Mechanical Engineering
CAL POLY

Mechanical Team Final Design Report

Same Polytechnic College

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Executive Summary

The purpose of this document is to communicate the research, findings, and recommendations of the mechanical engineering team regarding the Same Polytechnic College project. This report includes a discussion of the design process utilized by the interdisciplinary team to construct preliminary building designs for both classroom and dormitory building modules. The mechanical team conducted testing using the wind tunnel to verify major building envelope design decisions. The following report also includes an explanation of the thermal testing that the team conducted to measure the thermal conductivity, diffusivity, and specific heat of bricks made to mimic those made locally in Same, Tanzania. The test combines predictions made in EES, transient testing using thermocouples, calorimetry, and MATLAB. The report concludes with recommendations made by the mechanical team for future design implementations.

Document Summary

The mechanical engineering team focused on passive ventilation and thermal comfort studies for the Same Polytechnic College located in Same, Tanzania. The team aided in the initial concept design of both classroom and dormitory modules to be implemented on the campus. These preliminary designs can be seen in Appendix D. Once a preliminary design was determined, the mechanical students conducted several tests used to provide specific design recommendations to improve the thermal comfort of the modules.

The team focused on three major the categories. The first of which was a ventilation study of the dormitory module. A Plexiglas model was constructed of the current dormitory module and placed inside the Cal Poly wind tunnel at a scaled wind speed. The indoor air velocity in varying module locations and at varying building orientations was recorded. The results show that the large and small rooms are both receiving similar amounts of air flow. The indoor air velocity is maximized when the building in oriented with walls with less openings facing into the direction of prevailing wind. Further details on wind tunnel results can be seen in Chapter 7.

The next study conducted by the mechanical team was a building material test. Several material properties were determined including density, specific heat, thermal diffusivity and thermal conductivity. The calorimetry test result showed the test brick had a density of 1799 kg/m^3 and a specific heat capacity of 429 J/kgK. Both values were well below accepted values for typical structural brick. Using a numerical simulation along with a one-dimensional heat transfer test a thermal conductivity of 1.5 W/mK was determined. However, the validity of this value is in question since it is higher than the accepted value of 0.72 W/mK by a significant margin, which was not expected for a lower density material.

The final test category includes simulations of the module using DesignBuilder, a thermal modeling software. Several case studies were conducted by varying building material properties and building orientation. Further information on simulation results can be found in Chapter 7. Design recommendations for future iterations of the modules include applying white paint to the roofing material to limit solar heat gain, as well as including fans or other forced air systems whenever possible.

1.0 Introduction

Same Polytechnic College is a proposed vocational training institution in Same, Tanzania. The project was put forward to combat poverty levels in Tanzania by providing a sustainable method for improving the human condition through education. The project is a collaboration of Cal Poly-CAED, Arup, Arup Cause, Killefer-Flammang Architects (KFA), and The Mbesese Initiative for Sustainable Development (MISD). Preliminary designs for the college have been constructed by Cal Poly architecture, architectural engineering, civil engineering, electrical engineering, mechanical engineering students and professors with advising by the mentioned partnering institutions. The mechanical engineering team consists of students Katie Nute, Meghan Smith, and Long Hoang. The professors directly advising this team include: mechanical engineering professor Kim Shollenberger, architecture professor Thomas Fowler, and architectural engineering professor Kevin Dong. The goal of the mechanical engineering team is to design dormitory and classroom buildings to promote comfortable indoor conditions for future students and faculty at Same Polytechnic College. This report will provide details on the team's design process to select a final design for the dormitory and classroom buildings. Furthermore, this document will include information pertaining the manufacturing, testing and simulations, project budget, and analysis involved with assessing the designs' ability to achieve ideal indoor conditions.

2.0 Background

2.1 Customer Meetings and Interviews

In order to understand the project goals, the mechanical engineering team conducted numerous interviews and met with various members of the Same Polytechnic College team. The first meeting was held at the ARUP office in Los Angeles with a team comprised of professional engineers and architects, Thomas Fowler, Kevin Dong, and all relevant architecture, architectural engineering, civil engineering, electrical engineering, and mechanical engineering students from Cal Poly. Students were split into smaller interdisciplinary teams to learn and partake in the architecture design process. Preliminary sketches, plans, and models of dormitories, bathrooms, and classrooms were created throughout the workshop. Mechanical engineering students learned several design aspects to consider when constructing for a hot and humid climate as well as several customer requirements. Following the initial meeting at ARUP, the mechanical engineering students and their respective design teams met roughly two times a week until December 2017. Team members who traveled to Tanzania helped groups to incorporate Tanzanian culture into building designs by sharing valuable experience. Students decided that local resources and materials would be used to construct the buildings. As a result, material selection was limited based on what is available and commonly used in the area. Multiple phone interviews were conducted with representatives from The Mbesese Initiative for Sustainable Development to better understand how to design for the local community. For effective interactions between the user and building, the interviewees emphasized avoiding complex designs and features unfamiliar to locals. HVAC systems for buildings are uncommon in the area and were determined to be impractical because of issues regarding power outages and maintenance. Implementing HVAC systems increases the demand for electricity and can contribute to the pre-existing issue of frequent power outages. Furthermore, if a unit breaks down, the nearest technician may be further than six hours away by car and it can take months to schedule a time to repair the unit. As a result, passive ventilation was selected for cooling and circulation instead of HVAC systems. Ceiling fans are common in the area and will be used in addition to passive ventilation to provide sufficient ventilation and cooling effects. Meetings with Dr. Shollenberger were scheduled in order to discuss approaches to modeling ventilation and thermal gains. The analysis of heat gain and ventilation can be complex because there are multiple factors to consider and the elements are transient. Using software tools can be more efficient and yield better results compared to analysis by hand. Alternate strategies, such as utilizing building thermal massing or using ceiling fans, were considered and pursued when passive ventilation was determined insufficient to provide comfortable indoor conditions.

2.2 Precedence

In order to better understand both vernacular Tanzanian architecture and natural ventilation methods, several case studies were conducted on precedence architecture in central and Eastern Africa. The first case study, shown in Figures 1 and 2, is the Chipakata Children's Academy located in Zambia. This campus utilizes an elevated mono-sloped roof, louvered openings, and perforated walls. These elements all act as ventilation openings that were optimized based on the size of the internal space to provide adequate airflow. As a rule of thumb, buildings should be designed with a ventilation openings area greater than or equal to 5% of the gross internal floor area. Further discussion of natural ventilation analysis can be found in Section 5.2.

Figure 1. Chipakata Children's Academy [2].

Figure 2. Chipakata Children's Academy Layout [2].

The Francis Kéré Designs Education Campus, located in Kenya, gives more insight into established campus layouts. Building orientation plays an important role in passive ventilation and was optimized while still maintaining a logical campus layout. Wind driven ventilation is maximized when the longest axis of a building is perpendicular to the direction of the prevailing wind. The overhanging roof, seen in Figures 3 and 4, serves an important purpose as well. Shading all envelope openings especially on eastern and western facing walls was critical in a successful design.

Figure 3. Francis Kéré Designs Education Campus [3].

Figure 4. Francis Kéré Designs Education Classrooms [3].

The remaining case studies are smaller projects that helped lead the module design for dormitories and classrooms. The KWIECO Shelter House in Tanzania, as seen in Figure 5, is one example of a possible dormitory solution. The design includes covered walkways for increased shading and a metal mono-sloped roof. This building is also feasible to construct. The Same Polytechnic College will be easily constructed using local labor and resources. This criteria eliminated several construction methods such as concrete construction due to the lack of local skilled laborers. The use of reinforced masonry is seen throughout eastern Africa and was selected as a strong, low cost solution. Further information on material selection can be found in section 5.4. All building materials were thoroughly investigated for structural and thermal properties, more information on future testing pertaining to building materials can be found in Chapter 7 of this report.

Figure 5. The KWIECO Shelter House [4].

The Legson Kayira Community Center and Primary School in Malawi, shown in Figure 6, is an example of a classroom module. The center uses large trusses to provide openings for ventilation between the wall line and roof. This concept has been central in several preliminary designs at the architecture studio level. The use of double skin roof also provides a reduced heat transfer rate and maintain a cooler indoor air temperature.

Figure 6. The Legson Kayira Community Center & School [5].

The precedence investigation helped the mechanical team to determine what worked well in previous projects and inspired a design by streamlining the design process.

2.3 Summary of Technical Literature

The "Natural Ventilation Guidelines" slides presented by Salman Ilyas on September 23, 2017 at Arup contain information about potential barriers to natural ventilation. Climate, local topography, microclimates, building aesthetics, solar control, acoustics, air quality, and security are factors to consider when designing a building for natural ventilation. Problems that were addressed are thermal comfort, stagnant areas where air movement is minimal, odors and pollutants, overheating, and intrusive noise.

"Natural Ventilation of Buildings Theory, Measurement, and Design" by David Ethridge discusses topics such as the physical process of natural ventilation, various models to capture behaviors in natural ventilation, indoor quality standards, scale modeling, and the designing of features to facilitate natural ventilation [7]. Ethridge emphasizes the importance of control and predictability when designing a natural ventilation system. To design a system with a fair amount of control and predictability, governing equations for conservation of mass, momentum, and energy, and simplifying assumptions are used to form models to illustrate system behaviors. CoolVent, a natural ventilation simulator developed by MIT, applies these conservation laws assuming discrete "zones" that can be defined as "lumped parameters" to model and understand natural ventilation. "CoolVent: A Multizone Airflow and Thermal Analysis Simulator for Natural Ventilation in Buildings" by Maria-Alejandra Menchaca-B. & Leon Glicksman instructs users on how to use the CoolVent simulator as well as the fundamentals behind how the simulator works. It can determine natural ventilation flow rates and internal temperatures. This tool was used along with more detailed simulations and experimental measurements to verify models and assumptions. By deriving consistent model results from different methods the mechanical team increased confidence in the design and process.

DesignBuilder, an advanced modelling software that helps to develop energy-efficient buildings, was used to carry out natural ventilation and thermal load analysis. More information about simulation testing can be found in Section 7.2.

Although natural ventilation is sustainable, relevant disadvantages of natural ventilation include limited effect for cooling in hot and humid climates. As a result, the hierarchy of ventilation systems was considered to find alternate solutions and approaches to meet standards and specifications. The hierarchy begins at natural ventilation alone then moves towards using natural ventilation with local mechanical devices for internal flow. Mixed mode systems and air conditioning systems are at the bottom of the hierarchy and were not utilized in this project.

Thermal influences introduced by the sun were considered when designing the modules to meet acceptable standards. "Solar Engineering of Thermal Processes" by John A. Duffie & William A. Beckman was referenced to determine loads onto the building by the sun [8]. Shading structures were implemented to control sun exposure on the building envelope. The shadows cast by the sun and the duration of light is dependent of the time of the year and location. These relations are discussed by Duffie and Beckman along with additional design suggestions when considering the effects of the sun.

"Under the Acacia: The Same Polytechnic College Master Plan" is documentation provided by The Mbesese Initiative which goes into details about the development of the project, anticipated goals, planning principles, and the supporting infrastructure required to meet these goals [1]. Recommended passive and climate responsive design strategies are discussed on page 243-261 in the document. Natural ventilation is categorized into two types: wind driven ventilation and buoyancy driven ventilation. Wind driven ventilation systems include cross and single-sided ventilation. Zones of positive and negative pressures are induced by winds on the building. As a result, air naturally flows through this area to reduce the pressure differences. Buoyancy driven ventilation occurs from temperature differences in the air that are caused by the stack effect of natural stratification. Hot air rises and leaves through high openings and reduces the pressure near the ground to draw cooler air through openings. Important design considerations when implementing either types of natural ventilation are building form and dimensions, building orientation, open floor plans, ventilation openings, double skin or insulated roofs, sun-shading, thermal mass, daylighting, and ceiling fans. Open floor plans were also used to ensure sufficient air movement through the interior space. It is ideal to design the interior to promote air circulation by reducing resistance of flow due to obstructive objects. Thermal mass is utilized to moderate the internal temperatures of the building by having dense materials act as thermal sinks and storing the heat energy instead of passing it on to adjacent areas.

Building clusters were considered in the project. "Spacing of Buildings for Natural Ventilation" by P.V. Krishnan considers relative distances between each building unit to make sure that there is adequate room for natural ventilation. There is an optimal and a minimum for spacing to allow for natural ventilation. The length of the eddy is key in determining whether or not adjacent buildings receive the effective winds to have natural ventilation. A graph from experimental data is presented to determine the length of the eddy as a function of building height and length. The results are used to obtain an estimation of how separated each unit should be in order to meet minimum standards for natural ventilation.

2.4 Codes, Standards and Regulations

ASHRAE Standard 55 was used as the design standard for this project. Each building was evaluated to confirm it is in the adequate thermal comfort range. Thermal comfort is defined as the state of mind that expresses satisfaction with the thermal environment. Metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity are six key factors that must be considered when defining conditions for thermal comfort. These factors are individually defined by ASHRAE and can be seen in Table 1.

Table 1. ASHRAE definitions of the six factors that are considered when defining thermal comfort.

Term	Definition
Metabolic rate	The rate of transformation of chemical energy into heat and mechanical work by metabolic activities in an organism; expressed in met units
Clothing insulation	Heat transfer from the whole body and includes uncovered parts of the body
Air Temperature	The temperature of air surrounding the occupant
(Mean) Radiant Temperature	Uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space.
Air Speed	The rate of air movement at a point, without regard to direction
(Relative) Humidity	Ratio of the partial pressure of the water vapor in the air to the saturation pressure of water vapor at the same temperature and the same total pressure

Various methods for determining acceptable thermal conditions in occupied spaces are listed in ASHRAE Standard 55. The designed system must meet appropriate conditions in order to use any of the models and methods listed in this document to determine the range of thermal comfort. The comfortable indoor temperature range, shown in Figure 7, is dependent on humidity level. In order to comply with ASHRAE Standard 55 the indoor temperature must fall within the shaded area for a given humidity level.

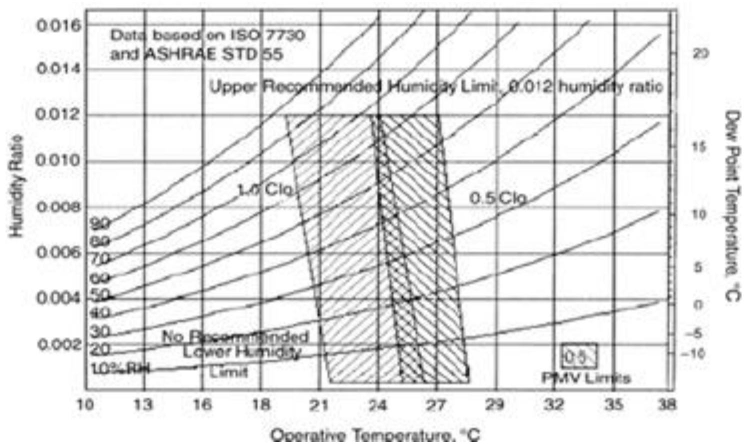

Figure 7. ASHRAE Standard 55 for Indoor Comfort.

3.0 Objective
3.1 Problem Statement

A collective group of Government personnel, college professors, graduate and undergraduate students, and an independent architecture firm are working together to design a polytechnic college in order to close the education gap and reduce poverty in Tanzania. Future students and faculty members of Same Polytechnic College need a campus designed to promote comfortable interior conditions which can be implemented feasibly with local resources. Due to a hot and humid climate, thermal comfort through passive ventilation must be optimized for a successful campus design. The mechanical engineering team focused on the elements of the module that most directly impact thermal comfort. These include envelope openings, shading, thermal massing, and building orientation. The design of these elements was heavily influenced by material availability, cost, required maintenance, and local culture. The mechanical team then validated the chosen design elements through physical thermal testing and wind tunnel testing, as well as computer modelling.

3.2 Boundary Diagram

Figure 8 demonstrates a sketch of the project scope as a boundary diagram. The figure includes the customer as a Tanzanian student. Within the scope are the building opening sizes, the roof slope and type of roof, the building materials, and temperature studies to verify the success of the implemented methods. Customer needs include comfortable indoor conditions in consideration with humidity, temperature, and adequate ventilation. The design for the project also must be low cost and low maintenance.

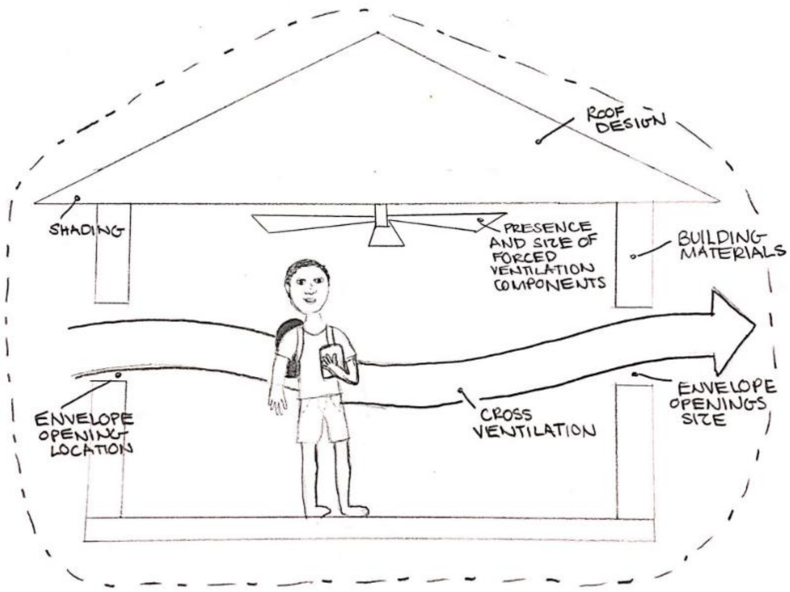

Figure 8. Boundary diagram of mechanical scope.

3.3 Quality Function Deployment

A Quality Function Deployment table was used to determine the engineering specifications for the project. The QFD table was constructed by first listing all of the customers and their respective needs and wants. The team had a brainstorming session in order to establish which needs and wants were crucial to the project. These criteria were then ranked based on their importance to each customer. In order to find the ranked importance of each specification per each customer's opinion, interviews were conducted individually with each customer. Next, a list of measurements was constructed i.e. indoor air temperature and indoor air change rate. These measurements were first established by a brainstorming session. Then in each customer interview, the team asked the customer's what their impressions were of the most important specifications for the design. The team cross-checked specifications and discussed each specification with the customer, deciding on a primary list of specifications. Then the team assigned a correlation value of low medium or high to each customer requirement. Finally, a value was assigned to each measurement discerning what value needs to be achieved to qualify a success. The QFD for this project can be found in Appendix A.

3.4 Engineering Specifications

A summary of the established specifications from the QFD table can be seen in Table 2. The specifications were established as a means of a list of measurable standards to achieve through the design. The specifications are also an important reference as a communication tool between the team and customers. The team wanted to ensure that each standard that is important to each of the customers was met and analyzed.

The average indoor temperature of each of the modules was analyzed via DesignBuilder. The outputs from DesignBuilder were compared to ASHRAE STD 55 (see Figure 7) to ensure a safe and comfortable indoor air temperature was met in each unit. However, ASHRAE STD 55 is a very conservative estimate for the comfort level of Tanzanians. Tanzanians have a lower metabolic rate and are more acclimated to hot and humid temperatures. Therefore, the shaded area regarding operative temperature from ASHRAE STD 55 is shifted up and to the right, to account for the difference in comfort level. Achieving this specification was particularly ambitious to this project due to the climate extremes of Tanzania.

The internationally applicable ASHRAE 55 standard is originally based on heat balance model and data obtained from experiments conducted in climate chambers. However, it has emerged from many field studies that the standard cannot predict the thermal comfort responses in many real world settings. "Indoor environment and adaptive thermal comfort models in residential buildings in Tianjin, China" presents results from a six-month field study about indoor thermal environment and adaptive behaviors in 43 residential buildings in Tianjin [6]. The study discusses the specific application of the indoor thermal environment of naturally ventilated buildings. In office buildings, occupants' activities are fairly well defined and invariant while their control over the indoor environment is somewhat restricted. In contrast, occupants in their own home have a vastly enlarged palette of adaptive comfort opportunities such as turning on/off AC, opening windows or doors for comfort ventilation, and changing their clothing insulation across a wider range. Meanwhile, occupants' activities in the various rooms of their home tend to be much more diverse in terms of met rate. Conclusions of the study implied that the sample of Tianjin residential building occupants were less sensitive to indoor temperature than office workers, which implies that Tianjin residents were more thermally adaptable. Furthermore, home occupants in Tianjin were found to be less sensitive to indoor air temperature variations, compared to office occupants. The temperature zone for acceptability ≥ 80% is between 21.0°C. This study supports the decision to shift the ASHRAE STD 55 specifications for thermal comfort for the Same Polytechnic College to the right in Figure 7.

The average indoor air change rate was analyzed in CoolVent. The specification of 10 Liters/ Second/ Person is a general safety standard from "*Natural Ventilation of Buildings Theory, Measurement, and Design*" [7]. It was necessary to provide sufficient outdoor air to dilute and remove indoor generated pollutants. Given that the Tanzanian climate is very humid, this specification must be met because the buildings must be properly ventilated in order to effectively protect against fungus.

The average indoor air velocity for comfort given by Salman Ilyas is 1-1.2 m/s. This is considered to be a slight draft of wind and is most comfortable for occupants. Since the indoor air velocity was found to be less than this standard, ceiling fans are necessary. Considering that the climate is hot and the average wind speed in Tanzania is 5 mph, which is very low, ceiling fans will be used in each room. Testing in the wind tunnel was completed to test air velocities inside versus outside the building. The tests gave results that the dormitory building design was successfully ventilated due to the window openings and ventilation holes. More information on preliminary testing can be found in Section 4.3.

Since the mechanical team used primarily envelope design, building material, and building orientation to provide passive ventilation, there is no specific costs associated with these functions. The goal was to design the ventilation to be as feasibly inexpensive as possible. The costs are measured as a cost-benefit analysis. For example, it is not ideal to have glass windows because of a high cost, however prototype tests will be completed in Phase 1 of construction to test if it may be necessary to have glass windows to maintain thermal comfort. If the design cannot be successful without glass windows, then they will be implemented. If glass windows will not be installed, then the only way to combat insects and the threat of associated infections is to seal window and door openings with mesh screens made of stainless steel or plastic.

In continuation with keeping the building costs low and in order to have materials that are blendable within the community, the building materials are to be retrieved within a 500 mile radius. Because the climate is hot and humid, there are major problems for materials and construction including swelling of organic materials and corrosion of metals. Materials must also have high thermal mass in order to absorb, store and release heat. Figure 9 shows common building materials in Tanzania.

Figure 9. Common building materials in Tanzania

Specifications 6, 7 and 8 from Table 2 were introduced by Salman Llyas, a professional mechanical engineer from ARUP. Due to a hot and sunny climate, the mechanical engineering team designed to reduce solar gains within the buildings. Avoiding direct solar gain is important, because it is the simplest and least costly way of passively controlling the temperature of a building. Sunlight can heat a space through the solid walls or roofs of the envelope. Sunlight also enters the space through windows, and heats interior surfaces. Aperture placement and area is an enormous factor in the amount of heat that is gained, so the team controlled these factors to keep solar gain less than 4 Watts/ ft^2 of wall area. Analysis was performed via DesignBuilder.

Additionally, the team designed the module to control the amount of internal loads to be less than 2 Watts/ ft^2 of floor area. Lighting and electrical appliances, such as chargers and laptops, all consume energy in the form of either electricity or fuel. People also generate heat based on their metabolic rate. All of these things are important in order to understand and optimize for high performance building design, and are important inputs for whole building energy analysis simulation. DesignBuilder has specific inputs for analyzing internal loads, such as wattage per light bulb, how many light bulbs per room, how many people per square foot in a space, and what that person's metabolic rate may be. However, electrical appliance specifics are designated to the electrical engineering team on the project.

Daylighting was also controlled by the mechanical engineering team through window placement and size, as well as the building orientation. 100-2,000 logs of daylight should be captured for a person to be able to comfortably read a book. This specification was also analyzed in DesignBuilder.

Table 2. Engineering specifications, risks, and methods for compliance pertaining to the scope of the mechanical team. The risk standards are: High (H), Medium (M), and Low (L). The compliance methods are: Analysis (A), Test (T), Similarity to Existing Designs (S), and Inspection (I).

Spec. #	Parameter	Requirement	Risk	Compliance
1	Average Indoor Air Temp.	Within comfort zone, ASHRAE STD 55	H	A, T
2	Average Indoor Air Change Rate	10 Liters/ Second/ Person	M	A
3	Average Indoor Air Velocity	1-1.2 m/s	M	T
4	System Cost	Cost-Benefit Analysis	H	A
5	Material Distance Traveled	Within 500 mile Radius	L	A, I
6	Solar Gain	< 4Watts/ ft^2 wall	M	A, T
7	Internal Loads	< 2 Watts/ ft^2 floor area	L	A, S
8	Daylighting	100-2,000 logs	L	A

Further details on the team's failure mode analysis that pertains to the above specifications can be found in Appendix I.

4.0 Concept Design Development
4.1 Design Process

The dormitory and classroom module concepts were developed by organized interdisciplinary teams. This process began with two smaller teams assigned to each module type with the mechanical engineering students distributed to multiple teams. Long Hoang worked on the classroom design team, Katie Nute worked with the first dormitory design team, and Meghan Smith with the second dormitory team. This allowed for mechanical students to be involved in the early development of both modules types. After several weeks working in four separate teams, the teams focusing on dormitories merged together, as did the two teams focusing on classrooms. The teams combined their best aspects from each design to make a third concept design. The larger teams then spent several weeks diving into deeper design considerations. The mechanical engineering students were then able to spend more time testing the final module to give more specific feedback to their teams about design decisions such as envelope openings and building orientation. Preliminary tests included passive ventilation testing using scaled plexiglass model and the Fluid Mechanics Laboratory wind tunnel. Basic simulations were also done using CoolVent, a natural ventilation modeling software.

4.2 Concept Models: Dormitory Design Module

The dormitory concept teams made several decisions early on in the design process. The module would be one story high due to limited skilled labor available for structural components and to fit in with local buildings. The design would include plenty of shaded common areas to address the cultural tradition of spending free time outdoors. The building material will be masonry because of its local availability and thermal performance. The masonry used in Tanzania is locally produced and varies greatly from products found in the United States in both is structural and thermal properties. For this reason, mechanical engineering students tested imitations of these Tanzania bricks manufactured at Cal Poly by an Architectural Engineering graduate student to assess and quantify its thermal properties and differences. More information on the test for thermal property of the bricks can be found in Chapter 5.

Below are the dormitory concept models developed in chronological order. The models were produced at quarter scale to allow for fast iterations. The first model, shown in Figure 10, was initially created by the smaller dormitory team which includes mechanical engineering student Katie Nute. The team's second iteration, shown in Figure 11, includes a refined roof structure and implements trusses to provide load support. The envelope openings were sized and placed to allow for crossflow passive ventilation.

Figure 10. Dormitory Module, first iteration.

Figure 11. Dormitory Module, second iteration.

The dormitory model shown in Figure 12 was conceptualized by the second dormitory design team. This group included mechanical engineering student Meghan Smith. This design implements a long pathway between two separate dormitory buildings under one shared roof. Openings are included to allow for stacked ventilation by utilizing buoyancy forces of hot air with a low-level inlet and high-level outlets. These two dormitory design teams later merged their ideas to produce the model shown Figure 13. The long hallway originally included in the design shown in Figure 12 was not incorporated into the next design iteration because it breaks the building spacing rule of thumb and would hinder adequate passive ventilation through both structures. The next concept created by the merged dormitory group includes two staggered units with a common area between them. Windows are placed along the module's longest axis and directed towards the prevailing wind. A raised roof design was originally proposed to facilitate passive ventilation and diverge loads away from weak masonry walls. Preliminary wind tunnel tests were conducted to determine the effect of altering building orientations relative to the prevailing wind on the air flow through various areas of the modules. Additional information on preliminary testing can be found in section 4.3.

Figure 12. Dormitory Module produced by Team 2.

Figure 13. Dormitory Module Merged Concept.

Concept Models: Classroom Design Module

The team designing the classroom modules addressed similar concerns highlighted by the dormitory team in the development of their module. Additional observations were made about the module's role in harvesting rainwater and solar power. The classroom module utilizes a mono-sloped roof to ease the task of water collection off the roof. Water will be captured and piped into tanks adjacent to the bathrooms to be filtered and used in toilets, sinks, and showers. Buffer zones are established between bathrooms and classroom in order to reduce the potential for air contamination due to winds traveling from the bathroom to the classrooms. The tilt of the roof is designed to be four degrees to optimize the efficiency of any solar panels placed on the roof of the module.

The classroom module is designed to seat thirty students and provide office space for faculty members. The following images showcase the iterative concepts that were considered in the process of designing the classroom module. The initial design in Figure 14 includes a large classroom with offices attached to the sides. It incorporates storage spaces shown in red to act as acoustic buffers between the offices and classrooms. The storage spaces were removed from later designs because it was determined that it would not be an efficient use of space in a developing nation with relatively little supplies and equipment.

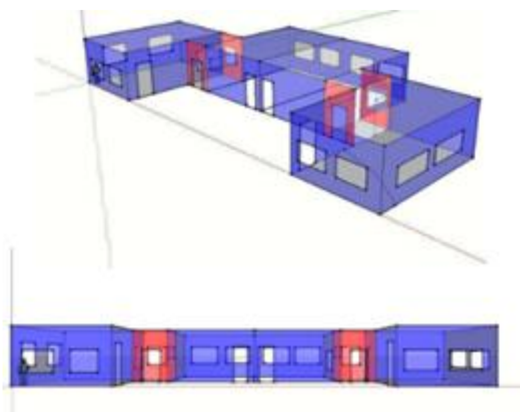

Figure 14. Initial Classroom Module Concept.

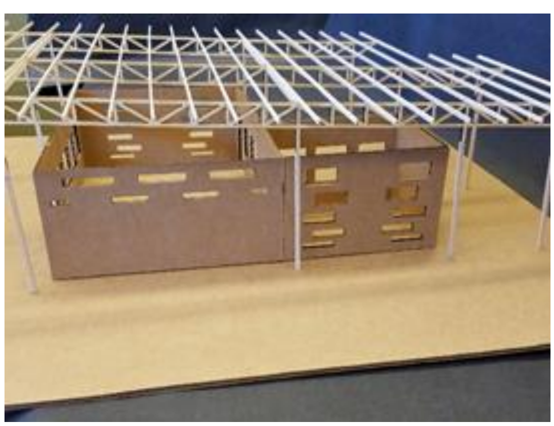

Figure 15. Merged Classroom Concept.

The merged concept shown in Figure 15, reflects a later iteration of the classroom module design. This module includes one classroom to seat thirty students and one office to be shared by two faculty members. Structural members are included in this iteration to support the roof and avoid structural failure in the non-load bearing walls. The classroom team used perforations in the walls as an architectural feature to encourage passive ventilation.

4.3 Preliminary Testing

In order to validate the design decisions made by each team pertaining to passive ventilation, a preliminary ventilation test was conducted. The mechanical engineering students produced a scale model of the dormitory unit out of Plexiglas to be tested in the Mechanical Engineering Department's wind tunnel. In order to get accurate data, the model was scaled by relating Reynold's numbers. As long as the Reynolds number of the model is equal to that of the actual building to be implemented the results are valid.

$$Re_{model} = Re_{actual}$$

$$\frac{U_m L_m}{\nu_m} = \frac{U_a L_a}{\nu_a}$$

The fluid being measured in both the testing and application would be air, meaning that the kinematic viscosity, remains constant. Therefore, the model was scaled by keeping the products of wind velocity and wall length equal. The scale of the model was 1:48 or one foot to a quarter of an inch. Using this scale, the students were able to test an actual wind speed of 2 mph using a wind tunnel speed of 96 mph. Plexiglas was selected to allow for future visual flow when testing using yarn or dry ice to visualize flow patterns throw the module and identify dead zones. The model used for wind tunnel testing is shown in Figures 16 and 17 below.

Figure 16. Wind Tunnel Model without Roof.

Figure 17. Wind Tunnel Model with Roof.

Figure 16 shows the dormitory model constructed without a roof. This model was used to simulate the large gap between the tops of the module walls and the roof. Figure 17 shows the module with an attached roof. Both modules were tested to find the indoor air velocities, and then compared in order to aid in the design decision of removing the roof gap. The results from several tests showed that the internal air velocity was on average 22% of the outdoor air velocity with the given window arrangement. When the model was placed with the window openings at a 45-degree angle to prevailing wind, only 33% of the indoor air velocity was maintained from the straight orientation. Finally, the indoor air speed in the longer four-person room was 66% of the speed in the smaller two-person room. The results validated the design decisions of facing envelope openings directly into the prevailing wind, keeping room dimensions square wherever possible, and providing a large surface area of openings and vents. However, results contained wide variations and further testing with a refined model is required. The refined model limits roof openings to those deemed necessary to insert the Pitot tube and record measurement. The new model was constructed with the help of graduate student Justine Neves using laser cut Plexiglas. Results of secondary wind tunnel testing is included in the design verification plan in Chapter 7, Section 3. Budget information on the cost of preliminary test models can be found in Appendix G.

4.4 Selected Concepts

The selected modules were chosen for their mechanical, structural, and architectural features. A Revit rendering of the selected dormitory module can be seen below in Figure 18. Each building houses six students totaling twelve students per unit. These modules are intended to be repeated to form dormitory clusters around campus. The module has a closed roof, instead of the gap seen in the previous iteration. The primary envelope openings faces northwest and southeast in order to maximize passive ventilation as deemed necessary by wind tunnel testing. The ceiling was added to ease pest control and provide residents with some additional privacy.

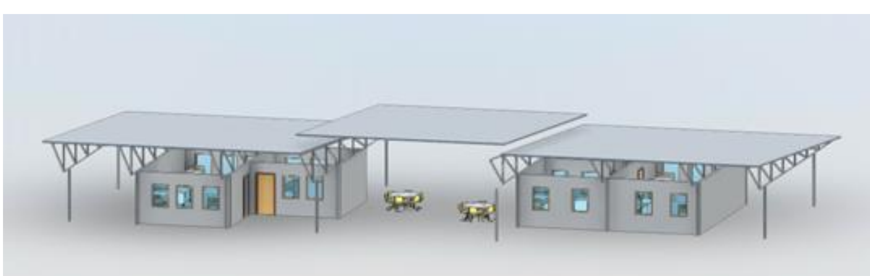

Figure 18. Revit Rendering of Selected Dormitory Module.

The final selected classroom concept can be seen in the rendering below in Figure 19. The module includes locally-inspired perforation patterns used for ventilation and daylighting. The orientation of the classroom and office modules will vary depending on the location on the campus. The structure of the module will remain the same, but the locations of perforations and window openings will change depending on the orientation to ensure conditions for natural ventilation.

Figure 19. Revit Rendering of Selected Classroom Module.

The current designs do have some associated risks. The safety of the occupants is a primary concern and will be later addressed in section 5.3. There are also several unknowns that could impact the success of the design. The cost of materials is a major unknown in our design. In Same, labor is much cheaper than materials, so it is fairly typical for things to be built on site. It can also be very difficult to transport selected materials.

Another unknown variable is the exact weather information at our site. The nearest weather tower with accessible data is approximately fifty miles away. Therefore, wind conditions at the building site could vary from values used to calculate passive ventilation. This also affects computer simulations which rely on accurate weather data. However, the mechanical team made simplifying assumptions to design for the worst possible conditions that may occur such that the structure will not fail under extremes.

5.0 Final Design

5.1 Functional Description

The final design of the Same Polytechnic College includes dormitory and classroom modules to house students and faculty and to create a conducive learning environment. A driving feature for the design is the level of simplicity needed for construction in Same because the local labor skill level is very low. Additionally, the local building masonry is heavy and structurally weak, so the building walls cannot function as supporting walls. Building materials must consider thermal and insulative properties, leading to choices in materials like masonry, steel, and corrugated asphalt. More information on material selection can be found in section 5.4. Corrugated shading structures cover the buildings to reduce heat gains to the buildings. The elevated shading structures serve to protect students from the harsh sun rays while outdoors. Indoor to outdoor transitions are also critical, as Tanzanians spend a lot of time outdoors. A covered courtyard was created in each dormitory module to implement an internal/external blend between spaces.

Passive ventilation is implemented to maximize thermal comfort, ventilation, and abide within the project budget. This is done by maximizing air flow into sized window openings and thoughtfully dimensioned rooms. A rule of thumb for the maximum cross-ventilation is that the width (or side of the building that is parallel to the wind direction) must be less than or equal to five times the height of the building, seen in Figure 20.

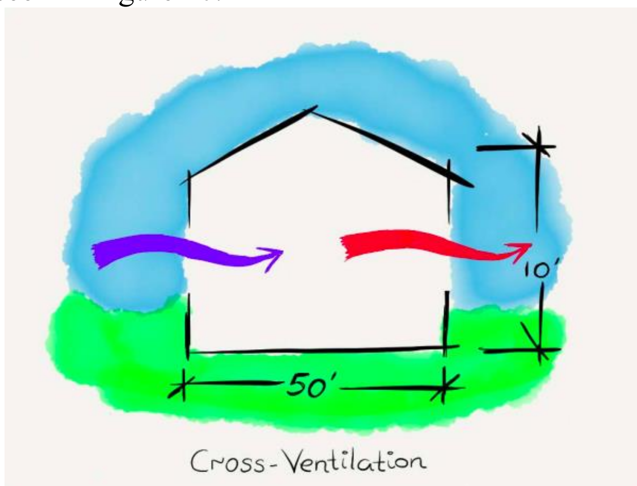

Figure 20. 5:1 (Width:Height) Cross-ventilation rule

The width for the dormitory module is 32 feet and the height is 9 feet, and the width for the classroom module is 35ft and the height is 9.5ft as seen in Appendix E, demonstrating that the designs were constructed to maximize proper cross-ventilation. The window open area must be greater than or equal to 0.05*(wall 1)*(wall 2), seen in Figure 21.

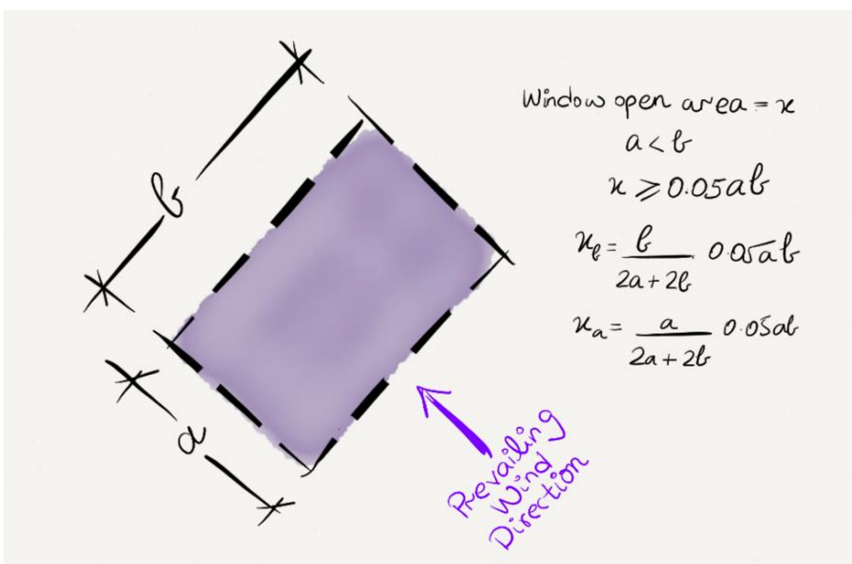

Figure 21. Window Open Area Rule of Thumb

For the dormitory module, there are 2 windows in the larger room, and 5 windows in the smaller room. The window dimensions are uniformly 3'x4', giving a window open area of 72ft^2 for the large room, and 60ft^2 for the small. Both exceed the necessary window area rule. The classroom module has two different sized window openings- seven 47.5"x37" windows and four 47.5" x

18.15” windows. This totals a window open area of $109ft^2$, giving plenty of open window area to maximize passive ventilation. Contrary to the images illustrating the dormitory and classroom modules in Appendix E, the tops of the buildings will be enclosed to address security and safety concerns.

5.2 Supporting Analysis

Various software tools, calculations, and tests were utilized to provide supporting analysis for the validity of the direction for our design. As shown in the previous section, preliminary calculations were done to ensure that proper cross-ventilation would be achieved with the chosen window areas for the classroom and dormitory module. In addition, wind tunnel tests were conducted to illustrate the effectiveness of positioning the building to have windows face the direction of the prevailing wind to increase interior wind speeds and ventilation. The calculated window area along with the ideal building orientation were later implemented in CoolVent to simulate indoor thermal conditions. Table 3 show key inputs in the CoolVent simulation to obtain the transient results show in Figure 22.

Table 3. Coolvent inputs used to analyze module passive ventilation with local weather data.

Description	Input
Analysis Type	Transient
Terrain Type	Flat Terrain
Ambient Temperature	30 °C
Relative Humidity	79%
Wind Speeds	4.5 m/s
Initial Temperature	22 °C
Building Orientation	Facing South East

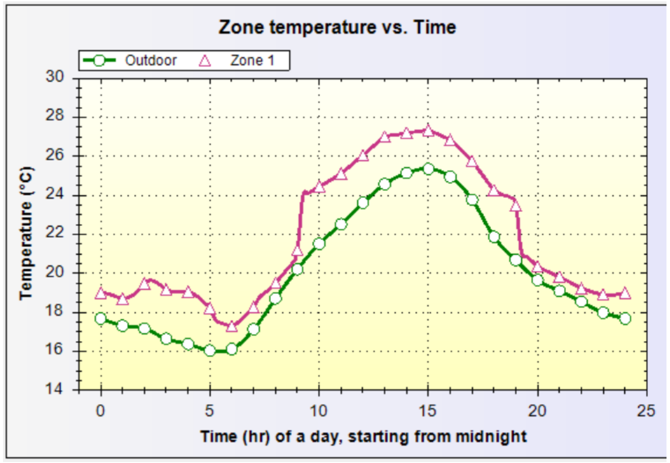

Figure 22. CoolVent preliminary analysis results. Warmer interior compared to external temperature.

The results indicate that merely altering window sizes and building orientation will not produce favorable indoor conditions. As a result, alternative strategies to provide a cooler and comfortable interior were investigated.

Simulations in DesignBuilder illustrated how protecting the interior from direct sunlight could significantly reduce the indoor temperatures. As a result, shading structures were introduced as a strategy to prevent direct heating of the interior and building envelope. As shown in Figure 23, the results show considerable differences in interior conditions as a result of using a shading structure.

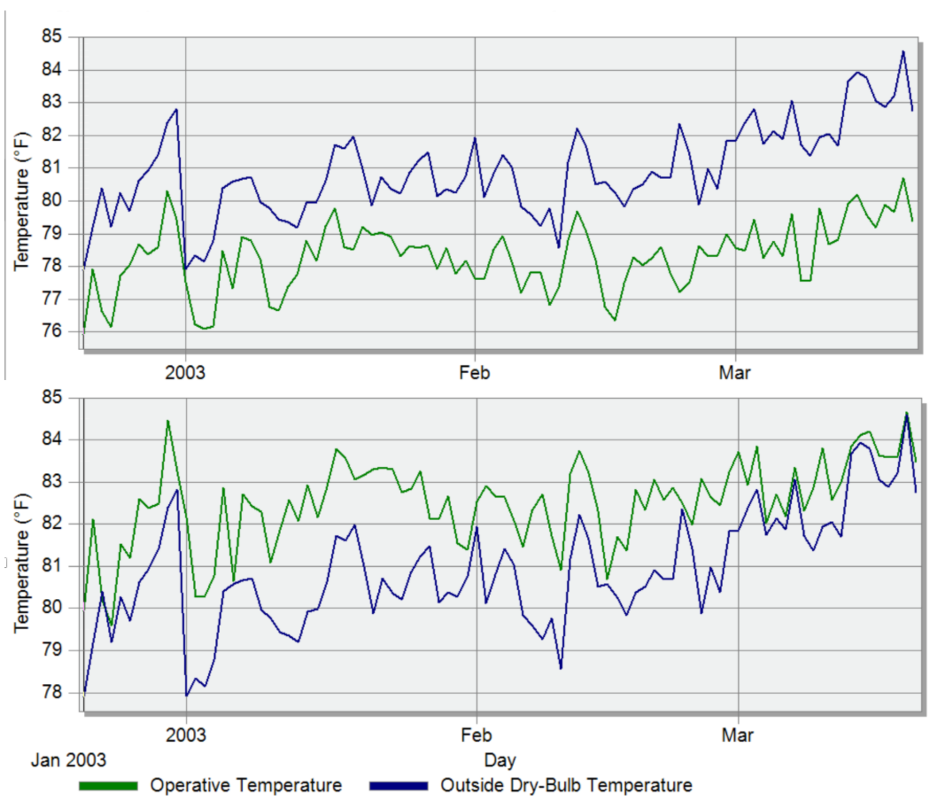

Figure 23. DesignBuilder preliminary analysis results for classroom module. (Top) Indoor operative temperature compared to outside dry-bulb temperatures as the result of reducing direct sunlight into building. (Bottom) Indoor operative temperature compared to outside dry-bulb temperatures as the result of more exposure to direct sunlight through window openings.

Angles of incidence and solar paths were analyzed through sun pegs generated by Climate Consultant, a software tool that analyzes local climates, to size the shading structures. The shading structures were designed to prevent sunlight from entering the windows at various angles of incidence during different times of the day and year. Figure 24 shows how the angles of incidence at critical times of the day were considered when implementing a shading structure for the classroom module.

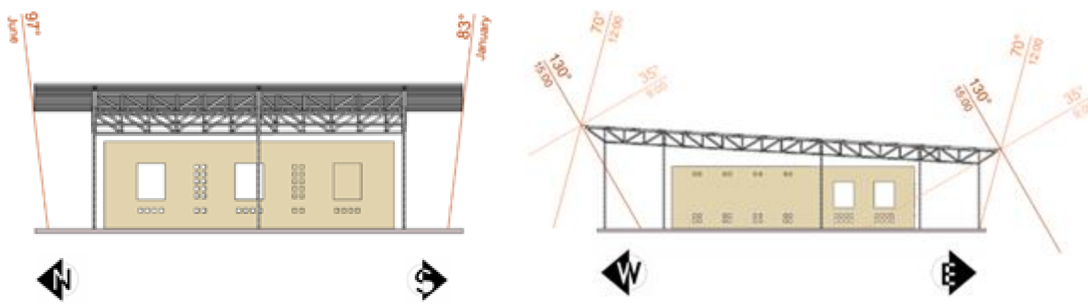

Figure 24. Incidence angles considered to size shade structure in order to limit direct solar gain on exterior walls.

5.3 Safety Maintenance and Repair

Consistent with the goal of sustainability and carbon positivity, the campus will retain its current ecological character to the greatest degree possible and integrate the campus and community. Infrastructure in Tanzania is very limited. Connecting the national water line to the site is possible, but no feasible due to the costs and procedures required. The campus site is located close to a national power grid line, and a connection point is available through the Tanzanian national electric company, TANESCO.

Renewable energy will be used in the form of solar to promote sustainability. Solar power uses PV panels to gather the heat from the sun and convert it into energy that is stored in a high-capacity battery. The batteries are similar to those used in cars, which are readily available in the developing world. Solar panels are also easy to install. When considering maintenance and repair, the allocation of the PV panels was an important decision. The architect students pushed for angled solar panels at about 20° on the roofs for aesthetics. However, because Same is near the equator, the optimum angle for the solar panels is 4° from the horizon. Additionally, the solar panels would need to be maintained and cleaned to keep them functioning. Servicing solar panels that are placed on the roof would be difficult, and so it was decided that the solar panels would be isolated in a solar farm, where they could be cleaned without having to climb onto a roof.

Initial iterations in the classroom and dormitory modules did not include an immediate enclosure below the shading structures. There is a high concern that individuals would feel unsafe or unprotected from the outdoor elements with a detached roof or having an open ceiling. Additionally, this allows for bugs and unwanted pests to enter the buildings. An enclosure below the shading structure was implemented to address the safety and infestation concern. A devised design aimed at solving the detached roof problem included adding mesh between the building walls and the overhang shade structure. This, however, provided too many maintenance issues to be feasible. If the mesh obtained holes, it would need to be entirely replaced. It would still also not protect occupants against wind or rain.

5.4 Material Selection

Selecting appropriate building materials for a campus in such a harsh environment is crucial to the success of the project. The weather in Same can be very hot and humid. This means materials can deteriorate at an accelerated pace. Metals are subject to corrosion and organic materials are subject to swelling. High humidity can also accelerate the growth of fungus and microbes on wood and other organic surfaces. This growth that can affect the indoor air quality and safety of occupants. Another factor for consideration is the large temperature fluctuations between day and night. This can lead to expansion and contraction of material that can also decreased material life. The roofing material also has a large effect on the indoor air temperature. A well-insulated roof with limited solar gain is necessary to limit heat gains. All of these factors needed to be considered in selecting both the building material and roofing.

Several options were considered for the module's primary building material. Burned clay bricks are the most common building material rural East Africa and can be cheaply produced on site. Burned clay bricks are typically hand formed and then stacked into a large pile with several tunnels at the base. Firewood is inserted into the tunnels and the bricks are baked on site. This process can lead to irregular brick quality because of the temperature differences throughout the stack. Deforestation and air pollution are also factors to consider in the brick baking process. A higher quality can be achieved with kiln fired bricks which are pressed extruded and fired in local kilns. Concrete masonry is typically hollow and has very good insulative properties, however the manufacturing process requires highly mechanized plants that are not local to the Kilimanjaro region. Stone masonry is locally available at a quarry near the Same Polytechnic site, however this manufacturer hand cuts the units which can lead to large variation in dimensions. Additional studies and simulations regarding the thermal properties of bricks and its effects on the indoor temperature can be found in Section 7.2.

The material option we finally selected is a compressed stabilized earthen block. These blocks are produced using a combination of soil and a stabilizing agent such as concrete. They are typically pressed using a manual or mechanical press and can be produced locally using native materials. Earthen blocks are more durable than burned clay bricks and can be produced with much tighter tolerances leading to improve building stability. Cost-wise the blocks are cheaper than concrete masonry and have a smaller carbon footprint than a fired brick.

Solar heat gain through the roof will be a major factor in the indoor air temperature and the comfort of the occupants. Corrugated metal roofs are typical in rural Eastern Africa and materials can be obtained locally. However, metal is extremely conductive and would quickly transfer solar heat into interior spaces. For this reason, two options were considered: insulation and a double skinned roof. Adding insulation below the corrugated metal panels would slow the rate of heat transfer and allow for convective cooling to take place. However, in a humid environment, insulation needs to be well sealed and protected from the elements and still may be subject to degradation. The second option utilizes an air gap as an insulation layer. We selected a double skinned roof with a layer of corrugated metal, an air gap which is open to natural ventilation to dissipate heat through convective cooling and then a second roofing layer above the unit. This method will require less maintenance and slow heat transfer to indoor spaces. Case studies to determine the effect of the roof material on the indoor temperature is explored in Section 7.2 and provides further commentary on the topic.

5.5 Cost Analysis

Determining the thermal properties of the brick through experimentation requires a certain amount of resources and money. Two tests were conducted to determine the thermal properties of the bricks. The first test, which is used to determine thermal diffusivity, involves a brick, four thermocouples, two thermocouple readers, a small piece of copper, a power supply, and a resistance heater. Purchasing the bricks for the thermal test was not required because an ARCE student provided us with two bricks from their own project. The thermocouples, thermocouple readers, copper piece, and power supply were obtained through the ME Department without charge. For our first iteration of the thermal test, adhesive required to secure the thermocouple between the copper piece and point source were purchased. Two flexible resistance heaters sold by Heat Scientific were purchased for $13.70 ($6.85 each). However, after the first round of testing, it was evident that the equipment that was being used was not sufficient and the heater had failed. As a result, we used a variable autotransformer to control the voltage ratio and a new resistance heater. The variable autotransformer was obtained through the ME department and the new cylindrical resistance heater was purchased from McMaster Carr for $24.17.

In terms of costs for manufacturing, the tooling required was done on campus and free of charge. The holes to insert the thermocouples and heat source were drilled in the CAED workshop. Furthermore, the copper piece were cut in Mustang 60 and soldering tools from the ME Department were used to fabricate the thermocouples and join necessary wires. Table 4 summarizes the costs associated with creating and assembling this test.

Table 4. Associated cost breakdown of structural prototype for material testing.

Description	Obtained Through	Quantity	Cost
Power Supply	ME Department	1	$0
Variable Autotransformer	ME Department	1	$0
High Temperature Adhesive	Halnziye	2	$14.09 ea.
Brick	ARCE Graduate Student	2	$0

Thermocouple	ME Department	4	$0
Thermocouple Reader	ME Department	2	$0
Copper Piece	ME Department	1	$0
Resistance Heater	Heat Scientific	2	$6.85 ea.
Cylindrical Resistance Heater	McMaster Carr	1	$24.17
Hole Drilling	Mustang 60 Shop	--	$0
Soldering Wire	ME Department	--	$0

The next test to characterize the thermal properties of the brick involved a calorimetry experiment to obtain the specific heat capacity of the brick. A foam tub was purchased from Walmart for $7.45 each and a thermometer from the ME Department were used to record the temperature of the water. A masonry saw obtained through the ARCE machine shop was used to cut portions of the brick to be tested. Table 5 lists all the items involved with the calorimetry test including their costs and where they were obtained.

Table 5. Associated cost breakdown of calorimetry test for material testing.

Description	Obtained Through	Quantity	Cost
Styrofoam Tub	Walmart	4	$7.47
Thermometer	ME Department	1	$0
Brick	ARCE Graduate Student	1	$0

Aside from the brick tests, other purchases were made in the process of designing and analyzing our classroom and dormitory modules. Materials were purchased to create a wind tunnel model to interpret scaled wind behavior in the classroom module. Three 18"x 32"x 1/8" Acrylic sheets were purchased from Art Central for $18.95 each. Epoxy glue used to put together the model was purchased from Home Depot for $9.62. Nuts and bolts were also purchased from The Home Depot for approximately $3.25. There were no costs involved with cutting the model structure and drilling the necessary holes. The acrylic sheets were laser cut in the dFab laboratory at Cal Poly and the holes on the acrylic model were drilled at Cal Poly in the Mustang 60 machine shop. Table 6 shows the costs associated with creating the wind tunnel model.

Table 6. Associated cost of wind tunnel model for preliminary testing.

Description	Obtained Through	Quantity	Cost
Acrylic Sheet	Art Central	3	$18.95 ea.

Nut and Bolt Pack	Home Depot	1	$3.25
Epoxy Glue	Home Depot	2	$9.52
Hole Drilling	Mustang 60 Shop	--	$0
Laser Cutting	dFab Laboratory	--	$0

Appendix F summarizes purchased parts for each test in detail. The total cost of the project, which includes planned experiments and testing models, can be seen in Appendix G.

6.0 Manufacturing Plan

The following chapter will serve to identify the process of how the local Tanzanian masonry is made. Locally made bricks are available to order, so the overall project will purchase such blocks to build the Tanzania Polytechnic College. The following section will also discuss how the Cal Poly bricks used for thermal testing were produced to mimic the Tanzanian masonry.

In Same, Tanzania a local mill builds solid blocks made solely of find sand, cement, and water. The blocks do not include a coarse aggregate due to its sparse availability. Because of the absence of coarse aggregate, the bricks were found to have a lower specific heat and density than accepted values for common bricks.

In order for the Same Polytechnic College team to get accurate predictions of the brick strength and material properties, a block was produced to match those in Same as closely as possible. The bricks made in Same are a specific size of 6x9x18 or 5x9x18 (W x H x L). The Same mill uses a mechanical press to form the bricks, however Cal poly students used a manual press built by student Leah Holleran. The manual press delivers significantly less compressive force than the mechanical one but was available for student use. The students used wood formwork to construct the blocks to fabricate the unique size and the grooves along the face for the rebar. Figure 25 shows the mechanical press used in Same (left) and the manual press used at Cal Poly (right).

Figure 25. Comparison between the Same mechanical brick press and the Cal Poly student made press.

To make the bricks, the ingredients are blended in a concrete mixer by adding half of the dry ingredients, then half of the water, then the rest of the dry ingredients and the remaining water. The ingredients are then poured and pressed into the formwork. The mixture content for the Cal Poly Senior Project Tanzania bricks is shown in Table 7 below.

Table 7. Composition of Cal Poly student made bricks to mimic the local Tanzanian bricks.

	Total Mixture (%)	Per Mix (lbs)
Sand	80	280
Cement	7	23
Water	13	28.4

After the mixture is made it is poured into the brick mold. The excess mixture is then scraped off and the brick is pressed. Figure 26 below shows the mixture filling the manual press mold at Cal Poly.

Figure 26. Cal Poly students pouring and pressing the cement mixture.

The compressive force is applied via rebar using the student's weight. This force is much less than the mechanical force used in the Same mechanical press. The Same press can apply about 600 lbs of force so it is understood that the Cal Poly bricks are less dense than those in Same. Figure 27 shows the process of scraping off excess mixture and compressing the brick via force applied to the rebar.

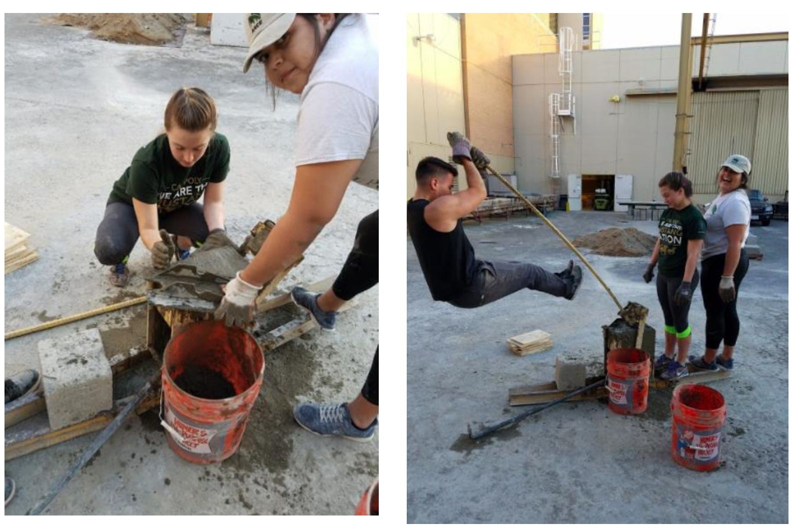

Figure 27. Cal Poly students scraping the excess mixture and then applying force.

Lastly, the bricks are extruded and the plate removed. This process and the final extruded brick can be seen in Figure 28 below. The final brick has a slot for structural rebar.

Figure 28. Leah Holleran removes top plate and reveals final extruded brick.

The assumptions made about the bricks proved to be correct when the mechanical team tested the bricks for their thermal properties. Further discussion of brick testing and findings can be found in Section 7.1.

7.0 Design Verification Plan

The mechanical team conducted two physical tests as well as several simulation tests in order to finalize the dormitory and classroom modules. The physical tests included a one-dimensional heat transfer analysis that was used to determine the physical properties of the primary building material: locally produced masonry block. The goal of the test was to determine the thermal conductivity, specific heat capacity, and thermal diffusivity of the block material. The results of the material test can be seen in section 7.1. Material properties were then used to improve the accuracy of simulation testing in DesignBuilder. The simulation tests included several case studies to investigate areas for design improvement. The second physical test was a secondary building wind tunnel test. An updated model was used to regenerate preliminary testing data for ventilation through the building with a new building façade and several addition orientations. A summary of all testing can be seen in the design verification plan in Appendix H.

7.1 Material Testing

The blocks that were tested were manufactured by Architectural Engineering student Leah Holleran at California Polytechnic State University. The manufacturing process used to create the bricks intentionally replicated the process used in Tanzania. Due to the lack of availability of a mechanical brick press, a donated manual press was used to form the blocks. The Cal Poly blocks also differed in size from the much larger blocks produced in Tanzania. While the size difference did not affect the material properties of the imitation bricks, the press style altered the brick density and did have some effect on test results. The Tanzanian blocks are on average much denser than those manufactured at Cal Poly because the mechanical press is capable of applying a much higher compression force during brick molding process.

In order to determine the initial properties: thermal conductivity and specific heat, a basic calorimetry experiment was conducted. Several large pieces of the brick material were removed in order to iterate the calorimetry study with multiple samples. Each sample was placed in water to record displacement and calculate sample volume. The samples were weighed and their densities determined. The samples were then heated in an oven to a temperature of 175 degrees Celsius and placed in separate insulated containers filled with a recorded volume of water at a recorded initial temperature. Once the bricks and water reached a constant temperature the temperature of the water was recorded. Using the governing equation seen in Equation 7 below we solved for the specific heat of each brick sample. The summary of the density and specific heat of each sample can be seen in Table 8.

$$mc\Delta T_{Brick} = mc\Delta T_{Water}$$

Table 8. Summary of calorimetry test results for two material samples.

Sample	Density (Kg/m^3)	Specific Heat (J/KgK)
1	1994	436
2	1575	422
Accepted Values Bergman Heat Transfer[10]	1920	835

The material test utilized a small resistance heater, four thermocouples, two thermocouple readers, and a variable autotransformer power source to power the resistance heater. A model of the test layout can be seen in Figure 29 below.

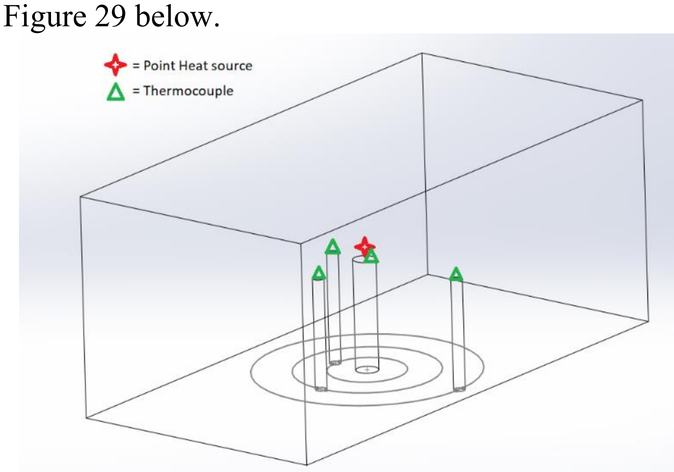

Figure 29. Structural prototype for material testing layout.

Four thermocouples were placed throughout the brick. The first thermocouple was placed directly on the heat source to measure the temperature of the heat source. The remaining three thermocouples were placed at radii of 1, 1.5, and 2 inches from the heat source. By varying the radial distance from the heater, we were able to record one dimensional heat transfer through the material. To find the material properties a numerical analysis was conducted to predict the temperature distribution within the brick. By varying the value of thermal diffusivity in the numerical model, we were able to match our theoretical results to our experimental results and determine the true thermal diffusivity of the material. A numerical model for one dimensional radial heat transfer was derived by Professor Kim Shollenberger. The energy balance seen below in Equation 1 was applied to each spherical node.

$$\dot{E}_{in} + \dot{E}_{out} + \dot{E}_{g} = \dot{E}_{st}$$

Equation 2 shows the energy storage term which is a function of material density, specific heat, volume and the temperature over time.

$$\dot{E}_{st} = \rho\, c\, V \frac{\partial T}{\partial t}$$

Using Fournier's law for conduction through a spherical coordinate system in the radial direction, the energy in term can be found. See Equation 3 below.

$$\dot{E}_{in} = q_r = -k\left(4\,\pi\, r^2\right)\frac{\partial T}{\partial r}$$

For the first node centered at a radius of one inch and in direct contact with the heat source, the temperature at any given time, p, can be found using Equation 4, where a_E is a function of the Fournier number and radius.

$$T_1^p = \left(1 + a_{E,1}\right)T_1^{p+1} - a_{E,1}\, T_2^{p+1} - \hat{Q}$$

The second node, centered at a radius of one and a half inches, is considered interior and is therefore a function of the temperature of the first node and the third node. The temperature of node two at any given time, p, can be found using Equation 5.

$$T_i^p = \left(1 + a_{W,i} + a_{E,i}\right)T_i^{p+1} - a_{W,i}\, T_{i-1}^{p+1} - a_{E,i}\, T_{i+1}^{p+1}$$

The final node is centered at a radius of two inches from the heat source. The temperature at node 3 can be calculated using Equation 6 seen below.

$$T_{N_r+1}^{p} = \left(1 + a_{W,N_r+1} + b\right) T_{N_r}^{p+1} - a_{W,N_r+1}\, T_{N_r}^{p+1} - b\, T_{¥}$$

The energy out term assumes that convective heat transfer occurs beyond the final node. This boundary condition was used in order to establish a steady state solution that would have been unattainable if insulation beyond the second node had been assumed. Further information on the derivation of theoretical temperature equations can be seen in Appendix K.

Numerical analysis was applied to the system of equation created to calculate temperature at each node. These equations solved for the final predicted temperature distribution using a MATLAB code produced by Professor Shollenberger. The MATLAB script can be seen in Appendix L. The results were then matched to the experimental test results by varying the value of thermal diffusivity used. When the predicted and experimental result matched a thermal diffusivity of 2.67 E-06 m^2/s was recorded. Finally, the thermal diffusion equation was used to solve for thermal conductivity. The K values was determined to be 1.75 W/mK. Figure 30 below shows the resulting MATLAB plot.

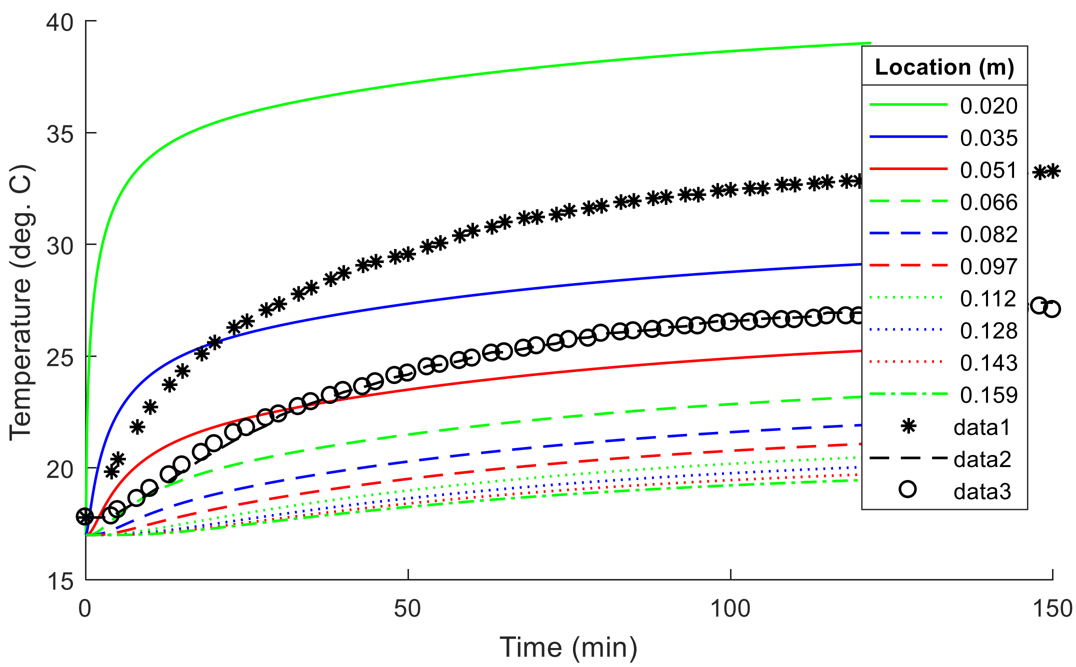

Figure 30. MATLAB plot of numerical and experimental temperature distribution results.

7.2 Simulation Testing

Simulations were used to determine the most effective design changes to improve thermal comfort in the dormitory and classroom modules. Simulations were conducted using DesignBuilder. DesignBuilder is an EnergyPlus based software tool used for energy, carbon, lighting, and comfort analysis. The mechanical team focused on the thermal analysis features to determine which design choices could lower indoor air temperature and increase occupant's comfort. This was achieved with a variety of simulation case studies. The first of which examined building material properties.

Several building material properties were varied in order to determine the impact on the temperature of the interior space. The density of the building material was one interesting aspect to consider. A dense brick allows for thermal storage, so that the building may stay cool throughout the course of the day using colder temperatures stored in the brick. However, a less dense building material acts as a better insulator and can protect occupants by absorbing less heat during the day. The effect of the density varies with weather conditions and façade design. Therefore, a case study was conducted using DesignBuilder to simulate a high and low-density building material and its effect on indoor air temperature throughout the day. The thermal conductivity, specific heat, and density were initially set to the values determined by the 1-D brick test. The density values were altered for each trial and the indoor temperatures were plotted to identify the effect of increasing the density of the brick. Figure 31 illustrates the results of the case study run in DesignBuilder.

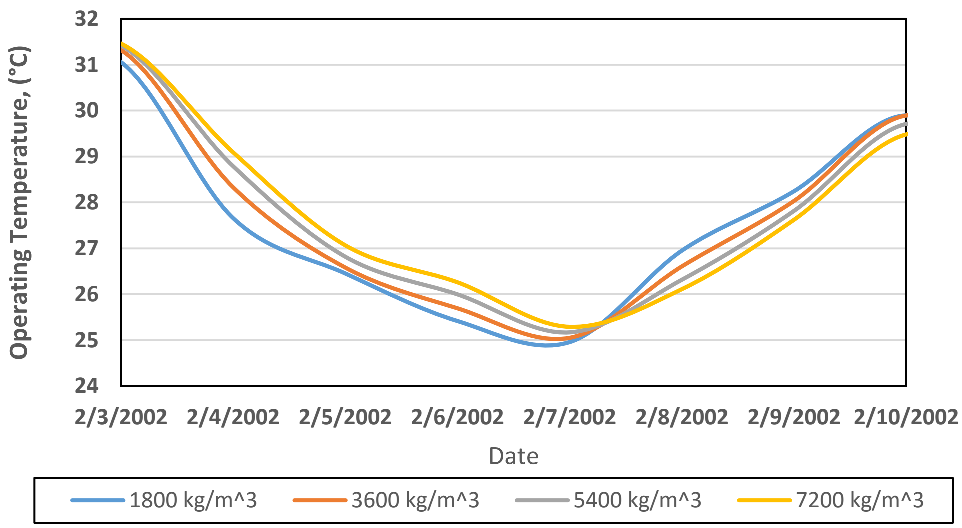

Figure 31. DesignBuilder plot of indoor air temperature with varying building material density.

The results indicate that a higher brick density does a better job at maintaining a stable indoor temperature compared to lower densities. During a phase where the temperature is decreasing, less dense bricks exhibit temperatures that are lower than denser bricks. On the contrary, phases where the indoor temperatures increase show that less dense bricks experience higher temperatures relative to the denser bricks. Denser bricks are better at maintaining stable temperatures during temperature swings due to their good thermal storage abilities.

Another case study simulated in DesignBuilder was done to determine the effect of roofing material on the interior temperatures over time. This simulation kept all the parameters of the building structure the same, such as thermal conductivity, density, and specific heat, while altering the roof material to analyze the changes in indoor temperature. The results of this case study simulated in DesignBuilder can be seen in Figure 32.

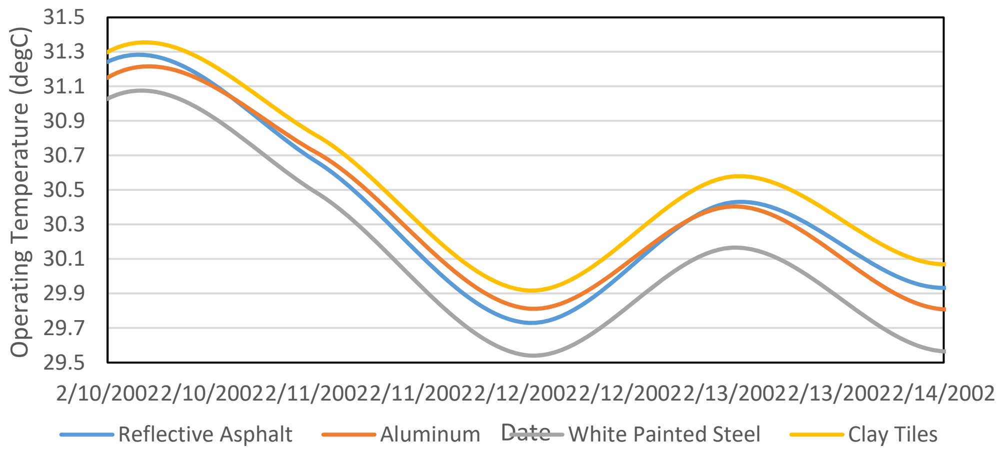

Figure 32. DesignBuilder plot of indoor air temperature with varying roof material.

The results of this case study suggest that along with the roofing material's thermal properties which include thermal conductivity, density, and specific heat, the finish of the surface has an important role in determining the indoor temperatures. Therefore, the combination of the appropriate roofing material along with a surface finish which absorbs less solar radiation should be sought to improve indoor conditions.

7.3 Secondary Wind Tunnel Testing

A second round of wind tunnel tests were conducted using an updated dormitory model. The intent of this test was to refine preliminary wind tunnel test results used the newly updated dormitory façade. The new model can be seen below in Figure 33 below. The model was laser cut out of Plexiglas and includes a fully closed roof with three opening to be used to insert the Pitot tube. The large room openings are actually one circular opening that can be repositioned to allow from testing in the front and back of the room. The circular shape allow for a slot to be angled at a variety of angles. All unused roof openings were covered with tap during testing.

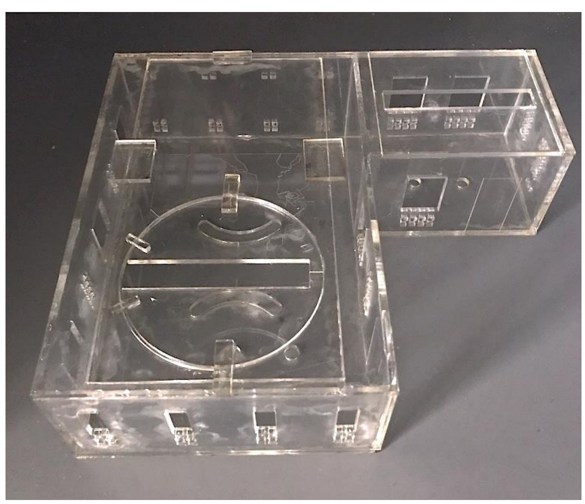

Figure 33.Secondary wind tunnel test model with updated façade openings and multiple Pitot tube entry points.

The model was placed at several orientations represented by several different wind directions. In every run the Pitot tube was pointed directly into the direction of prevailing wind. Each run represents a possible building orientation relative to wind direction on the campus site. A summary of the tested wind directions is shown in Figure 34. The corresponding results for the tested wind directions and Pitot tube locations can be seen in Table 9 below.

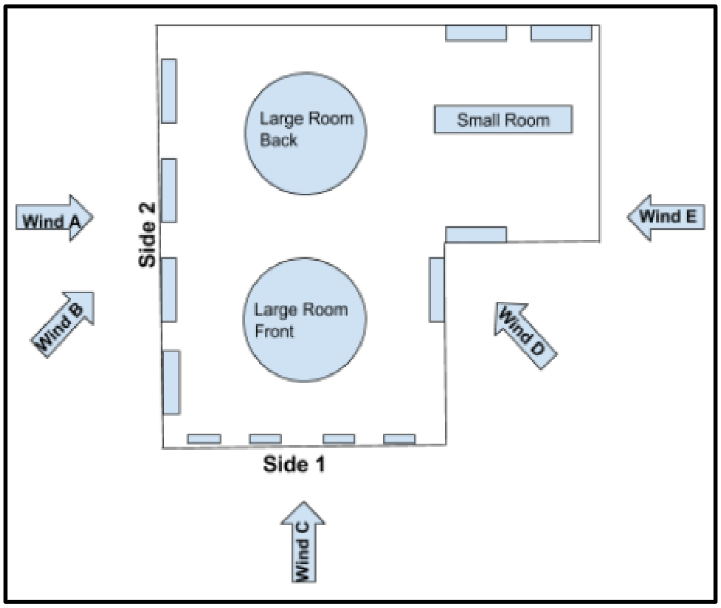

Figure 34. Schematic of secondary wind tunnel test arrangements.

Table 9. Secondary wind tunnel test data summary.

Pitot Location	Wind Direction	Scaled Velocity (mph)	Percent of Wind Speed
Large Room Back	C	2.07	107%
Large Room Back	B	1.97	102%
Large Room Back	D	2.35	121%
Large Room Front	A	2.13	110%
Large Room Front	E	2.38	123%
Small Room	E	2.36	122%
Actual Wind Velocity	No Model	1.93	100%

8.0 Project Management

8.1 Overview

The scope of this project included involvement in the early design process during fall of 2017. Mechanical engineering students worked directly with students in an Architecture studio class to determine preliminary module designs for both the classroom and dormitory modules. The remaining two quarters of this project were spent designing and conducting tests to provide useful design information to improve the initial module concepts. Testing results are included in this document along with design recommendations. The mechanical engineering team reported to Professors Shollenberger, Dong, and Fowler in order to assure all studies were as accurate and useful as possible. The final studies used a heat transfer analysis to determine thermal properties of local building materials as well as to simulate key design changes and their impact.

8.2 Project Management Deviations

Due to the interdisciplinary nature of this project the project management was very fluid. As opportunities to collect further useful information in the mechanical scope arouse, the mechanical team adjust the project timeline and goals. Although the project scope originally included a final redesign after testing results were collected, a case study strategy quickly emerged as the most productive method for interdisciplinary communication. Using information collected by mechanical students, architectural students will be able to alter their designs or building material selections. This method of mechanical consulting allowed for both the mechanical and architectural students to simultaneously work towards a better module design.

9.0 Conclusions

This document narrates the process and decision making used to come to the current stage of the design and highlights the next steps that will be taken to move the project forward. Customer meetings and interviews were held in order to obtain a better understanding of ways to design around local culture. Precedent studies were conducted to illustrate pre-existing designs created for the local area and potential solutions. Textbooks, scholarly articles, and presentation slides were used in order to gather background information about the mechanics behind passive ventilation and airflow, the Same Polytechnic Master Plan, and software tools and strategies to model natural ventilation and thermal loads. The objective and layout of the project was developed by first developing the problem statement, identifying our customer and potential areas of focus, creating a QFD, then defining engineering specifications. Iterations and prototypes were created during the design process to consider potential solutions and designs for the building modules. Concept models were then developed and preliminary tests were conducted to illustrate behaviors between airflow and the module designs. Taking the limitations on resources, local climate, culture, and previous iterations during the design process into consideration, concept models for the classroom and dormitory modules were selected.

Final designs for the classroom and dormitory were selected and justified through preliminary calculations, tests, and simulations. Concerns introduced during the concept model generation phase, such as safety and sustainability, were addressed in the final design by updating certain features. The selection of materials for major components in the classroom and dormitory modules was carefully analyzed. Tentative expenses for the project from experiments and tests were summarized to ensure that costs do not exceed the budget. Thermal tests were conducted to identify thermal properties of imitated Tanzania bricks. The numerical results obtained through the thermal tests were used in a simulation to analyze the effectiveness of using the bricks to aid indoor thermal comfort.

Several design recommendations should be considered for future iterations of both modules. Based on wind tunnel test results the dormitory module should be oriented with the door side facing into the direct of the prevailing wind in order to maximize cross flow ventilation. From thermal testing, it was determined that locally made bricks have significantly lower density and may act as a good insulator as opposed to thermal storage material due to the relatively warm temperatures experienced throughout the day in Tanzania. Ceiling fans or other forced air systems are recommended to improve thermal comfort whenever possible. Additionally, the roof on the modules must act as a good radiant shield and should be painted white in order to reflect as much solar radiation as possible.

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Appendix A: QFD House of Quality

Weight Chart	Relative Weight	Same Polytechnic Students	Kim Schollenberger	Kevin Dong/ Thomas Fowler	ARUP Cause	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	Average Indoor Temperature	Average Indoor Air Change Rate	Average Indoor Air Velocity	System Cost	Material Distance Traveled	Solar Gains	Internal Loads	Daylighting	Chipakata Children's Academy	The legson Community Center	KWEICO Shelter House	Row #
							Direction of Improvement	◇	◇	◇	▼	▼	▼	▼	◇				
|||||||||	19%	9	9	9	8	9	Comfortabe Indoor Temperature	●	○	●	▽	▽	●	●	●	5	3	4	1
||||||	12%	3	9	7	7	9	Safe Indoor Ventilation	○	●	●	▽	▽	○	○	▽	3	4	2	2
|||||||||	19%	9	9	9	8	9	Comfortabe Indoor Velocity	○	●	●	▽	▽	○	○	▽	3	4	2	3
||||	8%	0	6	5	9	9	Reasonable Cost	▽	▽	▽	●	●	▽	▽	▽	2	3	4	4
||||	8%	0	6	5	9	9	Utilize Local Resources	▽	▽	▽	●	●	▽	▽	▽	2	3	4	5
||||	9%	0	8	6	8	9	Optimal Solar Gain	●	○	○	▽	▽	●	●	●	2	2	2	6
||||	9%	0	8	6	8	9	Optimal Internal Heat Loads	●	○	○	▽	▽	●	●	●	3	2	2	7
|||||||	15%	6	7	8	7	9	Optimal Daylighting	○	▽	▽	▽	▽	○	○	●	3	1	1	8

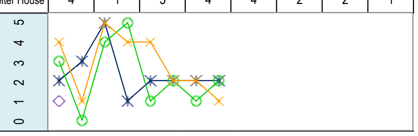
WHO: Customers

NOW: Current Product Assesment - Customer Requirements

	Average Indoor Temperature	Average Indoor Air Change Rate	Average Indoor Air Velocity	System Cost	Material Distance Traveled	Solar Gains	Internal Loads	Daylighting
HOW MUCH: Target	Within Comfort Zone, ASHRAE STD 55	10 Liters/Second/Person	1-1.2 m/s	Cost- Benefit Analysis	Within 500 Mile Radius	< 4 Watts/ft^2 (wall area)	< 2 Watts/ft^2 (floor area)	100-2,000 logs
Max Relationship	9	9	9	9	9	9	9	9
Technical Importance Rating	491.176	426.679	541.749	231.323	231.323	491.176	491.176	516.666
Relative Weight	14%	12%	16%	7%	7%	14%	14%	15%
Weight Chart								

Current Product Assesment - Engineering Specifications

Chipakata Children's Academy	2	3	5	1	2	2	2	2
The legson Community Center	3	0	4	5	1	2	1	2
KWEICO Shelter House	4	1	5	4	4	2	2	1



Appendix B: Decision Matrices

Function 1: Distribute Natural Resources					
Factors	**Cost**	**Maintenance Req'd**	**Local Materials**	**Architectural**	**Totals**
Weight	5	4	3	3	
Living Roof	2	1	5	5	44
Corrugated Skylights	4	3	4	4	56
Masonry Openings	2	3	5	4	49
Centralized Solar	4	4	3	2	51
Localized Solar	3	2	3	4	44
Airflow Nozzles	2	5	4	2	48
Wells for Water	4	3	3	2	47
Corrugated Walls	4	3	5	4	59
Greenhouse Water Collection	1	2	4	3	34

Function 2: Set an Example					
Factors	**Cost**	**Maintenance Req'd**	**Local**	**Architectural**	**Totals**
Weight	5	4	3	3	
No Hallways	5	4	4	3	62
Interactive Classroom Spaces	3	3	3	5	51
Common Spaces	2	3	4	5	49
Environmental Sustainability	3	2	4	5	50
Indoor Air Temp	2	3	4	2	40

Function 3: Achieve Indoor Temperature Goal					
Factors	**Cost**	**Maintenance Req'd**	**Local**	**Architectural**	**Totals**
Weight	5	4	3	3	
Indoor Water Feature	2	2	4	5	45
Tunnel Cooling	1	2	4	2	31
Fans	4	4	3	3	54
Air Nozzles increase Velocity	3	4	4	3	52
Trombe	2	3	2	3	37
Using Phase Change Material	2	3	3	3	40
Building Thermal Mass	4	5	5	4	67

Appendix C: Preliminary Analyses and Testing Details

Wind Tunnel Testing Data and Analysis

no roof

Big Room	Motor Frequency (Hz)	Pressure (in H20)	Pressure Averaged (in h20)	Pressure (psf)	velocity (ft/s)	velocity (mph)
Straight on	52	0.174				
Straight on	52	0.150				
Straight on	52	0.142				
Straight on	52	0.178				
Straight on	52	0.215	0.209	1.086	30.535	20.819

no roof

Small Room	Motor Frequency (Hz)	Pressure (in H20)	Pressure Averaged (in h20)	Pressure (psf)	velocity (ft/s)	velocity (mph)
Straight on	52	0.461				
Straight on	52	0.487				
Straight on	52	0.538				
Straight on	52	0.525				
Straight on	52	0.440	0.490	2.549	46.786	31.900
CCW 45	52	0.053				
CCW 45	52	0.040				
CCW 45	52	0.036				
CCW 45	52	0.054				
CCW 45	52	0.079	0.052	0.272	15.297	10.430

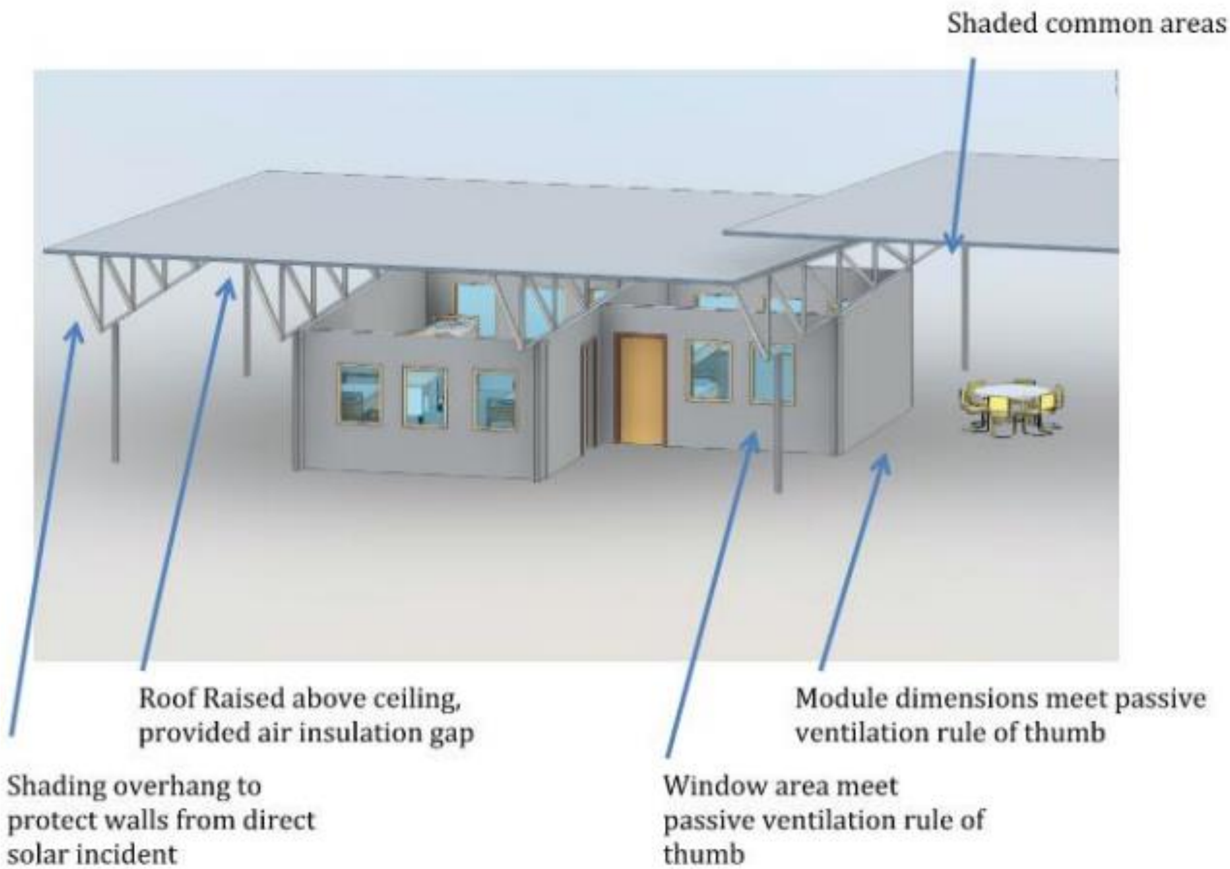
wind tunnel	Motor Frequency (Hz)	Pressure (in H20)	Pressure Averaged (in h20)	Pressure (psf)	velocity (ft/s)	velocity (mph)
	52	4.429				
	52	4.414				
	52	4.432				
	52	4.429				
	52	4.416	4.424	23.005	140.553	95.831

Velocity was found using a form of Bernoulli's equation:

$$v = \sqrt{\frac{2P}{\rho}}$$

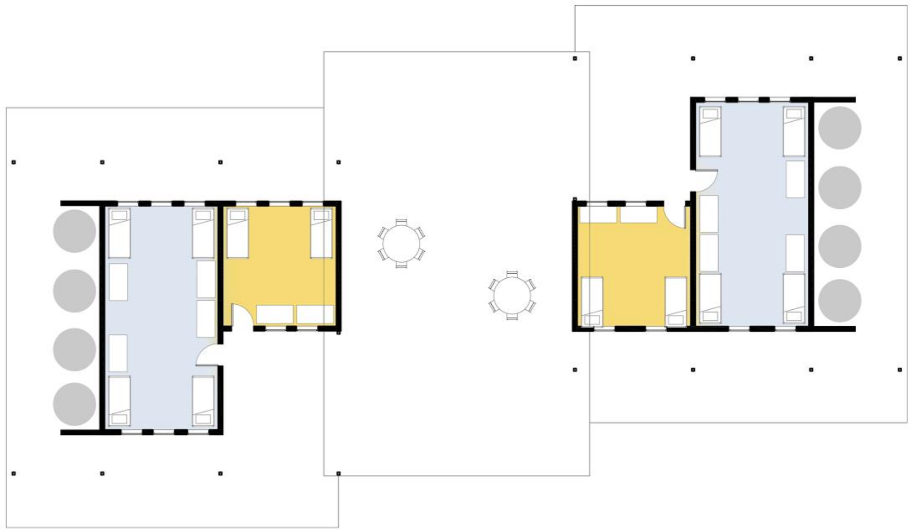
Where 'P' is the pressure from the wind tunnel apparatus and 'ρ' is the density of air.

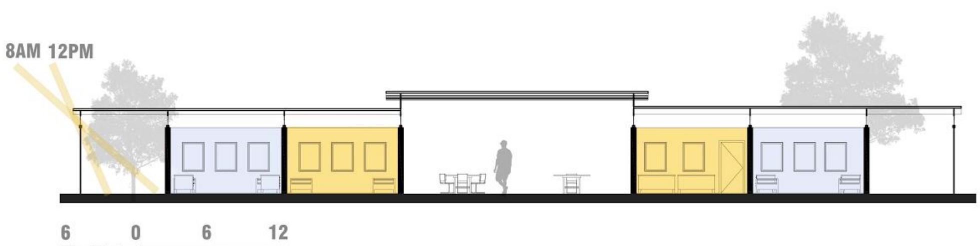
Appendix D: Concept Layout Drawings

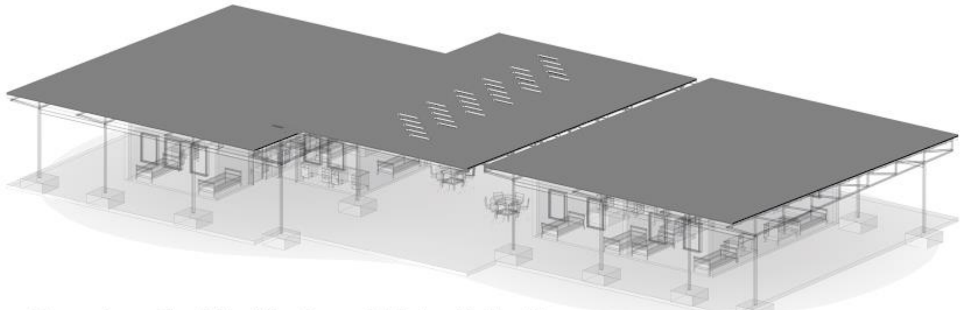


Appendix E: Complete Drawings Package

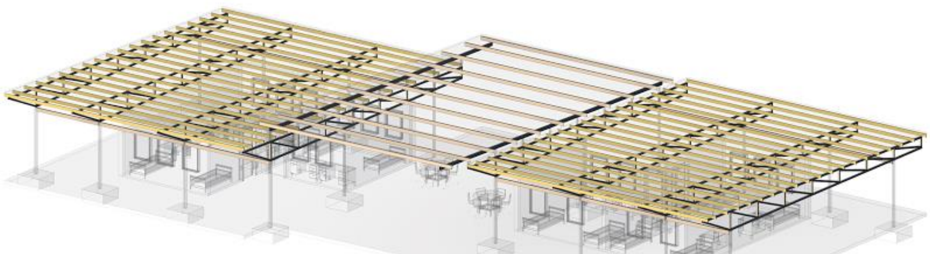
Dormitory Module



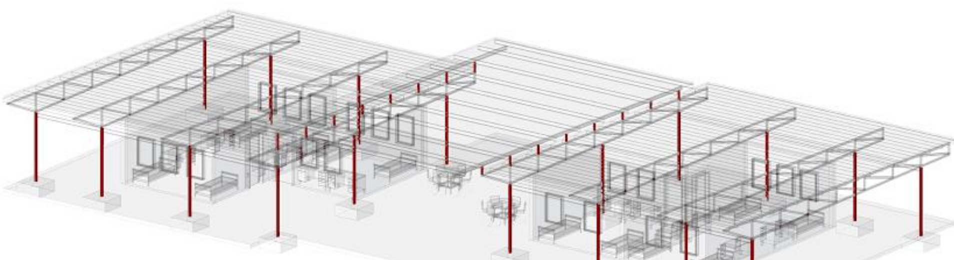




Monoslope Roof for Shade and Water Collection

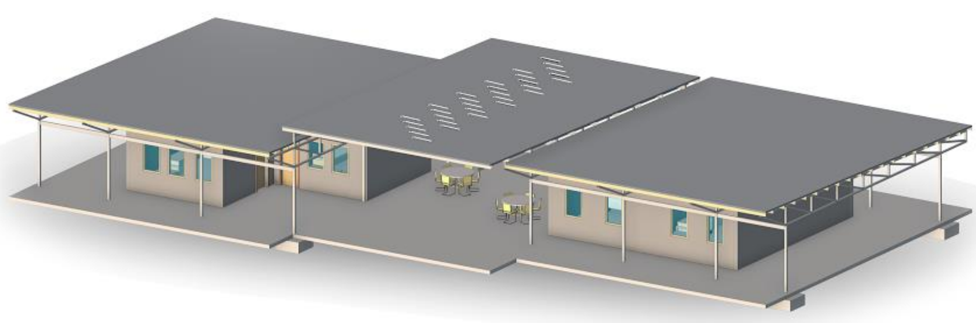


Wood and steel joists over HSS Trusses

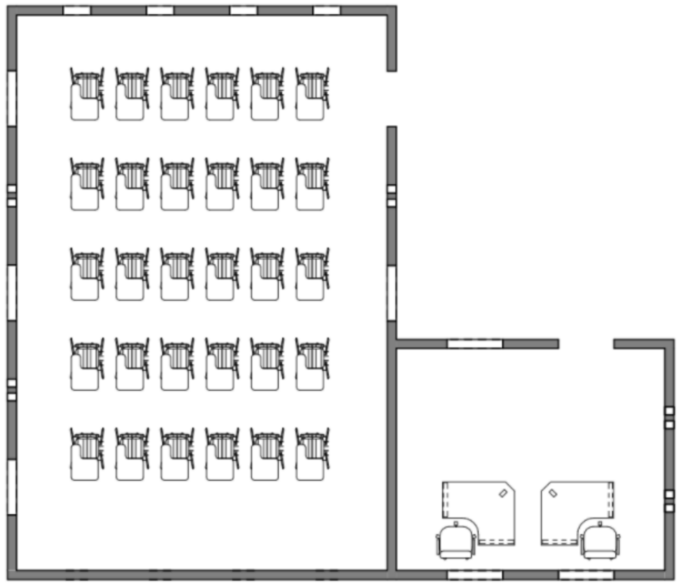


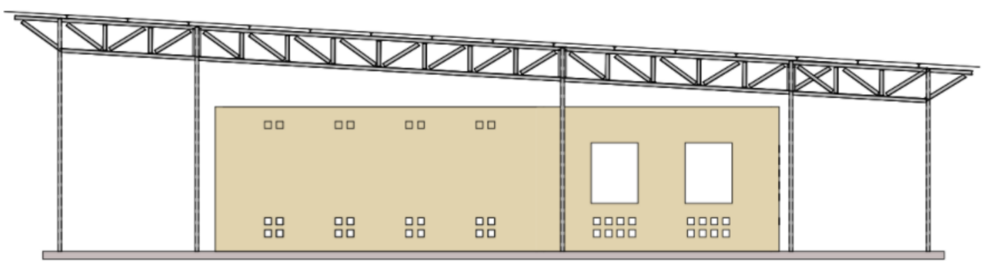
Steel HSS Column

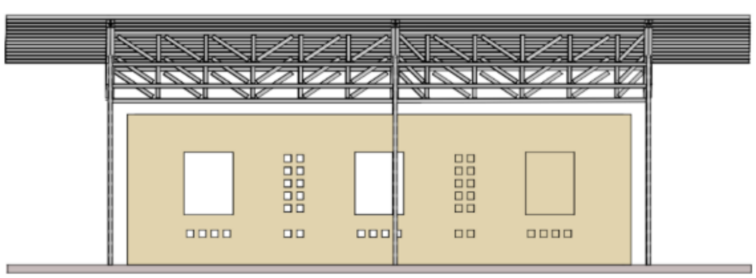
Masonry with painted Concrete finish

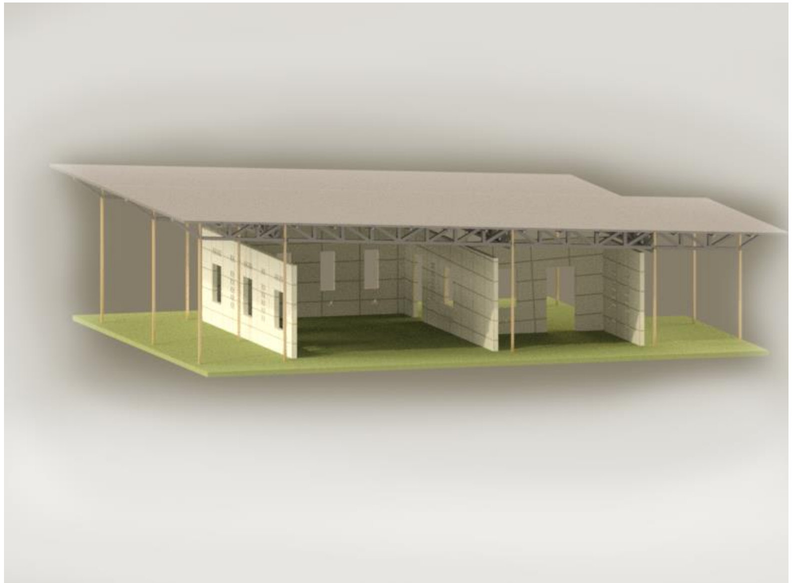


Classroom & Office Module

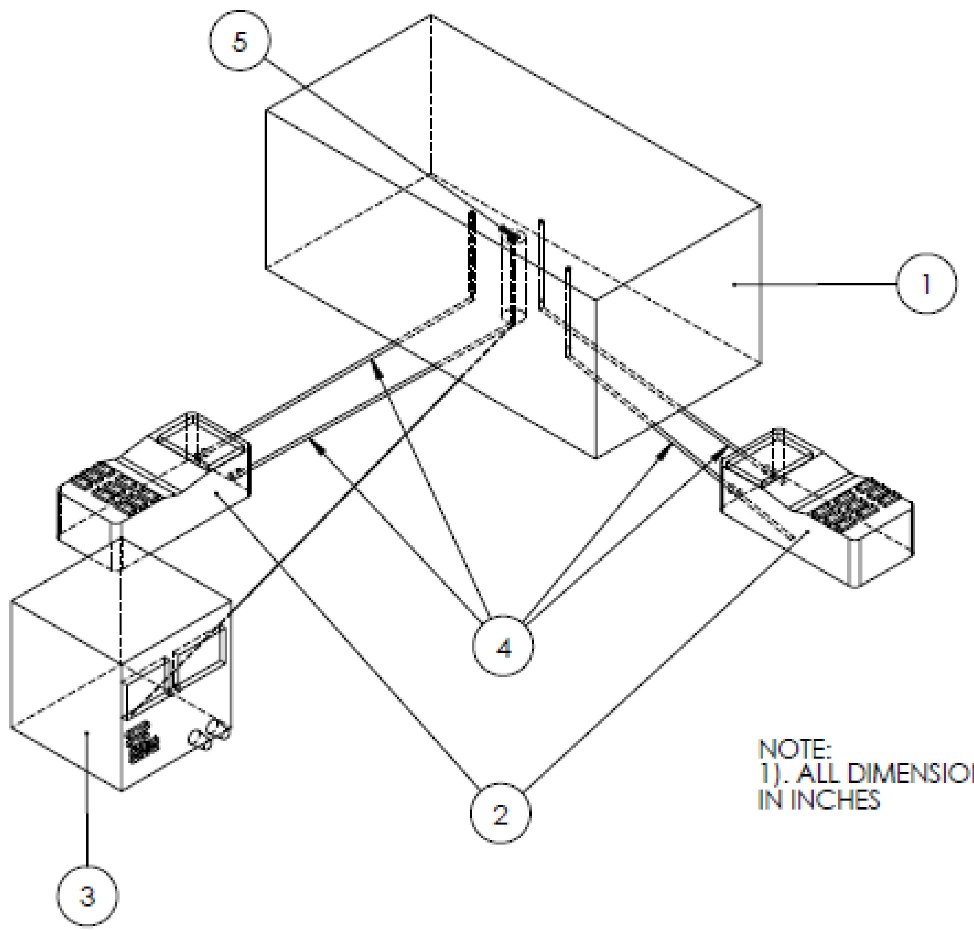








Structural Prototype



NOTE:
1). ALL DIMENSIONS ARE IN INCHES

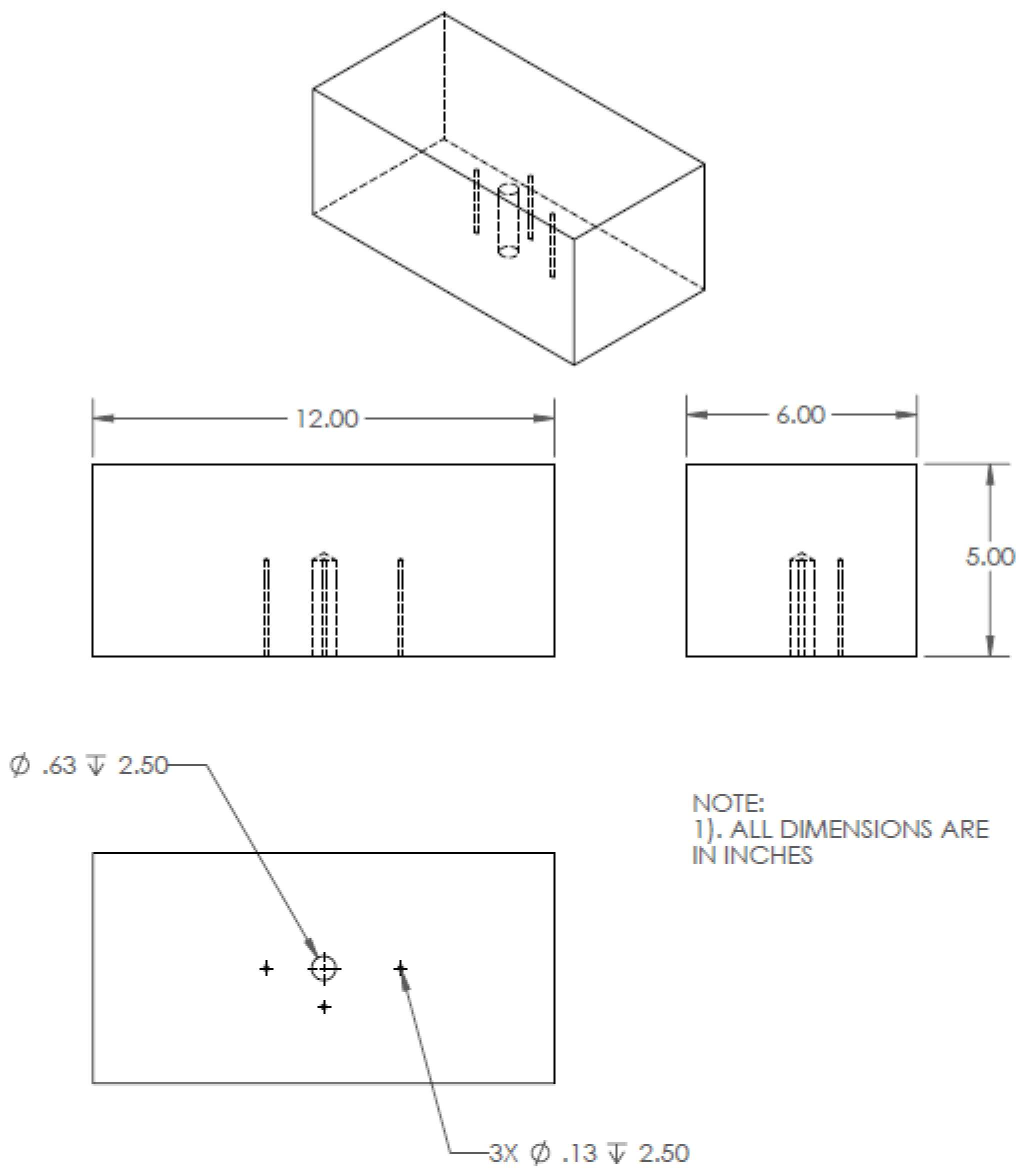
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	110000	Brick	1
2	102000	Thermocouple Reader	2
3	102002	Power Source	1
4	102001	Thermocouple	4
5	102003	Heat Source	1

NAME Long H. , Katie N., Meghan S. DATE 02/09/18

Brick Test Layout

SIZE A DWG. NO. REV.

SCALE 1:4 WEIGHT: n/a SHEET 1 OF 3



NOTE:
1). ALL DIMENSIONS ARE IN INCHES

NAME	DATE
Long H. , Katie N., Meghan S.	02/09/18

Brick Dimensions

SIZE A | DWG. NO. | REV.

SCALE 1:4 | WEIGHT: n/a | SHEET 2 OF 2

Appendix F: Purchased Parts Details

*****_Specifications and data sheets obtained by clicking name of item (in blue)_

Item	Detail	Used In	Vendor	Quantity
Resistance Heater	Flexible with adhesive back, 356°F max operable temperature	Brick Test	Heat Scientific	2
Cartridge Resistance Heater	240VAC ¼" Diameter, 1" Long Cartridge, 100W	Secondary Brick Test	McMaster-Carr	1
High Temp. Adhesive	Silicone Fluid, Maximum use Temperature range ~-20 - ~250°C	Brick Test	Halnziye	2
Styrofoam Tub	Extruded Polystyrene Foam, 17"x12"x14.4"	Calorimetry Test	Walmart	1
Acrylic Plexiglass	Acrylic Transparent sheets, 36"x18"x1/8"	Wind Tunnel Test	Art Central	3
Nut & Bolt Pack	Set of 4 nuts and bolts	Wind Tunnel Test	Home Depot	1
Epoxy Glue	Set in 5 minutes, handling strength in 1 hour	Wind Tunnel Test	Home Depot	2

Appendix G: Budget/Procurement List (vendors, purchasing details, full budget)

Testing Cost				
	Item	Quantity	Source	Cost
BRICK TEST				
	Brick	2	Manufactured by ARCE Graduate Students	N/A
	Thermocouple	4	Cal Poly ME Department	N/A
	Thermocouple Reader	2	Cal Poly ME Department	N/A
	Flexible Resistance Heater	2	Heat Scientific	$6.85
	High Temperature Adhesive	2	Halnziye	$14.09
	Copper Plate	1	Cal Poly ME Department	N/A
	Cylindrical Resistance Heater	1	McMaster Carr	$24.17
SubTotal		$66.05		
WIND TUNNEL				
	Plexiglass	3	Art Central	$18.95
	Screws	1	Home Depot	$3.25
	Epoxy	2	Home Depot	$9.52
SubTotal		$79.14		
CALORIMETRY TEST				
	Styrofoam Tub	$4.00	Walmart	$7.47
SubTotal		$7.47		

Total Cost	$152.66
Available Funding	$900.00
Remaining Funds	$747.34

Appendix H: Final Analyses And Testing Details

TEST PLAN										TEST REPORT			
Item #	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Qty	Type	Start date	Finish date	Test Result	Qty Pass	Qty Fail	
1	1,6	Design Builder Simulation	Meets ASHRAE STD 55	Long Hoang	CP, FP	1	Full Syst	1/11/18	4/30/18	Indoor Air Temperature		1	
2	2	CoolVent Airflow Simulation	10 Liters/ Person	Long Hoang	CP	1	Full Syst	10/16/17	3/20/2018	Airflow rates	1		Airflow rates for classroom module
3	2	Wind Tunnel Test using scaled wind speeds and plexiglass building model	10 Liters/ Person	Meghan Smith	CP, FP	8	Full Syst	10/5/17	5/5/2018	Percent outdoor air velocity in internal spaces	8		Guides classroom design towards shorter rooms angled directly into prevailing wind
4	1	Brick Thermal Properties test to fine tune DB model	Comparative to textbook values	Katie Nute	SP	4	Com	1/25/18	5/3/2018	Thermal conductivity, density, specific heat capacity, thermal diffusivity	2	2	Density and specific heat acceptable but low. Conductivity and diffusivity are unreliable via testing results.

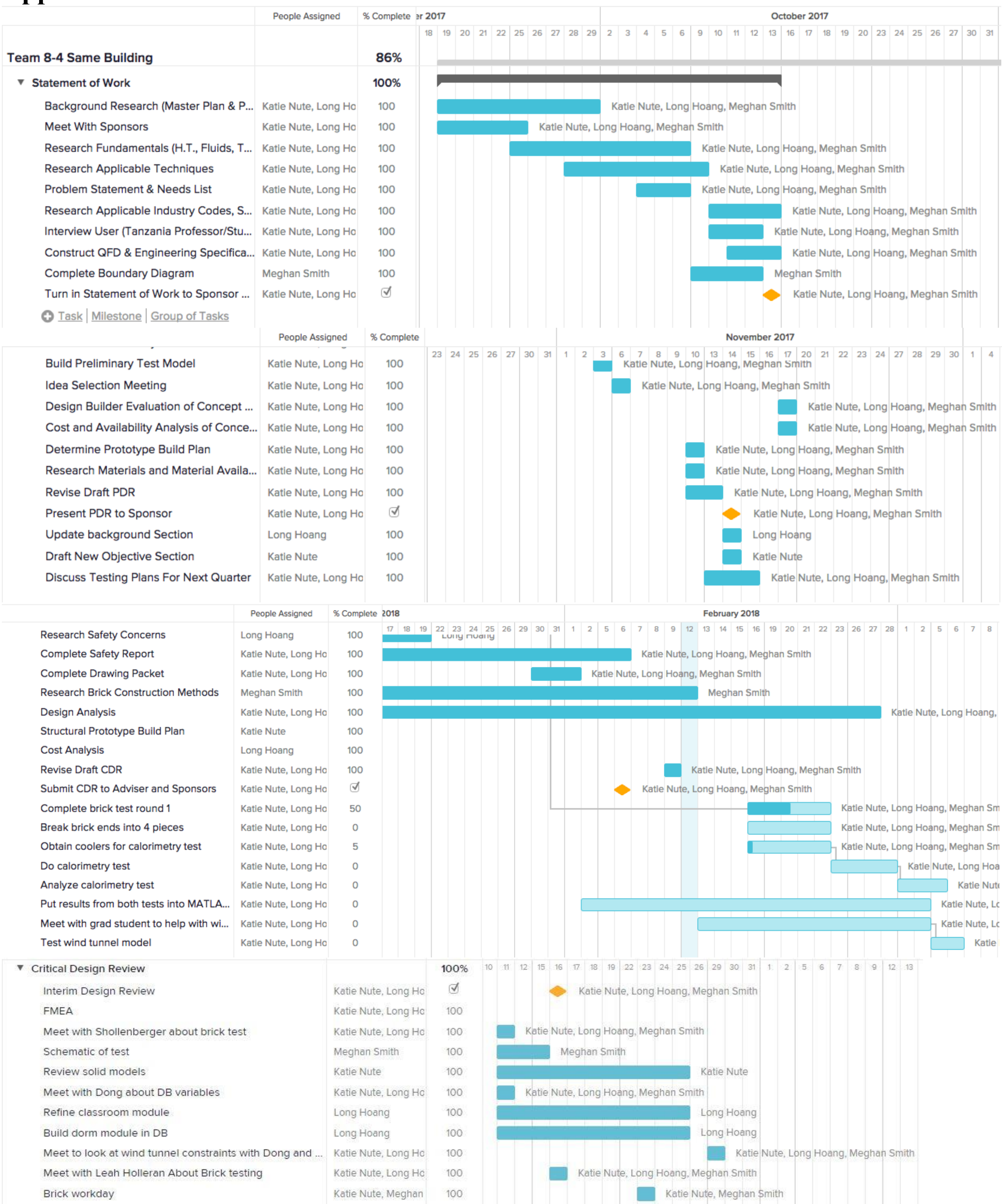
Appendix I: Safety Hazard Checklist, FMEA

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date
Windows, Allow natural Ventilation	Not enough ventilation, less than 10 litres/ person total	a.fungus forms b.stale air endangers user	8	1) high humidity from low airflow 2) lack of oxygen from low airflow	1) optimize window area and placement with DB	4	DB	5	160	Use DB to analyze	Long 3/4/2018
Windows, Allow natural Light	Not enough natural light, less than 100 logs	a.User cannot read	4	1) darkness	1) Sun studies	3	Sun Study	1	12	Follow rules of thumb for window open area	Meghan 1/20/2018
Vents, Allow natural ventilation	Not enough ventilation, less than 10 litres/ person total	a.fungus forms b.stale air endangers user	8	1) high humidity from low airflow 2) lack of oxygen from low airflow	1) Wind tunnel testing 2) Modeling in DB	4	DB	5	160	Follow rules of thumb for cross-ventilation	Meghan 1/20/2018
Roofing/ protect occupant	Roofing degrades, has openings, occupant feels unsafe	a. user feels unsafe b. user unprotected from elements	9	1) Lack of physical security 2) Exposure to elements	1) Consult with structural engineers 2) Research available materials	2	-	10	180	Refer to material data about roofing strength	Katie, 3/1/2018

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date
roofing/ reduce thermal gain	Thermal gain from roof increases interior temp to above acceptable range	a. user is uncomfortable	5	1) Indoor temperature/humidity out of range	1) Thermal modeling in DB	6	DB	5	150	Test different roofs and shading structures in DB, including material and color changes.	Long 3/1/2018
roofing/ collect water	Leaking, contaminates water, fails to collect	a. mold from leaks b.dehydration c.illness from contamination	9	1) Water seeps into walls 2) insufficient water collection 3) Water contamination	1) Basic calcs for roof area 2) precedence studies	4	Basic Calcs determine if enough water	7	252	Refer to material data about roofing chemical makeup/ contamination potential	Meghan, 1/15/2018
building materials/ reduce thermal gain	Thermal gain from walls increases interior temp to above acceptable range	a. user is uncomfortable	5	1) Indoor temperature/humidity out of range	1) Thermal brick testing	6	brick test and calorimetry	5	150	still need to run tests to find brick properties	All, 2/28/2018

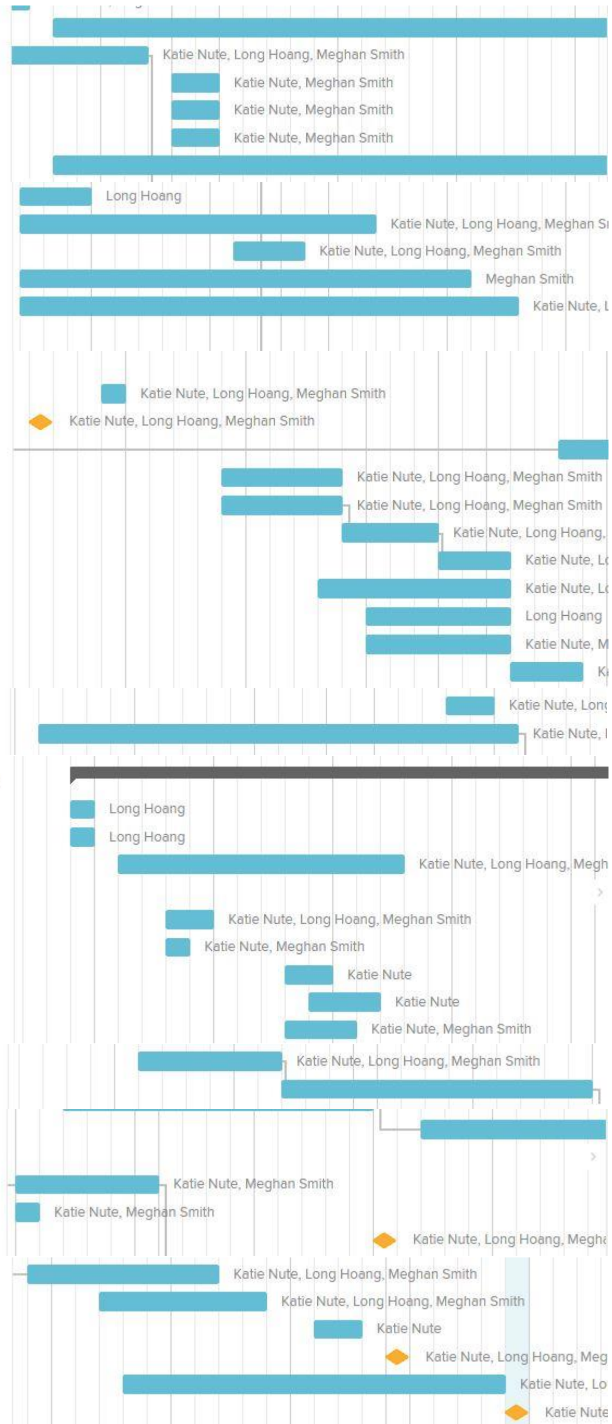
Rooms/ provide comfortable interior spaces	Not enough ventilation, less than 10 litres/ person total	a.fungus forms b.stale air endangers user	8	1) Room is too long 2)Room orientation doesn't allow adequate ventilation	1) Wind Tunnel Studies 2) Coolvent Studies	2	Coolvent	6	96	will run additional wind tunnel test with better model	All, 3/8/2018
Fans increase ventilation	average indoor air velocity below 1m/s	a. fungus forms b.stale air endangers user	8	1) high humidity from low airflow 2) lack of oxygen from low airflow	1) optimize window area and placement with DB	1	DB	10	80	include fan in each room	Long, 3/6/2018

Appendix J: Gantt Chart



klists

order point source heater	Katie Nute	100
Obtain materials for brick testing	Katie Nute, Long Ho	100
Solder Heat source Connection	Katie Nute, Meghan	100
Spot Weld Thermocouples	Katie Nute, Meghan	100
Solder Thermocouple Wires	Katie Nute, Meghan	100
Drill holes in brick	Katie Nute, Long Ho	100
Research Safety Concerns	Long Hoang	100
Complete Safety Report	Katie Nute, Long Ho	100
Complete Drawing Packet	Katie Nute, Long Ho	100
Research Brick Construction Methods	Meghan Smith	100
Design Analysis	Katie Nute, Long Ho	100
Structural Prototype Build Plan	Katie Nute	100
Cost Analysis	Long Hoang	100
Revise Draft CDR	Katie Nute, Long Ho	100
Submit CDR to Adviser and Sponsors	Katie Nute, Long Ho	☑
Complete brick test round 1	Katie Nute, Long Ho	100
Break brick ends into 3 pieces	Katie Nute, Long Ho	100
Obtain coolers for calorimetry test	Katie Nute, Long Ho	100
Do calorimetry test	Katie Nute, Long Ho	100
Analyze calorimetry Results	Katie Nute, Long Ho	100
Cut Copper Rods into Disks	Katie Nute, Long Ho	100
Order Thermal Adhesives	Long Hoang	100
Glue Resistance Heater to Copper Disks	Katie Nute, Meghan	100
Calculate density and specific heat	Katie Nute, Meghan	100
Adjustments to current experiments	Katie Nute, Long Ho	100
Meet with grad student to help with wind tunnel model ...	Katie Nute, Long Ho	100
▼ **Final Design Review**		**100%**
Update Design Description With Revisions	Long Hoang	100
Update Drawings with Revisions	Long Hoang	100
Write Operator's Manual	Katie Nute, Long Ho	100
Obtain Power Supply From Lab	Meghan Smith	☑
Verify resistance heater can heat up to desired temper...	Katie Nute, Long Ho	100
Run initial 1-D Brick Test	Katie Nute, Meghan	100
Calculations for new voltage with AC	Katie Nute	100
Purchase new resistance heaters as backup	Katie Nute	100
Make another thermocouple	Katie Nute, Meghan	100
Run Secondary 1-D Brick Tests	Katie Nute, Long Ho	100
Put secondary results from tests into MATLAB	Katie Nute, Long Ho	100
Input Experiment test results into DesignBuilder	Long Hoang	100
Simulate Different Ranges of Brick Properties on DB	Long Hoang	100
Test wind tunnel model	Katie Nute, Meghan	100
Meeting with Professor Dong	Katie Nute, Meghan	100
Discuss Potential Improvements in Design	Katie Nute, Long Ho	☑
Tabulate and Obtain Updated Wind Tunnel Test	Katie Nute, Long Ho	100
Make Project Expo Poster	Katie Nute, Long Ho	100
Print Poster	Katie Nute	100
Project Expo	Katie Nute, Long Ho	☑
Finish FDR Report	Katie Nute, Long Ho	100
Submit FDR Report	Katie Nute, Long Ho	☑



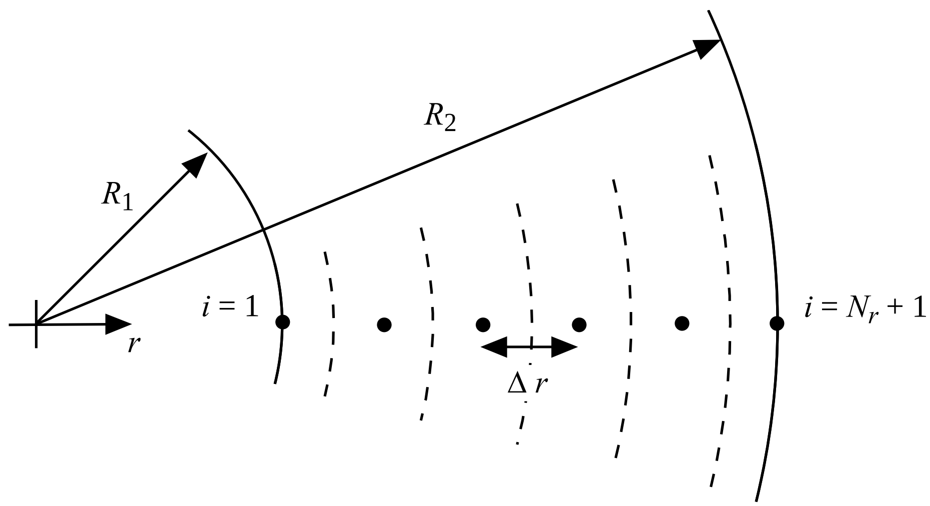
Appendix K: Material Test Equation Deviations

These derivations provided by Professor Shollenberger at California Polytechnic State University.

Transient, One-Dimensional Spherical Conduction

Below are the steps used to solve for the temperature distribution, $T(r, t)$, using the *implicit finite difference method* for transient, one-dimensional conduction in a spherical geometry.

Step 1. Discretize domain in space and time.



Define: i	node numbering in r-direction	
	N_r	number of elements in the radial direction - 1
	r	radial coordinate, $r = R_1 + (i - 1)\Delta r$
	R_1	inner radius where heat is supplied
	R_2	outer radius exposed to convection
	Δr	node spacing in r-direction, $\Delta r = (R_2 - R_1)/N_r$
	N_t	number of time steps
	p	index for time
	t	current time, $t = (p - 1)\Delta t$
	Δt	time step

Step 2. Derive finite difference equations from energy balance on each element.

Recall conservation of energy applied to a control volume (CV) can be given by

$$\dot{E}_{in} + \dot{E}_{out} + \dot{E}_{g} = \dot{E}_{st} \tag{1}$$

where: $\dot{E}_{in}$, $\dot{E}_{out}$ rate of energy transport into and out of CV

$\dot{E}_{g}$ rate of energy generation within the CV

$\dot{E}_{st}$ rate of change of energy storage within the CV

By Fourier's law for a spherical coordinate system, conduction in the radial direction is given by

$$\dot{E}_{in} = q_r = -k\left(4\,\pi\,r^2\right)\frac{\partial T}{\partial r} \tag{2}$$

where: k thermal conductivity

T temperature

For sensible heating only and an incompressible substance, $\dot{E}_{st}$ is given by

$$\dot{E}_{st} = \rho\,c\,V\,\frac{\partial T}{\partial t} \tag{3}$$

where: ρ density

c specific heat

V volume of the CV

Interior Node at r_i:

$$q_{r,i-1/2}^{p+1} + q_{r,i+1/2}^{p+1} = \dot{E}_{st,i}^{p\to p+1} \tag{4}$$

$$k\left(4\pi\,r_{i-1/2}^2\right)\frac{\left(T_{i-1}^{p+1} - T_i^{p+1}\right)}{\Delta r} + k\left(4\pi\,r_{i+1/2}^2\right)\frac{\left(T_{i+1}^{p+1} - T_i^{p+1}\right)}{\Delta r} = \rho\;c\,\frac{4\pi}{3}\left(r_{i+1/2}^3 - r_{i-1/2}^3\right)\frac{\left(T_i^{p+1} - T_i^{p}\right)}{\Delta t} \tag{5}$$

$$3\,Fo\left(\frac{\Delta r\,r_{i-1/2}^2}{r_{i+1/2}^3 - r_{i-1/2}^3}\right)\left(T_{i-1}^{p+1} - T_i^{p+1}\right) + 3\,Fo\left(\frac{\Delta r\,r_{i+1/2}^2}{r_{i+1/2}^3 - r_{i-1/2}^3}\right)\left(T_{i+1}^{p+1} - T_i^{p+1}\right) = T_i^{p+1} - T_i^{p} \tag{6}$$

where: Fo Fourier number, $Fo = \alpha\,\Delta t / \Delta r^2$

α thermal diffusivity, $\alpha = k/\left(\rho\;c\right)$

$$a_{W,i}\left(T_{i-1}^{p+1} - T_i^{p+1}\right) + a_{E,i}\left(T_{i+1}^{p+1} - T_i^{p+1}\right) = T_i^{p+1} - T_i^{p} \tag{7}$$

$$\boxed{a_{W,i} = 3\,Fo\left(\frac{\Delta r\, r_{i-1/2}^2}{r_{i+1/2}^3 - r_{i-1/2}^3}\right)} \quad \text{and} \quad \boxed{a_{E,i} = 3\,Fo\left(\frac{\Delta r\, r_{i+1/2}^2}{r_{i+1/2}^3 - r_{i-1/2}^3}\right)} \tag{8}$$

$$\boxed{T_i^p = \left(1 + a_{W,i} + a_{E,i}\right)T_i^{p+1} - a_{W,i}\,T_{i-1}^{p+1} - a_{E,i}\,T_{i+1}^{p+1}} \tag{9}$$

Boundary node at R_1:

$$Q + q_{r,\,i=3/2}^{p+1} = \dot{E}_{st,\,i=1}^{p\rightarrow p+1} \tag{10}$$

where: Q rate of thermal energy applied at R_1

$$Q + k\,4\pi\left(R_1 + \frac{\Delta r}{2}\right)^2 \frac{\left(T_2^{p+1} - T_1^{p+1}\right)}{\Delta r} = \rho\,c\,\frac{4\pi}{3}\left[\left(R_1 + \frac{\Delta r}{2}\right)^3 - R_1^3\right]\frac{\left(T_1^{p+1} - T_1^{p}\right)}{\Delta t} \tag{11}$$

$$\frac{Q\,\Delta t}{\rho\,c\,4\pi/3\left[\left(R_1 + \Delta r/2\right)^3 - R_1^3\right]} + 3\,Fo\left[\frac{\Delta r\left(R_1 + \Delta r/2\right)^2}{\left(R_1 + \Delta r/2\right)^3 - R_1^3}\right]\left(T_2^{p+1} - T_1^{p+1}\right) = T_1^{p+1} - T_1^{p} \tag{12}$$

$$\hat{Q} + a_{E,1}\left(T_2^{p+1} - T_1^{p+1}\right) = T_1^{p+1} - T_1^{p} \tag{13}$$

$$\boxed{\hat{Q} = \frac{Q\,\Delta t}{\rho\,c\,4\pi/3\left[\left(R_1 + \Delta r/2\right)^3 - R_1^3\right]}} \quad \text{and} \quad \boxed{a_{E,i} = 3\,Fo\left[\frac{\Delta r\left(R_1 + \Delta r/2\right)^2}{\left(R_1 + \Delta r/2\right)^3 - R_1^3}\right]} \tag{14}$$

$$\boxed{T_1^p = \left(1 + a_{E,1}\right)T_1^{p+1} - a_{E,1}\,T_2^{p+1} - \hat{Q}} \tag{15}$$

Boundary node at R_2:

$$q_{r,N_r+1/2}^{p+1} + q_{conv,\,N_r+1}^{p+1} = \dot{E}_{st,\,N_r+1}^{p\rightarrow p+1} \tag{16}$$

$$k\,4\pi\left(R_2-\frac{\Delta r}{2}\right)^2\frac{\left(T_{N_r}^{p+1}-T_{N_r+1}^{p+1}\right)}{\Delta r}+h\left(4\pi R_2^2\right)\left(T_\infty-T_{N_r+1}^{p+1}\right)=\rho\,c\,\frac{4\pi}{3}\left[R_2^3-\left(R_2-\frac{\Delta r}{2}\right)^3\right]\frac{\left(T_{N_r+1}^{p+1}-T_{N_r+1}^{p}\right)}{\Delta t} \tag{17}$$

$$3\,Fo\left[\frac{\Delta r\left(R_2-\Delta r/2\right)^2}{R_2^3-\left(R_2-\Delta r/2\right)^3}\right]\left(T_{N_r}^{p+1}-T_{N_r+1}^{p+1}\right)+3\,Fo\,Bi\left[\frac{\Delta r\,R_2^2}{R_2^3-\left(R_2-\Delta r/2\right)^3}\right]\left(T_\infty-T_{N_r+1}^{p+1}\right)=T_{N_r+1}^{p+1}-T_{N_r+1}^{p} \tag{18}$$

where:

- Bi — Biot number, $Bi=h\,\Delta r/k$
- h — convection coefficient
- T_∞ — temperature of fluid at R_2

$$a_{W,N_r+1}\left(T_{N_r}^{p+1}-T_{N_r+1}^{p+1}\right)+b\left(T_\infty-T_{N_r+1}^{p+1}\right)=T_{N_r+1}^{p+1}-T_{N_r+1}^{p} \tag{19}$$

$$\boxed{a_{W,N_r+1}=3\,Fo\left[\frac{\Delta r\left(R_2-\Delta r/2\right)^2}{R_2^3-\left(R_2-\Delta r/2\right)^3}\right]}\quad\text{and}\quad\boxed{b=3\,Fo\,Bi\left[\frac{\Delta r\,R_2^2}{R_2^3-\left(R_2-\Delta r/2\right)^3}\right]} \tag{20}$$

$$\boxed{T_{N_r+1}^{p}=\left(1+a_{W,N_r+1}+b\right)T_{N_r}^{p+1}-a_{W,N_r+1}\,T_{N_r}^{p+1}-b\,T_\infty} \tag{21}$$

Step 3. Solve system of equations.

The system of equations in matrix form is given by

$$\vec{T}^{\,p}=\left[A\right]\vec{T}^{\,p+1}+\vec{F} \tag{22}$$

$$
[A]=\begin{bmatrix}
(1+a_{E,1}) & -a_{E,1} & 0 & \cdots & \cdots & 0 \\
-a_{W,2} & (1+a_{W,2}+a_{E,2}) & -a_{E,2} & & & \vdots \\
0 & & \ddots & & & \vdots \\
\vdots & & -a_{W,i} & (1+a_{W,i}+a_{E,i}) & -a_{E,i} & 0 \\
\vdots & & & & \ddots & -a_{E,N_r} \\
0 & \cdots & \cdots & 0 & -a_{W,N_r+1} & (1+a_{W,N_r+1}+b)
\end{bmatrix},
$$

$$
\vec{F}=\begin{bmatrix}
\hat{Q} \\ 0 \\ \vdots \\ \vdots \\ \vdots \\ 0 \\ b\,T_\infty
\end{bmatrix}
$$

To solve this equation, set the initial temperature, $T_i^1 = T(r_i, t=0)$, and then solve for temperature at each future time using either matrix inversion or Gauss Seidel iteration.

Step 4. Use analytical steady state solution to check for steady state.

For a spherical coordinate system, one-dimensional conduction in the radial direction, and steady state, conservation of energy in differential form is given by

$$
\frac{1}{r^2}\frac{d}{dr}\left(k\,r^2\frac{d}{dr}\right)=0 \tag{23}
$$

Integrate twice to get

$$
T=-\frac{C_1}{k\,r}+C_2 \tag{24}
$$

Determine the constants of integration for fixed boundary temperatures using

$$
T(R_1)=-\frac{C_1}{k\,R_1}+C_2=T_1 \quad \text{and} \quad T(R_2)=-\frac{C_1}{k\,R_2}+C_2=T_2 \tag{25}
$$

$$C_1 = \frac{k\left(T_1 - T_2\right)}{\left(1/R_2 - 1/R_1\right)} \quad \text{and} \quad C_1 = T_1 + \frac{\left(T_1 - T_2\right)}{R_1\left(1/R_2 - 1/R_1\right)} \tag{26}$$

$$\boxed{T\left(r\right) = T_1 - \frac{\left(T_1 - T_2\right)}{\left(1/R_2 - 1/R_1\right)}\left(\frac{1}{r} - \frac{1}{R_1}\right)} \tag{27}$$

Solving for the radial heat flux from Eqn. (2)

$$q_r = -k\left(4\pi r^2\right)\frac{dT}{\partial r} = 4\pi k\frac{\left(T_1 - T_2\right)}{\left(1/R_1 - 1/R_2\right)} \tag{28}$$

For the boundaries at R_1 and R_2 by conservation of energy

$$q_r = Q = h\left(4\pi R_2^2\right)\left(T_2 - T_\infty\right) \tag{29}$$

Combining Eqn. (28) and Eqn. (29) we get

$$\boxed{T_2 = T_\infty - \frac{Q}{4\pi h R_2^2}} \quad \text{and} \quad \boxed{T_1 = T_2 - \frac{Q}{4\pi k}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)} \tag{30}$$

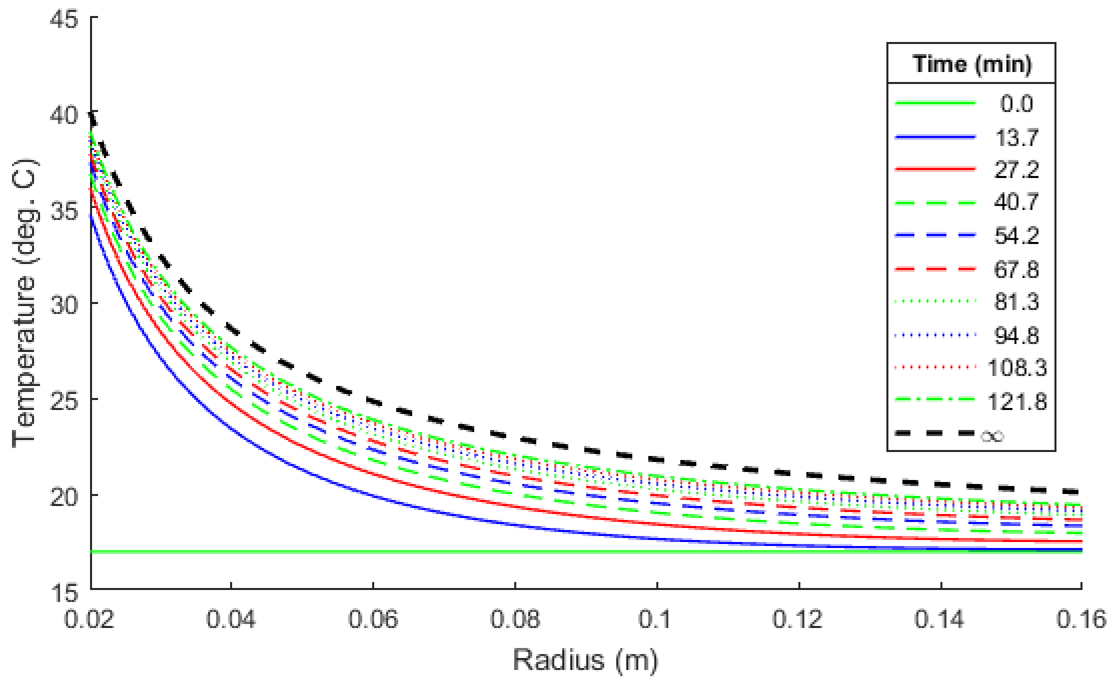
Appendix L:

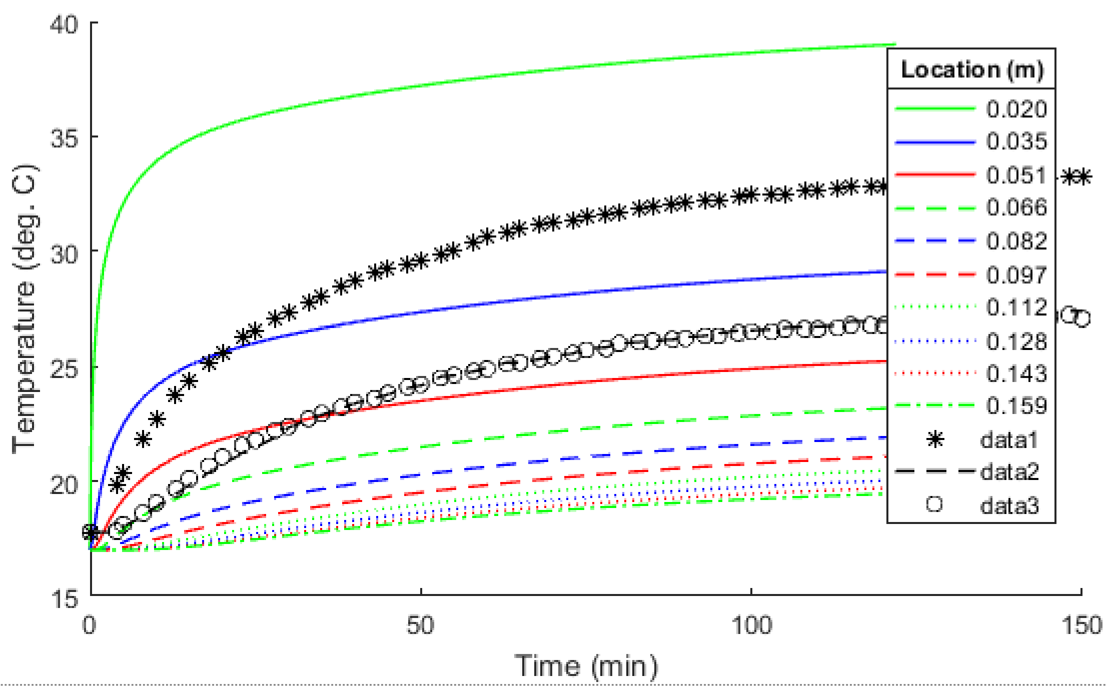
```
% Calculate temperature versus time and radius, T(r,t), for a sphere
% at initial temperture, T(r,t=0) = T_inf with boundary conditions:
%
% (1) Surface heating, Q, at inner radius, R_1
% (2) Convection to fluid with convection coeficient, h,
%     at temperature, T_inf, at outer radius, R_2,
%
% Solve energy balance equations using implicit-finite difference method.

clear, clc

% Define parameters
Q = 10;             % W, surface power (edited)
T_inf = 17;           % deg. C, initial and fluid temperature (edited)
h = 10;               % W/m^2-K, convection coefficient

k = 1.75;              % W/m-K, thermal conductivity, EDIT THIS
rho = 1500;           % kg/m^3, denoxsity (edited)
c = 436;              % J/kg-K, specific heat (edited)

alpha = k/(rho*c);  % m^2/s, thermal diffusivity

R_1 = 0.02;         % m, inner radius (edited)
R_2 = 0.16;         % m, outer radius (edited), 0.08 - 0.16 m
N_r = 100;            % number of nodes in radial direction


dr = (R_2 - R_1)/N_r; % m, element width
r = linspace(R_1,R_2,N_r+1); % m, radius for i-th node

N_t = 1e6;            % maximum number of time steps
dt = 10;              % s, time step

Fo = alpha*(dt/dr^2); % Fourier number
Bi = h*dr/k;          % Biot number

% Calculate coefficients for A matrix and F vector

A = zeros(N_r+1, N_r+1);
F = zeros(N_r+1,1);

% Boundary at R_1

dV    = (R_1 + dr/2)^3 - R_1^3; % m^3
a_E   = 3*Fo*(dr*(R_1 + dr/2)^2)/dV;
q_hat = (Q*dt)/(rho*c*(4*pi/3)*dV); % deg. C

A(1,1) = 1 + a_E;
```

```
A(1,2) = -a_E;
F(1)   = q_hat; % deg. C

% Boundary at R_2

dV  = R_2^3 - (R_2 - dr/2)^3; % m^3
a_W = 3*Fo*(dr*(R_2 - dr/2)^2)/dV;
b   = 3*Fo*Bi*(dr*R_2^2)/dV;

A(N_r+1,N_r)   = -a_W;
A(N_r+1,N_r+1) = 1 + a_W + b;
F(N_r+1)       = b*T_inf; % deg. C

% Interior nodes

for i = 2:N_r

    dV = (r(i) + dr/2)^3 - (r(i) - dr/2)^3; % m^3
    a_E = 3*Fo*(dr*(r(i) + dr/2)^2)/dV;
    a_W = 3*Fo*(dr*(r(i) - dr/2)^2)/dV;

    A(i,i+1) = -a_E;
    A(i,i)   = 1 + a_E + a_W;
    A(i,i-1) = -a_W;

end

% Steady state solution

T_2  = T_inf + Q/(4*pi*h*R_2^2);
T_1  = T_2 + (Q/(4*pi*k))*(1/R_1 - 1/R_2);
T_SS = T_1 - (T_1 - T_2)/(1/R_2 - 1/R_1)*(1./r - 1/R_1);

% Transient solution

T = T_inf*ones(N_r+1,1);
tol = 1; % deg. C
for p = 2:N_t
    T(:,p) = A\(T(:,p-1) + F); % Solve system of equations using iteration
    if max(abs(T(:,p)-T_SS')) < tol
        fprintf('Steady state reached at %6.2f hours. \n\n', p*dt/3600)
        N_t = p;
        break
    end
end
t = 0:dt:dt*(N_t-1);

N_steps = 10; % Number of profiles and times to plot
markers = ["-g","-b","-r","--g","--b","--r",...
           ":g",":b",":r","-.g","-.b","-.r"];
```

```
% Plot out temperature profiles at N_step times

fig1 = figure('Name','1-D Spherical, Transient Conduction Profiles',...
             'Units','normalized','Position',[0 0.5 0.5 0.35]);
xlabel('Radius (m)')
ylabel('Temperature (deg. C)')
hold on
p = ceil(linspace(1,N_t,N_steps));
for i = 1:N_steps
    plot(r,T(:,p(i)),char(markers(i)),'LineWidth',1,...
         'DisplayName',sprintf('%6.1f',t(p(i))/60));
end
plot(r,T_SS,'--k','LineWidth',2,'DisplayName','\infty')
lgd = legend('show','Location','northeast');
title(lgd,'Time (min)')
hold off

% Plot out temperature response at N_step locations

fig2 = figure('Name','1-D Spherical, Transient Conduction Response',...
             'Units','normalized','Position',[0 0 0.5 0.35]);
xlabel('Time (min)')
ylabel('Temperature (deg. C)')
hold on
p = ceil(linspace(1,N_r,N_steps));
for i = 1:N_steps
    plot(t/60,T(p(i),:),char(markers(i)),'LineWidth',1,...
         'DisplayName',sprintf('%6.3f',r(p(i))));
end
lgd = legend('show','Location','northeast');
title(lgd,'Location (m)')

% Plot Experimental Data
exp_data_A = xlsread('exp_data_B');
exp_time = xlsread('time_exp');

plot(exp_time,exp_data_A(:,1),'k*',... % data1 = 0.03m
    exp_time,exp_data_A(:,2),'k--',... % data2 = 0.05m
    exp_time,exp_data_A(:,3),'ko','LineWidth',1,'LineWidth',1,'LineWidth',1) % data3 =
0.06m
```

```
Steady state reached at   2.03 hours.
```





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Appendix M: User Manual (Assumptions for a Successful Design)

1. Surrounding Environment

Weather data provided by local weather station is utilized in Climate Consultant software to obtain usable climate data shown in Figure 1.

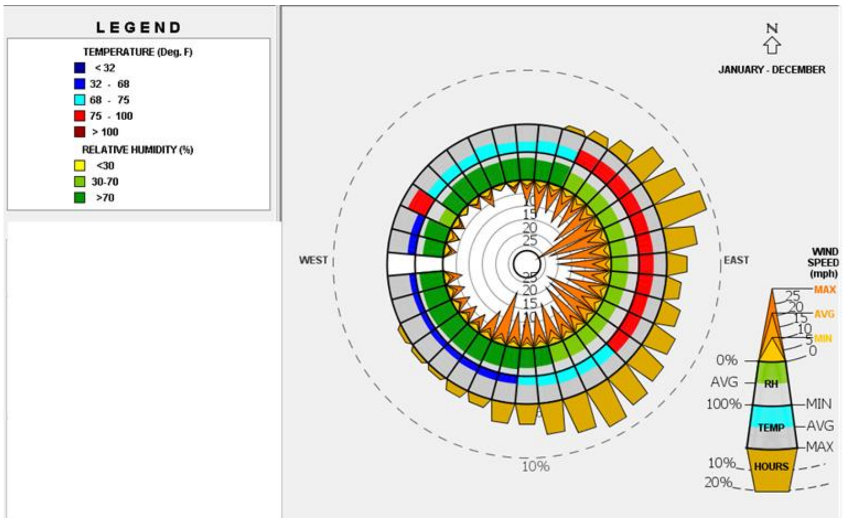

Figure 1. Climate Consultant results from input of Same, Tanzania weather data to determine wind speed and directions.

The results from Climate Consultant illustrate the direction of the wind is moving primarily from Southeast to Northwest with wind speeds ranging from 0 to 25 mph.

Assume that the building is only shaded by the overhangs provided in the design and no larger objects in the local environment affect shading patterns (ie: buildings, vegetation, trees, geographical landforms) in order to avoid unintentional or indirect heat gains and losses. Figure 2 illustrate these assumptions towards a simplified model.

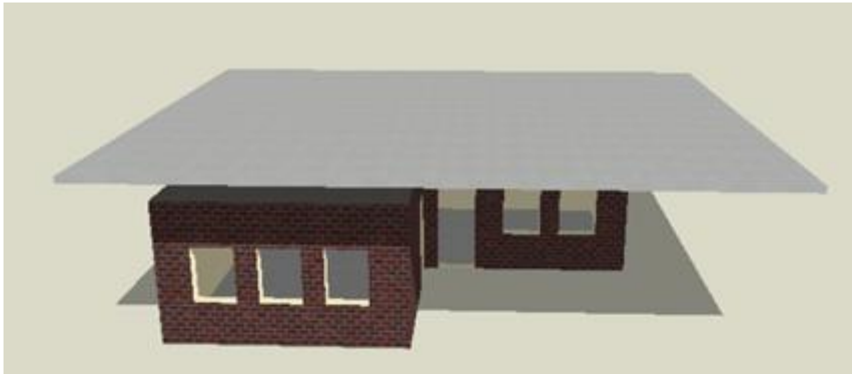

Figure 2. Rendered DesignBuilder dormitory module to study shading strategies and heat gains.

2. Building Envelope

2a. Windows and Openings

In a naturally ventilated building, ventilation is provided by natural forces such as wind-induced pressure differences or temperature-induced differences in air density. Air is introduced into the space through intentional openings in the building envelope. Rule of thumb calculations were completed in order to assure that the building modules met the cross-ventilation standard seen in Figure 3, as well as the window open area standard seen in Figure 4.

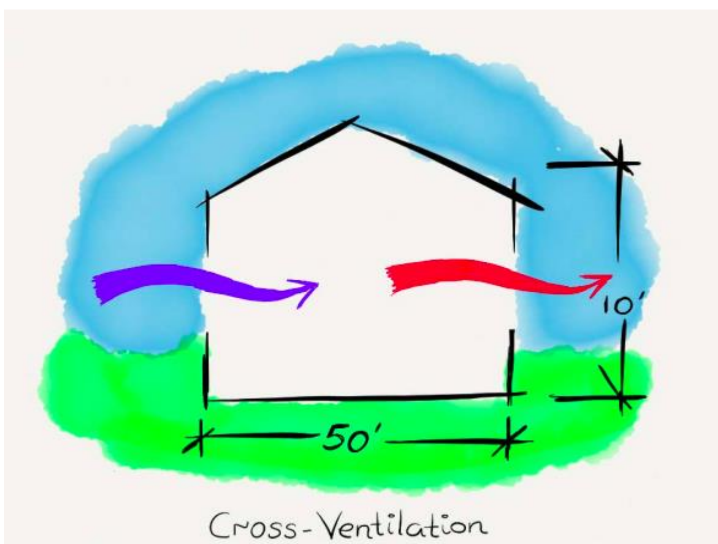

Figure 3. 5:1 Rule for maximizing cross-ventilation (ARUP).

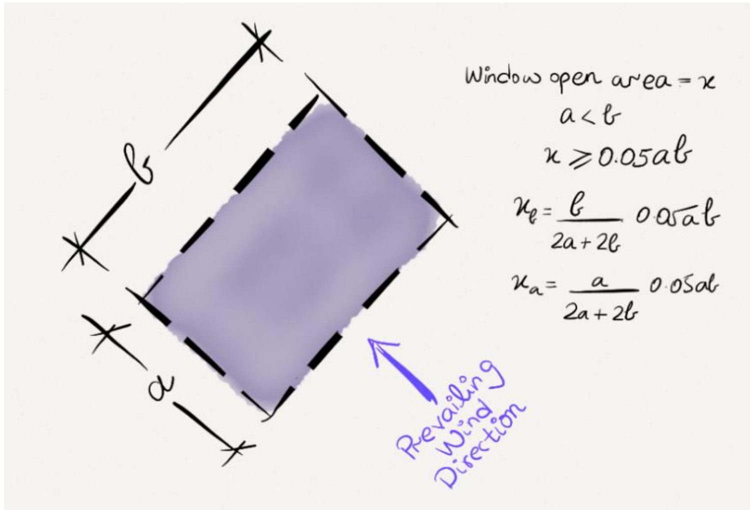

Figure 4. Window Open Area Rule of Thumb (ARUP).

2b. Assumptions

Windows are operable. User opens and closes their window via shutters; no glass is used. This is realistic to what will be implemented in the actual construction.

2c. Applications

Medium Load Areas, which are the dormitories and teaching classrooms, will be cross-ventilated and fan-assisted.

2d. Materials

From thermal testing, the mimicked Tanzanian bricks were found to have a much lower density, specific heat, and thermal conductivity than average bricks. The density of these bricks is lower than that of the actual bricks made in Tanzania, because in Tanzania they have the ability to apply much more compressive force. Denser bricks must be used for the wall materials than those that were made by Cal Poly CAED students.

The roof of the building must act as a good radiation shield. Therefore the roof should be painted with white, reflective paint. Figure 5 shows how varying the roof material and color can improve the operation temperature of the building.

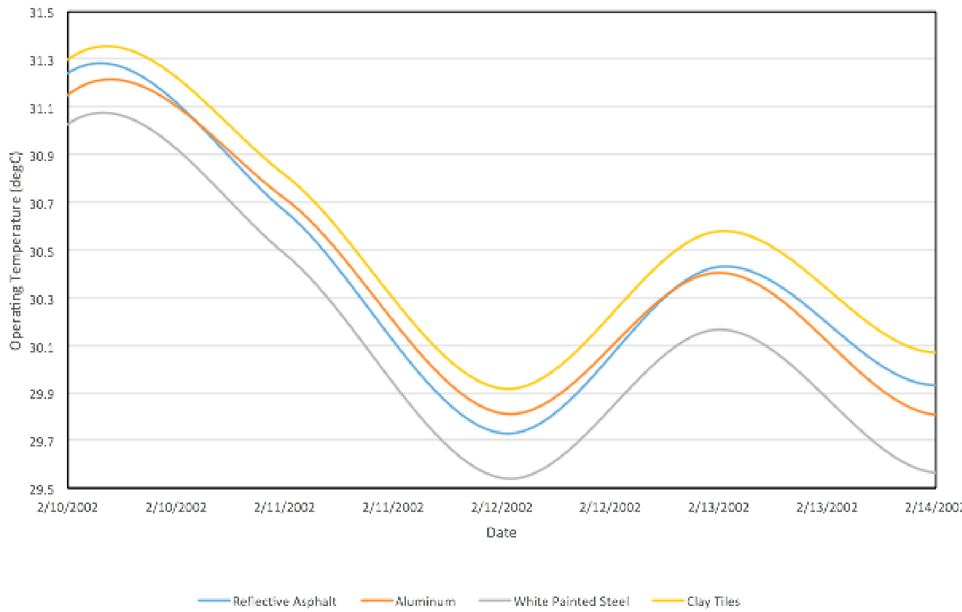

Figure 5. DesignBuilder case study showing various roofing materials.

3. Loads and Ventilation

3a. Natural Ventilation

Wind tunnel testing was conducted to determine the relative indoor air speeds in each room in the dormitory module at several building orientations. The tests were conducted with a scaled model at a scaled wind speed that represented an actual wind speed of 2 mph. The model was constructed of plexiglass which was well suited to model the scaled roughness of an actual building envelope. The results give a percentage of outdoor wind speed that can be used to directly compare rooms and orientations. The percentages are greater than 100% due to the increase wind speed through and around the building that resulted from the model covering a portion of the wind tunnel cross section.

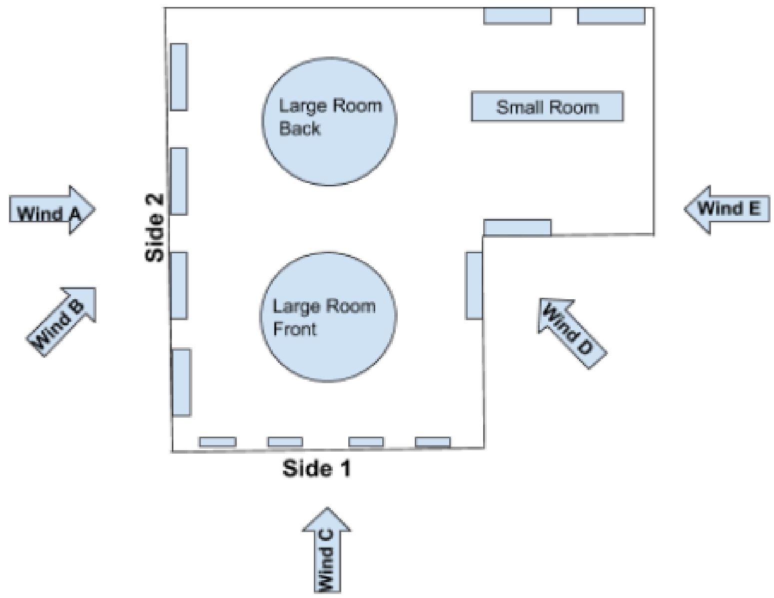

Figure 6. Dormitory model schematic used to interpret wind tunnel results.

Table 1. Wind Tunnel Study Results

Pitot Location	Wind Direction	Scaled Velocity (mph)	Percent of wind speed
Large Room Back	C	2.07	107%
Large Room Back	B	1.97	102%
Large Room Back	D	2.35	121%
Large Room Front	A	2.13	110%
Large Room Front	E	2.38	123%
Small Room	E	2.36	122%
Actual Wind Velocity	No Model	1.93	100%

3b. Suggestions based on Results

From the wind tunnel test results, the dormitory building side with the door should be facing the primary direction of the wind, to maximize cross-flow ventilation.