These include improving maintenance costs and requirements, decreasing payback time, adding the option for an interior dimming system, calculating efficiency losses over lifetime, and determining durability of the system in Michigan weather conditions.

11.2.2.1 Maintenance

One of the customers identified early in the design process was the operators of the system. With this customer in mind, the team developed specifications regarding minimal maintenance time and costs, and installation complexity of the system. The specification was set as less than bi-yearly cleanings and calibrations, with no additional tools or skill sets required. It is unclear if the current design will meet this specification, and calculations should be done for future work.

11.2.2.2 Energy Production

The specification developed at the outset of the project regarding minimum energy production was 1100 kWh/year of electricity, or its equivalent combination of heat and electricity, per square meter.

This means that, in order to achieve this specification, SolarFocus needs to offset 11,000 kWh/year of energy. Appendix Q describes the procedure used to simulate the amount of energy offset over the course of the year. We found an equivalent of 4,239 kWh offset. This is 38% of our desired output, suggesting that steps should be taken in the future to improve this amount.

11.2.2.3 Payback Time

University of Michigan standards led us to develop a specification of a payback time of less than 4 years. After the final design of SolarFocus was completed, we calculated the present value and compared to yearly cost savings. The actual payback time of SolarFocus is 10 years; this is significantly higher than our specification, however, we are confident that iterations of the design will result in decreased initial investment and a resulting decrease in payback time.

11.2.2.4 Dimming System

To optimize electricity savings of the SolarFocus system, an automatic dimming system should be combined with SolarFocus so that the lights will dim automatically when SolarFocus is providing sunlight into the atrium. The developed specification was that the light be adjustable to ± 50 (lux) and that automatic controls allow for heat adjustment of ± 5 (°F) and ± 50 (lux). While automatic dimming switches exist today, we did not look at their exact specifications in great detail.

11.2.2.5 Lifetime Losses

The team expects that the SolarFocus system will have minimal efficiency losses if properly maintained, however, this expectation has not yet been validated. The system should have an efficiency loss of less than 20% over its operational lifetime.

11.2.2.6 Weather Durability

The final specifications that will need to be considered deal with durability of the system under Michigan weather conditions. SolarFocus should be operable within a temperature range of -25° F to 115° F, winds up to 80 mph and snow up to 50 lbs. Early material selection included a polycarbonate mirror which is highly durable, and structural supports used for common road-side lighting, so the system should be able to be designed to meet these specifications; however, further testing will be necessary in order to prove this.

Another engineering specification for SolarFocus was that using this device would not create any additional energy costs for its users. Our preliminary solution to this requirement is that it will not be used during the cooling season (summer) months. However, we are confident that there are creative applications for SolarFocus during the cooling season so that the device is not just non-harmful in these months but rather helpful. Therefore, although our current solution is to not use SolarFocus during the cooling months, we recommend that additional applications be considered.

11.3 Design Critique

Given the lack of comparable technology in industry, it is unclear what unconsidered drawbacks may be associated with the SolarFocus system. A brainless control strategy is untested in operational conditions, however, this is a risk associated with any innovation. Some of the critiques associated with the current status of the system include: the process through which SolarFocus was designed should be streamlined in future iterations, the mirror selection should be optimized, the system power requirements should be calculated more specifically, the physical layout of the on-the-mirror sensor grid needs to be determined, the upfront cost of the system may be reduced, the aesthetics of SolarFocus considered, and the previously listed engineering specifications met.

11.3.1 Design Process

The development of SolarFocus has very much been through an analysis driven design process. The initial assignment was inspiring, if broad, and much of the semester was spent defining the project scope. Even with a project objective, there were many design iterations that were developed, analyzed, and rejected. Although this was necessary for the design outcome, it was time consuming and left less time for final design specification development. Initial designs were varied enough to include light tubes, solar concentrators, and roofing fiber optics. There was a significant jump from these iterations to even the level of design detail that currently exists. Because of this, some of the design aspects below are not completely developed. Now, with a clear goal in mind, the design process has the potential to be more efficient and based on troubleshooting the system.

11.3.2 Mirror Selection

The recommended mirror used for costs calculations was a polycarbonate industrial mirror from McMaster-Carr. It uses aluminum as a reflecting surface and is highly durable in inclement weather conditions. Though significantly less costly than using only polished aluminum, and much more efficient than using a standard mirror, this selection would benefit from further analysis. Due to the size of the system, the mirror component is currently a relatively large investment and optimization would reduce the initial investment required for SolarFocus.

11.3.3 System Power Requirements

The current design has two 24V stepper motors to allow for dual-axis rotational movement of the mirror. To power these motors, both the atrium-wall and on-the-mirror control systems, and the transmitter/receiver system, it is expected that the photovoltaic cells will be sufficient. There will be at least six 5V cells on the mirror acting as the on-the-mirror sensors and a solar powered battery attached to the motors. The manner in which these are connected has yet to be determined. Additionally, there will be at least 12 5V photovoltaic cells on the outer wall of the atrium which should sufficiently power that control system and the transmitter. Again, connections need to be designed and powering requirements further analyzed.

11.3.4 On-the-Mirror Photosensor Layout

Implementing brainless technology essentially eliminates the system's ability to "know" the location of the sun based on the time of day or year. Although the use of photovoltaic sensors on the mirror itself allows SolarFocus to have some self-correction, further optimization of the placement of these sensors is needed. Using calculations from the lighting simulation, the current design has three photovoltaic sensors on the east and west sides of the mirror. Each sensor will be anchored at 45°, 90°, and 135° respectively, to maximize conditions under which they can distinguish sun availability. Although the simulation validated placing cells on the sides of the mirror, the angles of each cell have not been calculated or optimized. Both the angles and spacing of the cells should be analyzed to create a system that will operate under most conditions. Proper positioning will allow for large-scale error correction and improved solar tracking of the system.

11.3.5 Initial Investment

As mentioned in the previous section, the engineering specification of a 4-year payback time was not met in this design. The high initial investment required for installation of SolarFocus is the predominant cause of the 10-year payback time, and future design iterations should reduce this investment. The initial cost is close to a 400% reduction in cost from the current industry equivalent to SolarFocus (similar in reflection simplicity but requires programming and memory), but the upfront investment should still be reduced. If the mirror selection is optimized and some material selection improved, cost may decrease. Currently, cost of installation is over $5,000, however, the system is eligible for a government rebate of 30% meaning it costs $3,600 for installation on G.G. Brown. If the $3,600 investment were reduced, SolarFocus would be a more competitive system, more marketable for both the G.G. Brown renovations and future residential applications, and become a more financially feasible addition. Although the energy offsets are a powerful financial motivator, such a high initial investment may be prohibitively expensive and prevent the installation of even a highly effective renewable energy system.

11.3.6 System Aesthetics

University of Michigan buildings are eligible to receive funding from an Art Fund, which could eventually supplement the initial investment in SolarFocus. To compete for this funding, the aesthetics of the system should be considered. Due to a lack of available time, the aesthetics were not part of the scope of this project, however there seems to be a significant potential for “artistic improvement”. The nature of the system is such that the most visible component is the reflective surface. If the mirror were redesigned to be many smaller mirrors reflecting together, they could rely on the same brainless technology but be more enjoyable to look at then a $10m^2$ polycarbonate mirror. The support structure itself could be improved upon; instead of using the equivalent of a light pole, the system could be redesign to resemble a more artistic statue. Another aspect of the system that has significant room for aesthetic improvement is the photosensor grid and accompanying apertures. At this stage, relatively long apertures are required for the specified photosensors (approximately 20inches). Much smaller photovoltaic cells are available, and as long as the 15:1ratio (discussed in Section 10.3.4) is maintained, the aperture size can be reduced to barely visible. So long as the system requirements developed this semester are met, there are no constraints on the artistic development of SolarFocus.

11.4 Sustainable Energy Impact

SolarFocus will provide environmental benefits which vastly outweigh its costs. We created a life cycle analysis which includes the materials required to make SolarFocus, installation, and waste at the end of its life cycle. This analysis shows that 0.698 metric tons of carbon will be created during its lifetime, while 46.7 metric tons of carbon will be offset during this same time period.

Our life cycle analysis attempted to include all aspects of the lifetime of SolarFocus. We used SimaPro 7.1 in order to perform this analysis. The inputs to our analysis are shown in Table 14. The assembly portion of this table gives the materials that will be necessary to create SolarFocus, the installation gives inputs associated with placing SolarFocus on G.G. Brown, and the waste gives the different ways which the materials of SolarFocus will be dealt with at the end of its lifetime.

Table 14: Summary of inputs to SimaPro Life Cycle Analysis

Assembly

Material	*Amount*	*Unit*	*Simapro Label*	*use*
Copper Wiring	50	USD	Wiring devices	Wiring of circuit
PV Cells	24	P	p-Si cell U	power/sensing
Battery	6	P	NiCd Battery AA-cell	6xAA batteries used, power storage in circuit
Prototype board	0.1	kg	Printed Board I	mount circuit
IC chips	100	cm^2	IC's (area) I	control motor
Low alloy steel	78.6	kg	Steel Low Alloy ETH S	78.6 kg steel pole, 10 kg mirror support
ECCS Steel	2	kg	ECCS Steel 50% Scrap	nuts, bolts, etc.
Aluminum	7.9	kg	Aluminum Ingots I	1/8"x10'x10' mirror
cement	600	kg	Cement (Portland) I	anchor system

Installation

Diesel usage	7.5	gal	Diesel equipment (gal)	1.5 gal/hour * 5 hours diesel generator

Waste

Material	*Waste Scenario*	Description
PV Cells	PV cell waste in LA chemical landfill S	Landfill waste of photocells
Copper Wiring	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell
Battery	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell
Prototype board	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell
IC chips	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell
Low alloy steel	Steel to MWI S	Incineration of steel
ECCS Steel	Recycling ECCS steel B250	Recycling of ECCS steel
Aluminum	Incin. Aluminum 2000 B250	Incineration of aluminum
cement	Concrete (inert) to landfill S	Landfill waste of concrete

Using these elements as inputs to SimaPro, we created a network of materials and energies associated with SolarFocus throughout its lifetime. A portion of this map is shown in Figure 30. This map also shows increasing environmental damage, as defined by ECO-Indicator 99 standards, using larger connections between elements. In addition to creating this network, SimaPro also allowed us to calculate ECO-Indicator 99 scores.

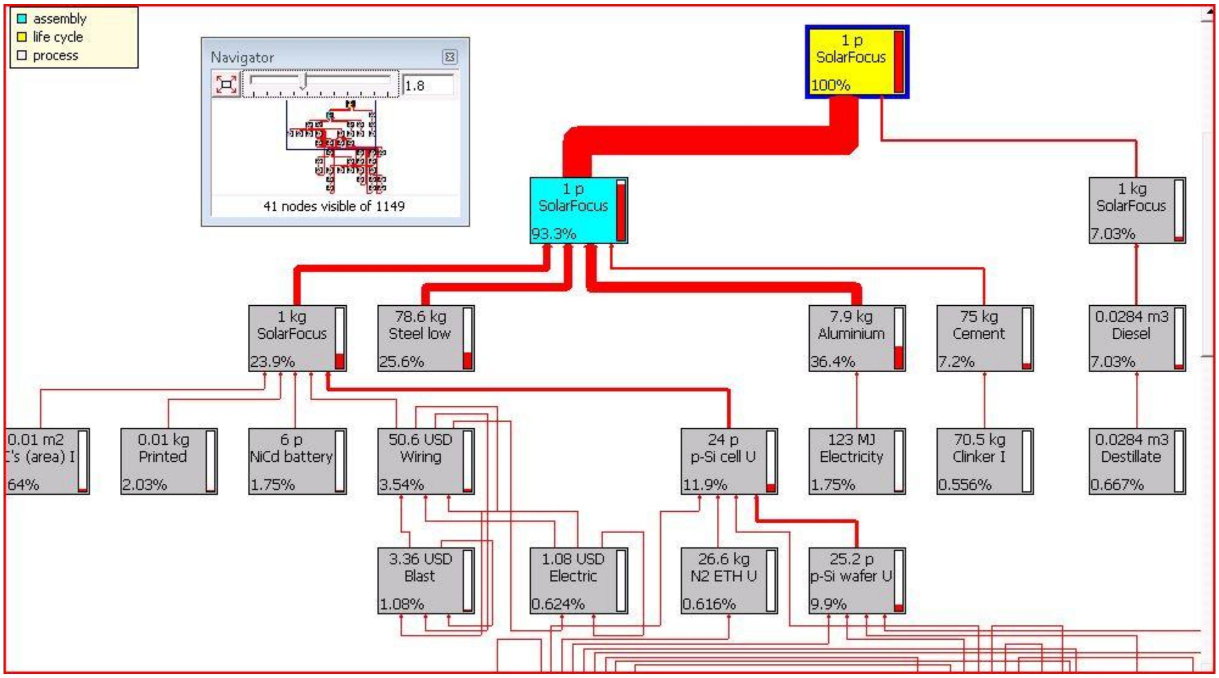


Figure 30: Network of Inputs Over Lifetime of SolarFocus

There are two elements which were not included in this analysis due to a lack of data, although we believe that they should be included for more accurate results. The first is the inclusion of stepper motors. We could not find any reliable data on environmental impact of building such motors, and chose not to include them. Another aspect that was not included was the apertures. 19" x 1.25" radius cylinders. However, while having both of these could only improve results, we feel that they would have marginal impacts on the overall analysis.

Our system will have a largest impact on carbon emissions reduction, so we will highlight carbon inputs versus carbon offsets of our system. Figure 31 shows the amount of carbon produced in the production of SolarFocus with the amount of carbon offset at various time intervals.

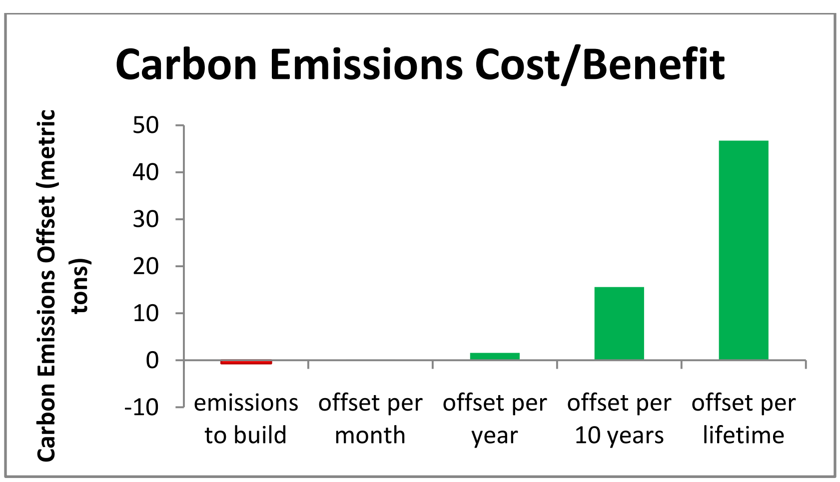


Figure 31: SolarFocus Saves Much More Carbon than is Used to Make it

It is easily seen here that SolarFocus quickly pays for itself in carbon emissions reduction, offsetting the amount of carbon inputs to create it in approximately 5 months, and saving 65 times as much carbon as it uses over its 30 year lifetime.

It is important to look at factors other than just carbon offsets, since these do not tell the full story. Figure 32 shows the impact of SolarFocus on human health, ecosystem quality, and resources—the three main categories of the ECO-Indicator 99 system.

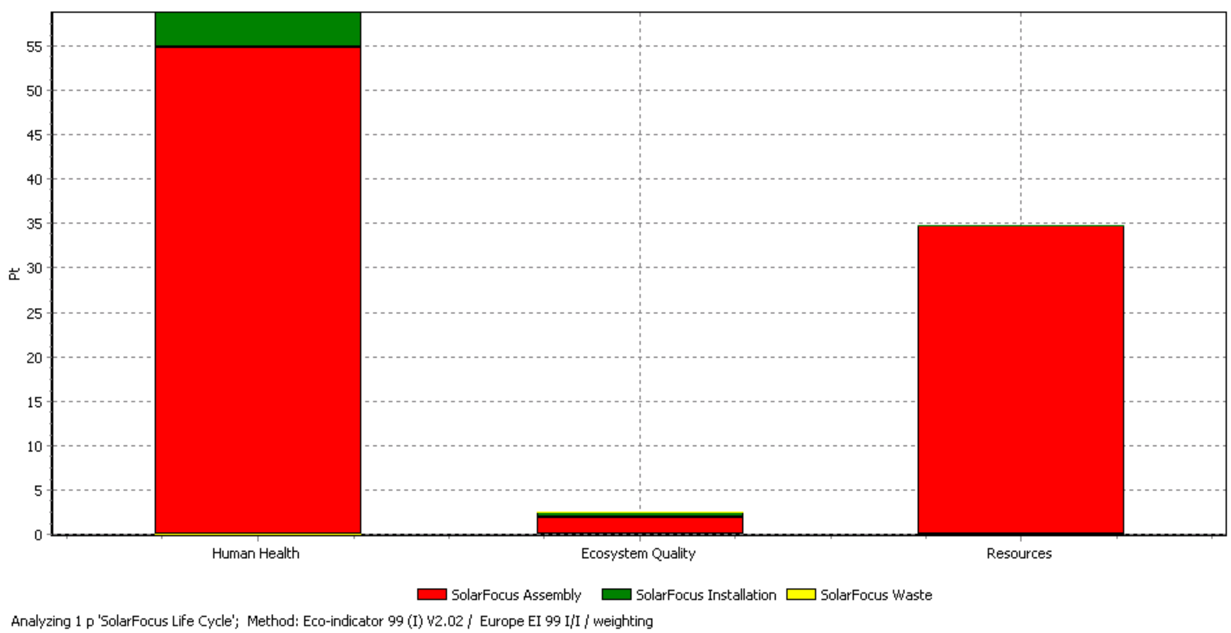


Figure 32: SolarFocus Impact on Human Health, Ecosystem Quality, and Resources

This figure shows several important aspects of SolarFocus. First of all, it shows that the vast majority of harm is caused by the production of materials that go into it. This suggests that minimizing materials will have the greatest effect on its environmental impact and should be a main focus of further development. It also shows that, while SolarFocus has many positive impacts in the area of carbon emissions, it does not do as well in other areas. When the categories of Figure 32 are further broken down, it can be seen that respiratory inorganics and minerals are the two main categories with high ECO-Indicator values. These likely come from the use of circuit components, which is largely unavoidable. These also are not significant enough to negate the positive impacts of SolarFocus.

12. Recommendations

Given the proven energy transfer, carbon offsets, and comparison to current products, we are confident in the added value of the SolarFocus' technology. We can therefore recommend that SolarFocus be implemented on G.G. Brown during the upcoming renovations. We recommend several steps be taken in order to prepare the design to be implemented on G.G. Brown.

First, the design of the support structure of SolarFocus needs to be finalized. This would involve static and dynamic analyses to ensure that the design is robust against all weather conditions. The exact placements of the physical stops that prevent the mirror from being positioned too far away from the atrium also need to be determined. The material choices for the structure can be refined as needed as the analyses are conducted. Final choices for photosensors and motors should be determined in compliance with our recommended specs. Also, as mentioned in the Design Critique in Section 11.3, the mirror selection should be optimized and power requirements calculated. The aesthetics of the system were beyond the scope of this semester, however, we recommend considering visual impact of SolarFocus is future design iterations.

There are also some final recommendations for the control system details. The threshold at which the control system takes step inputs from the on-the-mirror sensors needs to be finalized. Methods for this finalization were described in Section 10.3.3.3. The threshold of the differential between voltages on the photosensor grid also needs to be determined. We recommend integrating a light dimmer system with SolarFocus so that the electric lighting will fade automatically as it is offset by the sunlight. This will improve the amount of energy saved with the system installation. Although the current SolarFocus design uses a microcontroller, we recommend replacing the chip with logic chips for cost reduction. To continue work in building the control circuit, our team strongly recommends contacting Dragan Cerovcevic from CD Electronic in Ann Arbor.

Although not critical to the implementation of SolarFocus on G.G. Brown, we recommend that future developers of SolarFocus consider using smart materials for mirror actuation purposes. This option was considered as a replacement of the stepper motor that controls the north-south mirror rotation. The movement of the sun requires extensive east-west daily rotation of the mirror (up to 180°); however, the majority of the north-south rotational changes will come seasonally. As such, it may be possible to design the slower rotational change to occur without the use of a stepper motor. Although we decided to use two stepper motors instead, on the basis of simplicity, we still believe that it is worth further looking into using a smart material rotate the mirror from north to south with seasonal changes.

Finally, because the technology of SolarFocus is by no means specific to G.G. Brown or Ann Arbor, we recommend that it eventually be expanded to other commercial and residential buildings. However, because several of the details of our design *were* specific to G.G. Brown, this generalization will require additional work. It would have to be decided if the product should be sold as one-size-fits-all or continue to be custom made for each building. Also, if the room sizes are smaller, developers will have to be aware of the threat of reflecting sunlight into room occupants' eyes. It would also have to be proven that the product is environmentally and economically beneficial on smaller scales. Many of the engineering specifications developed in Section 5.3 (Table 4) will still apply and should be considered in any re-designs.

13. Conclusion

The purpose of SolarFocus is to design a simple, cost-effective system that will reflect solar power to areas that would not naturally receive sunlight. University of Michigan Chemical Engineering Professor Peter Woolf recognized the potential to harness and deliver the sun's abundant energy to north-facing rooms (like his office in G.G. Brown). We took his inspiration and developed a specific project scope; a scope which takes advantage of the upcoming on-campus renovations for G.G.Brown. After analyzing the current solar technologies we have determined that there is a lack of available brainless technology; current industry standards all include memory or programming for precise solar tracking. This reliance on "brains" has inflated the cost and accuracy needed for large scale harnessing of solar energy.

SolarFocus uses an innovative, brainless, control circuit to track the sun and reflect it into the north-facing G.G. Brown Atrium. The key components of the solar tracking and reflecting system are the mirror, two motors, a control system, and a photosensor grid. The photosensors will provide feedback through the control loop and consequently orient the mirrors to maximize solar energy intake. The final design includes the use of apertures to minimize external noise impact, outdoor grid placement to eliminate indoor noise, an on-the-mirror sensor array to determine availability of sunlight, and a validated control strategy. The measurable impacts of the SolarFocus installation on G.G. Brown include \$240 annual energy savings, or approximately 5.3% of annual atrium energy costs, 1.6 metric tons of annual CO_2 offsets, an investment in the forefront of solar energy harnessing technology, and close to a 400% cost reduction from industry benchmarks. The development of this technology over the last four months has marked the way for highly successful design iterations applicable residentially, commercially, or industrially.

14. Acknowledgements

The SolarFocus team is incredibly thankful to all of their supporters this semester; the success of the project would have been impossible without all of their help. In particular, the team would like to thank Professor Steven Skerlos (Section Instructor) and Professor Peter Woolf (Project Sponsor) for their guidance and feedback throughout the semester. Also, Professor Brent Gillespie for his help in designing the control logic for the feedback system, Mr. Bob Coury and Mr. Marv Cressey for their machining knowledge and help, and Mr. Dragan Cerovoevic of CD Electronic for all of his impeccable work on building the circuit itself.

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Appendix A: Bill of materials

Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
9V battery	1	N. Campus	N/A	$7.40	N/A	
Soldering	1	CD Electronics	N/A	$20.00	Dragan	
Balsa Wood	2	N. Campus	N/A	$3.71@	N/A	¼”x3”x36”
Glue	1	N. Campus	N/A	$3.99	N/A	
Solar Cell	2	Solarbotics	SCC3773	$8.00@	Solarbotics.com	6.7V, 31mA
Circuit Build	1	CD Electronics	N/A	$125	www.cdelectronic.com	
Allegro A3977	1	Digikey	A3977KLPTR-T	$3.81	www.digikey.com	Stepper motor driver
TSSOP to 28-pin DIP adapter	1	Cimarron Technology	03112B	$10.95	Cimarrontechnology.com	Converter from TSSOP to breadboard
Aluminum Rod	1	McMaster	9008K23	$13.71	Mcmaster.com	6’x ½”x ½”
Aluminum Bar	1	McMaster	6023K141	$7.69	Mcmaster.com	¾” x1” x$^1/_4$”
Angle Iron	2	McMaster	8968K23	$6.76@	Mcmaster.com	6’ length
LED Flashlight	1	Home Depot	7736D	$36.64	Homedepot.com	
Plywood	1	Home Depot	N/A	$5.90	Homedepot.com	3’x3’x$^1/_4$”

Appendix B: Description of engineering changes since DR3

Engineering Change	Reference
Photosensor array moved to outside of atrium wall to reduce indoor light noise acting as sensor input.	Section 10.3.1
Comparative sensors added to outdoor mirror for improved sun tracking. Reduces chance of ‘losing’ the sun during extended lag in input signals.	Section 10.3.3
Apertures added to photosensor array on atrium to prevent light noise from outdoor operating conditions.	Section 10.3.4

Appendix C: Design analysis assignment

Assignment 1: Material Selection Assignment

1. Reflective surface: This will reflect the sunlight into the G.G. Brown atrium. It needs to be durable to different weather situations, inexpensive, and highly reflective. Using CES to compare price and refractive index, the top 5 choices were: Polycarbonate, Alumina (85), Alumina (88), Polystyrene, and Polyethylene Terephthalate. Our final choice for the reflecting surface is a polycarbonate surface. It is an inexpensive material that is durable in water and sunlight. Although this surface is less reflective than the different aluminums, the cost benefit greatly exceeds that of aluminum.

PPC (Unfilled)

General properties

Designation

Polyestercarbonate or polyphthalate carbonate

Density		0.043	-	0.0434	lb/in^3
Price	*	0.987	-	1.09	USD/lb

Tradenames

Lexan

Composition

Composition (summary)

Copolymer of bisphenol-A polycarbonate and terephthalic acid.

Base		Polymer			
Polymer	*	0	-	100	%

Mechanical properties

Young's modulus	*	0.293	-	0.338	10^6 psi
Shear modulus	*	0.104	-	0.122	10^6 psi
Bulk modulus	*	0.538	-	0.565	10^6 psi
Poisson's ratio	*	0.388	-	0.404	
Shape factor		4.5			
Yield strength (elastic limit)		9.2	-	9.66	ksi
Tensile strength		10.3	-	11.2	ksi
Compressive strength	*	10.8	-	11.9	ksi
Flexural strength (modulus of rupture)	*	16.1	-	17.4	ksi
Elongation		78	-	122	%
Hardness - Vickers	*	18.6	-	20.5	HV
Fatigue strength at 10^7 cycles	*	4.12	-	4.47	ksi
Fracture toughness	*	3.06	-	3.38	ksi.in^1/2
Mechanical loss coefficient (tan delta)	*	0.0208	-	0.0232	

Thermal properties

Glass temperature	*	311	-	340	°F
Maximum service temperature	*	243	-	279	°F
Minimum service temperature	*	-54.4	-	-18.4	°F
Thermal conductivity		0.119	-	0.124	BTU.ft/h.ft^2.F
Specific heat capacity		0.296	-	0.302	BTU/lb.F
Thermal expansion coefficient		45	-	51	µstrain/°F

Electrical properties

Electrical resistivity		2.6e22	-	2.5e23	µohm.cm
Dielectric constant (relative permittivity)		3	-	3.27	

Dissipation factor (dielectric loss tangent)	0.0012	-	0.0016	
Dielectric strength (dielectric breakdown)	501	-	521	V/mil

Optical properties

Transparency	Transparent			
Refractive index	1.59	-	1.61	

Durability

Flammability	Slow-burning (UL94: HB)
Fresh water	Good
Salt water	Good
Weak acids	Good
Strong acids	Poor
Weak alkalis	Average
Strong alkalis	Poor
Organic solvents	Average
Sunlight (UV radiation)	Good
Oxidation at 500C	Very Poor

Primary material production: energy, CO2 and water

Embodied energy, primary production	* 9.57e3	-	1.06e4	kcal/lb
CO2 footprint, primary production	* 3	-	3.31	lb/lb
Water usage	* 5.4e3	-	5.95e3	in^3/lb

Material processing: energy

Polymer molding energy	1.14e3	-	1.26e3	kcal/lb
Polymer extrusion energy	440	-	485	kcal/lb
Polymer machining energy (per unit wt removed)	223	-	246	kcal/lb

Material processing: CO2 footprint

Polymer molding CO2	0.84	-	0.928	lb/lb
Polymer extrusion CO2	0.325	-	0.358	lb/lb
Polymer machining CO2 (per unit wt removed)	0.165	-	0.182	lb/lb

Material recycling: energy, CO2 and recycle fraction

Recycle	True			
Embodied energy, recycling	* 4.01e3	-	4.43e3	kcal/lb
CO2 footprint, recycling	* 1.26	-	1.39	lb/lb
Recycle fraction in current supply	0.1			%
Downcycle	True			
Combust for energy recovery	False			
Biodegrade	False			
Landfill	True			
A renewable resource?	False			

Links

ProcessUniverse
Producers
Reference
Shape
Structural Sections
No warranty is given for the accuracy of this data. Values marked * are estimates.

2. Base structure: This part will anchor the system to the ground, and allow the reflective surface to be raised at least 10 feet into the air. It needs to be inexpensive, durable in different weather, and strong enough to support the reflective surface. Using CES to compare price and Young's Modulus, the top 5 choices were: Steel, Alumina (85), Cement, Cast Iron, and Tungsten Carbide. The final choice for the base support is a steel structure. The base of SolarFocus can be compared to a light pole, and steel is used for this application. It is an inexpensive material that will be durable in different weather elements, and it is strong enough to support the SolarFocus design.

Low alloy steel, AISI 94B30 (tempered @ 205 C, oil quenched)

General properties

Designation

Low alloy steel, AISI 94B30 (tempered @ 205 C, oil quenched)

Density	0.282	-	0.285	lb/in^3
Price	* 0.479	-	0.527	USD/lb

Tradenames

SHARON 8600 SERIES A, Sharon Steel Corp. (USA);

Composition

Composition (summary)

Fe/.28-.33C/.3-.5Cr/.3-.6Ni/.75-1Mn/.15-.3Si/.08-.15Mo/P,B,S traces

Base	Fe (Iron)			
B (boron)	0			%
C (carbon)	0.28	-	0.33	%
Cr (chromium)	0.3	-	0.5	%
Fe (iron)	97.1	-	98.1	%
Mn (manganese)	0.75	-	1	%
Mo (molybdenum)	0.08	-	0.15	%
Ni (nickel)	0.3	-	0.6	%
P (phosphorus)	0			%
S (sulfur)	0			%
Si (silicon)	0.15	-	0.3	%

Mechanical properties

Young's modulus	29.9	-	31.3	10^6 psi
Shear modulus	11.5	-	12.3	10^6 psi
Bulk modulus	23.1	-	25.5	10^6 psi
Poisson's ratio	0.285	-	0.295	
Shape factor	15			
Yield strength (elastic limit)	202	-	247	ksi
Tensile strength	225	-	276	ksi
Compressive strength	202	-	247	ksi
Flexural strength (modulus of rupture)	202	-	247	ksi
Elongation	9	-	15	%
Hardness - Vickers	425	-	525	HV
Fatigue strength at 10^7 cycles	* 84.3	-	97.3	ksi
Fracture toughness	* 24.6	-	47.3	ksi.in^1/2
Mechanical loss coefficient (tan delta)	* 2.3e-4	-	2.9e-4	

Thermal properties

Melting point	2.65e3	-	2.76e3	°F
Maximum service temperature	* 329	-	383	°F
Minimum service temperature	* -63.4	-	-9.4	°F
Thermal conductivity	26.6	-	29.5	BTU.ft/h.ft^2.F

Specific heat capacity	0.102	-	0.113	BTU/lb.F
Thermal expansion coefficient	6.11	-	7.22	µstrain/°F

Electrical properties

Electrical resistivity	* 15	-	35	µohm.cm

Optical properties

Transparency	Opaque

Durability

Flammability	Non-flammable (UL94: exceeds ratings)
Fresh water	Good
Salt water	Average
Weak acids	Average
Strong acids	Poor
Weak alkalis	Good
Strong alkalis	Average
Organic solvents	Very Good
Sunlight (UV radiation)	Very Good
Oxidation at 500C	Good

Primary material production: energy, CO2 and water

Embodied energy, primary production	3.47e3	-	4.12e3	kcal/lb
CO2 footprint, primary production	2.01	-	2.22	lb/lb
Water usage	1.02e3	-	3.07e3	in^3/lb

Material processing: energy

Casting energy	430	-	476	kcal/lb
Forging, rolling energy	508	-	561	kcal/lb
Metal powder forming energy	1.43e3	-	1.58e3	kcal/lb
Vaporization energy	2.67e3	-	2.94e3	kcal/lb
Conventional machining energy (per unit wt removed)	935	-	1.03e3	kcal/lb
Non-conventional machining energy (per unit wt removed)	4.98e3	-	5.51e3	kcal/lb

Material processing: CO2 footprint

Casting CO2	0.238	-	0.263	lb/lb
Forging, rolling CO2	0.375	-	0.414	lb/lb
Metal powder forming CO2	1.06	-	1.17	lb/lb
Vaporization CO2	1.97	-	2.17	lb/lb
Conventional machining CO2 (per unit wt removed)	0.69	-	0.762	lb/lb
Non-conventional machining CO2 (per unit wt removed)	3.68	-	4.07	lb/lb

Material recycling: energy, CO2 and recycle fraction

Recycle	True			
Embodied energy, recycling	* 1.01e3	-	1.12e3	kcal/lb
CO2 footprint, recycling	* 0.562	-	0.621	lb/lb
Recycle fraction in current supply	39.9	-	44	%
Downcycle	True			
Combust for energy recovery	False			
Biodegrade	False			
Landfill	True			
A renewable resource?	False			

Notes

Typical uses

General construction; general mechanical engineering; automotive; tools; axles; gears; springs.

Reference sources

Data compiled from multiple sources. See links to the References table.

Links

ProcessUniverse
Producers
Reference

Shape
Structural Sections
No warranty is given for the accuracy of this data. Values marked * are estimates.

Assignment 2: LCA (Environmental Performance)

Rather than completing an LCA of two materials in our design, our team created a complete life cycle analysis, including materials, assembly and wasting. This section will analyze environmental impacts of this but, rather than comparing two materials which will be inputs, it will discuss the overall merits and demerits of the entire lifetime of our system.

The most environmentally significant input into our system, as will be shown by our LCA, is the material used to build it. Table 1 below summarizes these inputs, as initially defined in our cost analysis, the amounts estimated to be used, the SimaPro label used, and its use in our system.

Table 1: Summary of Material Inputs into SimaPro

Material	*Amount*	*Unit*	*Simapro Label*	*use*
Copper Wiring	50	USD	Wiring devices	Wiring of circuit
PV Cells	24	P	p-Si cell U	power/sensing
Battery	6	P	NiCd Battery AA-cell	6xAA batteries used, power storage in circuit
Prototype board	0.1	Kg	Printed Board I	mount circuit
IC chips	100	cm^2	IC's (area) I	control motor
Low alloy steel	78.6	Kg	Steel Low Alloy ETH S	78.6 kg in the steel pole support and 10 kg of steel tubing for mirror support
ECCS Steel	2	Kg	ECCS Steel 50% Scrap	nuts, bolts, etc.
Aluminum	7.9	Kg	Aluminum Ingots I	1/8"x10'x10' mirror
cement	600	Kg	Cement (Portland) I	anchor system

In addition to these materials, we also included the running of a diesel engine for machinery to install SolarFocus, and created likely waste scenarios for each of the input materials. These are shown in Table 2 below.

Table 2:
Installation

Diesel usage	7.5	Gal	Diesel equipment (gal)	this is 1.5 gal/hour * 5 hour use of a diesel generator

Waste

Material	*Waste Scenario*	Description
PV Cells	PV cell waste in LA chemical landfill S	Landfill waste of photocells
Copper Wiring	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell waste
Battery	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell waste
Prototype board	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell waste
IC chips	PV cell waste in LA chemical landfill S	*No 'electronics waste', so modelled as PV cell waste
Low alloy steel	Steel to MWI S	Incineration of steel
ECCS Steel	Recycling ECCS steel B250	Recycling of ECCS steel
Aluminum	Incin. Aluminum 2000 B250	Incineration of aluminum
cement	Concrete (inert) to landfill S	Landfill waste of concrete

Based upon these inputs, SimaPro calculated the amount of air emissions, water emissions, use or raw materials, and (solid) waste. However, due to the large amount of inputs which use different units, SimaPro would not display these graphically. What could be seen from these was that the materials of SolarFocus dominated all forms of emissions and waste. Because of this, the following analysis will focus on specific materials within the SolarFocus assembly, rather than comparing the assembly, installation, and waste stages.

It is very clear that, of the three meta-categories, resource use will be the biggest issue with SolarFocus. This is seen in Figure C.1. Human health will also be important to consider as well, but ecotoxicity does not appear to play a large role.

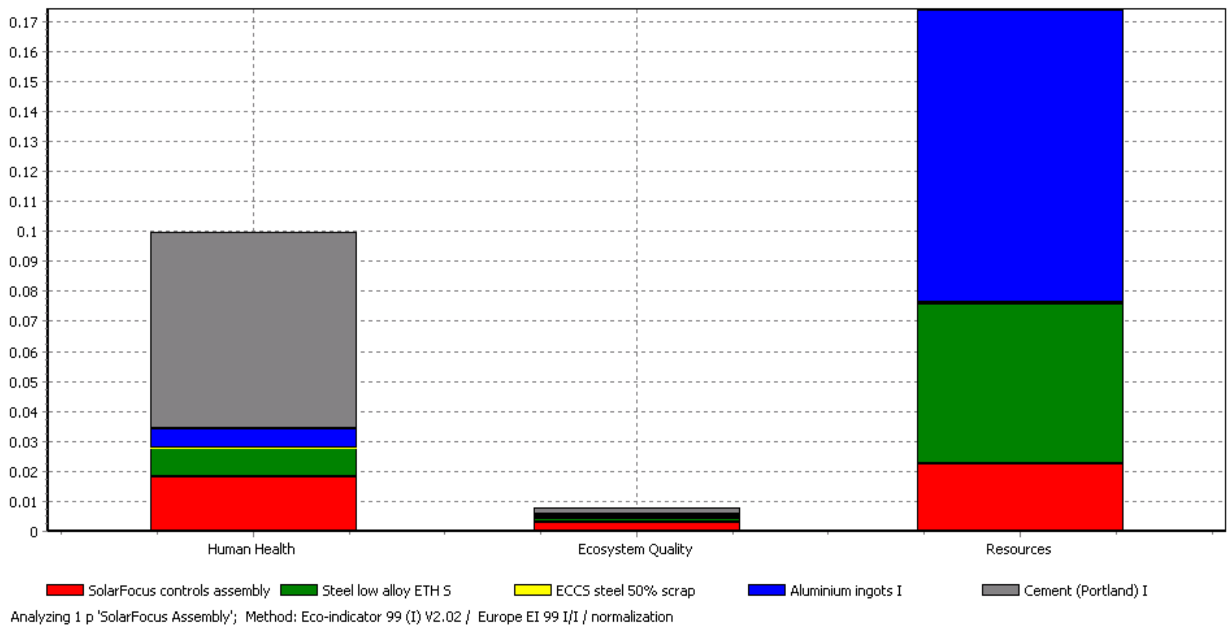


Figure C.1: Based Upon Meta-Categories, Human Health is Biggest Concern with SolarFocus; Cement Plays Large Role in This

Figure C.1 also gives valuable insight into the specific processes/materials which contribute to each of these categories. From this, it can be seen that the cement will have the greatest hazard to human health, while the aluminum and steel will have the greatest hazard to resources. This makes sense intuitively, since these three materials make up the majority of the support system of SolarFocus. Finding alternative materials instead of these, or at least minimizing their use, will greatly improve the system's Eco-Indicator 99 score. It is also important to note that the controls assembly has a reasonably large impact on both human health and resources. However, because this is mainly comprised of circuit components, there is not much room for improvement in this area.

Looking at the relative impacts of each aspect of SolarFocus' LCA points more strongly to the impact of the controls circuit, as seen in Figure C.2. This shows the controls to have a large contribution to almost every category, especially the categories of radiation and ozone layer damage. Once again, finding a way to minimize metals in the circuit would improve this, but will be very difficult to do.

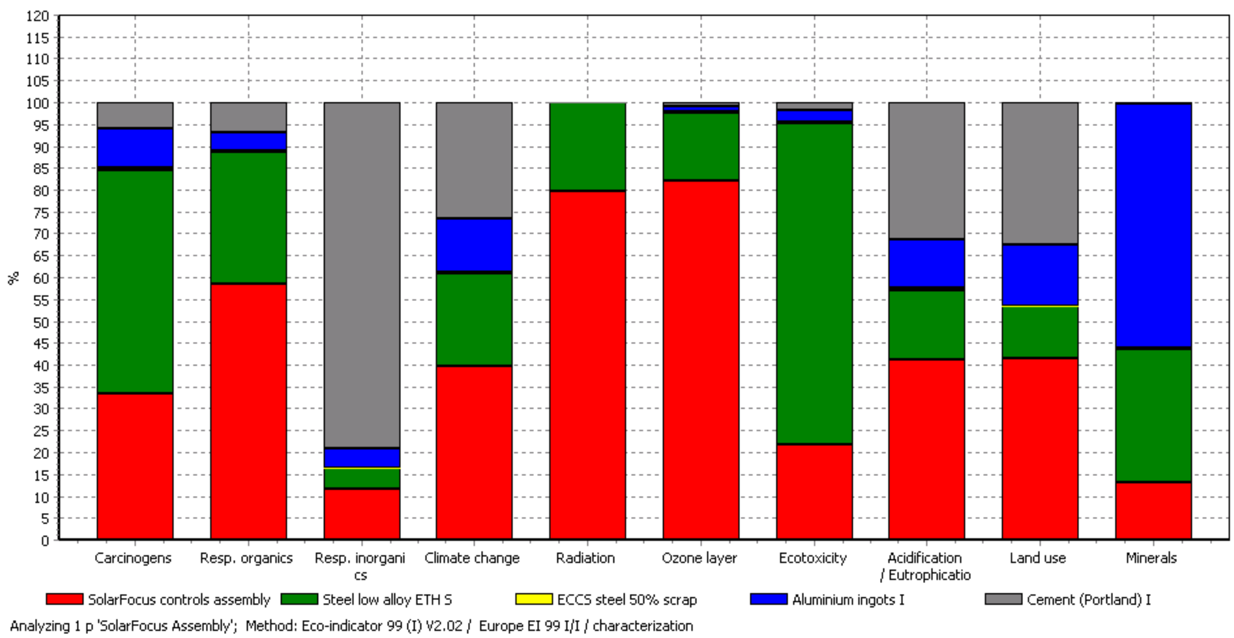


Figure C.2: Normalized, Disaggregated Data Shows Strong Impact of Controls Assembly

One final way in which to look at the graph is by total contribution of each individual component, rather than their contributions to each of a variety of factors. This is seen in Figure C.3.

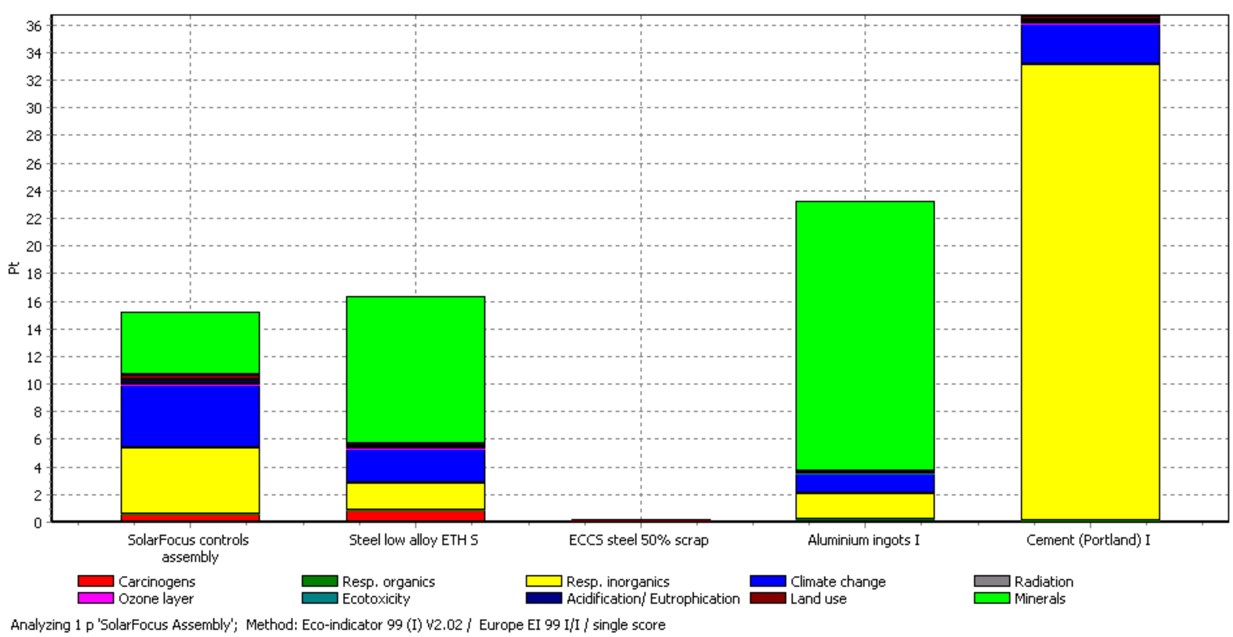


Figure C.3: Single Score Comparison of Assembly Shows that Steel is Most Detrimental

This graph shows that cement, aluminum, steel, and the controls assembly have highly detrimental impacts. Aggregating data like this shows that steel will have the largest impact, with most of that impact being in respiratory organics.

Assignment 3: Manufacturing Process Selection Assignment

SolarFocus is a unique technology for each different location of implementation. The designed system for the new G.G. Brown atrium is unique to the building. Therefore the production of the same system is one. With minor added geometry, this technology can be applied to any building. The SolarFocus technology would benefit users globally, but most importantly it will benefit the environment. Therefore, the production volume could be 1 million products on the market. The maximum number of this product in society is for the most part limitless. It could be implemented on every building looking to save on energy costs and reduce carbon emissions.

The two different components of the design will not change much when in production. The length of the base will either be larger or smaller, depending on the height of the building, and the size of the reflecting surface will increase or decrease depending on the size of the desired reflected light. The mirror material could be molded to the correct size and shape. This will allow the customer to have many options before purchasing. After being molded, the polycarbonate will need to be machined to the exact dimensions. The steel used for the support structure will need to be rolled and forged to shape the material into a cylinder. Once the steel has been shaped, additional conventional machining will be needed to make the structure to the correct size.

Appendix D: Additional background information

Applications of Solar Energy in Green Architecture

While green architecture also incorporates the use of renewable resources through wind, geothermal, water, and plant derivatives, solar energy is a powerful renewable which can be relatively non-disruptive to building structure. Solar technologies are often categorized into passive or active solar designs, though the two approaches are not mutually exclusive.

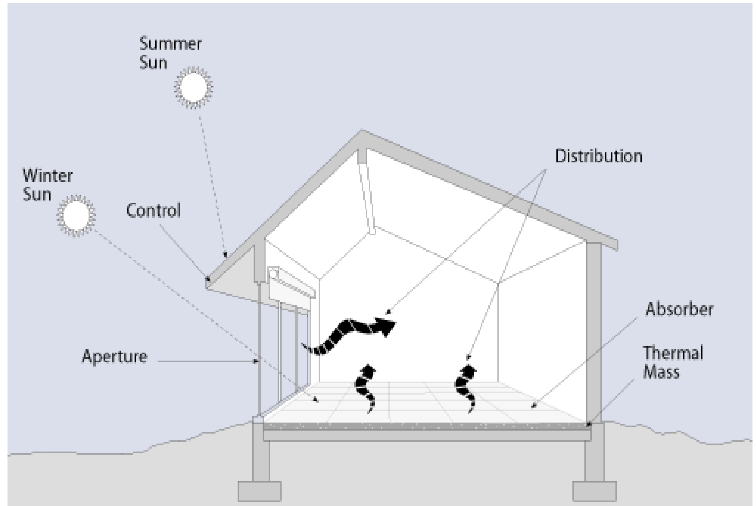


Figure D.1: Passive Solar Design Elements

Source: US DOE; EERE.
http://www.eere.energy.gov/de/passive_solar_design.html

Passive Solar

Passive solar design is the design and placement of buildings to enable solar heating without mechanical or electrical equipment. Also known as *climatic design*, this can be generalized to includ e technology that is able to generate usable solar energy without running equipment or input energy [4]. The most common form of passive design is space heating, or the Barra System. The five elements to effective passive solar design are an aperture, an absorber, a thermal mass, distribution, and control (Figure D.1). Winter sunlight shines directly through a window or aperture onto an absorber. This is often a dark wall or floor which is capable of absorbing as much heat as possible from the sun. Behind or beneath the absorbing surface is the thermal mass that allows for prolonged storage of the solar heat and then its gradual release. Distribution of the heat will occur naturally through convective and conductive heat transfer. Unwanted solar heat in the summer is usually prevented through the use of brise soleils, or permanent sun-shading, awnings and overhangs to prevent the high summer sun. Done correctly, passively designed buildings can reduce heating bills by up to 50% [5]. Other passive solar systems include the practice of daylighting that allows for effective internal lighting and heating from a natural light source. Most commonly this will take the shape of well-placed windows, adjustable light shelves or reflectors, skylights, or light tubes. Solar energy can also be passively used in solar chimneys and solar furnaces, water heaters, or earth sheltering. The passive approach is a less costly alternative than active control and requires no maintenance or operation costs, with no harmful emissions. However, the passive approach has less consistency and energy generation than its counterpart of active solar design.

Active Solar

Usually more expensive and complicated than passive solar, active solar design allows for enhanced heat transfer and facilitates alternative uses for solar energy than merely heating a space. Like passive solar design, active solar techniques generate usable solar energy; however, active solar uses mechanical or electrical equipment for improved energy transfer. Through this, buildings that were not designed for passive solar absorption are able to use solar energy for cooling, heating, and ventilation. Often, active solar technology is used for sun tracking which can improve efficiency of energy-capture by 30-40% [6]. As sun location varies with seasons, latitude and time of day, sun-tracking devices are programmed to track the progression across the sky. This type of equipment is frequently used to orient and monitor the movement of solar photovoltaic panels. It is also used in solar concentrators to orient the reflectors and lenses towards the sun, though this application has a very high accuracy requirement. On a larger scale, active technology can be used to preheat water or ventilated air, providing not only direct energy offsets but reducing necessary fossil fuel energy requirements as well. While active solar approaches provide advantages to large-scale projects, they can have excessively large maintenance and operational costs associated with them. Unlike passive solar design, the conscientious design and placement of the building plays a much smaller role in the solar power benefits of active devices.

Solar Design

The most effective designs are those that combine both active and passive techniques to create a zero-energy or very low emission building. By offsetting energy costs, a structure can reduce power grid dependency and peak load requirements, allowing for even greater future energy savings. A remarkable testament to industrial solar power is the solar furnace in Odeillo, France (Figure D.2). Reaching temperatures of up to 3000°C and energy generation up to 10 MW/m^2 at the focal point, the curved array of mirrors generates enough power to melt iron ore into steel [7].

Figure D.2: Odeillo Solar Furnace

Source: Procedes, Materiaux et Energie Solaire UPR 8521
http://www.promes.cnrs.fr/TOUT-PUBLIC/Les-fours/eng-lesfours1.htm

Alternate Actuation Methods

Before a stepper motor was chosen to provide the actuation for Solar Focus, several alternative actuation methods were considered. The basic technologies of these methods are described below.

DC Servomotor

A DC servomotor is type of electric motor

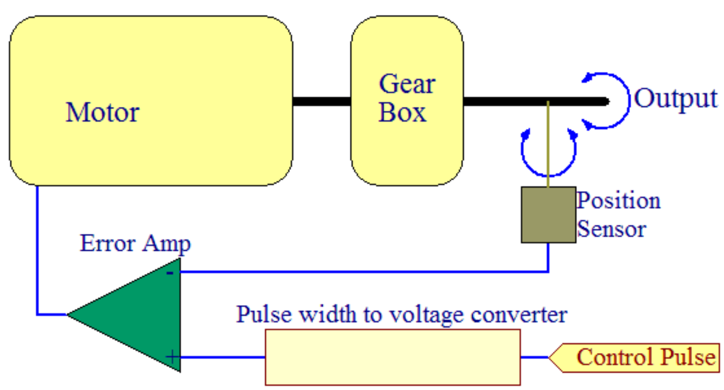


Figure D.3: DC Servomotor

Source: www.digitalnemesis.com/info/docs/rcservo/

that can generate rotary motion. A servomotor contains closed-loop feedback for position control. The motor moves toward an inputted position, using an encoder to monitor its position compared to the input. It uses feedback to guide its motion towards this point. A block diagram of a servomotor with its control system is shown in Figure D.3. Servomotors are frequently used in hobbyist applications as they are fairly cheap and are easily controlled remotely [32].

Hydraulic

Hydraulic motors provide rotary actuation while hydraulic pistons provide linear actuation [32]. Hydraulic motors and pistons typically function as part of a hydraulic circuit that contains a hydraulic pump, control valves, filters, and reservoir [34]. The pump receives input power and supplies amplified torque or force to the hydraulic motor or piston, respectively. The amplification used in hydraulic systems is similar to the force amplification for a mechanical lever. The valves of a hydraulic system can be controlled in order to direct the work done by the hydraulic system. Hydraulic motors are advantageous since they produce minimal heat and the system can be remotely connected via pipes to the piston or pump [34].

Pneumatic

Pneumatic motors and pistons use fluid power in the form of compressed gas to produce mechanical motion [32]. The main components of a pneumatic system are parallel to those of a hydraulic system. The fluid in pneumatic systems is compressible and has a lower magnitude of pressure capabilities compared to the hydraulic counterpart [35]. Pneumatic motors are advantageous because they are lightweight and are used often for hand tools [35].

Smart Materials

A smart material is a material that significantly changes its properties in a predictable manner in response to changes in its environment [36]. A piezoelectric material is a smart material that can be used for actuation. A piezoelectric material produces electric voltage when it experiences deformation due to a mechanical force. Conversely, when an electrical voltage is supplied to a piezoelectric material, it deforms and therefore produces a mechanical force [37]. This principal of piezoelectric materials is used for piezoelectric motors, which use the ultrasonic vibrations of the material to create linear or rotary motion [38]. Piezoelectric motors are used for many electronics applications and positioning control due to the quick response time and precision [38]. Another smart material is a shape memory alloy (SMA). An SMA is smart in that it can “remember” a shape formed in the high-temperature austenite phase as it is heated back to austenite from the martensite phase. This characteristic alloys SMAs to be used for unique applications in robotics actuation and biomedical devices [39].

Appendix E: Customer requirements, ranked by importance to each customer

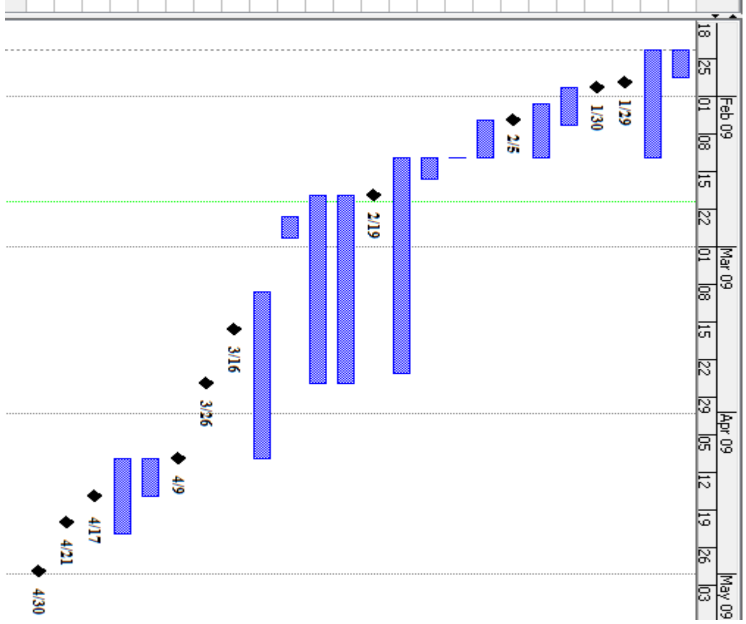
				CUSTOMERS				
	Occupant `		Sponsor	Construction	Operations	Environment		WEIGHT
Reduces energy required by building	1	9	9	1	9	9	38	1.00
Cost effective	3	9	9	1	9	3	34	0.89
Can it be added to existing plans or building	1	9	9	9	1	3	32	0.84
Meets common practice building light standar	9	9	3	1	9	1	32	0.84
Maintains efficiency over lifespan	1	9	9	1	3	9	32	0.84
Interface well with current systems	9	9	9	1	3	1	32	0.84
LEED certified	1	9	9	1	3	9	32	0.84
Reduces emissions	1	9	9	1	3	9	32	0.84
Doesn't require manual adjustment	3	3	9	1	9	1	26	0.68
Space effective	9	9	3	1	3	1	26	0.68
Usable in summer	9	9	3	1	3	1	26	0.68
No harm if walking in line of light	9	9	1	1	3	1	24	0.63
Doesn't need constant adjustment	3	3	3	3	9	1	22	0.58
Low initial investment	1	9	9	1	1	1	22	0.58
Easy to control settings (hot/cold, lighting)	9	3	3	1	3	1	20	0.53
Adjustable to various buildings	1	3	9	1	3	3	20	0.53
Durable (weather resistant)	3	9	3	1	3	1	20	0.53
Self- powered	1	9	3	3	3	1	20	0.53
Does not require specialized skill/tool set for	1	3	3	3	9	1	20	0.53
Long lifetime	1	9	3	1	3	3	20	0.53
Not eye sore	9	3	3	1	1	1	18	0.47
Light not too bright	9	3	1	1	3	1	18	0.47
Easy to install	1	3	3	9	1	1	18	0.47
Uses environmentally friendly materials and p	1	3	3	1	1	9	18	0.47
Weatherproof	3	3	3	1	3	1	14	0.37

Appendix F: Engineering specifications, ranked by importance to each customer requirement

SPECIFICATIONS \ CUSTOMER REQUIREMENT	Reduces energy required	Cost effective	Can be added to existing plans or building	Meets common practice building light standards	Maintains efficiency over lifespan	Interface well with current systems	LEED certified	Reduces emissions	Doesn't require manual adjustment	Space effective	Usable in summer	No harm if walking in line of light	Low initial investment	Easy to use	Adjustable to various buildings	Durable	Self-powered	Easy to maintain	Long Lifetime	Not eye sore	Light not too bright in room	Easy to install	Uses environmentally friendly materials and production/manufacturing	TOTAL SPEC IMPORTANCE:
WEIGHT	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	
Reduces building energy costs by 2.5%	9	3		3	3	3	9	3			3				3		1		3					35
Minimum energy production of 100 ccf natural gas or 1100 kWh electricity	9	9			9	1	3	9			3				1	1	1							39
Requires no additional powering	3	3			3		1	1							1		9	3						17
Greater than 40% efficiency under peak conditions	3	9		3	9		3	3									1							27
Doesn't add cooling costs in summer	3	3						3			9													14
Less than 20% efficiency loss over lifetime	3	9			9		3	0									1	1	9					27
30 year lifetime	9	9			3		3	9								9		3	9					41
Doesn't heat room to more than 72F	3	9	3			9		9	3		9										1			37
Self-controlled with in 5 degrees and 50 lux		1		9		9			9		1			3							9			29
Can withstand any temp between -25° and 115° F					1						9					9		3	3					15
Can withstand winds up to 80 mph					1						9					9		3	3					15
Can withstand up to 50 lb. snow					1						9					9		3	3					15
Reduces emissions by 2.5%	9		3	1	3		9	9			3				1	1	1							34
Product pay-back time of 3 years	1	9	9		3	1	3	3			1		9				1		1		1	3	1	34
No operational carbon emissions	9			1			3	9			1					1		1						22
Light level adjustable to ± 50 lux	3	1	1	9		9								9							9			29
Has 2-axis motion	9	3			3		3	3	9		3			3							3			30
Total mechanism and mounting cross sectional area less than to mirror surface area		1								9			3					3		9		3		16
Max light intensity 850 lux	1	3	3	9		3			3			9		3							9			30
Carbon footprint less than 150 kg of carbon							3	9															9	14
Max $400 per unit initial capital investment		9											9											13
Range of motion - -60 deg < θ_{az} < 60 deg; 90 deg < θ_{al} < 130 deg	3			3			3	3	9		1			3	3									21
Greater than 68 ft away from building for each 12 ft building heig	3		3					3							3							3		11
Less than twice yearly maintenance for seasonal adjustments		1	1			1			9		3			9	1			9						21
Can operate through windows with visible light transmittance le than 40% and Solar Heat Gain larger than 40%	3	3	9	1		3	1	1						1	3			3			1			22
Maximum unit weight 100 pounds		1	1							9			3	3	3			3		9		9	1	23
No additional skill/ toolset required for maintenance			3			3			1									9	1			1		11
Install time less than 8 hours		3	3			3				1				1								9	1	14

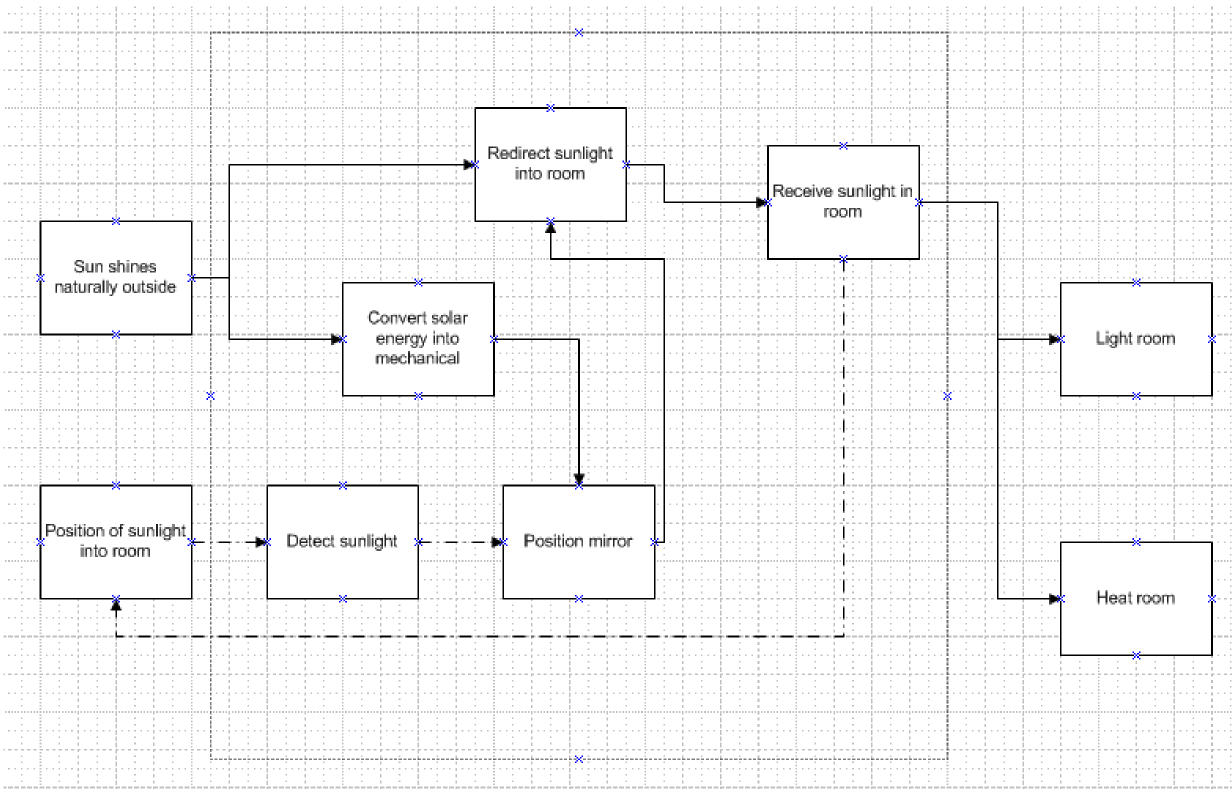
Appendix G: Gantt chart

	Name	Duration	Start	Finish
13	Literature Review	4 days?	1/23/09 8:00 AM	1/28/09 5:00 PM
18	Research Engineering Fundamentals	15 days?	1/23/09 8:00 AM	2/12/09 5:00 PM
9	Design Review 1 - Engineering Specifications	1 day?	1/29/09 8:00 AM	1/29/09 5:00 PM
1	Brainstorm Session	1 day?	1/30/09 8:00 AM	1/30/09 5:00 PM
10	Generate Concept Ideas	6 days?	1/30/09 8:00 AM	2/6/09 5:00 PM
19	Design Control Loop	9 days?	2/2/09 8:00 AM	2/12/09 5:00 PM
11	Choose Top Concepts	0 days?	2/5/09 8:00 AM	2/5/09 8:00 AM
14	Calculations for Top Concepts	6 days?	2/5/09 8:00 AM	2/12/09 5:00 PM
15	Choose Final Concept	1 day?	2/12/09 8:00 AM	2/12/09 5:00 PM
16	Finalize Concept Design	3 days?	2/12/09 8:00 AM	2/16/09 5:00 PM
20	CAD Work	29 days?	2/12/09 8:00 AM	3/24/09 5:00 PM
8	Design Review 2 - Alpha Design	1 day?	2/19/09 8:00 AM	2/19/09 5:00 PM
21	Design Modifications	26 days?	2/19/09 8:00 AM	3/26/09 5:00 PM
22	Detailed Calculations	26 days?	2/19/09 8:00 AM	3/26/09 5:00 PM
12	Spring Break	5 days?	2/21/09 8:00 AM	2/27/09 5:00 PM
17	Prototyping	24 days?	3/9/09 7:00 AM	4/9/09 5:00 PM
7	Safety Review	1 day?	3/16/09 7:00 AM	3/16/09 5:00 PM
6	Design Review 3 - Final Design	1 day?	3/26/09 7:00 AM	3/26/09 5:00 PM
5	Design Review 4 - Alpha Prototype	1 day?	4/9/09 7:00 AM	4/9/09 5:00 PM
23	Prototype Testing and Improvement	6 days?	4/9/09 7:00 AM	4/16/09 5:00 PM
24	Scale back up to G.G. Brown	11 days?	4/9/09 7:00 AM	4/23/09 1:00 PM
4	Design Expo	1 day?	4/16/09 1:00 PM	4/17/09 1:00 PM
2	Final Report Due	1 day?	4/21/09 7:00 AM	4/21/09 5:00 PM
3	Prototype Delivered	1 day?	4/30/09 7:00 AM	4/30/09 5:00 PM



Appendix H: Functionality block diagram

Solid line: flow of energy
Dotted line: flow of information



Appendix I: Brainstorm session solutions to sub-problems

1) Reflect and direct sunlight
    a. Concentrate or reflect
    b. Disperse
    c. Controlled scattering
    d. Parabola to the apex & then out
    e. Multiple v. Single mirror system
    f. Varying degrees of freedom of mirrors
    g. Parabola v. Circle- shaped mirrors
    h. Many small flat mirrors
    i. Spray paint/ coating on a mold (for curved surfaces instead of curved mirror)
    j. Decouple motion? Optimizing both ends; sun into mirror and sun into window
    k. Reflecting into house v. other mirrors
    l. Fresnel lens

2) Control and power movement
    a. Pneumatics
    b. Hydraulics
    c. Electric motors
    d. Passive (steam, water, hot bags, etc)
    e. Shape memory alloy
    f. Thermally expanding material
    g. Piezoelectric motor
    h. Linear, circular, angular motors (Turrets?)
    i. Pumps/ water mill

3) Self-protect from elements
    a. Tulip (weather/nighttime)
    b. Goes straight to vertical
    c. Slippery material/coating
    d. Heat coils
    e. Go down past 90 degrees
    f. Windshield wiper
    g. Best not to have to ADD anything to it
    h. Cover/garage door→ folds shut/cupboard, folds together/tri-fold
    i. Outside sensor to re-open? How to know surrounding environment?
    j. Defogging
    k. Temperature control/sensor
    l. Jacket for temperature protection

(Appendix I, continued)

4) Control quantity of heat and light directed into room
    a. Adjust mirror @ greater than values to redirect
    b. Filter/lens
    c. Turn off (w/ use of voltage across mirror)
    d. Blinds, awnings, overhangs
    e. Pupil dilation/ light adjusting aperture? (like a camera)
    f. Opaque covering
    g. Redirect to PVs
    h. IR filter in summer

5) Utilize heat and light once it enters the room
    a. Prism
    b. Fan
    c. Trombe wall
    d. Light refractors
    e. Multiple mirrors
    f. Light dispersing material
    g. "Textured" mirrors at random angles
    h. Stained glass
    i. Air movement
    j. Conductive materials
    k. Materials that radiate
    l. Heat storing material/slow release
    m. Direct toward ceiling or floor (do nothing extra)
    n. Light tubes

Appendix J: Preliminary decisions to be made for broad concepts

Mirror Orientation	**Mirror Location**	**Reflection System**	**Actuation System**
Reflect down into room	Across street	Multiple mirrors direct to different places	Hydraulic piston/pump system
Reflect up into room	In parking lot on lamps	Multiple mirrors direct to same place	Pneumatic piston system
	On corner of roof	Single mirror	DC servomotor
		Mirror reflecting to light shelf	DC stepper motor
			Piezoelectric motor
			Thermally responsive material

Appendix K: Decisions for future consideration

Self-protection from elements	**Utilization of heat and light once in room**	**Control quantity of heat and light in room**
Mirror adjusts to vertical position	Prism	Redirect to PVs
Slippery Coating on Mirror	Fan	IR filter to block heat
Heat coils	Light-dispersing material	Program control system to redirect motor at light threshold
Split up mirrors into small sections	Materials that radiate	Blinds/Awnings
Mirror adjust to point on ground	Materials that store or slowly release heat	Opaque Covering
Windshield wiper		
Temperature sensor		
Mirrors Fold Together		

Appendix L: Initial prototype development

Our concept consists of two separate parts; a concept idea for G.G. Brown and a prototype that proves the feasibility of such a system providing a significant amount of energy to the G.G. Brown atrium. This section describes in full detail the proposed concept for G.G. Brown, gives an alpha design of the prototype system, and a description of how this prototype will function to prove our concept.

Concept Description

The driving purpose of this project is to create a system that can be added onto the G.G. Brown renovation atrium. However, before this can be done, it is important that we prove that our system can provide the amount of energy predicted by our models and can be controlled in an effective manner. With this in mind, we will be creating a proof-of concept prototype, as well as a description for how to scale it up to a project the scale of G.G. Brown. This section will first discuss our concept and how it can be used on G.G. Brown. This will be followed by a more detailed description of our prototype.

This design will guide our prototype in one main way – our prototype will be made to imitate, as closely as possible, all physical and geometrical considerations. One of the main considerations is that our prototype mirror should be oriented in a similar manner to our G.G. Brown concept. Also, in order to track maximum motion of the sun, the SolarFocus system will have to have a range capable of covering all positions of the sun.

Prototype Design

The main goal of our prototype will be to validate the concept that solar energy may be controlled and redirected. To this end, we will build a tabletop prototype that will have all of the functionality of our proposed G.G. Brown SolarFocus system, but scaled down and without considering aesthetics and weatherproofing conditions that will be necessary for a final SolarFocus design. The two main components of our prototype will be the physical redirection and control of the sun and the electrical feedback control system that will be required to operate this physical system.

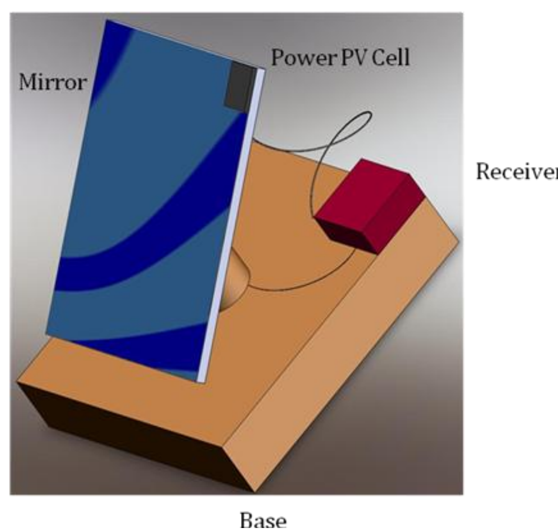


Figure L.1: Initial Prototype Sketch

Energy Control System

Our energy control system will consist of a small (approximate 1 ft^2) mirror, the driving mechanisms for this mirror, and the support structure necessary to secure and hold the mirror. This is shown in Figure L.1.

The most important part of this system is the mirror, since it is the component that will be redirecting all energy. We are going to benchmark several different mirrors, ranging from bathroom mirrors to solar mirrors, in order to benchmark their performance and cost. The results from these benchmarking tests will guide our mirror choice.

This mirror will be controlled by two stepper motors. These motors will both be mounted in the base of the system, with one controlling azimuth motion and the other controlling altitudinal motion. The motors will be powered by a solar cell mounted on the mirror, with the goal of keeping the system power self-contained. The solar cell will be chosen as the cheapest cell that has the capability to provide necessary power for system control. This cell will be attached to a battery, which will store energy and allow it to function in a variety of external conditions. We are currently focusing on 5V input stepper motors, which means that these solar cells must provide rated at greater than 5V.

The stepper motors will receive their input signals from the receiver mounted on the base of the system. This receiver will provide the coupling between our indoor sensing system and our outdoor mechanical system, and will also be powered by the solar cell mounted on the mirror.

Sensing and Control System

Our sensing and control system will consist of an array of solar panels, a control board, a room-light controller, and a transmitter. It may also contain a battery and/or amplifier if they are deemed necessary for energy management. A physical layout of this system is shown in Figure L.2, and a block diagram of the system is shown in Figure L.3.

Physical Description of Sensing System

The most important feature of our physical layout is the placement of the photovoltaic cell array (Figure L.2). These cells will convert incoming light into voltages. This layout must provide enough resolution to guide the motion of our motor, without involving excess cells. For our prototype, these cells will be mounted on the bottom

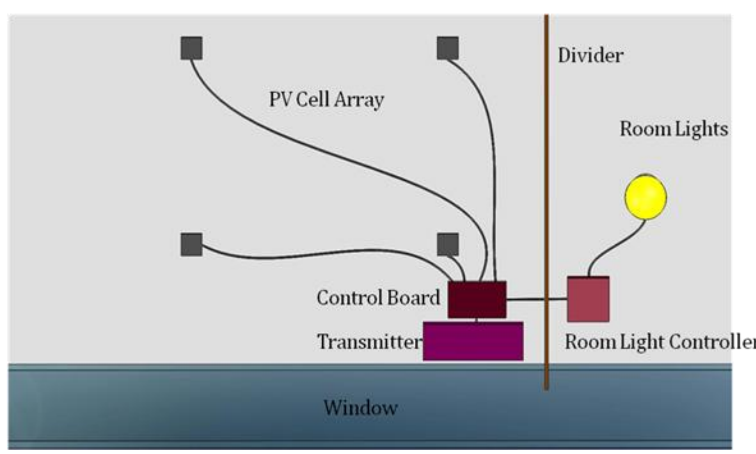


Figure L.2: Physical Layout of Sensory System

of a board representing the ceiling of the G.G. Brown atrium. They will be placed in a manner to scale all conditions of the atrium.

Placement of other components of the sensory equipment does not matter as much as that of the solar cells. It is important that the transmitter be placed near the window, so that we can use a transmitter requiring minimal power.

The other important physical aspect of this system is the room light. This will be a standard light bulb that will represent the lighting system of the atrium. This light bulb will allow us to prove that we can control indoor lighting with our control system, since controlling several lights will be only minimally more difficult than controlling one. In our prototype, this light will either be physically located far from our sensory equipment or we will create a divider between them. This will replicate the G.G. Brown atrium, since the lights in the atrium will be at the same level as our sensors and will be supplying little to no light to them. If this bulb provides light to our sensory equipment, it will provide a DC offset to the voltage that they read out which will not be seen in the atrium.

Block Diagram of Sensory Equipment

A block diagram of our sensory equipment provides much greater insight into the function of our sensory equipment than the physical diagram, so this section will describe the block diagram seen in Figure L.3. This diagram traces energy, in the form of signals and power, through our entire system. Outdoor equipment is relatively simple and has already been described, so this section will focus on the indoor system.

The input to our system will be light from the SolarFocus reflector. This light will be measured by the photo sensor array as described above. Our entire system will be controlled through manipulation of the voltages read by these sensors. For the following discussion, it will be helpful to assume that photovoltaic cells PV 1 and 2 are on the left side of the room (while PV 3 and 4 are on the right) and that PV 2 and 4 are located nearest the north-facing window (while PV 1 and 3 are further from the window). The suggested control method can be scaled to a larger area by simply including more cells in the photo sensor array.

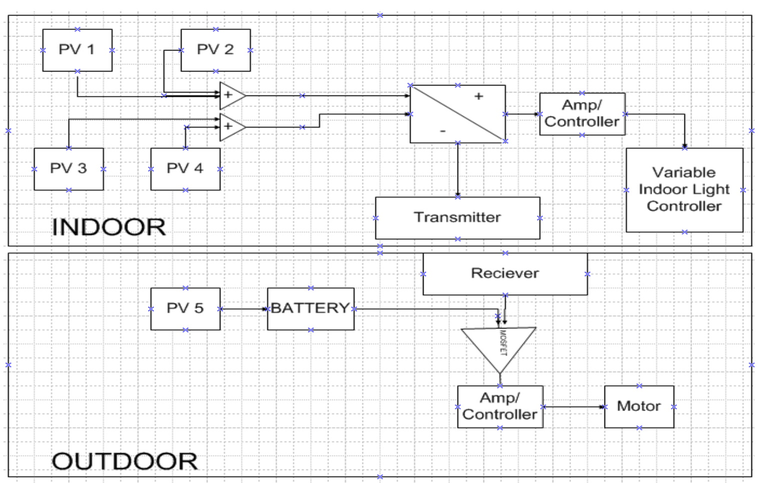


Figure L.3: Block Diagram of Prototype

In order to track the sun throughout the day, outputs from the left side of the room will be compared to outputs of the right side of the room, according to V(1) + V(2) – [V(3) + V(4)]. If the light, and therefore all energy, is centered correctly in the room, this will give an output voltage of zero. As light moves toward the right side of the room, an increasingly negative voltage will be created. This voltage will be fed to the transmitter and used to control the motion of our stepper motor. This will cause no motion when the output voltage is near zero, westward motion of the mirror when the voltage is greater than a reference voltage V_{ref}, and eastward motion when the voltage is below $-V_{ref}$. A similar method will be used to control the light in the north-south plane, except that this will be based on the equation V(2) + V(4) – [V(1) + V(3)].

In addition to finding the difference in light intensity in different areas of the room, our control board will sum all voltages, in order to gain a measure of the total amount of light entering the room from our system. This summed voltage will be used to control the in-room lighting system. We will use a store-bought variable light controller to control room lighting but, rather than requiring physical motion of the switch from the user, we will bypass the switch and use our signal to control the lighting output.

The final function that we would like to build into our sensory system is a reset option for the beginning of each day. The sun will set in the west each day (requiring a specific mirror angle), and will rise in the east the following day (requiring a very different angle). We are concerned that this angle will be too large for energy to be reflected onto the sensor array, rendering our system unable to find the room. We will use the voltage from PV 5 (located on the corner of the mirror) as a reference voltage to be compared to the summed voltage used to control the indoor lighting system. If V(5) exceeds the summed indoor voltages by a given amount, it will initiate a home function which will send the system clockwise until a voltage is read by the indoor sensors. This will give the system the capability to reorient itself each morning as the sun rises, without having to implement timers, clocks, or other forms of additional control.

Appendix M: Creation, validation, and discussion of simulation model

Creation of 3D Model

The initial 3D model of the G.G. Brown atrium with SolarFocus was constructed in Google Sketchup Pro 7. The model included not only the renovated G.G. Brown atrium (Figures M.1 and M.2), but also surrounding North Campus structures and geography. Many of the dimensions for the model were taken from provided architectural drawings while design details and lighting placements were inferred. These details were important for generating 'real-world' lighting analyses that included ambient effects such as surrounding building shadows, ground cover reflectivity, weather changes, and everyday operational use. This model was constructed with the intent to use a lighting analysis plug-in to perform all necessary analyses on the model. However, due to excessive technical obstacles with the plug-ins, this 3D model was unable to be used for the lighting simulation. Although these obstacles set back our progress significantly, we recognized that this model was still very valuable aesthetically (Figures M.1 and M.2). Throughout the semester, this model proved to be very useful as a visual for the renovated atrium equipped with SolarFocus.

Figure M.1: View of SolarFocus and Entire G.G. Brown Renovation Model

Figure M.2: View of G.G. Brown Atrium from Parking Lot

Simulation Validation Measurements

In order to investigate the reliability of the Radiance simulations, the lighting levels incident on the angled mirror in the simulation were taken at a specific time of year to be compared to known sunlight radiation data for Ann Arbor. The average light level on the mirror in the simulation at noon on April 15th under sunny sky conditions was 85,200 lux or 811.4 W/m^2. For the sake of comparison, this can be assumed constant over the noon hour of to give 811.4 Wh/m^2.

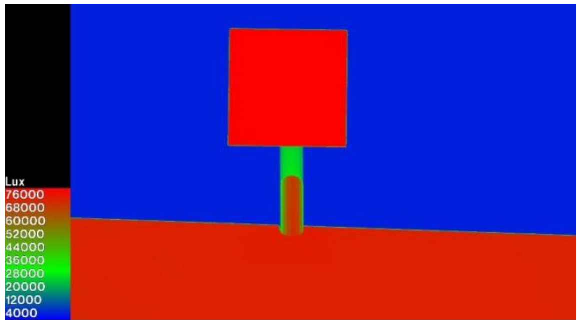


Figure M.3: Measurement of Lux Levels on Mirror and Ground

To validate these results, we combined accepted horizontal radiation with and geometry calculation that accounted for the set slant of the mirror at this time and date. The solar angles are already determined for each moment of the day, and data for April 15th at 12pm show that the θ_{alt}= 57.35° and θ_{az}= 0°. Although the average sunlight radiation is lower in April, for comparison to the lighting simulation, data from a sunny day was used. Horizontal light levels were converted to approximately 900 Wh/m^2, or 9kWh for the 10 m^2 mirror. Given these energy levels, and average angle data, efficiency of reflection was calculated as approximately 90%, or 8.1 kWh. This number then converts to 810 Wh/m^2 of energy on the mirror surface. This number clearly validates the 811.4 Wh/m^2 from the lighting simulation.

The efficiency calculations were the basis for validating the results of the lighting simulation. The solar angles are already determined for each moment of the day, and data for April 15th at 12pm show that the θ_{alt}= 57.35° and θ_{az}= 0°. Although the average sunlight radiation is lower in April, for comparison to the lighting simulation, data from a sunny day was used. Horizontal light levels were converted to approximately 900 Wh/m^2, or 9kWh for the 10 m^2 mirror. Given these energy levels, and average angle data, efficiency of reflection was calculated as approximately .90%, or 8.1 kWh. After reflection to the atrium, this will be decreased to approximately 7.05 kWh for the SolarFocus system. Converted back into lux the energy reflected will be 850,500 lux before window transmission, and 740,250 lux on the inside of the atrium.

Discussion of Validity of Lighting Simulation

The lighting simulation in Ecotect and Radiance proved very useful in determining the annual energy transfer, the size of reflection on the back wall of the atrium (and therefore the recommended size of the photosensor grid), and in validating the fly's eye error correction logic. As with any test, the outputs should be analyzed with common sense and compared with other known factors to confirm their validity.

The annual energy delivery of SolarFocus determined by Radiance was about 70% of the preliminary optics and radiation data calculations for our design. This discrepancy could be due to a variety of factors. First, it could be that the simulation is a more accurate representation of real life because it took into account light scattering, atmospheric conditions, and other ambient reflections and noise. This would simply mean that our initial energy calculations were idealized we should defer to the outputs of

Radiance for our energy calculations. This option was assumed because it is the more conservative energy savings estimate and seems to be more representative of real life.

Nevertheless, the possibility that the lighting simulation or post-simulation computations are less accurate than the initial estimates is not rejected. It is possible that the settings, simulations, or measurement methods in the lighting simulations were distorted. This can be checked by comparing the outputs of the simulation with known factors throughout the energy transfer analysis. As discussed above, the energy incident on the ground and on the mirror surface during simulations is comparable to accepted radiation data. The investigation can therefore move forward to the reflection of sunlight into G.G. Brown because we know that the discrepancy appears somewhere in between when the light is incident on the mirror to when the light is incident on the back wall of G.G. Brown (where the final energy values came from). However, due to the fact that the radiation levels can only be measured in Radiance where light is visible (therefore not in the space between SolarFocus and G.G. Brown, on the north windows, or inside of G.G. Brown before light hits the wall), the energy transfer between the mirror and the back wall cannot be further investigated.

The next step in the investigation of the discrepancy was to pinpoint any observed uncertainties in the analysis. The biggest observed uncertainty was the measurement of the reflection size on the back wall of G.G. Brown. This measurement was done manually by comparing the light reflection's length and width with distance markers on the back wall of the atrium. These measurements needed to be approximated at times because the light fades gradually around the border of the reflection. Additionally, the unique area of each simulation's reflection was not taken but instead an average of a few representative situations was used for all analyses. These uncertainties could have contributed to the discrepancy in the two energy transfer estimates.

The other noted uncertainty in the lighting simulations was that the lux levels on the reflection were not averaged by the program but instead had to be averaged manually by taking several representative values throughout the area of the reflection. This technique is not flawless and could have produced discrepancies.

In conclusion, although the lighting simulation in Radiance eventually produced exciting and promising results, our work with this program was not without pain and uneasiness. The program is still in its Beta version and therefore has various kinks and extreme rigidity. The majority of these obstacles have been discussed in this section, and because of them, the results should be accepted with discretion. Finally, because of the rigidity of the program, it is recommended that future lighting analyses be done under the guidance of an expert in whichever program is used.

Appendix N: Operating signal-to-noise ratio test

The second test, in addition to the aperture test, that our team created was an operating conditions test. Included below is our design of experiment and fabrication plan for this test. We completed fabrication of this test, but it was never fully run. The main reason for this is that, as mentioned before, the main result we were looking for from it was the operating signal-to-noise ratio of our system, and the aperture test proved that this will not be an issue. In addition to this, there were a few glitches in our control circuit. We were unable to isolate the exact problem, but one of our photosensors was not properly outputting a voltage to our system. This negatively affected any results which would have been produced because ambient noise was no longer being offset in the circuit creating the illusion that increasing ambient noise improved the operation of our system. We were still able to see that our circuit can take in voltages from photosensors and output signals to a stepper motor, so this result does not affect our confidence in our control system. However, because of the time that would have been necessary to find and correct this problem and the results of our aperture test, we decided that it was not necessary to run. Included below is the proposed design of experiment and the fabrication plan which we followed in creating the test.

Design of Experiment

- For each iteration, we will start with no external lighting, then gradually add light untl system no longer functions properly
- For each iteration, we will run once without apertures and once with apertures, recording the signal-to-noise ratio at failure of each

Test 1 – Basic setup

HOW

- Lights will be symmetrically distributed (left to right) around sensor array
- Start with no lights on, turn on one light on either side of sensor array
- Test
- Repeat until no longer functions, measure this signal-to-noise ratio, record this value
- Repeat with apertures mounted

WHY

- This test looks at the most basic performance of our system and will give a baseline of how well it can operate under very basic light pollution. It will also give a baseline of what kind of difference is seen when including the apertures on the sensors.

Test 2 – Asymmetrical lighting

HOW

- Place all lights on the left side of the sensor array

- Start with no lights on, turn on one light on either side of sensor array
- Test
- Repeat until no longer functions, measure this signal-to-noise ratio, record this value
- Repeat with apertures mounted

  WHY
- This test looks at the effect of having lighting distributed asymmetrically in a room. Some real life sources of this are having, more lights on one side of the room or more lights near one of the sensors, a cloud covering the sun reflecting onto one side our grid but not the other, etc. By putting ALL lights on one side, we are testing the most extreme case. It also gives us the opportunity to show that apertures negate the negative effects of asymmetrical lighting in a room.

Test 3 – Direct lighting

HOW

- Take one of the lamps (one that has a moveable, directional light) and shine directly onto the left sensor.
- Start with no lights on, turn on one light on either side of sensor array
- Test
- Repeat until no longer functions, measure this signal-to-noise ratio, record this value
- Repeat with apertures mounted

WHY

- This test also looks at asymmetrical lighting, but of a different nature than Test 2. The asymmetry will be much greater in this test, since a light will be pointed directly at one of the sensors. This test will simulate an upwardly directed lamp or the sun reflecting off of something other than the sun. This will look at the robustness of our design to intense lights other than the sun.

Appendix O: Fabrication plan

Fabrication

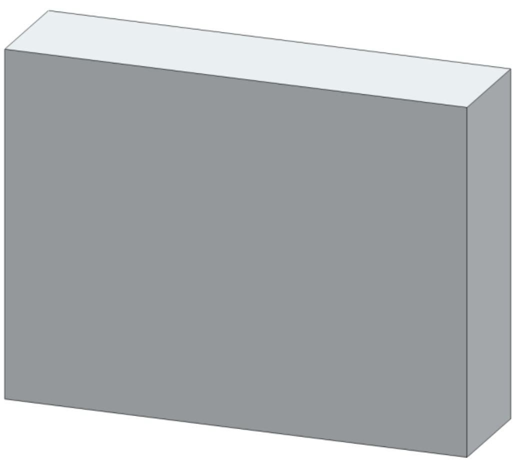
The test requires relatively little fabrication. We will drill holes for feet in the track, machine brackets out of blocks of aluminum, machine the attachment for the stepper motor, and machine the attachment from the motor to the penlight. The circuit will be soldered together.

Track

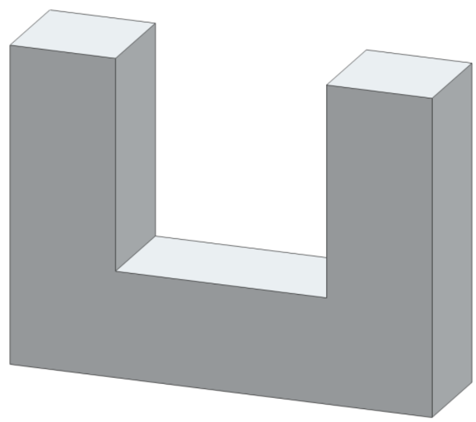
In order to make the track, the only fabrication necessary is drilling a hole 1" from either end. This hole will be 0.25" in diameter.

Brackets

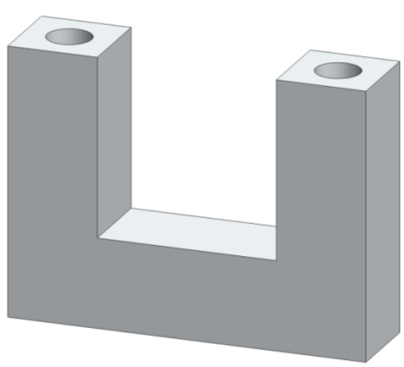
To connect the motor to the track, we will make two sliding brackets. Each of these will start as a 3/4" x 1/4" x 1" block of aluminum (Figure O.1a). The first operation that we will perform is creating a channel that is 1/2" deep and 1/2" across (Figure O.1b). This will be done using an end mill. We will then drill a 1/8" hole on either side of this channel, in the center of the remaining material (Figure O.1c).



(a)



(b)

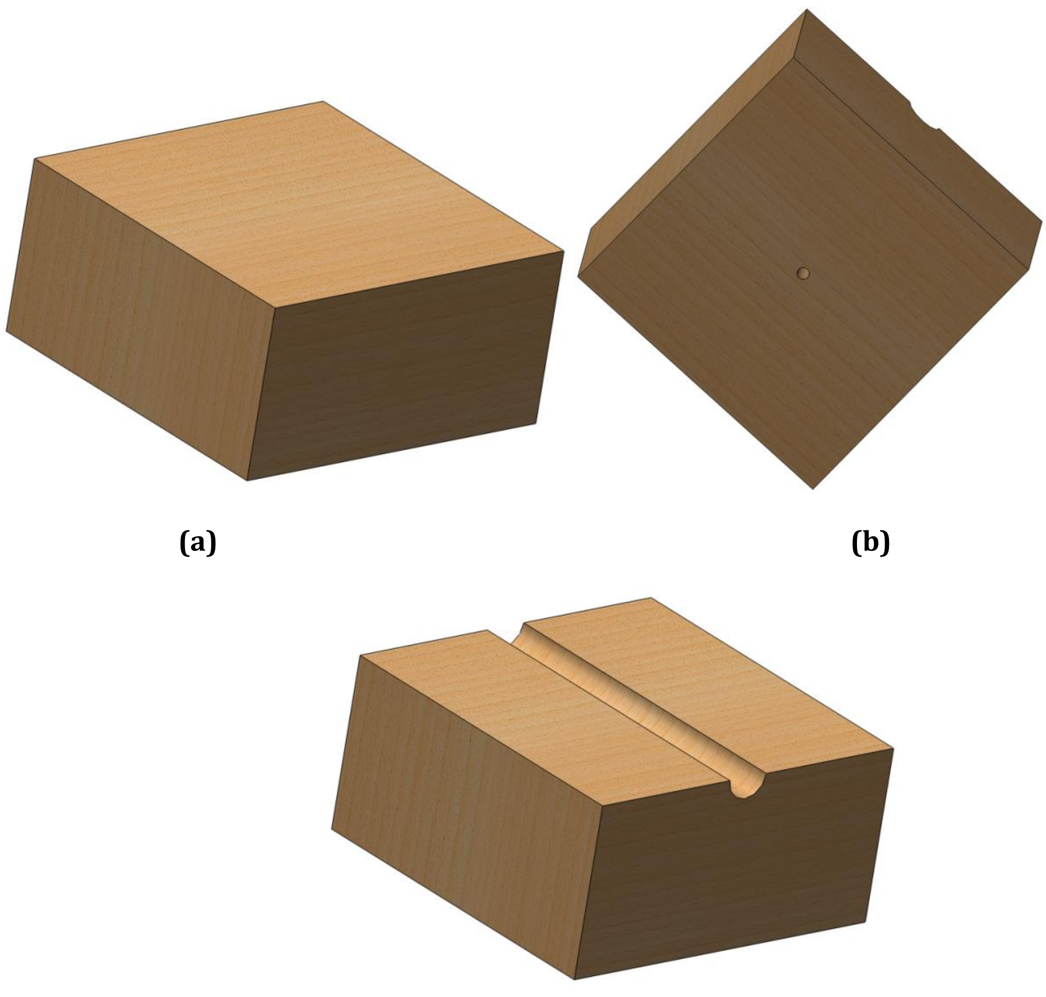


(c)

Figure O.1: Manufacturing of Brackets (a) Initial Block (b) Mill Channel (c) Drill Holes

Penlight mount

To connect the penlight to the motor, we will start with a 4” x 4” x 2’ block of balsa wood (Figure O.2a). We will drill a .0787” (2 mm) radius hole in the middle of the bottom (Figure O.2b), which can be press-fit onto the stepper motor. We will then rotate the block 90^{o} and machine out a 1/4” radius channel to contain the penlight (Figure O.2c).



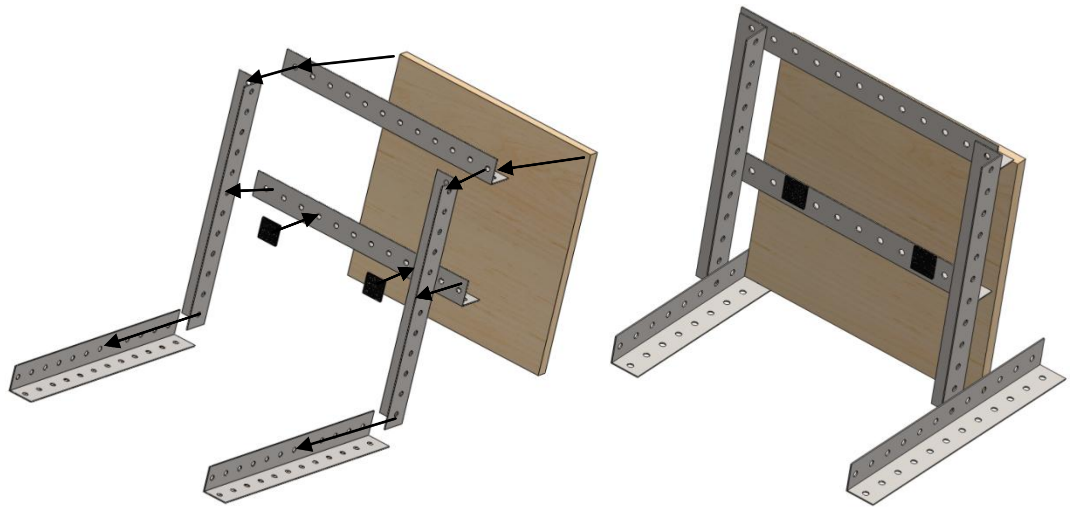
(a) (b)

(c)

Figure O.2: Manufacturing of Penlight Mount (a) Initial Block (b) Drill Hole (c) Mill Channel

Sensor Frame

The frame will be made entirely of 1’ lengths of angle iron, which we will create from the lengths of 6’ angle iron using a bandsaw. First, we will assemble the frame, which consists of three segments fixed at 90^{o} to each other. To this frame, two base segments will be attached, in a perpendicular plane. We will then add one more length of angle iron 4” off the ground, for photosensor attachment. Finally, we will screw a piece of plywood to the back of this frame, which will give added rigidity and will also provide a solid surface for measuring the amount of light hitting our photosensors. The rest of the fabrication is to assemble the various pieces, as seen in Figure O.3a, the sensor array is shown in Figure O.3b.



(a) (b)

Figure O.3: Assembly of Sensor Frame (a) Exploded View (b) Assembled View

Circuit

We will be assembling our circuit using all of the parts mentioned above. We will initially build our circuit on a breadboard in order to facilitate easy changes and troubleshooting.

Appendix P: Further fly's eye validation in Radiance

To validate the fly's eye, in the Radiance simulation we took lux level measurements on different sides of the mirror during different times of day and positions of the mirror. The goal was to measure the results of the photosensor grid "losing track" of the sun during a period of cloudiness or nighttime. This was done by aligning the mirror to reflect into the atrium at a certain time of day and measuring the lighting levels incident on both the surface of the mirror and the perpendicular edge (where the fly's eye sensors are located) of the mirror. If a period of no sunshine begins after this, the mirror would stop following the sun and stay in its current position. The next step was to simulate when the sunlight returns. In this case, when the sunlight returns the mirror would still be positioned to reflect from the sun's position before the period of cloudiness. By changing the time and not rotating the mirror accordingly, this will simulate the fly's eye light intake when the mirror is misaligned. At this setting, the lighting levels were taken on the surface of the mirror and the perpendicular edges. The comparison of light levels on the edge of the mirror between when the mirror is correctly aligned and when it is misaligned can help prove the fly's eye concept.

Appendix Q: Annual energy transfer

A primary purpose of the lighting simulation was to determine the energy transfer that SolarFocus could provide to the G.G. Brown atrium each year. This was done by simulating the varying weather conditions for Ann Arbor and measuring the lux levels reflected into G.G. Brown at specific points throughout the year. The detailed methodology of measuring the lux levels is given below.

1. In Ecotect, set the desired date and time and manually rotate the mirror so that the sunlight reflects into the set target grid on the atrium's back wall.
2. Set the weather conditions (cloudy, partly cloudy, and sunny) for the simulation and the desired camera views for lighting measurements.
3. Export current model to Radiance and render to generate lighting level measurements for each camera view.
4. Measure and record average lighting levels on the reflection on the atrium's back wall, subtracting the ambient average lighting levels in the atrium.

This process was repeated for 9 am, 12 pm, and 3 pm on the 15th of each month of the year and for each of the three types of weather conditions at these times. The size of the mirrors reflection on the back wall was also recorded. Once these data had been obtained by the simulation, the total energy transfer could be calculated through a series of steps, described below.

1. The lux level measurement for each of the three times of day at each weather condition was averaged to give a correctly weighted lux level for each weather condition.
2. This lux level measurement was then converted to watts/m^2 using the luminous efficacy of sunlight at 105 lux/(watt/m^2) [44].
3. The watt/m^2 was multiplied by the area of the light spot on the back wall to give the total weighted watt level for each weather condition of each month.
4. The next step was to combine weather data from the National Oceanic and Atmospheric Administration's (NOAA) weather archives with the representative power levels for each weather condition of each month [47]. The number of cloudy, partly cloudy, and sunny hours for each month, along with the number of total daylight hours for each month for Ann Arbor were used to determine the multiplier for each type of weather condition set in Ecotect for each month. For example, if there are 240 hours of sunlight, 90 hours of partly cloudy skies, and 70 hours of cloudy skies in September, then the weighted watt level for sunny skies received a multiplier of 240 to represent the watt-hours of sunny skies throughout the year. This was repeated for partly cloudy and cloudy skies for each month to give the total number of watt-hours of energy supplied by SolarFocus for the year.
5. The sun's spectrum data was used to determine the proportions of heat and light energy supplied to the atrium over the year. As mentioned above, sunlight emits 50% of its radiation in the infrared spectrum, 41% in the visible spectrum, and 9% ultraviolet spectrum, so 50% of the watt-hours go toward heating while 41% go toward lighting [28].
6. The energy offsets in heating and lighting could then be converted to monetary savings for G.G. Brown by multiplying by the price of natural gas and electricity for G.G. Brown.

Appendix R: Kelley Maynard Bio

I'm from Jackson, MI, where I lived my entire life before coming to U of M. I developed an interest in mechanical engineering based on its applicability to a variety of disciplines and purposes. I've also had an interest in human anatomy & physiology since high school, so I saw biomechanical engineering as an excellent way to further specialize my mechanical engineering degree. Next year I will be staying in Ann Arbor and entering the Master's program in biomedical engineering.

Over the past two years I've developed a strong interest in global health and I'm hoping to integrate that into my engineering career. Last year I studied public health in Argentina and discovered ways I could potentially combine these two areas. At U of M I am also involved in Engineering Global Leadership (EGL), the Tauber Institute, and M-HEAL. As an EGL student, I take classes in the B-school; I recently took a class on social entrepreneurship which inspired me to consider the business/sustainability aspects of efforts such as global health design. It's obvious that I have a broad variety of academic interests, but I do dream of combining as many of these as possible into my future career.

Appendix S: Justin Koehn Bio

Hello, my name is Justin Koehn. I was born in Kalamazoo, Michigan, and I grew up in Gobles, Michigan. My city is a really small farm area. I knew everyone in my graduating class, and mostly everyone in the city. My grandfather and dad are well known in the area because they are carpenters. I ended up graduating with 53 people, so coming to the University of Michigan was a big shock for a small town kid.

I am interested in Mechanical Engineering because of the wide range of futures it holds. I was really excited about working in a third world country developing/ designing health care items or just things to make other people's life better. I was thinking about working with Engineers with out Borders.

My future plans have changed now. I want to go on staff with my church in Ann Arbor, New Life Church. I want to become a pastor eventually, and be part of a church-planting team, possibly to Western Michigan University.

Some interesting facts about me: I want to become a basketball coach at some point in the future. My dad was a high school coach for many years, and I would love to follow in his footsteps. Another fun fact is that I used to be a part of 4-H. I showed steers at the state and county fair. It helped me a lot in paying for college.

Appendix T: Patrick Hughes Bio

I am from Muskegon, Michigan which is about 45 minutes west of Grand Rapids. Muskegon is right along Lake Michigan and has some of the best beaches in the state. I am planning on going to Honduras upon graduating, rather than trying to get a job here in the US. I will be helping to start a microfinance organization in the Lempira region, which is in the south of Honduras. I am not planning on doing engineering work after graduation due to excessive amounts of it during school. I am considering graduate school upon return from Honduras—possibly in business in the area of social entrepreneurship.

Appendix U: Katie Caruso Bio

Born in Chicago, my family moved to Minneapolis, MN where I developed an insatiable love for any and all winter and water sports! Through high school I was enrolled in French Immersion and am fully fluent; this also sparked a hunger for travel that I am constantly trying to fulfill. At Michigan I have enjoyed involvement in a broad range of community and engineering activities. I frequently walk dogs at the Humane Society of Huron Valley and one of my favorite experiences has been working with children at Motts Hospital to encourage and aide in their scholastic goals. I have also been heavily involved in developing a program for childhood education at the Ann Arbor Safe House.

I chose to study mechanical engineering because I think there’s an incredible potential for simple technologies to revolutionize the quality of life for people around the world. Working with BlueLab on campus has helped me to identify areas of particular interest and I’m looking forward to continuing efforts to bring a reliable, cost effective, source of water to low-income rural farming communities. The past four years have served as a strong educational starting point for future endeavors, and I’m excited to see what kind of impact I can make with my technical background. Clearly I have broad interests and have articulated that academically by pursuing a duel degree in Moral Philosophy.

I am very excited to return to Chicago this summer as a full time employee of BP Pipelines and Logistics.