Solar Decathlon Africa - Team OCULUS

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Design of the Mechanical Systems for Team OCULUS in Solar Decathlon Africa 2019

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Abstract

The Solar Decathlon is an international, net-zero building design competition that seeks to raise awareness about the importance of energy efficiency and sustainability. Competing teams are tasked with designing, building, and showcasing a residential structure that meet the requirements of the competition's ten contests. Team OCULUS, comprised of college students from Worcester Polytechnic Institute in Worcester, MA, two Moroccan universities, and one Nigerian university, will compete in the Solar Decathlon Africa 2019 which will take place in Ben Guerir, Morocco in September 2019. Team OCULUS is divided into smaller teams based on student expertise. This report details the work of the Mechanical Team of Team OCULUS. The Mechanical Team was responsible for the design of the heating, ventilation, and air-conditioning (HVAC) system, the sizing and selection of mechanical equipment and appliances, the design of the photovoltaic system, and the development of a whole-house energy balance. These tasks led to the design of a compact mechanical unit to save construction time on site and reduce interior floor space. There were also miscellaneous tasks assigned to the Mechanical Team, such as designing the lighting system for the building and the selection of an electric car to be used in the competition. As a smaller group of a larger team, the Mechanical Team collaborated and communicated regularly with other students to ensure a coordinated and compatible design.

Keywords: Solar Decathlon, net-zero, building design, sustainability, energy efficiency, mechanical design, HVAC, Morocco, energy balance, photovoltaic system

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Capstone Design Statement

The goal of this project was to design effective and efficient mechanical systems for the net-zero energy house designed by Team OCULUS to compete in the Solar Decathlon AFRICA 2019. The scope of this project includes design of a photovoltaic (PV) array, design of a building Heating-Ventilation-Air-Conditioning (HVAC) system, selection of appliances, creation of a whole-house energy balance, and coordination of all building mechanical elements.

A successful mechanical design for the OCULUS building would provide sufficient energy to power the mechanical system, lighting, water heating, and all other appliances. Furthermore, the HVAC system would have to provide ample cooling and heating to keep the interior temperature and humidity of the building within the competition guidelines. Beyond these basic design goals, our team weighed economic and constructability considerations, and applied application of engineering principles within our scope of the project.

Our team made several design decisions to reduce the cost of our design. For example, originally designed the mechanical unit frame out of welded tubular steel. To make the unit more easily constructible, we decided to construct the frame of the unit out of extruded aluminum profiles and connection pieces. Through the company FramingTech, a manufacturer of such profiles and connections, we were able to negotiate an educational discount on these materials, making this design decision more economically viable than welded tubular steel. After reviewing the competition guidelines for appliance performance, we selected appliances that would be available in Morocco with the help of our Moroccan teammates. This decision allowed the team to avoid unnecessary shipping costs for locally selected appliances and interconnection issues with American appliances and the Moroccan electrical standards.

Our team designed many of the elements of this project to be easily constructible. To reduce construction time on-site, our team designed a central mechanical module to house the indoor HVAC equipment, the water heater, and several appliances. This module was designed to share a wall with the bathroom to minimize on-site plumbing connections. The module was also designed to host the majority of service entries for the building, including water and electrical supplies. FramingTech products were selected for the mechanical unit frame for their ease of construction. Products from DuctSox, a manufacturer of fabric ducts, were selected for the mechanical system for their easy installation and light weight.

Collaboration with other members of Team OCULUS was a critical part of this project. Much like any large scale architectural project, the mechanical design team had to negotiate spacial and aesthetic considerations with the architectural designers and structural team. Moreover, the building envelope design directly influenced the thermal heat gain within the space. The mechanical design team was made up of two architectural engineering students within the mechanical track and one dual major civil and mechanical engineering student. This mixture of knowledge allowed the team to both design mechanical elements such as the HVAC system and also structural elements, such as the solar panel framing. In addition, our team worked closely with the plumbing designer on Team OCULUS to ensure that our designs were compatible with their work. During the selection of appliances and equipment, our team collaborated with the Moroccan students on Team OCULUS to ensure our selections were available in Morocco.

Success of Team OCULUS requires extensive teamwork and coordination alongside careful scheduling and project management. The mechanical team had to find a careful balance between taking time to research and optimize systems with producing architectural drawings and construction documents to allow work to move forward within a tight schedule. Communication between Team OCULUS members was perhaps the most critical element due to the ever-changing and shifting nature of the design. To successfully communicate, the team utilized a hierarchical team structure with a designated project manager and team leaders. Furthermore, the team held weekly meetings, used Skype to communicate with Moroccan team members, and utilized Slack, a group communication platform.

Sound engineering principles were employed throughout all aspects of this project. The photovoltaic system design was essential to this project because it determines the amount of energy available for consumption by the building design. After carefully reading the competition rules and performing research on solar panel performance, the team was able to select an efficient panel type and arrangement for the array. We created a spreadsheet to track energy use alongside generation to ensure the building would never consume more energy than the solar array would generate over the course of the competition period. Professional design and engineering softwares were used in this project. DesignBuilder, an energy modeling software, was used to verify our thermal load calculation. RISA, a 3D structural analysis software, was used to analyze the structural integrity of the mechanical unit frame.

When approaching the HVAC design, the team first gathered weather data from the site of the competition, Benguerir, Morocco. With this weather data, the team performed a load calculation following the American Society of Heating, Refrigeration, and Air-conditioning Engineers' (ASHRAE) industry standards to determine thermal heat gain within the house. We used the total thermal heat gain to size the HVAC equipment for the mechanical design. To stay aligned with the goals of the OCULUS house, the HVAC system needed to be highly efficient, provide sufficient cooling and air distribution to maintain internal comfort levels, and minimize floor space. Upon researching HVAC system efficiencies and discussing our findings with an HVAC professional, the team found that a ducted split system would meet these requirements the most effectively out of the systems we considered.

Beyond the solar array and HVAC system, there were a number of smaller miscellaneous design challenges the team faced. These included lighting design, research and selection of an electric car and assisting with plumbing design.

The Solar Decathlon Africa 2019 competition is centered around social impact and sustainability. Raising awareness, and showcasing, net-zero sustainable building design is one of the goals of the competition. During the competition, visitors from around the world come to tour and learn about the competing teams' finished buildings. The competition also scores each competing team on their communication and social awareness efforts. Team OCULUS decided that our design would be marketed as a catalyst for ecotourism in several countries in Africa. Using this model, our design would help to educate ecotourists and the hosting communities on energy efficient, sustainable building design. Other members of Team OCULUS have been working to promote our design work to the public as part of the competition's market appeal contest. Our team has also presented to several groups throughout the project's duration, informing them of our ideas and work towards energy efficiency and sustainability. Furthermore, Team OCULUS has been working with the competition organizers to leave our building at the competition-site as a lasting showcase of our design.

The competition scores competing teams on sustainability in addition to market appeal and communications and social awareness. As a result, our team worked to ensure that our design incorporated principles of sustainability. For example, we designed the central mechanical unit to be pre-assembled, minimizing on-site building material waste and imperfections. We selected materials, such as the bamboo panel enclosure for the mechanical, that had less negative impacts on the environment than more traditional building materials. The bamboo panel enclosure products we selected are made from a fast-growing bamboo species that are sustainably harvested and shipped using low emissions transportation methods. These products are also very durable and built to last, minimizing the need for material replacements over time.

While the competition design challenge does not directly reflect a full professional design experience, it incorporated aspects of professional responsibility and engineering ethics. The competition outlines several requirements for on-site damage mitigation, student safety, and waste and contamination. Competition officials require teams to follow standardized building codes to minimize public health and safety risks for visitors touring our house. The competition rules require all teams to self-report any known rule or building code infractions. Our team routinely discussed our work with professionals and faculty to identify potential errors and warranties in our design. During the development of Team OCULUS's marketing strategy of ecotourism, we considered possible ethical drawbacks, such as the possibility of our design attracting wealthy, privileged tourists at the expense of hosting community.

Executive Summary

The Solar Decathlon Africa 2019 (SDA 2019) is an international competition for college students to design and build a net-zero energy residence. Competition officials judge the competing designs based on ten contest categories: architecture, engineering & construction, market appeal, communications & social awareness, appliance performance, home life & entertainment, interior comfort conditions, sustainability, electrical energy balance, and innovation. The competition will take place for the first time on the African Continent and will be hosted in Ben Guerir, Morocco in September 2019.

Students from Worcester Polytechnic Institute (WPI) in Worcester, MA, USA, have partnered with students from two Moroccan universities and students at a Nigerian university to form Team OCULUS that will compete in the SDA 2019. Based on students' expertise, the WPI team divided into smaller groups to work on specific aspects of the project design. The Mechanical group of Team OCULUS was responsible for the design of the heating, ventilation, and air-conditioning (HVAC) systems, the selection of appliances and mechanical equipment, the design of the photovoltaic systems, and the development of a whole-house energy balance.

To design the HVAC system, our team gathered weather data from EnergyPlus, and material properties of the building envelope from students on Team OCULUS working on this part of the design. Utilizing competition rules, our team completed a thermal load calculation using the American Society of Heating, Refrigeration, & Air-conditioning Engineers' (ASHRAE) cooling load temperature difference (CLTD) method (American Society of Heating, Refrigeration, & Air-conditioning Engineers, 1980). After verifying this calculation with simulation software, we selected HVAC equipment to meet the house's thermal load and utilized an innovative duct system. Our team selected appliances for our design based on the competition rules that outline specific performance requirements for each appliance. To save construction time on-site and floor space within the house, we designed a central mechanical module to house the HVAC equipment and several appliances, as well as plumbing equipment, a toilet, and an electrical panel. This module will also provide counter space in the kitchen.

To ensure that our design could generate the most electricity within competition guidelines, we researched photovoltaic system manufacturers in order to select the most efficient brand of solar panels. Our team then calculated the optimal tilt angle for the panels using simulation software in conjunction with local weather conditions. We also designed a support frame for the solar panels. Finally, our team created an energy balance spreadsheet to track all of the energy consumption and generation in our design and to ensure that our design was net-zero and met competition requirements.

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1. Introduction

The Solar Decathlon is a university-level competition created by The United States Department of Energy. The competition was first hosted on the national lawn in Washington D.C. in 2002 and featured twenty university teams showcasing net-zero energy houses. The name “Solar Decathlon” comes from the competition’s use of solar energy and the ten contest categories which the competition judges use to score each house (see Appendix A). Since 2002, 141 teams from six continents have competed in the solar decathlon (U.S. DOE Solar Decathlon, 2017). Ultimately, the goal of these competitions is to promote innovations in solar technology and spread awareness about the potential of solar energy.

Solar Decathlon AFRICA 2019 is the first ever Solar Decathlon hosted on the African Continent. With a high amount of annual sunshine and established projects such as the Noor Power Station in Ouarzazate, Morocco shows great potential to become a solar power juggernaut. The host organization for Solar Decathlon AFRICA is Institut de Recherche en Energie Solaire et en Energies Nouvelles (IRESEN). IRESEN is a Moroccan organization which conducts research in solar technology and educates Moroccans about the potential of transitioning to solar energy as a primary source (IRESEN, 2019). The competition-site is located at The Green Energy Park in Ben Guerir next to IRESEN’s existing solar research facility.

The goal of this competition is to raise awareness of sustainable housing, and sustainability, in general, and moreover to highlight the benefits of using renewable energy in everyday life and adopting a more environmentally conscious way of living. It also encourages students to think creatively to design, construct, and implement the available technologies in their house project. The competition is expected to have an impact on the environmental, social, and economic nature in Morocco, and potentially in the continent of Africa. The objective of the competition is to promote the use of the natural resources and to aid the acceleration of integrating renewable energy and sustainable living in Africa.

The Architectural Engineering program at WPI submitted a proposal in the Spring of 2018 after IRESEN released a request for proposals (RFP) in December 2017. The effort was led by Professor Steven Van Dessel and Professor Tahar El-Korchi. Upon IRESEN's approval of the proposal, Van Dessel formed Team OCULUS to design a house for Solar Decathlon AFRICA 2019. Team OCULUS is comprised of students from WPI, ENSAM and ENSIAS. The project team was broken up into smaller groups to tackle different aspects of the design challenge. Our group is responsible for design of the mechanical systems.

1.1 Problem Statement

Team OCULUS is presented with the challenge of designing and building a net-zero building that implements innovative technology, while maintaining an aesthetically pleasing appearance that also blends in with the local environment of Morocco. For the mechanical aspect of this project, the building should be powered through the use of solar panels with a size no larger than 10kW rated DC capacity. The team will be judged upon the implementation of low-energy mechanical systems and sustainable appliances, as well as the electrical energy consumption and the innovation of the systems.

Another aspect of the Solar Decathlon competition is the purpose the building will have after the contest. The OCULUS is designed to be highly customizable to accommodate any needs the user might have. This is because the designed purpose of the house is to be used for ecotourism. Ecotourism is defined as "responsible travel to natural areas that conserves the environment, sustains the well-being of the local people, and involves interpretation and education". This house aims to host tourists without having a footprint in the Moroccan environment in terms of energy usage and water waste. It also will have implemented elements from the Moroccan and sub-Saharan cultures and art to promote cultural awareness and respect. The main goal of team OCULUS is to introduce ecotourism and its principles to the tourism industry in Morocco.

1.2 Design Solution

To approach the design of the building mechanical system, our team started by determining the requirements of the Solar Decathlon competition. The rules of the competition layout interior lighting level requirements along with temperature and humidity. The Solar Decathlon contest number 8 is the health and comfort contest and details the requirements for indoor conditioning. Sensors will be used to measure certain criteria for evaluation and scoring. (see Appendix A for further details). There are also a number of appliances required for the house to successfully complete the competition challenges. The Solar Decathlon contest number 5 of the rule book is the appliance contest. To receive all the allowable points for the contests, the solar house must have the following: refrigerator, freezer, clothes washer, dryer, dishwasher, oven, cooking surface, standard home electronics including a television, and shower (see Appendix A for Appliance subcontest scoring).

Table 1-1: Criteria used for the Solar Decathlon Africa Comfort contest.

Subcontest	**Rules**
Temperature	Maintain indoor dry-bulb air temperature between 22 and 25°C
Humidity	Maintain indoor air humidity between 45% and 55%
Light Level	Maintain indoor light level above 300 lux

The main points of focus when designing a solution were 1) system efficiency, 2) minimizing space, 3) quality of system and 4) simplicity of installation. Based upon the format of the competition, the system will have limited electricity and must be installed in a short period of time. However, there are also a large number of requirements for the system and the Moroccan climate requires a robust cooling system to reach the interior comfort requirements. In order to minimize the space taken up by mechanical systems, the team had to carefully coordinated all system components including appliances, HVAC systems and plumbing fixtures. For each component, the energy usage, water usage, cost and weight were considered and tracked. Additionally, the whole system is designed to be easily installed as one unit and hooked up at a single point to minimize on-site labor.

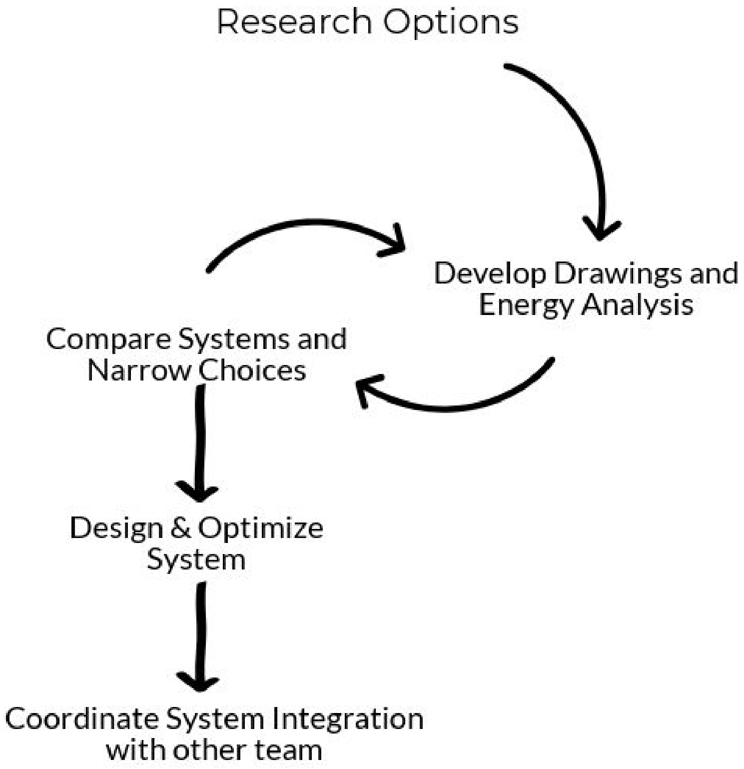


Figure 1-1: Design development workflow.

1.2.1 Location and Weather

Morocco features a mixture of climates including temperate coastal regions, tall mountains and the arid Saharan desert. Typically, Morocco does not receive large amounts of rainfall and receives a high annual solar radiation which makes it a great location for using photovoltaic panels. The site of the competition is in Ben Guerir, a small city 60 km (37 miles) north of Marrakech. Mohammed VI Polytechnic University is a prestigious university located in Ben Guerir along with one of IRESEN's solar research facilities. This region of Morocco is located between the cooler coastal region and higher elevation mountains and is characteristic of dry desert like conditions.

Properly designing a building for this region requires accurate weather information. The team used a software called Climate Consultant to analyze weather data from Ben Guerir. This software takes EnergyPlus Weather files (epw) which can be found on the EnergyPlus online database and performs data analysis and presents results in a graphical format. The climate conditions that were of the greatest importance to our team were dry bulb temperature and humidity (see Figure 1-2). During the competition months, the dry bulb temperature typically reaches temperatures close to or above 38°C (100°F) during the middle of the day but cools off significantly at night. Conversely, the humidity spikes in the early morning and drops during the middle of the day. Based on this weather data, our team set design conditions for the peak HVAC loads which are important to the cooling analysis.

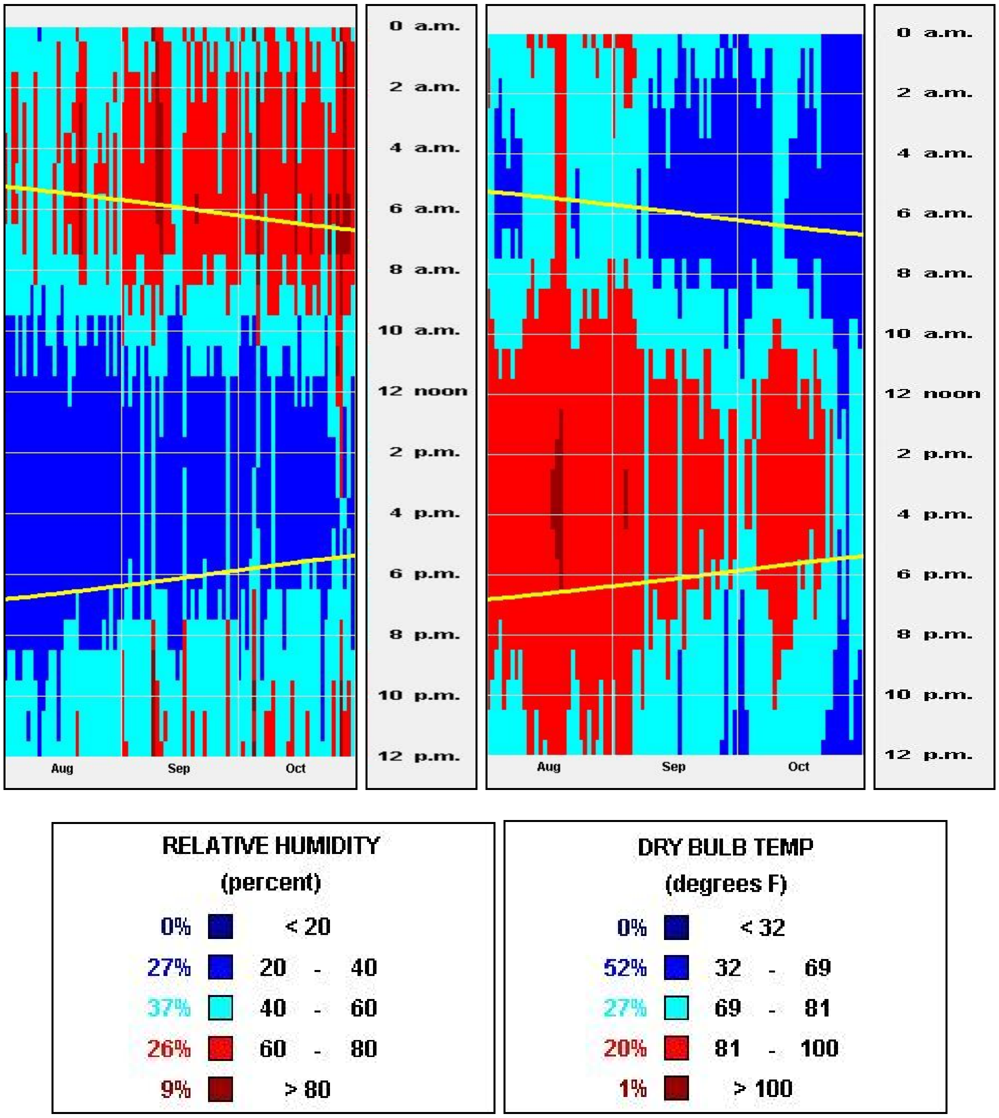


Figure 1-2: ClimateConsultant timetable plots of Ben Guerir weather data for August, September, and October. Color blocks in the plots correspond to a range of average daily dry-bulb temperature and humidity data. The ranges represented by each color are shown in the keys below each plot.

In addition to weather, Team OCULUS considered local architectural styles and Moroccan and African culture. Many of the traditional and vernacular Moroccan architectural concepts minimize energy demand by using passive strategies to reduce heat gain and solar penetration. These strategies include the use of thermal mass, sun shading and light colored exterior finishes (Attia & Geoffrey, 2013). Additionally, popular themes in Moroccan architecture include emphasizing privacy, central courtyards and roof openings, and large flexible areas for dining and hosting guests. Common building materials include colorful patterned tiles, carved wooden trim, wicker, and mudbrick. This research informed our team to better create a solution that was appropriate for the people of Morocco and African in general. Furthermore, this research revealed traditional Moroccan architectural strategies which improve the thermal performance and minimize energy demand. For example, the use of thick mud and brick walls provides a huge thermal mass which is capable of absorbing much of the extreme heat during the day and slowly release it during cooler hours of the night.

1.2.2 Building Shell

The central concept of the OCULUS house is a geodesic style dome with a large skylight perched on the top. This approach minimizes wall to floor area ratio and creates a space which lends itself to natural air movement and ventilation. Furthermore, the idea of an open and moveable floor plan was essential to the building. Several methods were considered to create an open floor plan: use of curtains as moveable partitions, emphasis of multipurpose furniture and minimized spacial footprint of necessary appliances. For the OCULUS house, The use of appliances is mandatory; however, we decided to group them tightly to allow for more open space in the house.

Our team worked alongside the building envelope team to optimize the insulation properties and reduce heat gain through the envelope. The primary considerations when designing the envelope were thermal efficiency, cost and minimizing leakage. Figure 1-3 shows the five layers of the finalized envelope design. The bottom plywood layer provides a sturdy base and an interior finish. The roofing underlayment acts as a vapor barrier and provides waterproofing properties. The nine inches of Rockwool Cavity Rock insulation provide insulation. Furthermore, it is made from recycled materials and has some fire resistance properties. The outermost layer is a wicker facade supported independently by steel rods. Combined, the envelope layers achieve an R value of 38.7 hr.ft^2.F/Btu at 75 degrees Fahrenheit.

The building is built upon a 10 centimeter (concrete slab on grade which acts as a thermal mass. This was an important element to consider when calculating the cooling load.

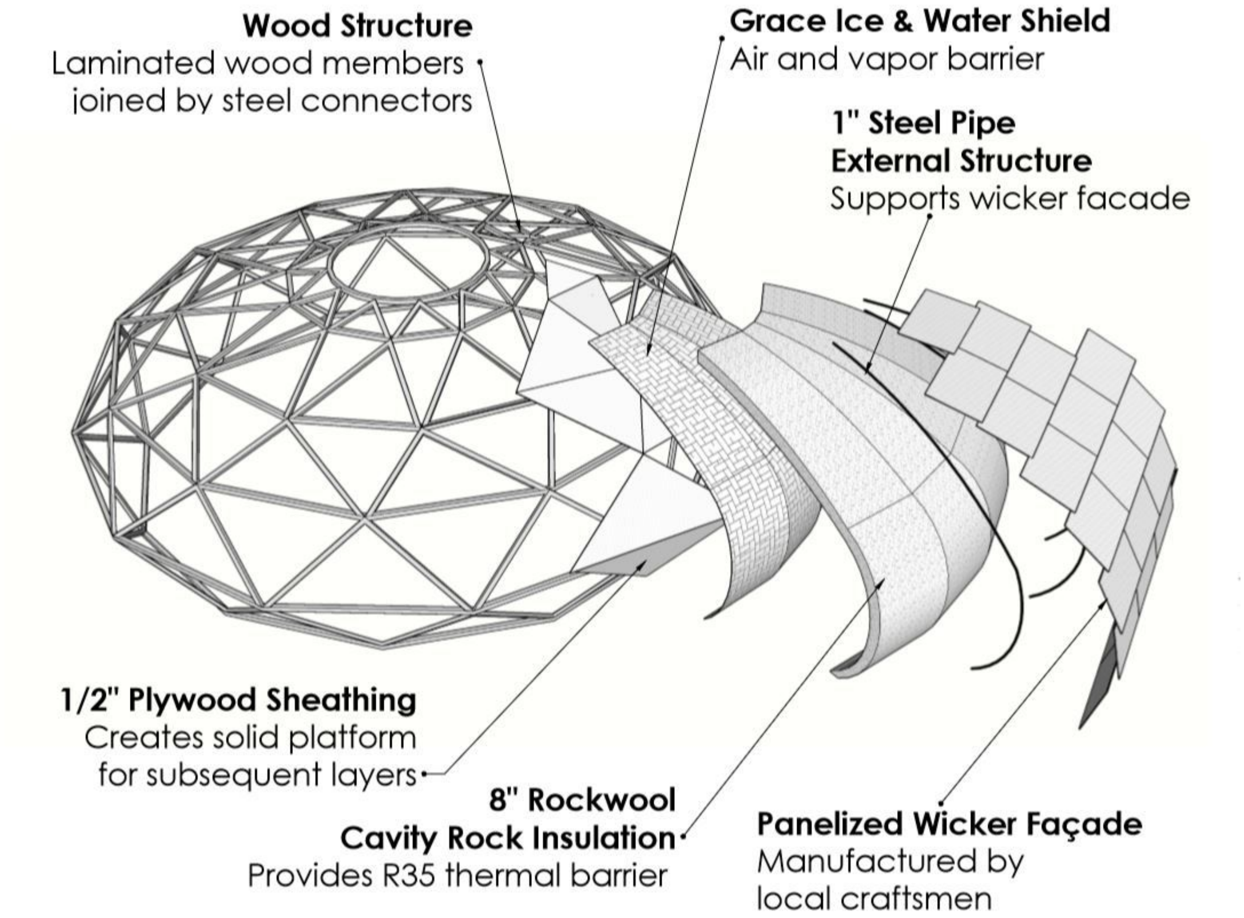


Figure 1-3: Building Envelope of OCULUS structure.

The aspects relevant to the design of mechanical systems are the insulation properties of the envelope, the total volume of inside air, surface area of the building skin and glazing, and the floorplan. The open floor plan influenced the design of the air distribution system. Due to the lack of internal walls, air circulation in the building is easy to achieve without excessive ducts. The high insulation properties of the envelope helps to minimize the total cooling load and reduce the size of the required system. The floor plan also influenced the design and placement of the mechanical unit as to minimize spacial footprint and minimize disturbances to the open space. Based on the non-traditional building materials and the curved geometry of the envelope design, we figured that our design would have low air-tightness. This means that a considerable amount of outside air would permeate through the building envelope to the interior space. This undesirable design characteristic was accounted for in our thermal load calculations as infiltration (see Section 2.1.1).

2. HVAC Design

The Solar Decathlon Africa competition has 10 criteria; each criteria has a contest. HVAC design and climate control pertains to two contests within the Solar Decathlon Africa Rules. Contest 8 (Health & Comfort) outlines the assessment criteria for interior comfort based on temperature, humidity, and lighting intensity, and Contest 9 (Electrical Energy Balance) describes the assessment of our structure's energy usage based on energy performance, performance ratio, and temporary generation-consumption correlation (IRESEN, 2018). The specific scoring guidelines for these contests can be found in Appendix A. Based on these scoring guidelines, we decided on the following design conditions:

Table 2-1: Design conditions based on competition rules and scoring guidelines.

Design Criteria	Value
Indoor DB Temp	22℃ (72℉)
Indoor Relative Humidity	50%

2.1 Thermal Load Design

The purpose of the mechanical system of our house was to ensure that our design meets the competition requirements outlined in the previous section. A load calculation attempts to account for all of the thermal energy exchange between the interior and exterior of the building design. This calculation includes radiative, conductive, and convective heat transfer through windows, walls, roofs, floors, and other elements of the building design. Performing this calculation for extreme conditions allows the designer to effectively size the mechanical system for the structure. In order to perform a load calculation, the designer must know properties of the materials used in the design, as well as details of the design's exterior conditions.

2.1.1 CLTD Calculation

The first step of performing a thermal load calculation was establishing design conditions for the interior and exterior of the building. For the outdoor design conditions, we utilized public domain weather data for Ben Guerir, Morocco from EnergyPlus, a simulation software developed by the U.S. Department of Energy. We utilized the software Climate Consultant 6.0, an open source software that organizes weather data in the EnergyPlus format into graphs and charts, to examine trends and patterns in the weather data. We were ultimately looking for fluctuations in dry-bulb temperature and relative humidity for an average day during the competition month of September, as these are the two criteria that are evaluated during the competition. Appendix B displays the charts and graphs from Climate Consultant 6.0, as well as weather data from ASHRAE for the neighboring municipality of Marrakech, Morocco, that our team used to set the outdoor thermal design criteria shown in the Table 2-2.

Table 2-2: Outdoor design conditions for cooling load calculations based on weather data.

Design Criteria	Value
Outdoor Dry-Bulb Temperature	42℃ (108℉)
Outdoor Relative Humidity	70%

Because the Solar Decathlon Competition Africa 2019 takes place in September, we utilized weather data from this month to simulate the weather during the competition period. We used a conservative design outdoor temperature of 108°F (42.22°C) which was a bit higher than the average recorded high temperature for the month of September. The average relative humidity for the month of September was 50%, but looking at hourly data showed us that humidity fluctuates between approximately 30% and 70% for the average day in September. As a result, we set our design humidity to 70% relative humidity (RH).

The interior design conditions were established based on the competition requirements for internal thermal comfort (see Figures A-02 and A-03). We selected design values for internal dry-bulb temperature and relative humidity that were in the middle of the target ranges outlined by the competition rules. Table 2-3 shows these interior design conditions used in the load calculation.

Table 2-3: Indoor design conditions for cooling load calculations based on competition rules.

Design Criteria	Value
Indoor Dry-Bulb Temperature	23.8℃ (73℉)
Indoor Relative Humidity	50%

Next, we completed a cooling load calculation using the American Society of Heating, Refrigeration, & Air-conditioning Engineers (ASHRAE) Cooling Load Temperature Difference (CLTD) method. For this method we modeled our structure as an octagon with a flat roof, as the CLTD method cannot account for curved geometries. The building envelope team on Team OCULUS provided us with building envelope characteristics and details for us to use in the load calculation. Table 2-4 shows this information.

Table 2-4: Building envelope characteristics for cooling load calculation based on envelope team's design.

Envelope Characteristics	Value
Wall/Roof U-value	0.03 BTU/hr*ft^2*℉ (0.17 W/m^2*K)
Skylight Glass U-value	0.57 BTU/hr*ft^2*℉ (3.24 W/m^2*K)

For internal heat gain calculations, we utilized ASHRAE data from the 2001 ASHRAE Fundamentals Handbook for typical household appliances (American Society of Heating, Refrigeration, & Air-conditioning Engineers, 2001). This data can be found in Appendix C in figures C-01 and C-02. For infiltration, we again used a basic residential ASHRAE formula based on the Sherman and Grimsrud (1980) method. This model includes wind speed, temperature difference, and basic coefficients for stack effect and shelter class. The full thermal cooling load calculation, shown in Figure C-03, yielded a total cooling load of 30,614 Btu/h, or about 2.5 tons. This total was used to size our HVAC split system. A summary of the thermal load calculations can be found in Tables 2-5, 2-6 and 2-7.

Table 2-5: Thermal cooling load of building envelope according to our CLTD cooling load calculation.

Load Portion	Value
Roof	10,950 BTU/H (sensible)
Walls	1,532 BTU/H (sensible)
Floor Slab	1,521 BTU/H (sensible)
Total Envelope Load	**14,003 BTU/H (sensible)**

Table 2-6: Thermal cooling load of building internal heat gains and outside air according to our CLTD cooling load calculation.

Load Portion	Value	
Internal Heat Gains	5,572 BTU/H (sensible)	902 BTU/H (latent)
Infiltration	1,268 BTU/H (sensible)	5,399 BTU/H (latent)
Bathroom Exhaust	660 BTU/H (sensible)	2,811 BTU/H (latent)
Total Internals & Outside Air Load	**7,500 BTU/H (sensible)**	**9,112 BTU/H (latent)**

Table 2-7: Total thermal cooling load of building according to our CLTD cooling load calculation.

Total Sensible Load	**21,503 $\mathrm{BTU/H_s}$**
Total Latent Load	**9,112 $\mathrm{BTU/H_l}$**
Total Cooling Load	**30,614 BTU/H**

Approximately half of the total cooling load (14,003 BTU/h, sensible) was due to conductive heat gain through the building envelope. A majority of this building envelope load (10,950 BTU/h, sensible) was due to sensible conductive and radiative heat gain through the circular skylight. This informed us that the skylight dome of our structure was a critical component of the design and required careful attention. As a result of the load calculations, we informed the envelope team that a controllable shading device would be beneficial. The internal sensible heat gains from appliances, equipment, lights, and people (5,572 BTU/h, sensible) were a significant portion of the remaining cooling load. This indicated to us that it was important to select energy efficient appliances and equipment to reduce heat gain inside the structure. The majority of the latent cooling load (8,210 BTU/h, latent) came from outdoor air entering the building due to bathroom exhaust and infiltration. The latent portion of the cooling load accounts for the moisture in the air and gives an indication of the dehumidification required in the space. This led us to examine the latent capacity of the HVAC system to make sure that our design could effectively control internal humidity independently of temperature. While lowering the fan speed on an adequately sized HVAC system for this scenario seemed to cover the dehumidification capacity, we discovered there maybe need for humidification at certain hours of the day. This could be achieved by simply using a plug-in humidifier.

Because the weather data indicated that heating might only be required for a few hours a day, if at all, we decided to install electric heat within our HVAC split system. While a heat pump system would be more energy efficient than an electrical resistance heat system, the high SEER value system that we ended up selecting for our design did not come with the option to include a heating heat pump system. Our team did not find an economically viable mechanical system that was capable of energy efficient cooling and heating using a heat pump. Because most of the energy consumed by the HVAC system would be for cooling purposes, we decided that a system with a high cooling efficiency and a slightly lower heating efficiency would be acceptable.

2.1.2 Cooling Load Verification with Simulation Software

To verify our CLTD cooling load calculation, we employed the software DesignBuilder which utilizes EnergyPlus weather data to produce detailed simulations. We modeled our structure as a dodecagon, following the segmented floor structure, with a slanted roof and flat skylight.

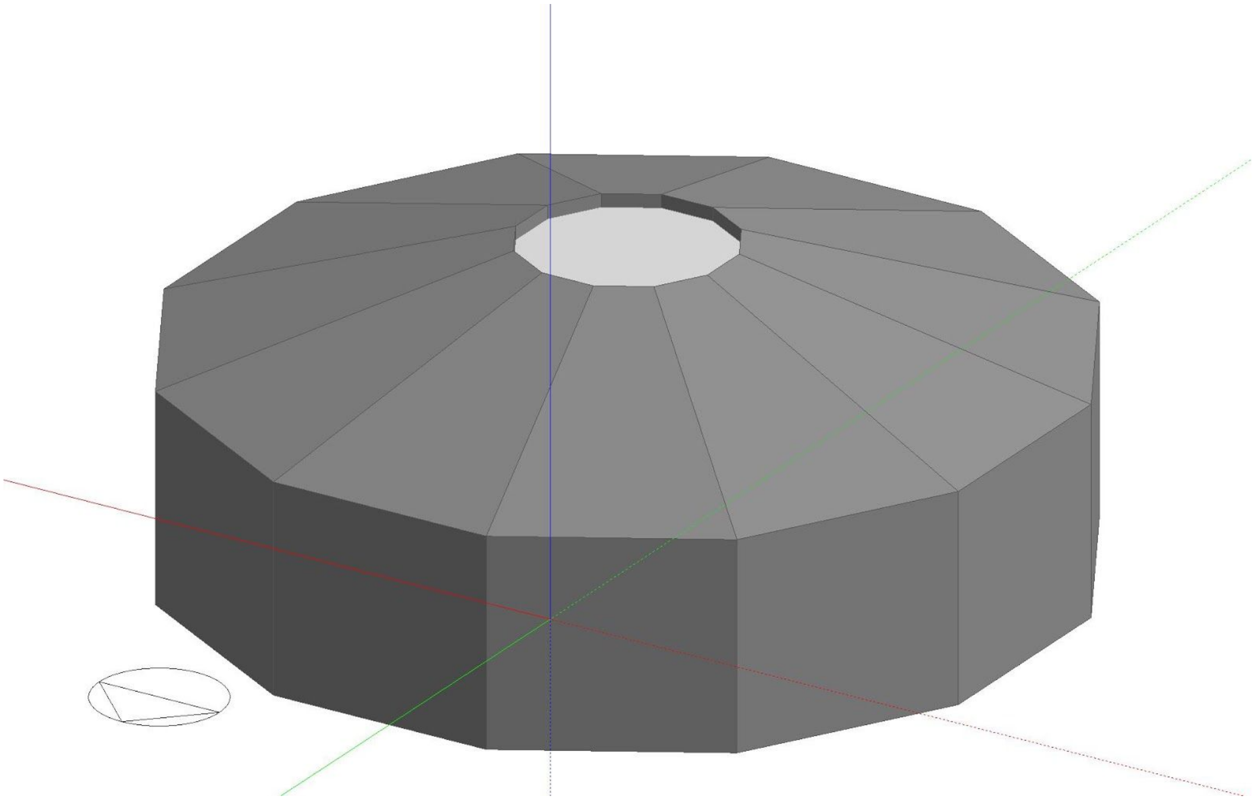
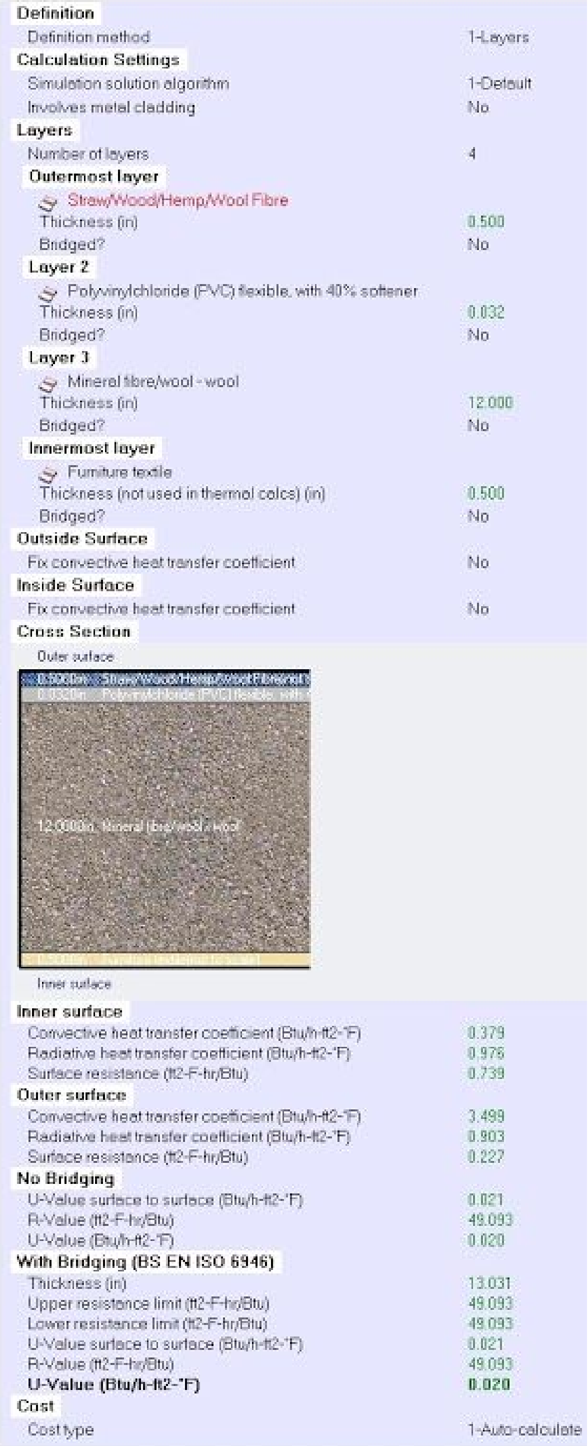


Figure 2-1: Our DesignBuilder geometric model.

Leaving the human activity settings as a default (office work), we adjusted the construction of the model to the following settings:

Wall & Roof:



Definition	
Definition method	1-Layers
Calculation Settings	
Simulation solution algorithm	1-Default
Involves metal cladding	No
Layers	
Number of layers	4
Outermost layer	
Straw/Wood/Hemp/Wool Fibre	
Thickness (in)	0.500
Bridged?	No
Layer 2	
Polyvinylchloride (PVC) flexible, with 40% softener	
Thickness (in)	0.032
Bridged?	No
Layer 3	
Mineral fibre/wool - wool	
Thickness (in)	12.000
Bridged?	No
Innermost layer	
Furniture textile	
Thickness (not used in thermal calcs) (in)	0.500
Bridged?	No
Outside Surface	
Fix convective heat transfer coefficient	No
Inside Surface	
Fix convective heat transfer coefficient	No
Cross Section	
Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.379
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.739
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	3.499
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.903
Surface resistance (ft2-F-hr/Btu)	0.227
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.021
R-Value (ft2-F-hr/Btu)	49.093
U-Value (Btu/h-ft2-°F)	0.020
With Bridging (BS EN ISO 6946)	
Thickness (in)	13.031
Upper resistance limit (ft2-F-hr/Btu)	49.093
Lower resistance limit (ft2-F-hr/Btu)	49.093
U-Value surface to surface (Btu/h-ft2-°F)	0.021
R-Value (ft2-F-hr/Btu)	49.093
U-Value (Btu/h-ft2-°F)	**0.020**
Cost	
Cost type	1-Auto-calculate

Floor:

Definition	
Definition method	1-Layers
Calculation Settings	
Simulation solution algorithm	1-Default
Involves metal cladding	No
Layers	
Number of layers	3
Outermost layer	
EPS Expanded Polystyrene (Standard)	
Thickness (in)	4.000
Bridged?	No
Layer 2	
Cast Concrete	
Thickness (in)	8.000
Bridged?	No
Innermost layer	
Linoleum	
Thickness (in)	0.250
Bridged?	No
Outside Surface	
Fix convective heat transfer coefficient	No
Inside Surface	
Fix convective heat transfer coefficient	No
Cross Section	
Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.060
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.966
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	3.499
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.903
Surface resistance (ft2-F-hr/Btu)	0.227
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.064
R-Value (ft2-F-hr/Btu)	16.861
U-Value (Btu/h-ft2-°F)	0.059
With Bridging (BS EN ISO 6946)	
Thickness (in)	12.250
Upper resistance limit (ft2-F-hr/Btu)	16.859
Lower resistance limit (ft2-F-hr/Btu)	16.859
U-Value surface to surface (Btu/h-ft2-°F)	0.064
R-Value (ft2-F-hr/Btu)	16.859
U-Value (Btu/h-ft2-°F)	**0.059**
Cost	
Cost type	1-Auto-calculate

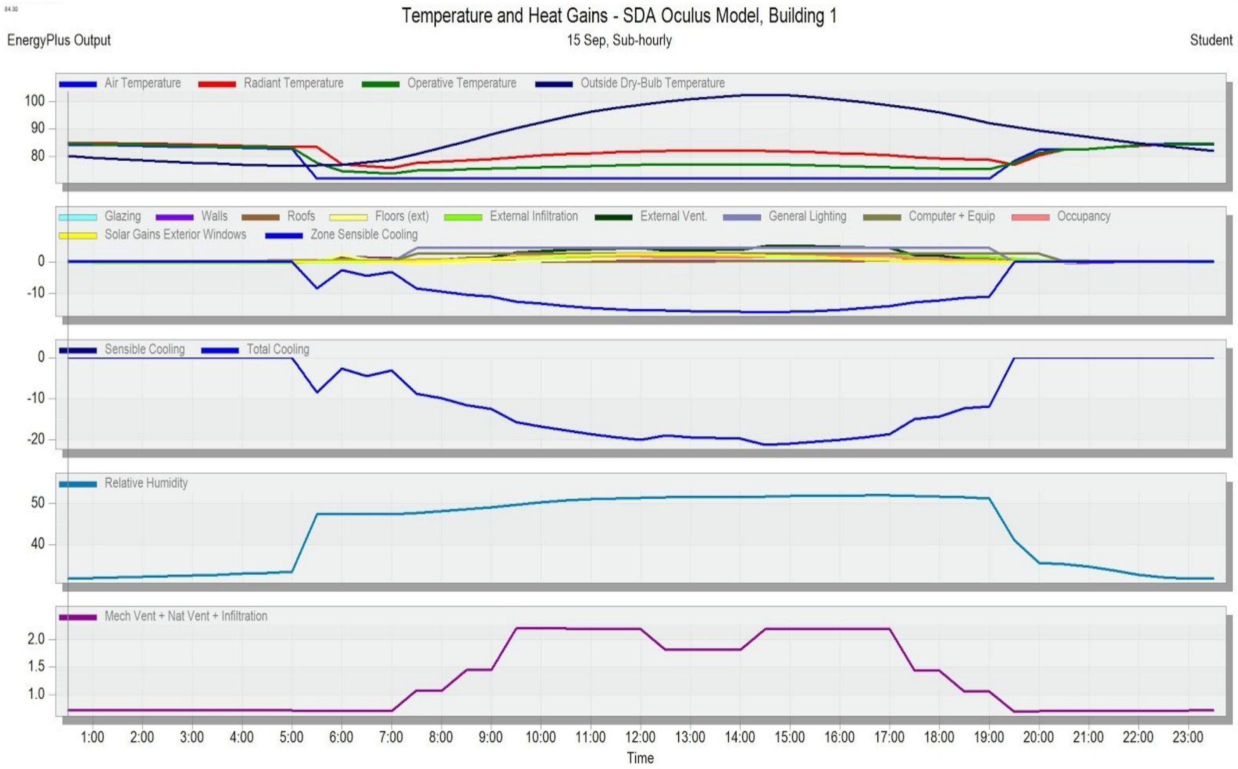
Figure 2-2: DesignBuilder settings for the walls and roof of our model.

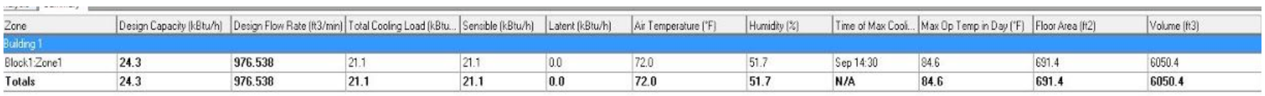
Glazing (skylight):

General	
OCULUS Glazing	
Category	Project
Region	General
External Glazing	
Glazing	Trp LoE Film (55) Clr 6mm/13m Air
Frame construction	Aluminium window frame (with thermal break
% Glazing area opens	0
Internal Glazing	
Glazing	Project internal glazing
Frame construction	Painted Wooden window frame
% Glazing area opens	20
Roof Glazing	
Glazing	Trp LoE Film (55) Clr 6mm/6mm Air
Frame construction	Aluminium window frame (with thermal break
% Glazing area opens	0
External Shading	
Detailed Shading Data	
Window shading	No
Roof window shading	No
Local shading	No

Figure 2-3: DesignBuilder settings for the glazing of our model.

Using these settings, we ran a cooling load simulation for the building. The results are shown in Figure 2-4:





Zone	Design Capacity (kBtu/h)	Design Flow Rate (ft3/min)	Total Cooling Load (kBtu...	Sensible (kBtu/h)	Latent (kBtu/h)	Air Temperature (°F)	Humidity (%)	Time of Max Cooli...	Max Op Temp in Day (°F)	Floor Area (ft2)	Volume (ft3)
Building 1											
Block1:Zone1	**24.3**	**976.538**	21.1	21.1	0.0	72.0	51.7	Sep 14:30	84.6	691.4	6050.4
Totals	**24.3**	**976.538**	**21.1**	**21.1**	**0.0**	**72.0**	**51.7**	**N/A**	**84.6**	**691.4**	**6050.4**

Figure 2-4: Results of our DesignBuilder cooling load simulation.

The resulting total cooling load simulation of 21.1 kBtu/h (21,100 Btu/h) was lower than the result from our CLTD cooling load calculation of 30,614 Btu/h. This difference is due to the fact that our DesignBuilder model does not include the outside air load from the bathroom exhaust and generous infiltration. This difference is approximately equal to outside air load shown in Table 2-4. As a result we believe that our CLTD load calculations are accurate and suitable for sizing our HVAC system.

2.2 System Selection

There are many available options and configurations for a HVAC system and each option has benefits and drawbacks. Given the cooling load calculation along with the primary design goals of the OCULUS house our team weighed the benefits of each system. Efficiency was the most important factor when considering systems. Our team began by researching the efficiency measurement used to describe HVAC equipment.

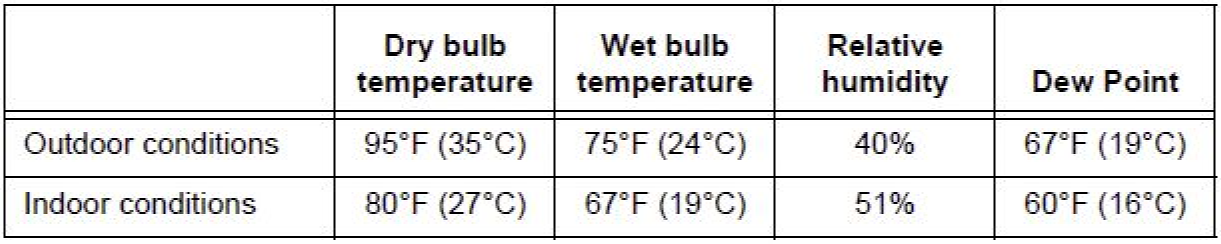
There are three primary efficiency ratings assigned to HVAC equipment available on the market. These are the Seasonal Energy Efficiency Rating (SEER), Energy Efficiency Rating (EER), and Coefficient of Performance (COP). COP is the simplest measurment of these; it is a unitless ratio of power output to power input, both measured in watts (see Figure 2-5). The EER is the ratio of cooling power generated, measured in BTU, to the electrical energy used, in watt-hours (see Figure 2-6). The units of EER are BTU/W/h. When measuring the EER, a standard set of testing conditions are used. These are typically an outdoor dry bulb temperature of 95°F and a humidity of 40% and an indoor air temperature of 80°F and a humidity of 51% (see Figure 2-7). The SEER values of a system are similar to the EER but instead of one set of test conditions the SEER represents the performance of the system averaged over a full season (see Figure 2-8). To achieve this, test conditions ranging from an outdoor temperature of 82°F to 95° are used. The United States Department of Energy has standardized this test to allow buyer to compare perspective system options (Power Knot, 2011). Since the SEER value testing is more likely to resemble the actual performance of a system in the real world, our team decided this was the most important measurement to compare when selecting a system.

$$\text{COP} = \frac{\text{power output}}{\text{power input}}$$

Figure 2-5: Coefficient of Performance Ratio (Power Knot, 2011).

$$\text{EER} = \frac{\text{output cooling energy in BTU}}{\text{input electrical energy in Wh}}$$

Figure 2-6: Energy Efficiency Ratio (Power Knot, 2011).



	Dry bulb temperature	Wet bulb temperature	Relative humidity	Dew Point
Outdoor conditions	95°F (35°C)	75°F (24°C)	40%	67°F (19°C)
Indoor conditions	80°F (27°C)	67°F (19°C)	51%	60°F (16°C)

Figure 2-7: Design conditions for EER testing (Power Knot, 2011).

$$\text{SEER} = \frac{\text{output cooling energy in BTU over a season}}{\text{input electrical energy in Wh during the same season}}$$

Figure 2-8: Seasonal Energy Efficiency Ratio (Power Knot, 2011).

Beyond the efficiency of the HVAC system, there are several other important factors to consider. One of the most important of these is method of air distribution. As a general rule of thumb, it is uncomfortable to have a high velocity of distribution airflow within a building because occupants will feel air drafts on their exposed skin. Furthermore, occupants may feel uncomfortable if there is a difference in air temperature between head height and floor height. There are also systems which do not use airflow at all but use radiative cooling through chilled water pipe systems. These are most commonly located in the floor or ceiling. Regardless of distribution method, a well conditioned space should have an even temperature throughout without creating significant air velocity from terminals (INNOVA, 2002).

Additional considerations for our design include: noise level, space, and ease of use are three further considerations. For the OCULUS solar house, these were not driving factors but still deserved consideration during the selection process. A noisy system is disruptive to the human comfort. Since the house emphasized an open floor plan, we also minimized the spacial footprint of the system. Ease of use is less essential but still improves the quality of a system. A complicated and hard to operate system is not aligned with the house which will be simple to operate and maintain.

Based upon these criteria, our team did some surface level research on different types and configurations of HVAC systems. For small buildings, some of the most common cooling systems include packaged evaporative coolers, packaged terminal units, and split systems. A packaged evaporative cooling unit was initially very appealing due to very limited energy usage and simplicity. An evaporative cooler works by moving hot dry outdoor air across a wetted pad or membrane and through ducts into the indoor space (see Figure 2-9). To operate, an evaporative cooler needs only water and enough electricity to operate a blower. However, packaged evaporative systems struggle to operate in humid climates and typically cannot provide large amounts of cooling (Bhaskar, Ramya, & Siva Krishna, 2016). Although the competition-site is fairly dry, our weather research showed the possibility for humid conditions along with extreme heat. We concluded that this type of system may not be able to provide enough cooling and would not provided air within the humidity requirements of the competition.

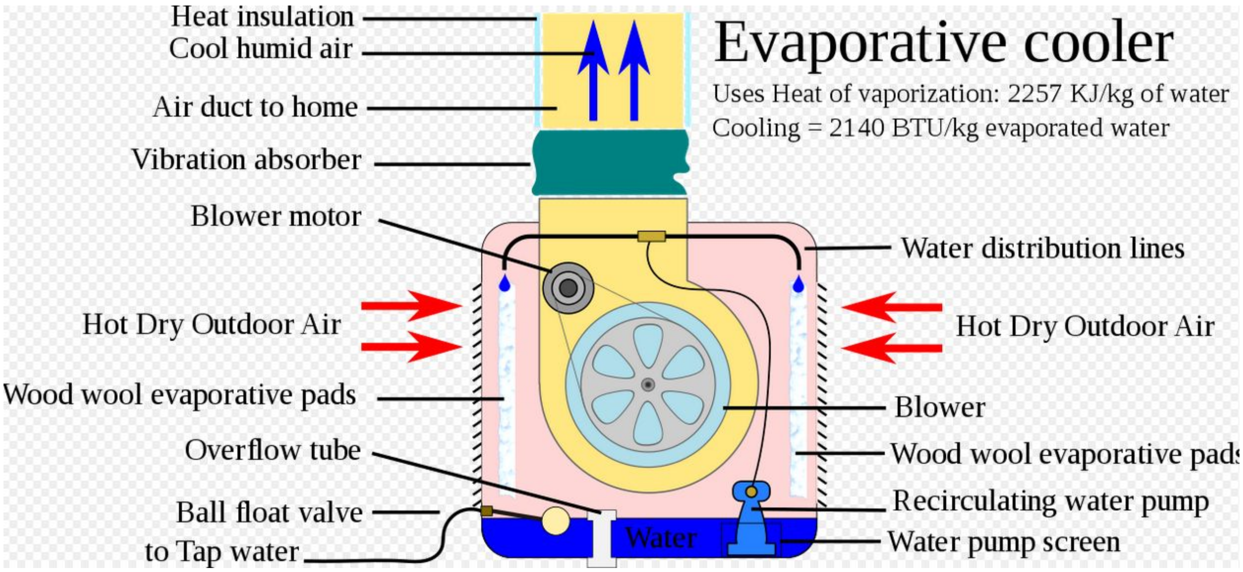


Figure 2-9: Packaged evaporative cooler components (Bhaskar, Ramya, & Siva Krishna, 2016).

Packaged terminal units and through-wall units are simple and widely available around the world. They can be easily installed with minimum technical know-how. These aspects were appealing to our team because they would dramatically decrease installation time and requirements and conceptually could be easily installed by anyone. However, our research showed that these systems are typically the most inefficient cooling systems. Furthermore, the equipment often has a relatively short life and requires maintenance (Allen, & Iano, 2012). Due to the inefficiency, our team did not seriously consider any of these systems.

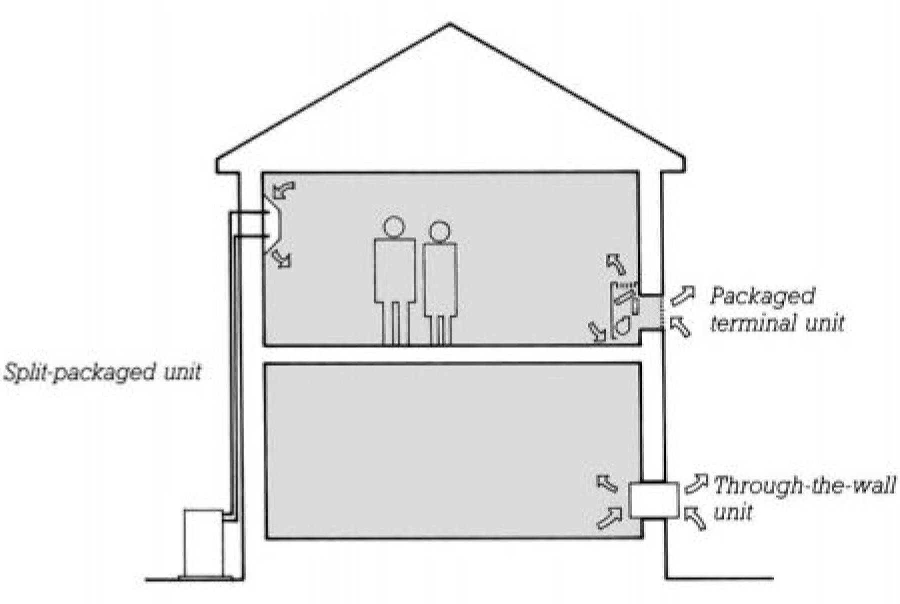


Figure 2-10: Packaged terminal units and through-the-wall units (Allen, & Iano, 2012).

Split systems have dramatically improved in efficiency over the last few decades and are now among some of the most efficient systems available. A split system can be configured as either a ducted system or a ductless system (as pictured in Figure 2-10). A ductless system (often referred to as a mini-split system) consists of an outdoor compressor unit, refrigerant lines and an indoor evaporator unit. The indoor units in a mini-split system are typically small wall mounted units which cycle air through the space. These systems are very flexible because the wall mounted units take up very little space and can be mounted almost anywhere. The main drawback to a mini-split system is the way air is distributed through one point. This may cause high supply air velocity and may result in uneven air distribution within a space.

A ducted split system is very similar to a mini-split but rather than a small wall mounted indoor evaporator, the refrigerant lines are connected to an air-handling unit which pushes air through ducts and into the conditioned space. The addition of an air-handling unit slightly lowers the efficiency of these systems but the use of ducts allows for better air distribution.

2.2.1 Equipment

The first component in a ducted split system is the outdoor compressor unit. A compressor operated by condensing refrigerant from a gaseous state to its liquid state and causing the latent heat to be removed from the refrigerant. The refrigerant is pushed through a set of coils and a fan blows air across those coils. After being condensed back to a liquid state, the refrigerant moves to the air-handling unit. The air-handling unit pulls in warm return air and moves this air across lines of refrigerant. This process allows the heat from the return air to transfer to the refrigerant and in turn cooling the air. Once the air is sufficiently cooled, the air-handling unit uses a blower to push air into the duct system. Air moves through the duct system and is distributed through the duct terminals and into the conditioned space.

Our team chose to use a compressor and air-handling unit designed by the international HVAC company Lennox. The selected units are the Dave Lennox Signature Collection XC25 compressor and CBX40UHV Air handler (see Figure 2-11 and Figure 2-12). The XC25 is one of the most efficient compressors available on the market right now with a SEER value of 26. The XC25 is able to meet this incredibly high SEER value by using a variable speed fan. Many compressors have fans with one or multiple speeds and depending on the weather conditions will switch between these speeds. The XC25 has a completely variable fan which can operate at 1% to 100% of its maximum speed and will constantly adjust with the changes in outdoor air conditions. This ensures that the XC25 is never using more energy that needed. The CBX40UHV is also a variable air speed unit with four different fan speeds. This allows for more control over the air distribution within the space. Furthermore, this allows for our team to adjust the system in order to achieve more or less dehumidification of the supply air. Running the air handling unit at a slower speed will provide more latent cooling power therefore providing less humid supply air. The average relative humidity in Morocco for the month of September is close to 50% and therefore outside air will require minimal moisture control when entering the building.

These two units working together will operate very efficiently compared to other available equipment and will be able to provide cooling in even the most extreme circumstances.

Additionally, Lennox makes a number of advanced thermal sensors and smart thermostats which allow for easy monitoring and control of the system.

Figure 2-11: Dave Lennox Signature Series XC25 and iComfort Wi-Fi Thermostat.

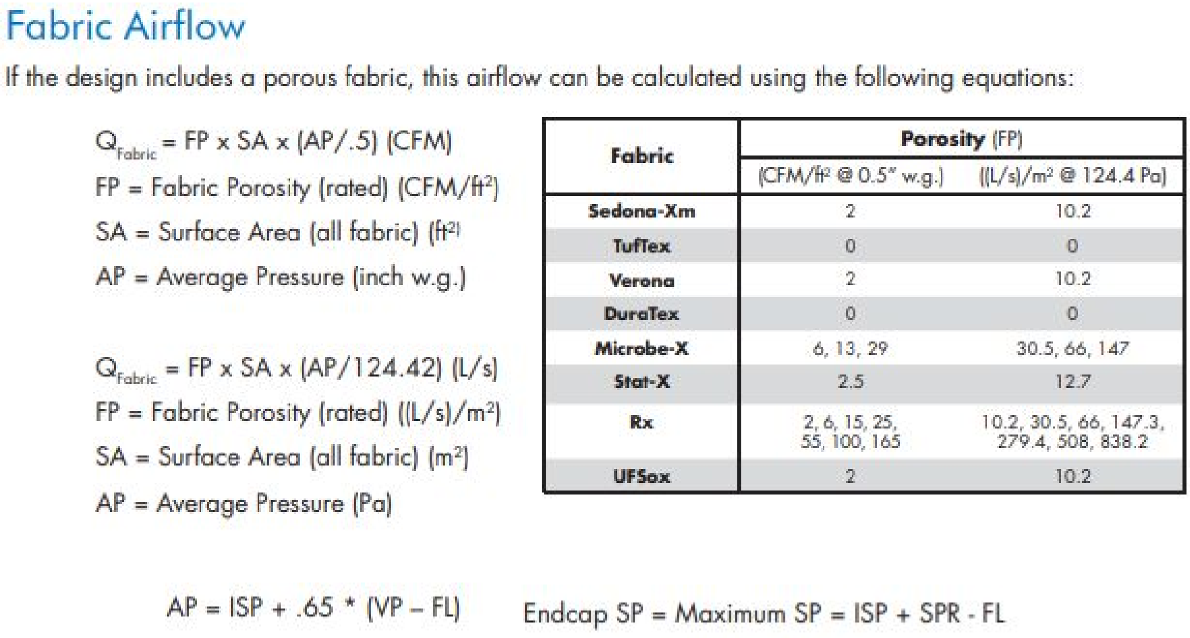
Figure 2-12: Dave Lennox Signature Series CBX40UHV.

2.2.2 Ducts

The reason for selected a ducted system was to improve the quality of air distribution through the space. The dome shape and open floor plan of the OCULUS house lends itself to great internal air movement and circulation. Following design principles of symmetry and evenness throughout the space, our team decided on a circular ring of ductwork suspended from the building structure. By designing for a ring, all areas of the house would receive freshly conditioned air. Furthermore, the placement of the ring utilized the curved shape of the structure to create air movement and mixing.

In furtherance of utilizing newer technology, our team researched alternative options for the duct material. A fairly new product of fabric ducts is not yet widely popular but offered promising features. Fabric ducts are in many ways in light with the design goals of the OCULUS house. They are low cost, use natural materials, can be easily installed and are lightweight. Furthermore, fabric ducts can be designed to have tiny pores which allow air to diffuse out of the duct along the entire length. This helps to create an extremely even distribution of air and further reduces the velocity of the exit air to prevent uncomfortable drafts within the space. Fabric ducts can even be taken down and washed for easy long term maintenance without any special tools or technical experience. The team chose to work with DuctSox to design a fabric duct system.

When designing a fabric duct system, many of the same principals from a standard metal duct are used. However, fabric ducts act in a slightly different way in terms of air distribution and pressure drop. We first used a ductulator to estimate the size of our round fabric ducts given the airflow from the CBX40UHV air handling unit. Based on an airflow of 1100 cubic feet per minute, we selected a round fabric duct size of ten inches. To check the pressure drop and exit air velocity, we developed a spreadsheet using the equations from the DuctSox design guide (see Figure 2-13). This spreadsheet showed an exit velocity of 0.106 meters per second and a total pressure of 0.132 w.g. (inches of water). This exit velocity is less than 0.3 meters per second and therefore an occupant would be unable to feel this air movement. Additionally, the Lennox air handling unit can easily overcome this pressure drop. The proposed duct layout wraps around the whole building to provide even air distribution throughout (see Figure 2-14 & 2-15).



Fabric Airflow

If the design includes a porous fabric, this airflow can be calculated using the following equations:

Q_{Fabric} = FP x SA x (AP/.5) (CFM)
FP = Fabric Porosity (rated) (CFM/ft^2)
SA = Surface Area (all fabric) (ft^2)
AP = Average Pressure (inch w.g.)

Q_{Fabric} = FP x SA x (AP/124.42) (L/s)
FP = Fabric Porosity (rated) ((L/s)/m^2)
SA = Surface Area (all fabric) (m^2)
AP = Average Pressure (Pa)

Fabric	**Porosity** (FP)	
	(CFM/ft² @ 0.5" w.g.)	((L/s)/m² @ 124.4 Pa)
Sedona-Xm	2	10.2
TufTex	0	0
Verona	2	10.2
DuraTex	0	0
Microbe-X	6, 13, 29	30.5, 66, 147
Stat-X	2.5	12.7
Rx	2, 6, 15, 25, 55, 100, 165	10.2, 30.5, 66, 147.3, 279.4, 508, 838.2
UFSox	2	10.2

AP = ISP + .65 * (VP – FL)

Endcap SP = Maximum SP = ISP + SPR - FL

Figure 2-13: DuctSox pressure and airflow design equations (DuctSox, 2016).

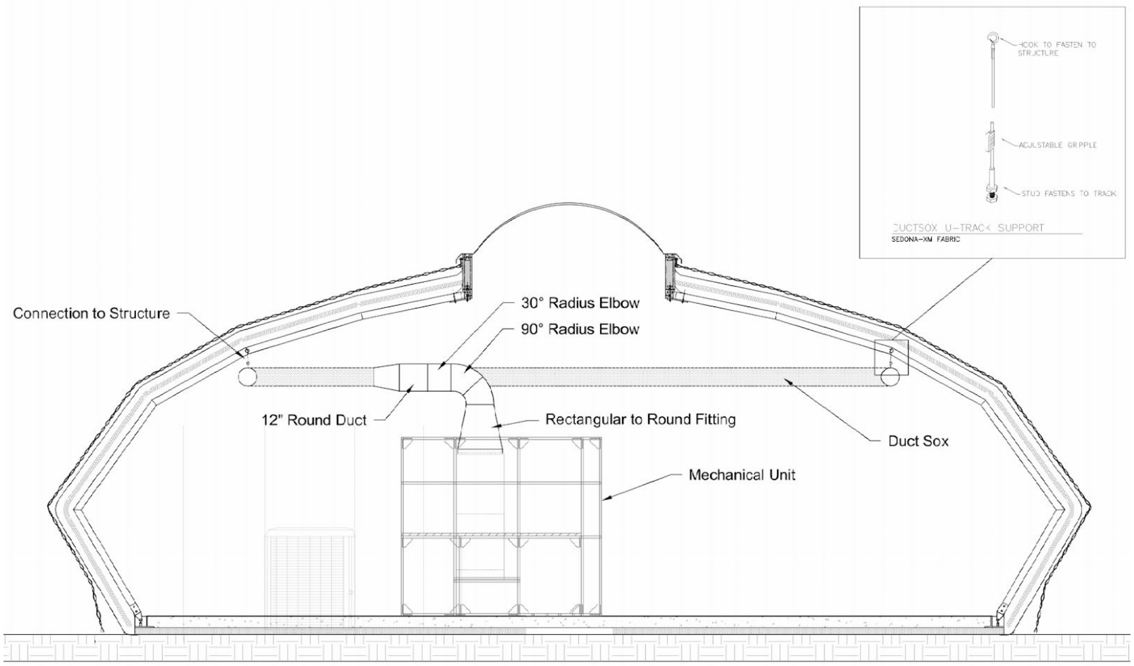


Figure 2-14: Proposed duct design section view.

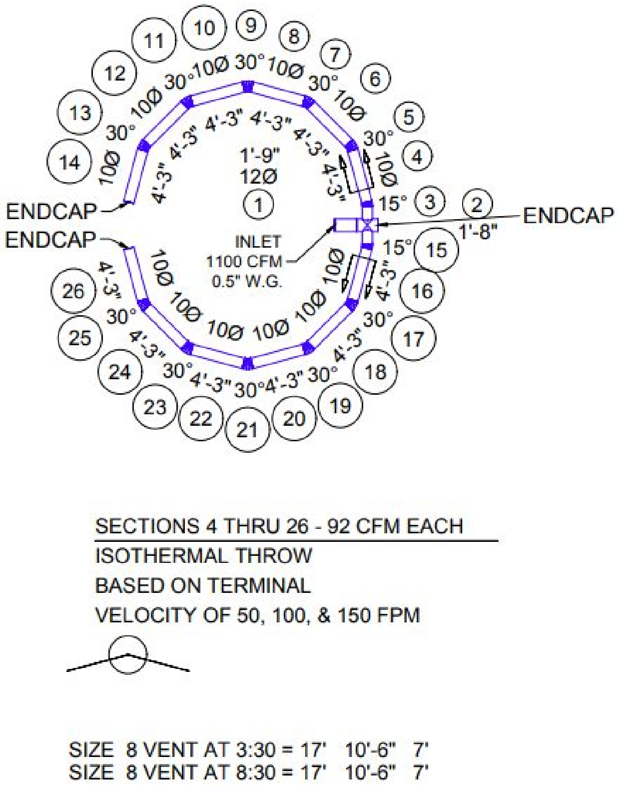


Figure 2-15: DuctSox representative finalized duct layout.

2.2.3 Bathroom Ventilation

Section 8-4 of the Solar Decathlon Africa Building Code outlines requirements for bathroom ventilation. The code outlines three options for bathroom ventilation (IRESEN, 2018):

1. Mechanical ventilation system that provides 23.6 liters per second (L/s) of intermittent air exchange. This is the equivalent of 50 cubic feet per minute (CFM) of intermittent air exchange.
2. Mechanical ventilation system that provides 9.4 liters per second (L/s) of continuous air exchange. This is the equivalent of 20 cubic feet per minute (CFM) of continuous air exchange.
3. Natural ventilation through windows in the bathroom space that allow an opening of 0.14 square meters (m^2). This is the equivalent of a 1.5 square foot (ft^2) window opening.

Because the bathroom does not contain any exterior walls in our design, we were limited to a mechanical bathroom ventilation system. In order to eliminate potential fluctuations in the building air balance with an intermittent system, we decided on the second option for a continuous 9.4 L/s (20 CFM) of bathroom exhaust. Perhaps more importantly, this option also helps to force fresh air into the space as our design for the mechanical system does not incorporate any fresh air intake. Continuous low flow bathroom exhaust has a reputation for being unable to exhaust bathroom odors and moisture in a reasonable amount of time. For the purposes of this competition, the toilet will not be operational and will therefore produce no odors. Moisture removal from the bathroom would only be a potential issue during the hot water draw portions of the competition. According to the competition rules, hot water draws occur a maximum of three times a day and must be performed in the span of 10 minutes for each draw (IRESEN, 2018). Because these hot water draws occur infrequently and will not release as much moisture into the air as perhaps a regular shower would, we decided that negating these concerns with continuous low flow bathroom exhaust was acceptable.

We selected an exhaust fan from the manufacturer Aereco, an international company specializing in ventilation products for buildings. Aereco's GBP line of exhaust fans are designed for low pressure applications in bathrooms, kitchens, and cellars. We selected the GBP c 10/30 W model (product code: GBP443) exhausts 10-30 cubic meters of air per hour (m^3/h) and features a pull cord activated boosted airflow. This product is displayed below.

Figure 2-16: Aereco GBP c 10/30 W exhaust fan/extract unit (product code: GBP443).

Our team decided to incorporate this exhaust fan into the central mechanical module of our design to increase ease of constructability. The mechanical module shares a wall with the bathroom, providing a wall-mounted toilet and cabinet space to the space. We decided to install this exhaust fan above the toilet in the shared wall of the mechanical unit and bathroom. Ducting for the fan will run down the inside of this wall, through a central slab opening in the floor under the mechanical module, through a below grade service channel, and up to the outdoors. The exhaust fan can be seen in the drawings for the mechanical module, shown in Appendix E.

3. Appliance Selection

The mechanical team was responsible for researching and selecting the major appliances for the house. Contest 5 of the competition is broken down into several sub contests which measure each of these appliances. To achieve all the points in contest 5, the house must have a refrigerator, freezer, clothes washer, dryer, dishwasher, oven, cooking surface, standard home electronics including a television, and a shower. When selecting these appliances, energy efficiency and quality were the most important considerations. Many of the appliances selected are smaller than average due to the goals of reducing the amount of immovable space within the house. Furthermore, smaller appliances are characteristic of Moroccan homes and emphasize the concept of less waste material, water and electricity.

3.1 Water Heater

Water heaters are critical in modern residential building design. Domestic water heaters take in water from the building's water source, such as a municipal water supply or a private well, and heat it to a desired temperature to supply building systems, fixtures, and appliances with hot water. Sink faucets, shower heads, dishwashers, and clothes washers are some of the fixtures and appliances that typically require hot water. In many U.S. homes, the building's heating system is hydronic, meaning it uses hot water circulated through radiators to warm interior air. In hydronic heating systems, water is usually heated in a container with an open flame under it. These types of water heaters are usually called boilers and can also provide hot water for fixtures and appliances. Other types of water heaters include storage tank-type water heaters and on-demand tankless water heaters. Like boilers, these types of water heaters can be gas, oil, or natural gas fired or electrical resistance heated (U.S. Boiler Company, 2018).

Another more efficient type of water heater is a heat pump water heater. This kind of water heater uses a heat pump system to remove heat from the surrounding air and transfer it to water. A heat pump uses electricity to move a refrigerant fluid through a loop of piping to absorb and release heat at the respective ends of the loop. Essentially, a heat pump operates as a refrigerator in reverse. Figure 3-1 is a diagram of heat pump water heaters.

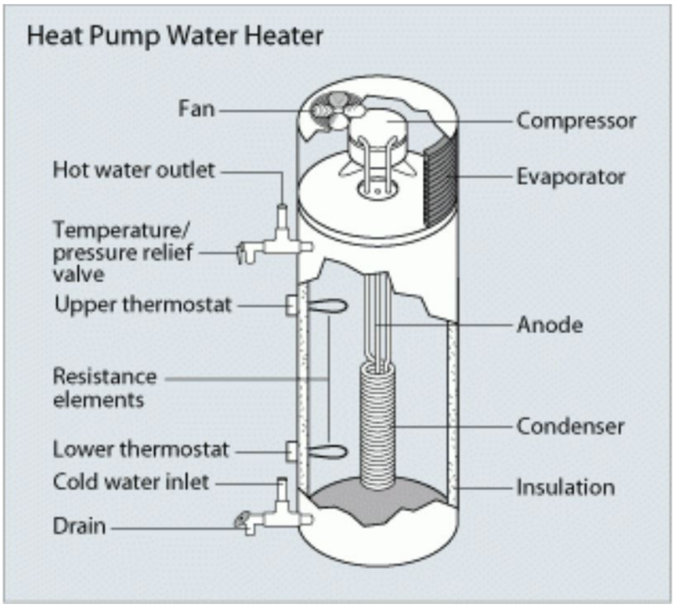


Figure 3-1: Diagram of a heat pump water heater (Office of Energy Efficiency & Renewable Energy, 2018).

The water heater that we selected is a hybrid between a heat pump water heater and an electrical resistance storage tank-type water heater. This product, manufactured by Rheem Water Heating, combines the energy efficiency of a heat pump system and the quick heating time of an electrical resistance heater. As part of Rheem's Performance Platinum series, the XE65T10HD50U1 model is Energy Star rated and one of the most efficient water heaters on the market. The hot water heater in our design needed to meet the demands of the competition's hot water draw subcontest. According to the competition rules (see Appendix A), the maximum demand of hot water in a single day would be three consecutive hot water draws. This would total 150 liters of water (about 40 gallons) at 45℃ (about 113℉) in under 30 minutes. Because most water heaters can heat water to well above 45℃ and because the flowrate of hot water is dependant on the plumbing system, our main focus was selecting a water heater with a capacity of at least 150 liters. Our team selected a 65 gallon (about 246 liters) water heater to ensure that three consecutive hot water draws could be fulfilled in any given competition day. Figure 3-2 is a picture of the selected water heater.

Figure 3-2: Rheem XE65T10HD50U1 hybrid water heater.

3.2 Washer and Dryer

The sub contest clothes washer from the rules describes the ways in which the washer will be judged during the competition. The selected washer will earn points by completing a load of bath towels which will be provided by the competition organizers: IRESEN. A complete load must include as wash and a rinse cycle and the load must be uninterrupted to receive maximum awarded points. During the competition period there are several days in which the team will be asked to complete two loads of laundry per day.

The clothes drying sub contest details how the drying process can earn points. Unlike the clothes washer, a simple successful completion of a cycle is not enough to earn full points. Instead the clothes dryer will earn points based on the weight of the towels after a drying cycle. Full points will be earned if the total weight of the towels is less than or equal to the weight before washing. Reduced points will be earned if the total weight is under 110% of the weight before washing. Additionally, there is a time limit on the drying period which will be decided by IRESEN. The use of passive drying (such a clothes line) is allowed to either take the place of a dryer or supplement the clothes drying process. Our team decided not to utilize a passive drying system due to risk of underperformance or humid weather conditions.

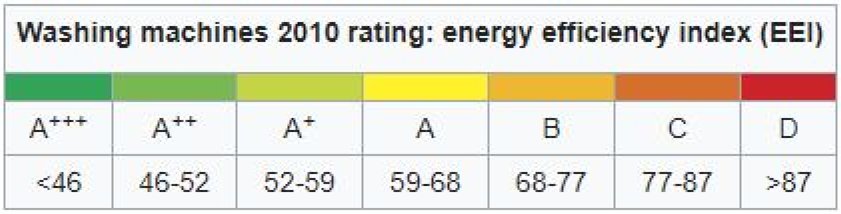
There are a few options for washer and dryer styles available on the Morocco today. The main options for washer styles include a combined washer and dryer unit, a ducted washer and a ductless washer. When an emphasis on saving space, the team instinctually started by looking at a combined washer and dryer unit. A combined washer and dryer unit operates with one central drum which can operate both washing and drying cycles. This is clearly a space saving option however there are a number of drawbacks. Further research revealed the tendency of these units to struggle with clothes drying. From our research, we learned that drying cycles often take three or more hours hours and frequently fail to successfully dry clothes (Prelusky, 2018). This is a concern because the competition limits the amount of time alloted for a drying cycle. Additionally, there is no increase in efficiency between a combined washer and dryer unit and a standard separate washer and dryer. A ducted drying unit offers the benefit of removing additional moisture from inside the house but requires additional space, coordination and installation for the duct work. Furthermore, when a ducted dryer expels air from the building, hot outside air will enter the building as infiltration for makeup. This infiltration will increase the total cooling load and require additional work from the HVAC system.

A ductless dryer operates by using a condenser to remove moisture from clothing. This type of dryer will add moisture to the interior space when drying clothes. Although controlling humidity is important to the competition, research shows that the moisture added by a ductless dryer would likely not be significant enough to push the interior humidity outside of the comfort range which is between 30% and 70% (INNOVA, 2002). Additionally, a ductless dryer offers the benefit of easier installation, making it the clear choice for the OCULUS house.

The team selected on the Bauknecht TKPRIME85A2BW condenser dryer and Bosch WAB202S2ME washing machine (see Table 3-1). The selected appliances are primarily available in European countries because they need to be available for purchase in Morocco. As such, their energy efficiency is scored on the European Energy Union grading system. The European Energy Union (EEU) grading system scores appliances on their efficiency and assigns them a letter grade between A and G. For washing machines, the efficiency is based up an energy efficiency index (EEI) where the baseline is given as 100% is equal to 334 kWh per year based on 220 washing cycles (see Figure 3-3). Clothes dryers are scored by the EEU using slightly different method. The energy efficiency is based off kWh per kilogram of load (see Figure 3-4).

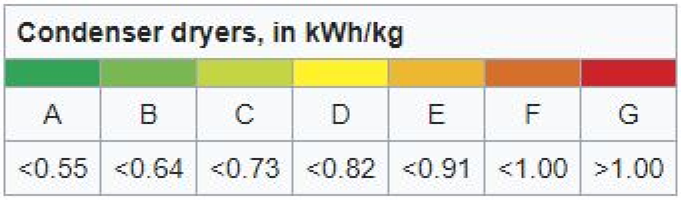
Table 3-1: Selected washer and dryer performance.

Appliance	Product #	EEU Grade	Energy Usage	Percent of Baseline
Clothes Dryer	TKPRIME85A2BW	A++	<.55 kWh / kg	n/a
Clothes Washer	WAB202S2ME	A+++	153 kWh/year	46%



Washing machines 2010 rating: energy efficiency index (EEI)						
🟩	🟩	🟩	🟨	🟧	🟧	🟥
A^{+++}	A^{++}	A^{+}	A	B	C	D
<46	46-52	52-59	59-68	68-77	77-87	>87

Figure 3-3: European Energy Union washing machine grading criteria.



Condenser dryers, in kWh/kg						
🟩	🟩	🟩	🟨	🟧	🟧	🟥
A	B	C	D	E	F	G
<0.55	<0.64	<0.73	<0.82	<0.91	<1.00	>1.00

Figure 3-4: European Energy Union condenser dryer grading criteria.

3.3 Kitchen Appliances

The competition requires a refrigerator, freezer, dishwasher, and cooking surface. The volume requirements for the refrigerator and freezer must be at least 170L and 56L respectively. This is actually a fairly small volume which nearly all full sized refrigerators meet. There are no other performance requirements for the fridge or freezer so energy efficiency, size and availability were the primary considerations. The Bosch KGN36KL35 was selected. It is a slender unit which meets the volume requirements and scored an A++ with an estimated energy usage of 260 kWh annually. This value, along with the energy usage of all other appliances, was factored into the daily energy balance spreadsheet and the internal heat gains portion of the HVAC calculations. (see Section 5.3 and Section 2.1.1)

Figure 3-5: Bosch KGN36KL35 refrigerator and freezer.

The dishwasher is required to run one full, interrupted wash and rinse cycle and be able to hold eight sets of dishes. When selecting a dishwasher, the energy efficiency, water usage and size were the biggest considerations. The Bosch SMS46II08E dishwasher was selected due to its' high energy efficiency and low water usage. It scored an A++ on the EEU rating system with an estimated .92 kWh consumption and 9.5 liter water consumption per cycle. Additionally, the selection of a stainless steel Bosch dishwasher fits in with the refrigerator.

Figure 3-6: Bosch SMS46II08E dishwasher.

The only competition requirement for the cooktop is the ability to evaporate 2 kilograms of water in one hour. Due to our space constrictions, a smaller cooktop was desirable. The Bosch PKF645B17E electric cooking plate was an appropriate fit due to its’ consistency in manufacturer and small footprint. Electric heating is inherently inefficient. However, our use of the cooktop will be limited during the competition so this inefficiency is a minor concern compared to other appliances.

Figure 3-7: Bosch PKF645B17E electric cooking plate.

3.4 Complete Schedule

After individually selecting all appliances, the team compiled a complete schedule to organize selections and simplifying ordering. This schedule also includes relevant information from appliances spec sheets which reduces the difficulty in finding information about each appliance. Other members of Team OCULUS benefit from the simple and easy to understand format of the schedule. The table below is a simplified version of the complete schedule.

Table 3-2: Schedule of appliances.

Appliance	Manufacture	Product #	Energy Usage
Water Heater	Rheem	XE65T10HD50U1 - 696010	-
Clothes Washer	Bosch	WAB202S2ME	153 kWh/year
Clothes Dryer	Bauknecht	TKPRIME85A2BW	<.55 kWh / kg
Refrigerator/Freezer	Bosch	KGN36KL35	260 kWh/year
Dishwasher	Bosch	SMS46II08E	.92 kWh/cycle
Cooktop	Bosch	PKF645B17E	-

4. Mechanical Unit

Mechanical systems must be carefully incorporated within a building to achieve the ultimate architectural goals of a space. After sizing and selecting system components, it is critical that the mechanical designers work closely with architects and other designers to integrate the mechanical system seamlessly into the space. The HVAC units and water heater take up space inside the building and typically are not attractive. Additionally, system components need to be hooked up to electricity and water. These hook up points require openings in the envelope or foundation. The architects also need to consider the sound created by these mechanical systems.

When approaching this challenge in the context of the OCULUS house, the team started with the overarching architectural themes and goals of the building. One of the primary goals of the building is ease of assembly. With a limited amount of construction time alloted by the competition, it is essential to consider the installation requirements of every building element. Furthermore, one of the goals of this project is to create a template for a house which can be easily built without extensive construction experience or heavy machinery. Another primary goal of the OCULUS house is an open and flexible floor plan. The house has been designed with as few fixed components as possible. However, mechanical equipment is one of the building elements which must be fixed in place. As such, the team aimed to reduce the footprint and integrate all of the equipment with the rest of the space.

4.1 Unit Design

The first approach the incorporating the mechanical equipment was to position it around the perimeter of the house. This approach would allow more space in the center of the house to be left open. To further push the equipment to the perimeter, the team attempted to use the space lost by the outward curve of the dome shape. We designed a frame which would cantilever out beyond the edge of the floor slab to hold the blower and would use the weight of the water heater to achieve balance (see Figure 4-1).

Although this approach preserved more of the open central floor space, it ran into some trouble. One of the major issues was the inherent design flaw of placing rectangular appliances and equipment next to an angled triangle geometric structure. In order to fit, all of the equipment would have to be positioned at odd angles and created a lot of loss space because it could not truly be positioned all the way against the wall. The other major problem which the team realized during the design was the difficulty of accessing all of the mechanical components after installation. Because the initial design featured all mechanical elements stacked up against the perimeter, it would be nearly impossible to access the components against the exterior wall.

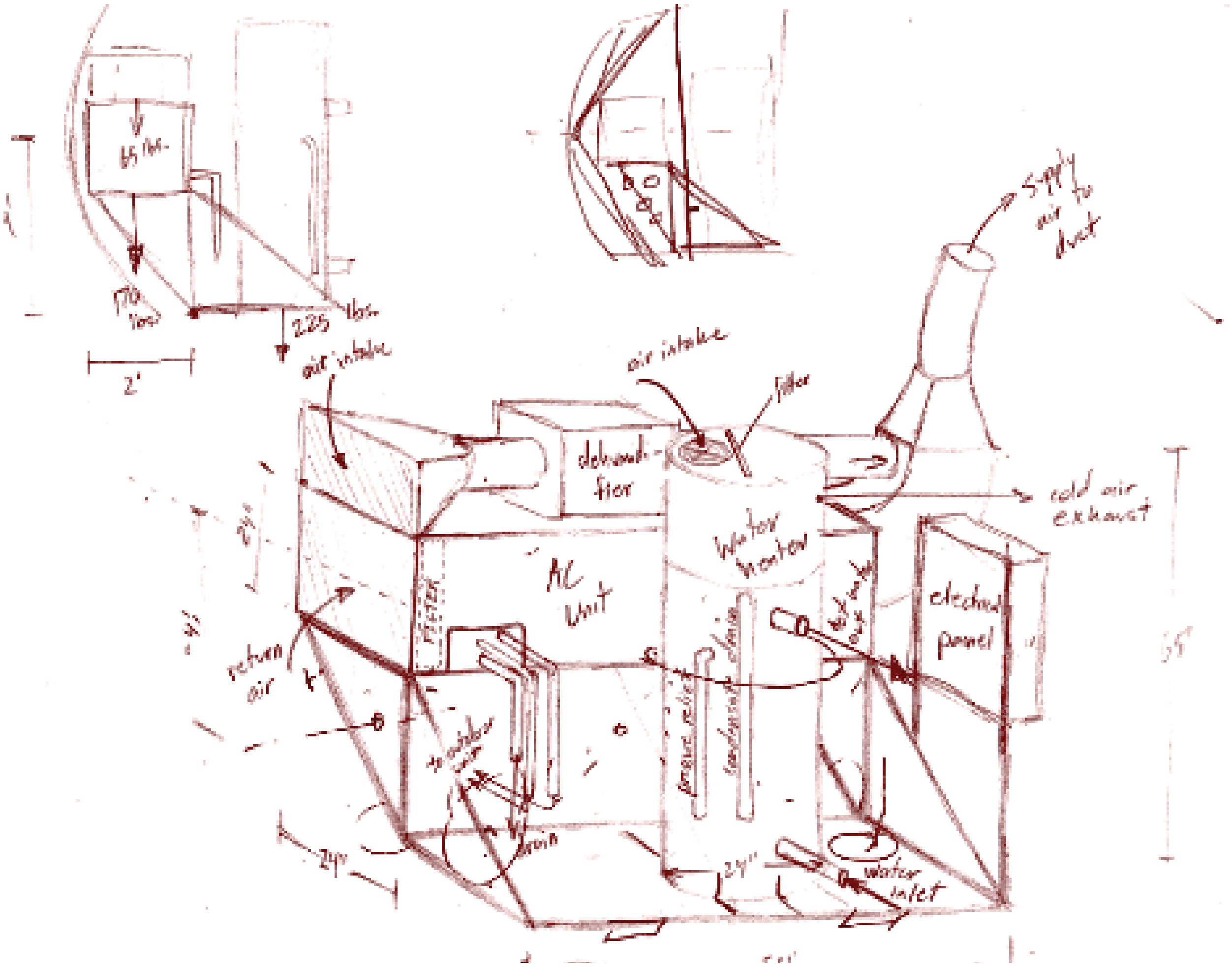


Figure 4-1: Original mechanical component configuration concept with cantilever frame.

As a modification of the first approach, the mechanical components were spread out along a large amount of the perimeter. This allowed easy access to each component and also prevented the mechanical equipment from protruding as far into the space. However, all of the equipment, kitchen and bathroom could not be placed between the two doors, which lie 120 degrees apart. Furthermore, the amount of plumbing and electrical wiring was much more due to the spread out nature of this design. The other issue with this design is that it would require each element to be moved and installed individually.

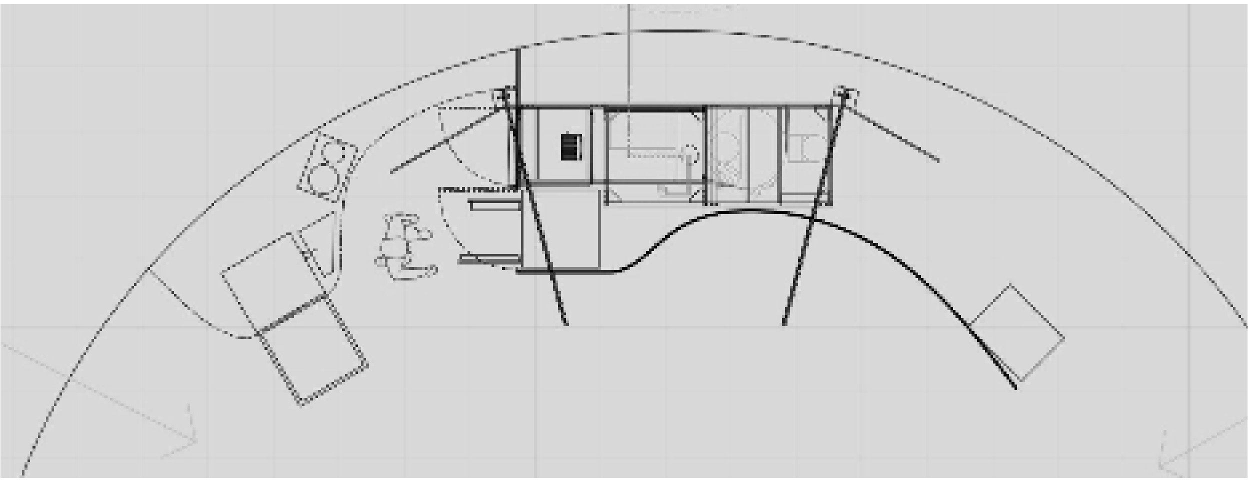


Figure 4-2: Second mechanical component configuration concept.

After many ideas and iterations, the team chose to design a centralized mechanical unit containing the blower, water heater, electrical panel, toilet, clothes washer, clothes dryer, dishwasher, cooktop and refrigerator. The unit will have structural framing members to contain all components, such that it may be preassembled and dropped in on-site. There will be a single opening in the slab located in the middle of the unit for all plumbing and electrical connections. The location of the unit is close to the perimeter but allows enough room to walk around the outside. This space on the outside of the unit can be utilized as kitchen space and the space above the dishwasher, washing machine and dryer is designed to serve as a countertop. The frame will be covered with a veneer finish to give a cabinet-like look to the unit. Furthermore, there will be hinged panels to allow easy access to all components. See Appendix E for further details.

Although this design takes up slightly more floor space, it is the most compact arrangement of the mechanical systems. Furthermore, this unit allows for easy integration of the bathroom and kitchen within the space. It will be very easy to install and perform maintenance on if necessary.

4.2 Structural Integrity

The mechanical unit will be fabricated using aluminum profiles that will be attached to each other with special connectors (Figure 4-4). Our team has been working closely with FramingTech, the company that will be providing Team OCULUS with the parts necessary to assemble the frame. The purpose of this frame is to be assembled separately and then transferred in the house in order to reduce installation time. The total weight of the appliances that will be supported by the frame is 208 kg (458 lbs) and an additional 91 kg (200 lbs) of bamboo paneling that will be covering the frame to make it aesthetically pleasing. Each connector can hold a maximum weight of 4000 N, which makes the frame structurally sound for transportation and support of the appliances.

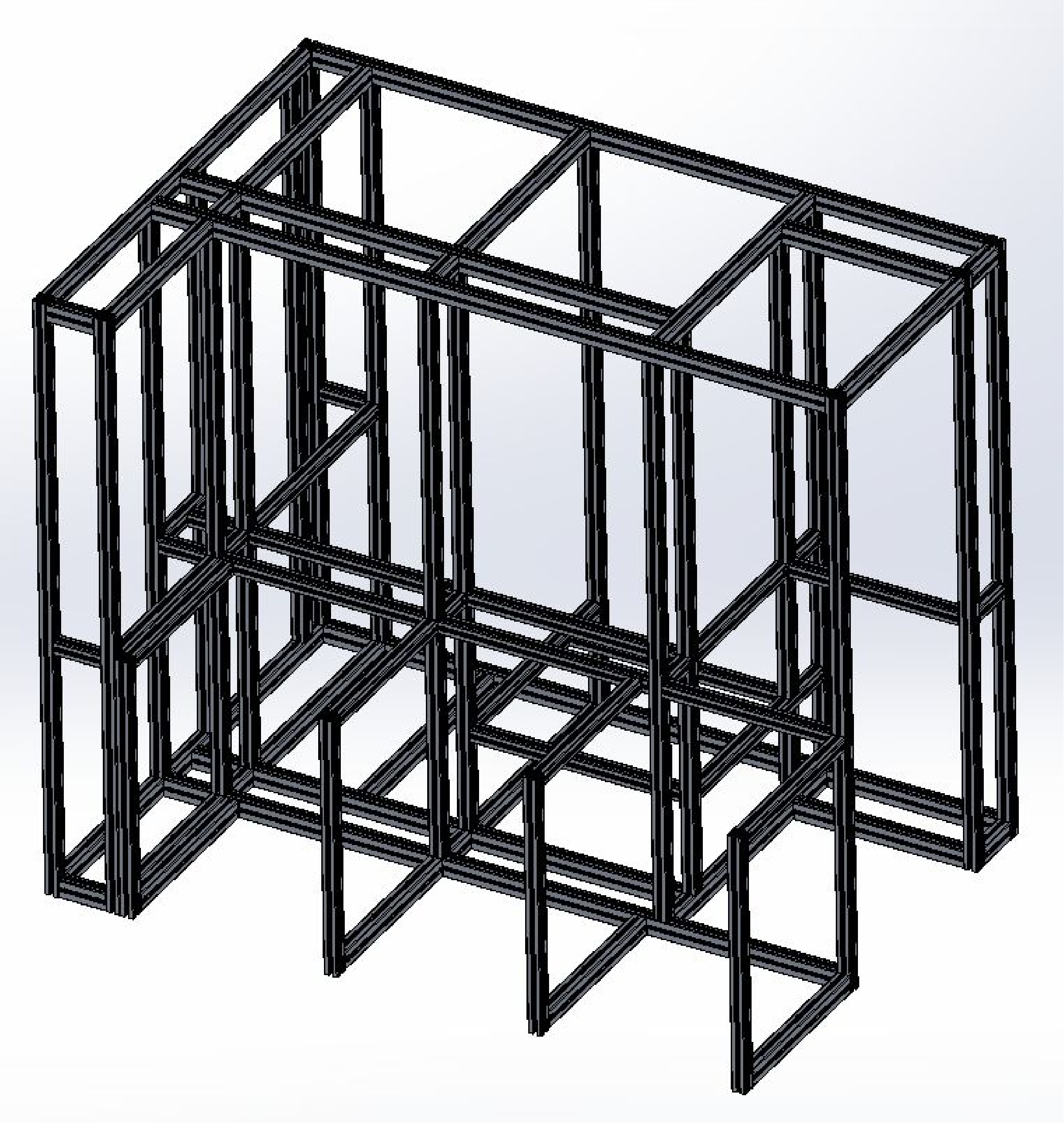


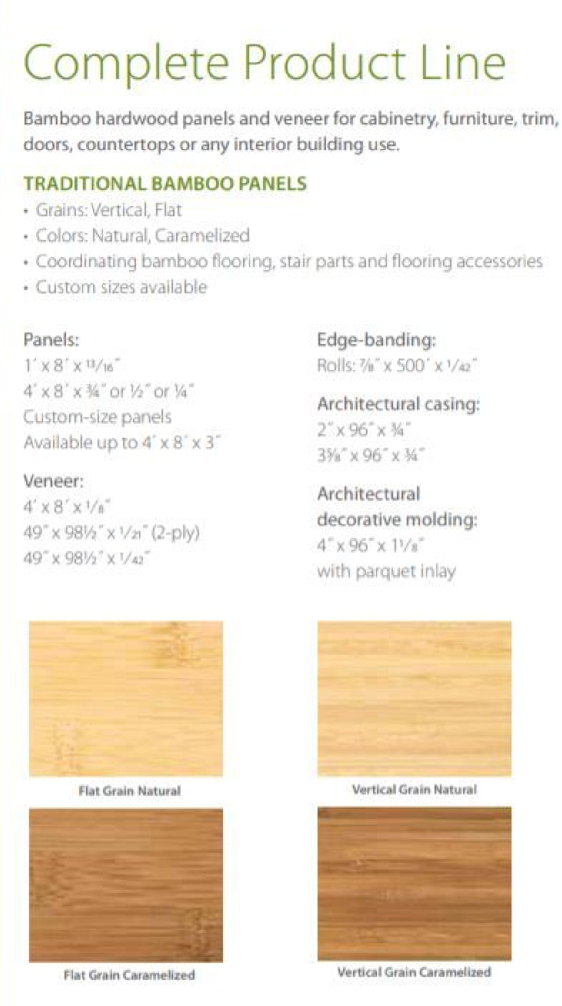
Figure 4-3: 3D model of the mechanical unit frame.

Figure 4-4: The connections used to hold the frame profiles together.

4.3 Aesthetic Considerations

Working closely with the architectural designers on Team OCULUS, our team decided to enclose the central mechanical unit with laminated bamboo panels. Bamboo can be more sustainably harvested than traditional lumber due to its fast growth. Bamboo also has dense fibers, making it a durable material for many applications. This decision was consistent with the architectural vision of the building design, giving the unit a warm, natural, sleek aesthetic. For uniformity, we decided to make the countertop of the mechanical unit out of a bamboo material as well. Further collaboration with designers on the team led to the decision to clad the exterior of the bathroom, which sits adjacent to the mechanical unit, in the same material.

Our team researched bamboo panelling products and found a company that manufactures bamboo countertops, bamboo plywood and panels, and bamboo veneer. Based in California, Teragren Inc. specializes in high-quality bamboo building materials. With a commitment to sustainability, Teragren claims their products are carbon-negative because of bamboo's carbon sequestration capacity and because they use low emissions transportation methods. Teragren also ensures durable, quality products by exclusively utilizing a specific type of matured bamboo from China. Plywood panels and veneer, and countertop products from Teragren are shown below.



Complete Product Line

Bamboo hardwood panels and veneer for cabinetry, furniture, trim, doors, countertops or any interior building use.

TRADITIONAL BAMBOO PANELS

- Grains: Vertical, Flat
- Colors: Natural, Caramelized
- Coordinating bamboo flooring, stair parts and flooring accessories
- Custom sizes available

Panels:
1′ x 8′ x 13/16″
4′ x 8′ x ¾″ or ½″ or ¼″
Custom-size panels
Available up to 4′ x 8′ x 3″

Veneer:
4′ x 8′ x 1/8″
49″ x 98½″ x 1/21″ (2-ply)
49″ x 98½″ x 1/42″

Edge-banding:
Rolls: 7/8″ x 500′ x 1/42″

Architectural casing:
2″ x 96″ x ¾″
3⅝″ x 96″ x ¾″

Architectural decorative molding:
4″ x 96″ x 1⅛″
with parquet inlay

Flat Grain Natural

Vertical Grain Natural

Flat Grain Caramelized

Vertical Grain Caramelized

Figure 4-5: Bamboo panels/plywood and veneer (Teragren Inc., 2017).

TERAGREN® TRADITIONAL BAMBOO COUNTERTOP/TABLE TOP

Vertical Grain Caramelized face with Chestnut strand bamboo core or
Vertical Grain Natural face with Wheat strand bamboo core

- 30″ x 96″ x 1½″ or 36″ x 72″ x 1½″
- Can be finished with a food-safe mineral oil/beeswax finish; optimal for countertops intended to be used as a cutting surface
- Sold unfinished

Natural

Caramelized

Figure 4-6: Bamboo countertops (Teragren Inc., 2017).

Using cabinetry design concepts, we designed blocking to be bolted to the FramingTech profiles of the unit's frame so that the bamboo panels could be nailed to the outside of the unit (see a complete mechanical unit drawing set in Appendix E). The countertop would be secured to the frame in a similar way. Our team selected Teragren products for their sustainable manufacturing and transportation practices, and for their durability and quality. Our team realizes, however, that alternative products may be available. Ideally, we would like to find similar products in Morocco or the surrounding areas to eliminate the need to ship U.S. products to the competition location. Using local materials and employing local craftsmanship would help to decrease the environmental impact of using these products. Our team is currently researching and evaluating these options.

5. Solar Panels and Energy Balance

One of the most important aspects of this project is the energy generation that will provide the building with power. The power generation method implemented is solar energy through the use of a photovoltaic system. The research to determine the most efficient model took place in the initial stages of the project. Some of the brands researched were SunPower, Panasonic, LG, and First Solar, with the most efficient models being the LG NeON, followed by the X-Series Solar Panels from SunPower.

5.1 Solar Panel Energy Calculations

The number of solar panels needed was determined by dividing the total required capacity of the photovoltaic system, stated by the Solar Decathlon rule to be no larger than 10kW DC rated capacity, by the nominal power per panels for each brand. The results in the number of solar panels needed for different systems are shown in Table 5-1. The system that seems to require the least number of solar panels to generate the desired amount of energy for OCULUS is the LG NeON LG365Q1C-A5 series with 27 solar panels.

Table 5-1: Different solar panel models and their efficiencies.

Brand	Name	Model	Efficiency	Nominal Power per panel	Number of panels to generate 10kW
SunPower	X-Series Solar Panels	SPR-X21-335-BLK	21.00%	335 W	30
		SPR-X21-345	21.50%	345 W	29
	E-Series Solar Panels	SPR-E20-327	20.40%	327 W	31
		SPR-E19-320	19.90%	320 W	31
Panasonic	N325 Photovoltaic Module HIT®		19.40%	325 W	31
		40mm	19.40%	325 W	31
LG	NeON R	LG365Q1C-A5	21.10%	365 W	27
		LG360Q1C-A5	20.80%	360 W	28
		LG355Q1C-A5	20.60%	355 W	28
First Solar	FIRST SOLAR SERIES 6	FS-6420 FS-6420A	17%	420 W	

5.2 Solar Panel Frame

The photovoltaic system of choice will be fixed on a frame by the side of the house in contrast to the traditional residential systems that are usually fixed on the house's roof. The reason for that is the unique shape of the structure and the number of panels required to generated the energy needed. Additionally, installing the panels on a frame will make the maintenance of the photovoltaic system more simple, especially the removal of dust or sand. The frame will be made of steel channel beams, with the lower side of the frame at a one-meter height and a 32° angle towards the sun.

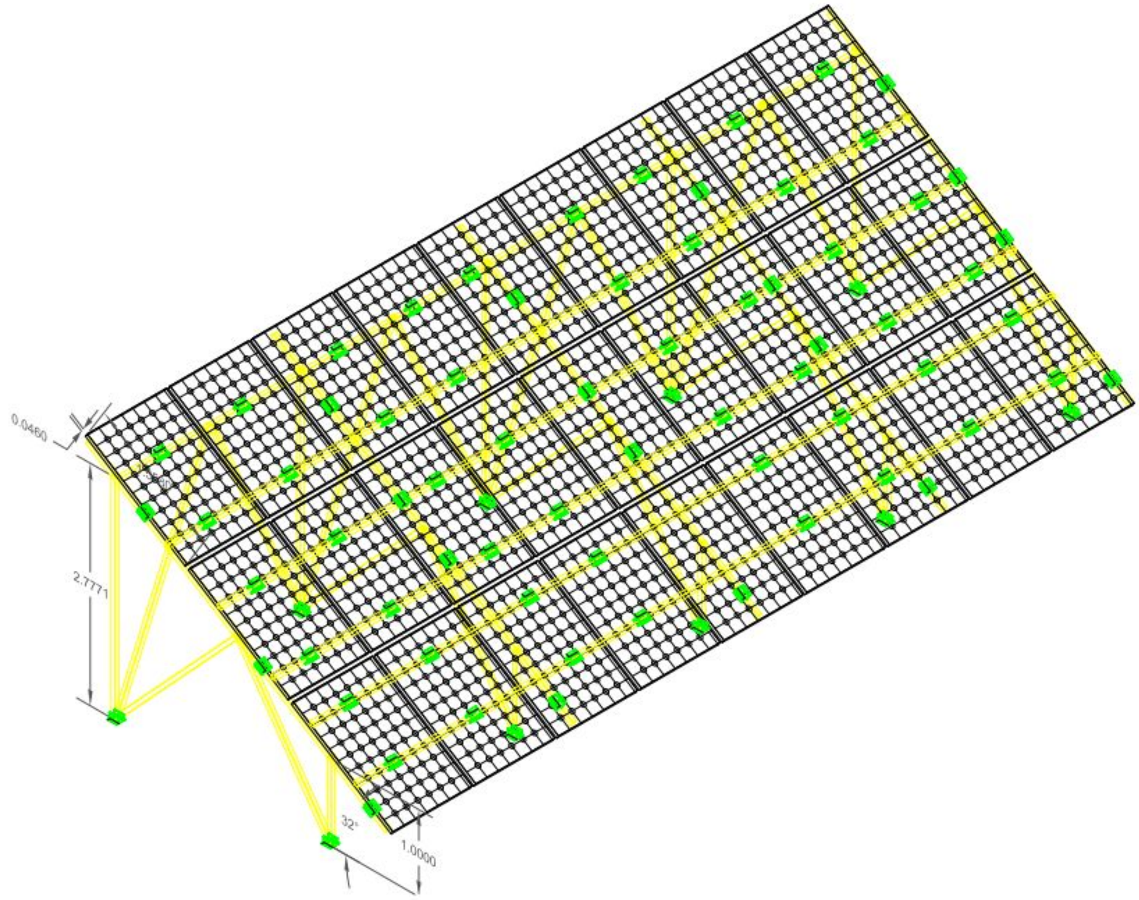


Figure 5-1: 3D model of the photovoltaic system, equipped with 27 panels (SunPower x-series)

The structural integrity of the frame was determined by using RISA 3D. Distributed loads were applied across the frame bars. Each panel weights 18.6 kg (41 lbs). After conducting a structural analysis (dead load, live load, wind load, snow load, earthquake load) on a component of the photovoltaic system frame, it was determined that it can sustain the load with minimum deflection on the members. In Figure 5-2, the axial deflection of the members is presented (more information in Appendix G). The analysis shows that the members can withstand the different potential loads applied on them, which makes the system structurally safe for use.

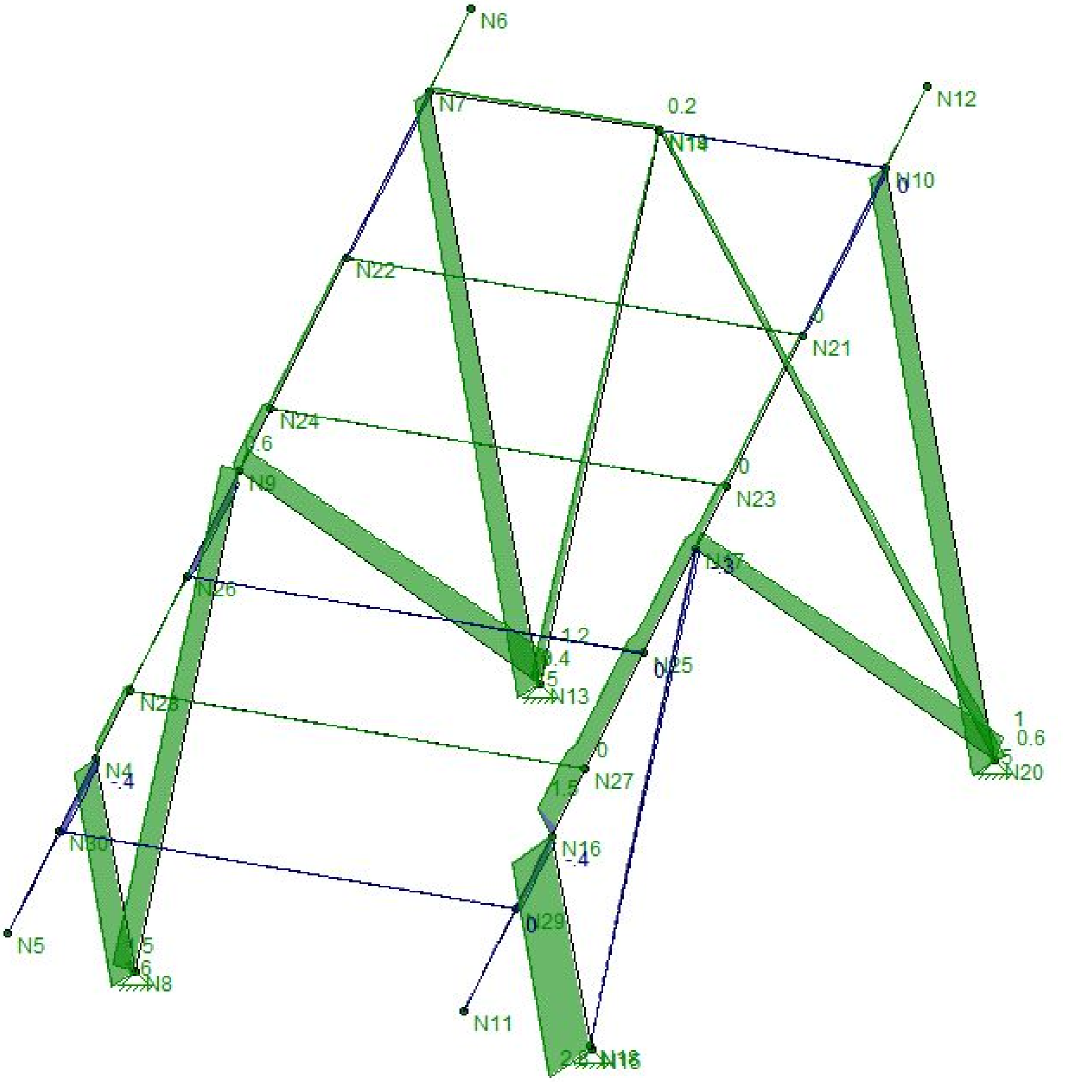


Figure 5-2: Axial loads on the frame members

5.3 Energy Usage

The OCULUS house is designed to operate entirely off its' PV panel system. As such, it is essential not only to track the amount of energy generated by the PV system but also the amount of energy consumed by the house. The HVAC system is a large energy draw but there are many other factors to consider such as kitchen appliances, charging the electric car and lighting. To track all these factors the team developed a spreadsheet.

This spreadsheet is broken down with a schedule showing 24 hours each day which allows us to track when each device is likely to be turned on or in use. The spreadsheet also estimates how much power each device will use. These estimates come from specification sheets for all appliances and equipment. This spreadsheet shows hour by hour use of energy and tallys daily totals. It also incorporates an estimation of the power generated by the PV panels each hour. This spreadsheet is easy to manipulate to model different situations by simply changing the schedule for each appliance. For example, one day may be very hot and require the HVAC to be running for almost the whole day. Another day may require consecutive hot water draws. Many of the competition contests are unscheduled which means our team should be prepared to deal with the most extreme circumstance. The Table 5-2 and Figure 5-3 show a break down of the estimated daily energy usage by category.

Table 5-2: Daily energy usage breakdown.

Category	**kWh per day**
Appliances	7.215
HVAC	17.58
Water System	5
Lighting	2.382
Car	4.1
Misc	2.1

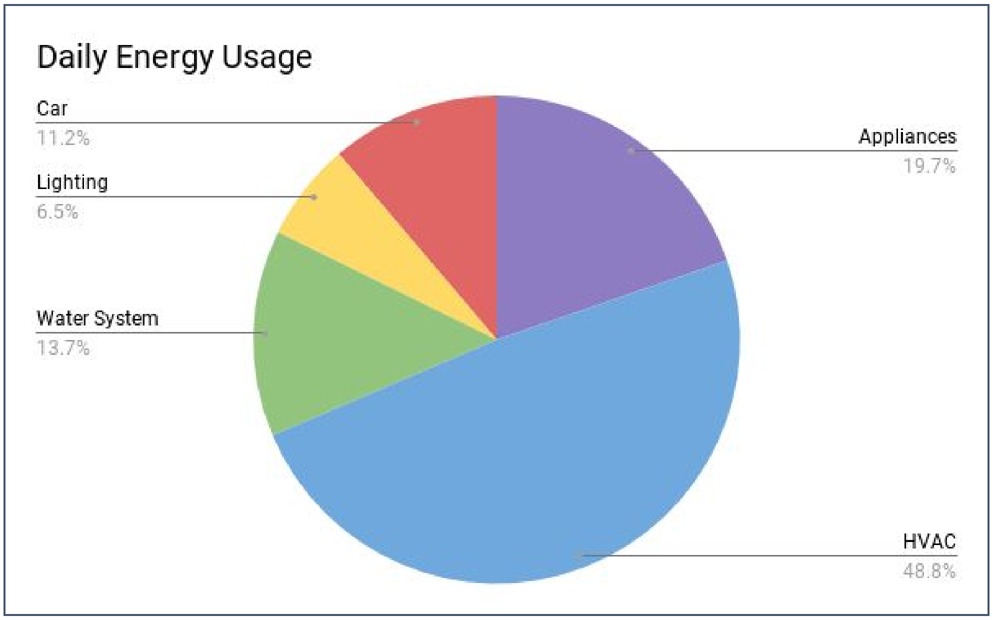


Figure 5-3: Daily energy use distribution.

6. Miscellaneous

6.1 Lighting Design

Our team was tasked with completing the lighting design for the OCULUS house. Beyond the basic necessity of lighting, the comfort subcontest also specifies a minimum lighting level inside the house of 300 lux which is about 30 foot candles. During the day, the central skylight provides some of this light. Our team performed a daylight analysis using a lighting software called DIALux to determine how much natural light would enter the house through the skylight. See Figure 6-1 for a summary of the daylight study. This study revealed that additional artificial lighting is required to supplement the natural lighting even during peak daylight hours. Furthermore, this artificial lighting will need provide illumination at night.

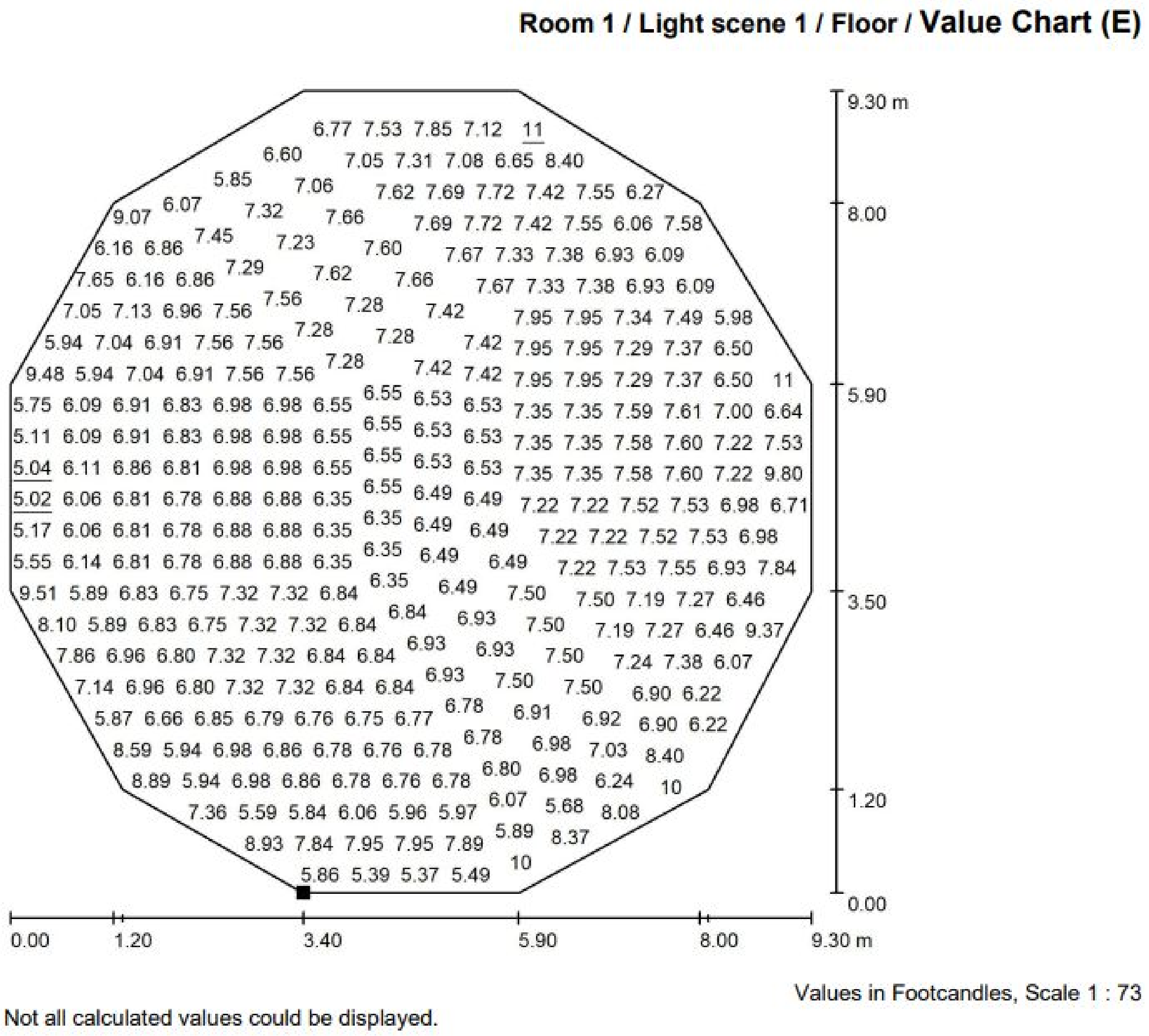


Figure 6-1: Daylight distribution across floor plan during peak daylighting hours.

6.1.2 Lighting Requirements

Although the competition only specifies one light level, a well designed lighting system should consider the functionality of different spaces within the house. For example, a bedroom does not need a high level of illuminance but the kitchen stove should be very well lit because cooking requires performance of visual tasks with a mild risk of injury. The following table shows appropriate light levels for the following spaces.

Table 6-1: Illuminance requirements for residential spaces.

Space	Foot Candles Needed	Lux Needed
Living Room	10-20	110-220
Kitchen General	30-40	320-430
Kitchen Stove	70-80	750-860
Kitchen Sink	70-80	750-860
Dining Room	30-40	320-430
Bedroom	10-20	110-220
Hallway	5-10	50-110
Bathroom	70-80	750-860

6.1.3 Fixture Selection

There are several different types of bulbs and fixtures available on the market. When selecting bulbs, there are several factors to consider such as brightness, efficiency, color temperature and color rendering index (CRI). The bulb brightness will determine how many bulbs and fixtures are required to achieve the desired illuminance level. Efficiency is a ratio of light energy produced and electricity. The color temperature of a bulb determines the color quality of the emitted light and is on a spectrum between 2700 K and 6500 K. The lower end of the spectrum is considered warmer and the higher end is considered warmer (see Figure 6-2). Due to the natural qualities of warm red light, humans prefer this type of light in the home and in the evening. Cooler light is more preferable for working environments. The CRI of a bulb determines the quality in which colors will be perceived under this light. Daylight is considered the be the most pure form of light and has a CRI of 100. Finally, it is important to consider a bulb's ability to dim. Dimming can help save energy by reducing the power usage. Dimming also allows for personal customization and can be desirable for the night when bright light can interfere with Circadian rhythm.

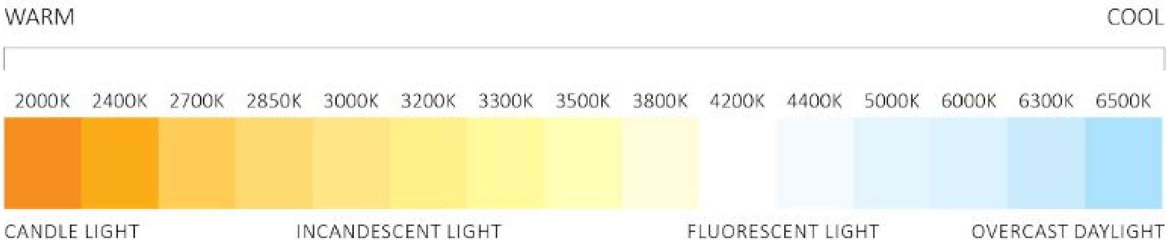


Figure 6-2: Color temperature spectrum in Degrees Kelvin (Elemental Led, 2015).

Each lighting fixture should be designed to serve a purpose within the space. There are three categories for purpose: general, task, and decorative. A fixture should be designed with one of these purposes in mind but may also fit into more than one of these categories. Lighting fixtures come in a number of styles including pendant, suspended, recessed, and track. The fixtures in a space should provide a mixture of general lighting and task lighting depending on what tasks are likely to be performed in that space.

Our team selected two fixtures for use throughout the OCULUS house. The Mino 2.5 Curve is a suspended linear LED fixture which provides the general lighting throughout the space (see Figure 6-3). The curved style of this fixture also accentuates the building's curved geometry and matches the curved duct layout. This fixture emits direct light down into the space and indirect light which bounces off the upper building envelope. Due to the irregular shape of the house and lack of a horizontal ceiling, suspended lighting fixtures will be the easiest in install. The Mino 2.5 fixture can be suspended directly from the structural wooden members.

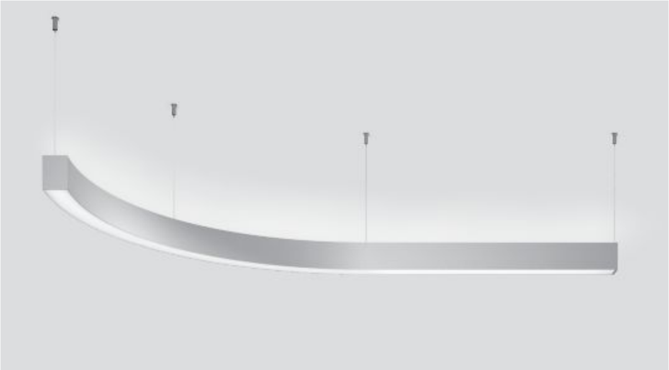


Figure 6-3: Mino 2.5 LED light fixture.

The second fixture selected was the S50 Maxi Track System fixture (see Figure 6-4) This is a track lighting system with multiple spotlights which can be moved or angled as desired. The adjustability of this fixture makes it perfect to accompany the flexible floor plan design of the house. Our team selected this fixture for use in the kitchen area which requires a higher light level for performing visual tasks.

Figure 6-4: S50 track lighting fixture.

Additional fixtures may be chosen to supplement the light design but these two fixture will provide the primary lighting for the building. For example, small tabletop lamps will likely be used within the sleeping pods. The bathroom will also feature a strong ceiling mounted down light.

An exact design for the placement of light fixtures has not yet been created due to the many changing design aspects over the course of the project. However, the general concept is to place three or four Mino fixtures suspended around the middle of the building. Due to the lack of walls within the space and the uplighting and downlighting provided by these fixtures, light will be able to reach all parts of the floor area. The S50 will be attached to a structural member above the kitchen area to provide adjustable task lighting in the kitchen.

6.2 Electric Car

According to the Solar Decathlon Africa rules, each team is expected to provide an electric vehicle within its solar envelope during the contest week, as well as include a car charging station in the infrastructure of the house. The decision towards the electric car was made according to the following criteria: efficiency, cost, availability in Morocco. It is clearly stated that the vehicle of choice must be electric and that hybrid vehicles and non-electric vehicles are not accepted. Each team shall complete 40 kilometers driving in no more than 65 minutes, four times during the contest week. Additionally, the vehicle must be equipped with four wheels at least two side-by-side seats. Based on the rules and the criteria stated above, different brands and car models were considered for the competition, as shown in Table 6-2.

Table 6-2: A selection of electric vehicles that could be used at the competition.

Car model	Cost (USD)	Battery	Distance covered when 100% charged	Energy needed for 40km/65 min
NISSAN LEAF (2016)		30 kWh	172km	6.98kWh
NISSAN LEAF S (2018)	$29,990	40 kWh lithium-ion battery	243km	6.58kWh
2018 Chevrolet Bolt EV	$36,620	60 kWh 350 V lithium-ion	382km	6.28kWh
2018 Hyundai Ioniq Electric	$29,500	28 kWh 360 V lithium polymer	199.5km	5.61kWh
2018 Kia Soul EV	$32,250	30 kWh 360 V lithium-ion	177.03km	6.78kWh
Renault Zoe	$24,112	41 kWh lithium-ion battery	400 km	4.1kWh
2018 Tesla Model X P100D		100 kWh	465.1km	8.6kWh
2018 Tesla Model X 100D		100 kWh	474.75km	8.42kWh
2018 Tesla Model X 75D		75 kWh	381.41km	7.87kWh
2018 Tesla Model S	$74,500	75 kWh lithium ion	435km	6.9kWh
2018 BMW i3	$44,450	33 kWh 353 V lithium-ion	183.46km	7.2kWh
Volkswagen e-Golf		100kW	201.17km	19.88368047

The vehicles highlighted are the ones that seem to be the most efficient, with the dominating one being the Renault Zoe, which was the model selected for the Solar Decathlon competition, especially since, as a french manufacturer, Renault is available in Morocco.

6.3 Plumbing

Collaboration and coordination with other members of Team OCULUS was essential to an effective design. Our project work overlapped heavily with the plumbing and water systems and thus required us to work with the member of Team OCULUS assigned to these aspects of the building design. We met with this team early in our design process to understand critical components and equipment in each other's work. Throughout each iteration of the mechanical unit design, our team collaborated with the plumbing and water systems designer to ensure that connections between equipment and system components were contructable and accessible. The most notable aspects of this collaboration were the connections to and from the water heater, the dishwasher, the clothes washer, and the bathroom and kitchen fixtures, such as sinks, toilets, and shower fixtures. For example, knowing that flexible PEX piping was going to be used for all of the water connections allowed us to reduce the space in the middle of the mechanical unit where the building's service entry was located. We also discussed drainage requirements for the bathroom shower and co-designed the bathroom floor to act as a drain pan for the shower.

Working alongside the plumbing designer allowed us to solidify some of the site details of the building as well. After designing the service entry tunnel under the building slab, we worked out the positioning of outdoor equipment and laid out the rough locations of connection lines on the site. Early in the design process, for example, the plumbing designer was planning on incorporating a greywater reuse system. The components of this system were to be positioned under the elevated floor of the structure. Upon learning that we were able to cast a slab directly on the ground of our site, this portion of the water system had to be eliminated and the water service entry had to be coordinated within the connections tunnel under the slab. Overall, our team felt that our frequent communication with the plumbing designer helped us to design compatible, effective systems.

7. Conclusion

Participating in the preparation for the Solar Decathlon Africa competition has been an insightful experience. Our team was exposed to all the different processes of designing and building a house. An essential part of the project has been the collaboration between the different subgroups of Team OCULUS. In such a large-scale project, it is important to collaborate effectively with other trades and disciplines, especially during the early in the design process, and maintain constant communication and coordination throughout the design process. Despite our team's solid collaboration with the plumbing designer throughout this project, collaboration between other members of the team could have been improved. Communication with the Moroccan students was particularly challenging. Another important aspect of communication was working with representatives and product specialists since that offered us useful information and design expertise.

During this project, our team designed an innovative heating, ventilation, and air-conditioning (HVAC) system and completed its load calculations, generated a list of potential appliances and mechanical equipment to be implemented within the house, designed a photovoltaic system that will provide the house with sufficient electricity, selected an electric car model according to the competition requirements, and developed a whole-house energy balance. All these designs and information will be used to construct a house in Ben Guerir, Morocco, in September 2019 for the Solar Decathlon Africa Competition. It is important to note the realization that highest efficiency does not necessarily translate to the best choice, even in a competition level, since availability, price, shipping time, maintenance, of the equipment/appliances are all significant facets to weigh when making a selection. Our team worked its best effort to meet all the requirements of the competition and prepare adequately to implement all these systems in the house. We are hoping that the material and information we have been preparing during this year will be able to help Team OCULUS succeed in the Solar Decathlon Competition.

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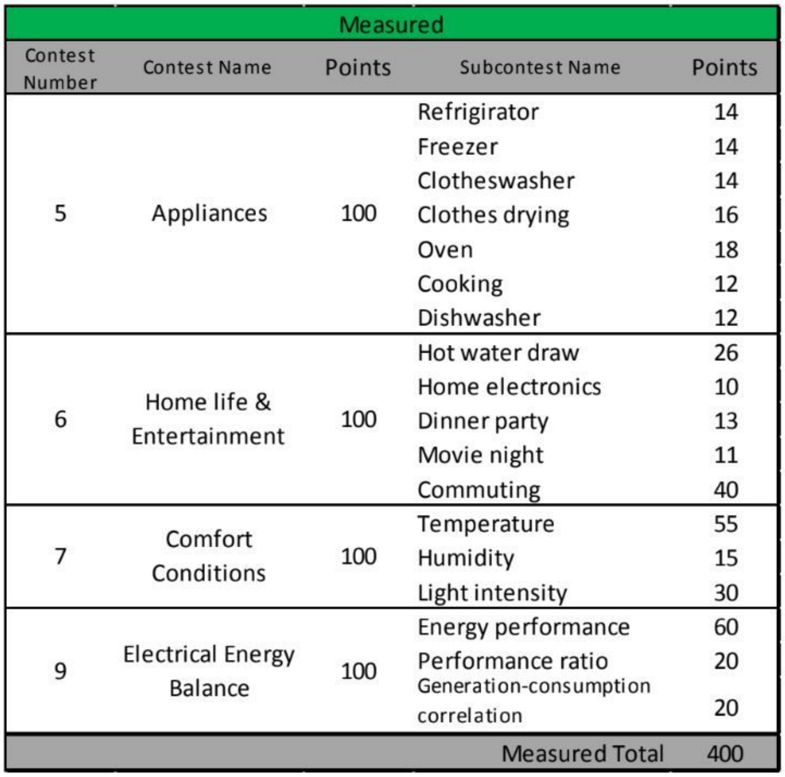
Appendix

Appendix A

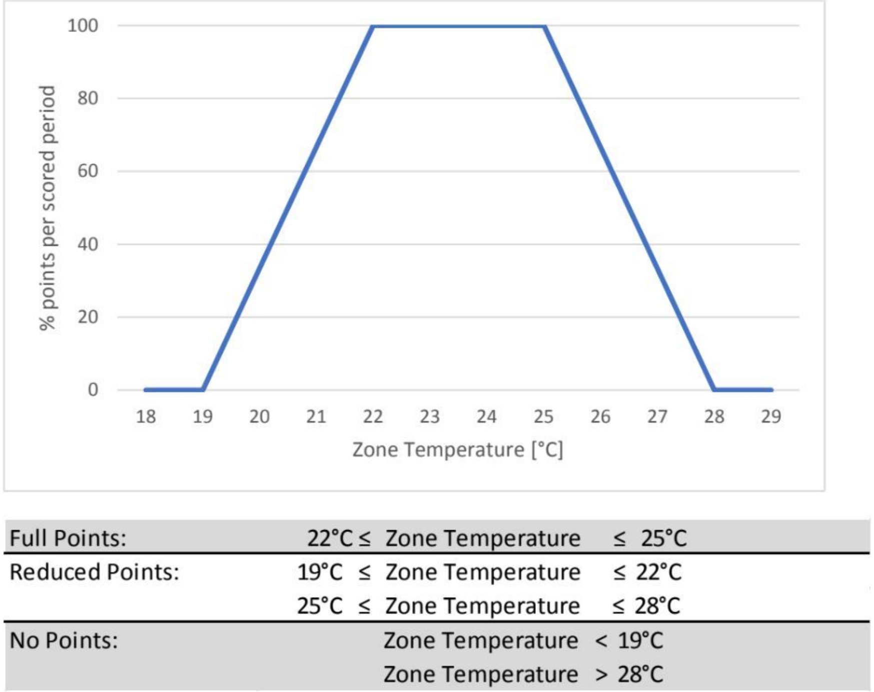
There are mainly two contests within the Solar Decathlon Africa Rules that pertain to the HVAC design. Contest 8 (Health & Comfort) outlines the assessment criteria for interior comfort based on temperature, humidity, and lighting intensity, and Contest 9 (Electrical Energy Balance) describes the assessment of our structure's energy usage based on energy performance, performance ratio, and temporary generation-consumption correlation (IRESEN, 2018). The point weight of each measured contest and subcontest are shown in the table below:



Measured				
Contest Number	Contest Name	Points	Subcontest Name	Points
5	Appliances	100	Refrigirator	14
			Freezer	14
			Clotheswasher	14
			Clothes drying	16
			Oven	18
			Cooking	12
			Dishwasher	12
6	Home life & Entertainment	100	Hot water draw	26
			Home electronics	10
			Dinner party	13
			Movie night	11
			Commuting	40
7	Comfort Conditions	100	Temperature	55
			Humidity	15
			Light intensity	30
9	Electrical Energy Balance	100	Energy performance	60
			Performance ratio	20
			Generation-consumption correlation	20
			Measured Total	400

Figure A-01: Point weight of Measured Contests and Subcontests, from Solar Decathlon Africa Rules (IRESEN, 2018). Note that Contest 7 should actually be titled Contest 8.

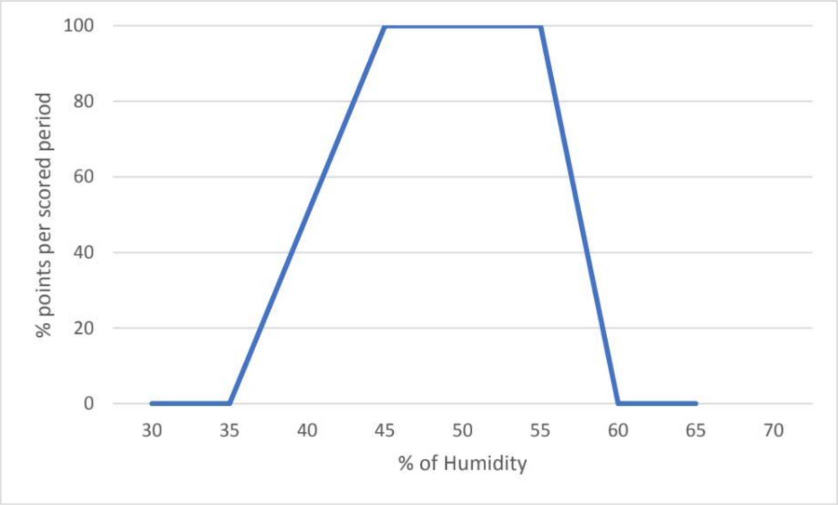
Within Contest 8, the three subcontests of temperature, humidity, and lighting intensity are scored based on the measured deviation from the specified target. For temperature, the specified target range is 22-25 degrees Celsius dry-bulb. The competition organizers will measure interior DB (dry bulb) temperature in at least two different zones of our house during the scoring period (IRESEN, 2018). The time-averaged value of these measured temperatures will be used to score our team's performance during each scoring period, following the scoring function shown below:

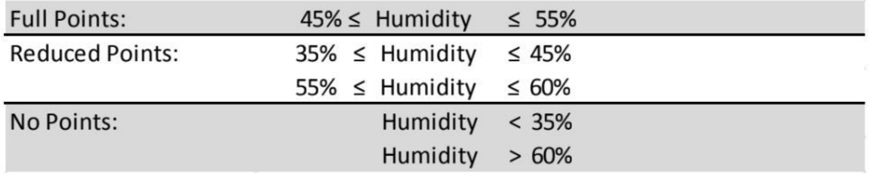


Full Points:	22°C ≤	Zone Temperature	≤ 25°C
Reduced Points:	19°C ≤	Zone Temperature	≤ 22°C
	25°C ≤	Zone Temperature	≤ 28°C
No Points:		Zone Temperature	< 19°C
		Zone Temperature	> 28°C

Figure A-02: Scoring function for Zone Temperature subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

For humidity, the specified target range is 45-55% relative humidity. The competition organizers will measure interior RH (relative humidity) in different zones of our house during the scoring period (IRESEN, 2018). The time-averaged value of these measured humidities will be used to score our team's performance during each scoring period, following the scoring function shown below:

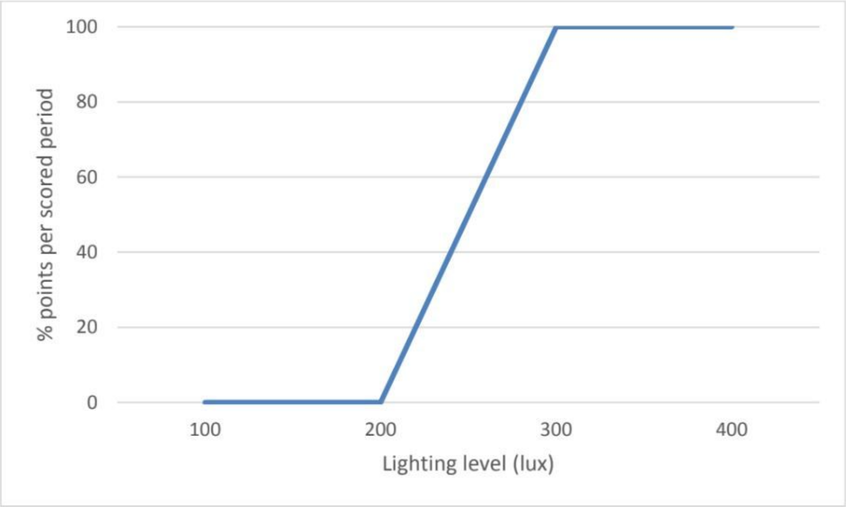




Full Points:	45% ≤	Humidity	≤ 55%
Reduced Points:	35% ≤	Humidity	≤ 45%
	55% ≤	Humidity	≤ 60%
No Points:		Humidity	< 35%
		Humidity	> 60%

Figure A-03: Scoring function for Humidity subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

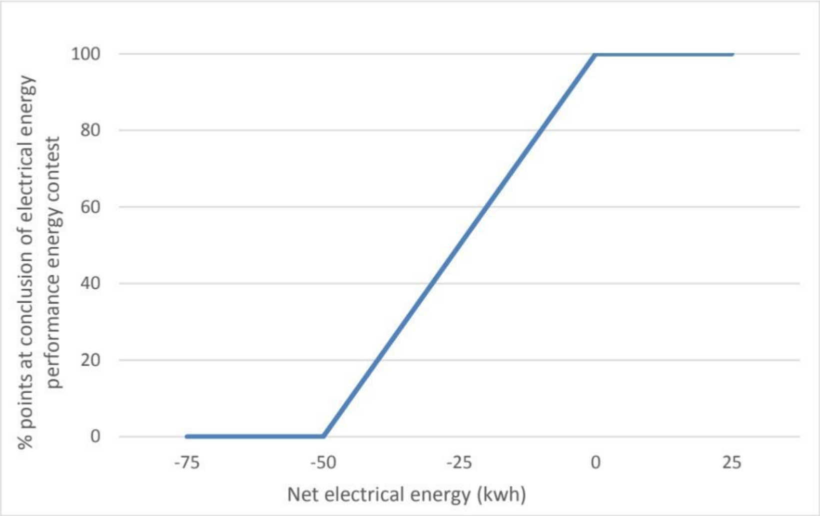
For light intensity, the specified target range is 300 lux or above. The competition organizers will measure interior illuminance in the approximate center of our house's interior at a height of 1 meter from the floor during the scoring period. There must not be any light-emitting devices within 50 centimeters of the measurement devices (IRESEN, 2018). The measured illuminance will be used to score our team's performance during each scoring period, following the scoring function shown below:



Full Points:		Lighting level	≥ 300 lux
Reduced Points:	200 lux ≤	Lighting level	≤ 300 lux
No Points:		Lighting level	< 200 lux

Figure A-04: Scoring function for Lighting level subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

Within Contest 9, the three subcontests of energy performance, performance ratio, and temporary generation-consumption correlation are each assessed uniquely. The energy performance subcontest is scored based on the measured deviation from the specified target. The specified target range for this subcontest is to have a net electrical energy balance of 0 kilowatt-hours or higher. In other words, our photovoltaic system must produce at least as much electricity as our house consumes during the energy performance period (IRESEN, 2018). Organizers will use electricity metering to score this subcontest, following the scoring function shown below:



Full Points:		Net electrical energy	≥ 0 kwh
Reduced Points:	-50 kwh ≤	Net electrical energy	≤ 0 kwh
No Points:		Net electrical energy	≤ -50 kwh

Figure A-05: Scoring function for Energy performance subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

For performance ratio, the team with the highest performance ratio will score the full amount of points available (IRESEN, 2018). All other teams will score a fraction of the full points, following the equation below:

$$Points\ obtained = \frac{Teams'\ performance\ ratio}{Highest\ performance\ ratio} * Total\ points$$

Figure A-06: Scoring equation for performance ratio subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

For temporary generation-consumption correlation, points are awarded to designs that directly consume the most simultaneously generated electricity. These points will only be evaluated during periods where all designs are free of shadows (IRESEN, 2018). Points are based on the correlation between electricity generation and electricity consumption, following the equation below:

$$\xi = \frac{\mathrm{E_{Gl}} + \mathrm{E_{bat\_l}}}{\mathrm{E_L}}$$

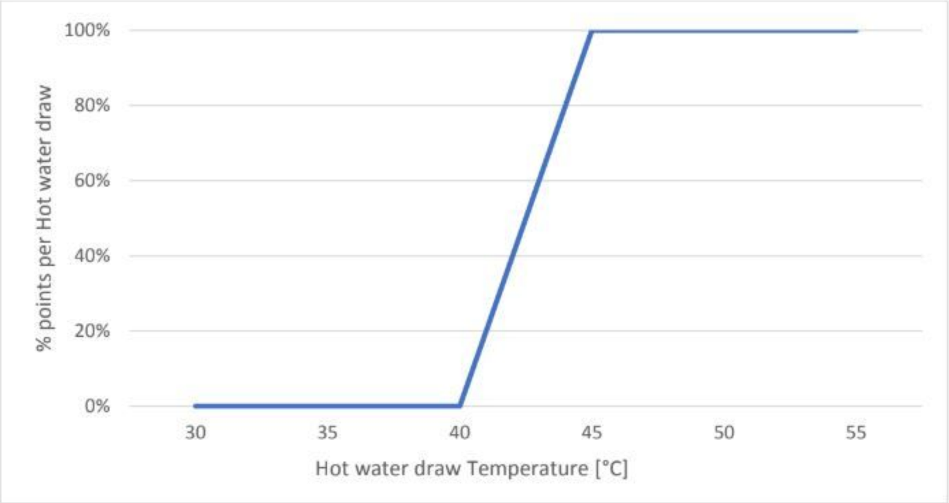
Figure A-07: Correlation equation for Temporary generation-consumption correlation subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

In this equation, E_{Gl} stands for the amount of electricity generated and simultaneously consumed by the electrical loads. E_{bat_l} stands for the amount of electricity supplied by any batteries in the electrical system to the electrical loads. E_L stands for the total electricity consumed by the electrical loads (IRESEN, 2018). Points for this subcontest are calculated based on the following equation:

$$\text{Points obtained} = \text{Total Subcontest points} * \xi$$

Figure A-08: Scoring equation for Temporary generation-consumption correlation subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

Contest 6, Home Life & Entertainment, contains a subcontest for a hot water. During the competition period, organizers will collect hot water from the building's shower fixture up to three times per day. The schedule of these hot water draws will vary from day to day to simulate everyday washing and bathing. According to the competition rules, 50 liters (about 13.2 U.S. gallons) of hot water at a temperature of at least 45 degrees Celsius (about 113 degrees Fahrenheit) collected from the building's shower fixture in under 10 minutes constitutes one hot water draw. If the temperature of the hot water is below 45 degrees Celsius, points for this subcontest will be awarded based on the following scoring function.



Full Points:		Hot water draw Temperature	≥ 45°C
Reduced Points:	40°C ≤	Hot water draw Temperature	≤ 45°C
No Points:		Hot water draw Temperature	< 40°C

Figure A-09: Scoring function for hot water draw subcontest, from Solar Decathlon Africa Rules (IRESEN, 2018).

In addition to the competition rules, the Solar Decathlon Africa 2019 competition requires that participating teams abide by certain building codes. Because this competition was international, organizers decided to let teams follow the building codes and regulations of their home country. Provisions of the International Building Code (IBC), however, should be followed to ensure public health and safety during the competition. The 2015 International Residential Code, with 2015 IBC amendments, and the 2014 National Electric Code are the specific codes governing this competition. The organizers of the Solar Decathlon Africa 2019 provide some amendments to these codes to ensure that competing designs are suited to the competition requirement. These amendments are outlined in the Solar Decathlon Africa Building Code (IRESEN, 2018).

Appendix B

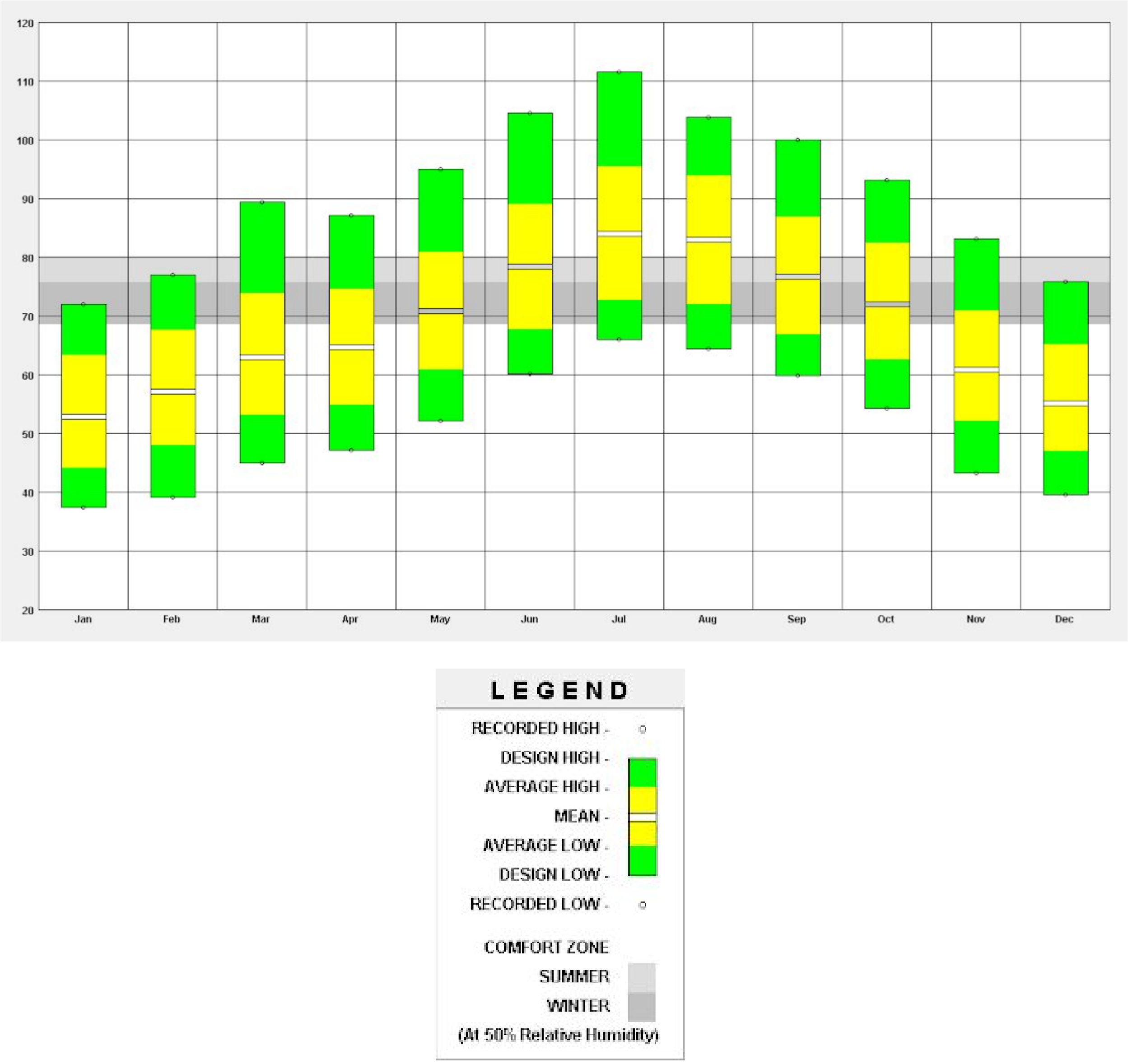


Figure B-01: Climate Consultant 6.0 graph of monthly temperature ranges for Ben Guerir, Morocco.

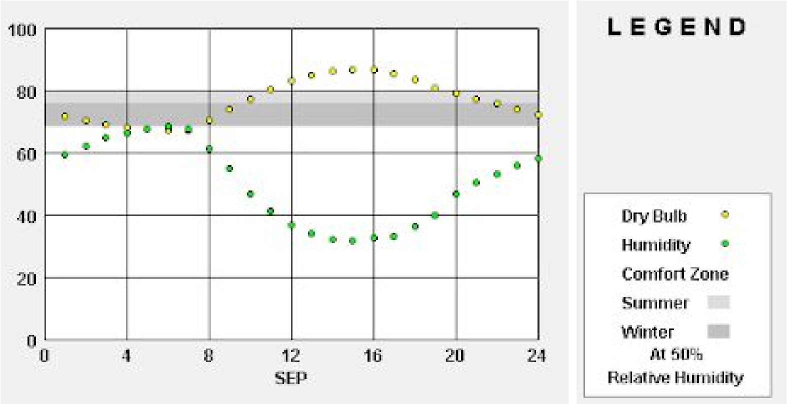
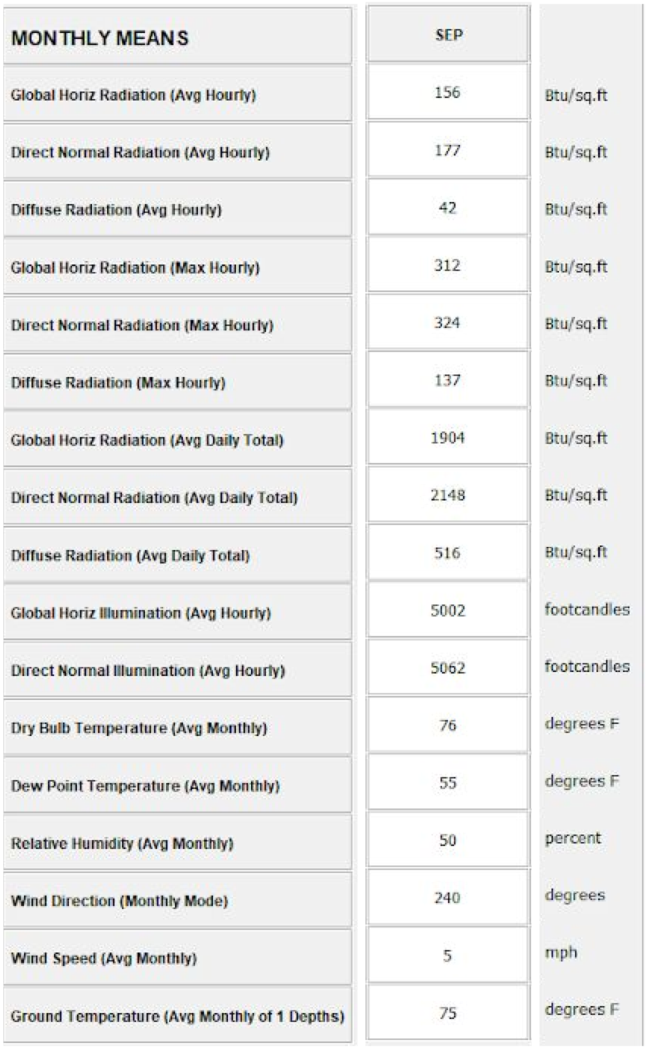


Figure B-02: Climate Consultant 6.0 graphs of hourly dry-bulb temperature and relative humidity levels by month for Ben Guerir, Morocco.



MONTHLY MEANS	SEP	
Global Horiz Radiation (Avg Hourly)	156	Btu/sq.ft
Direct Normal Radiation (Avg Hourly)	177	Btu/sq.ft
Diffuse Radiation (Avg Hourly)	42	Btu/sq.ft
Global Horiz Radiation (Max Hourly)	312	Btu/sq.ft
Direct Normal Radiation (Max Hourly)	324	Btu/sq.ft
Diffuse Radiation (Max Hourly)	137	Btu/sq.ft
Global Horiz Radiation (Avg Daily Total)	1904	Btu/sq.ft
Direct Normal Radiation (Avg Daily Total)	2148	Btu/sq.ft
Diffuse Radiation (Avg Daily Total)	516	Btu/sq.ft
Global Horiz Illumination (Avg Hourly)	5002	footcandles
Direct Normal Illumination (Avg Hourly)	5062	footcandles
Dry Bulb Temperature (Avg Monthly)	76	degrees F
Dew Point Temperature (Avg Monthly)	55	degrees F
Relative Humidity (Avg Monthly)	50	percent
Wind Direction (Monthly Mode)	240	degrees
Wind Speed (Avg Monthly)	5	mph
Ground Temperature (Avg Monthly of 1 Depths)	75	degrees F

Figure B-03: Climate Consultant 6.0 chart of general weather data for Ben Guerir, Morocco.

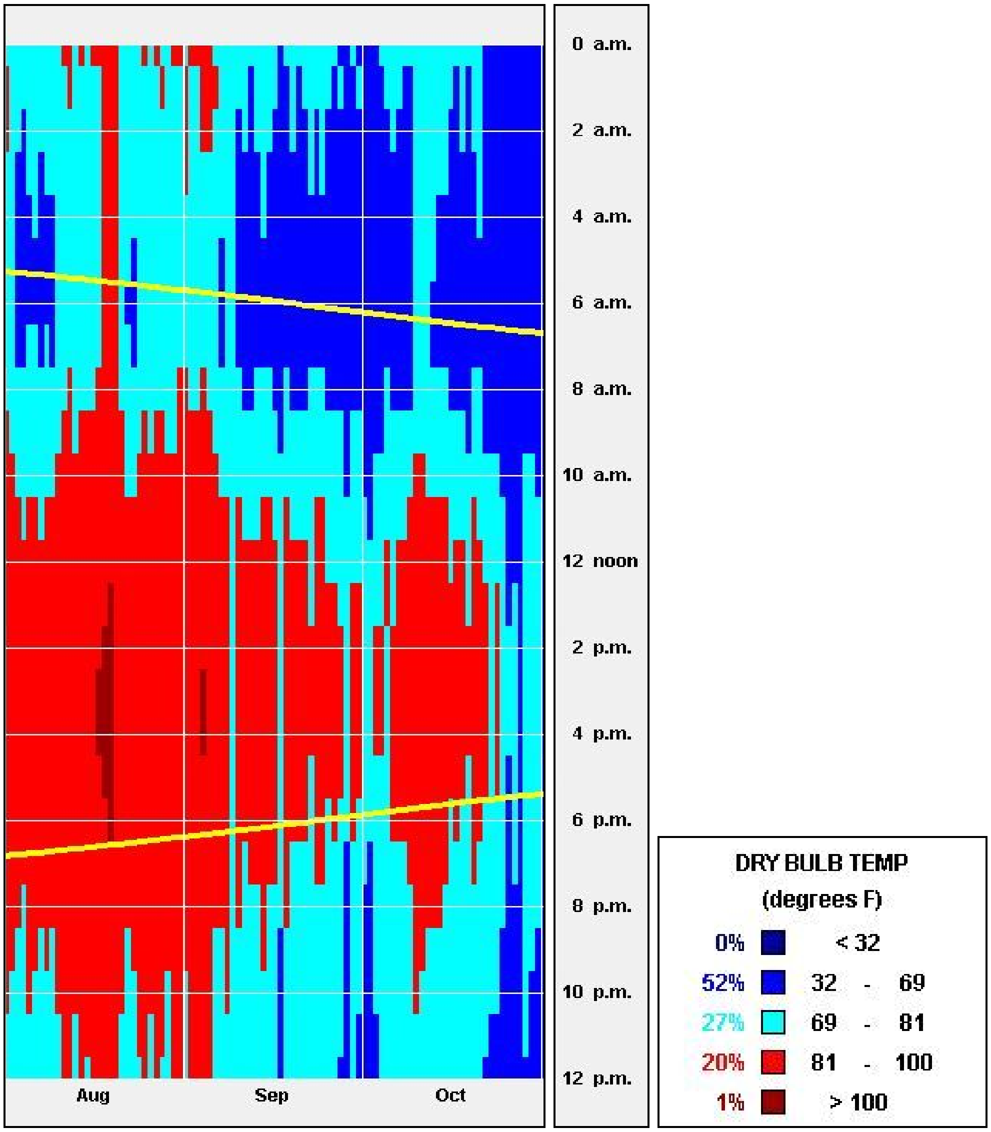


Figure B-04: Climate Consultant 6.0 timetable plot for dry-bulb temperature data for Ben Guerir, Morocco.

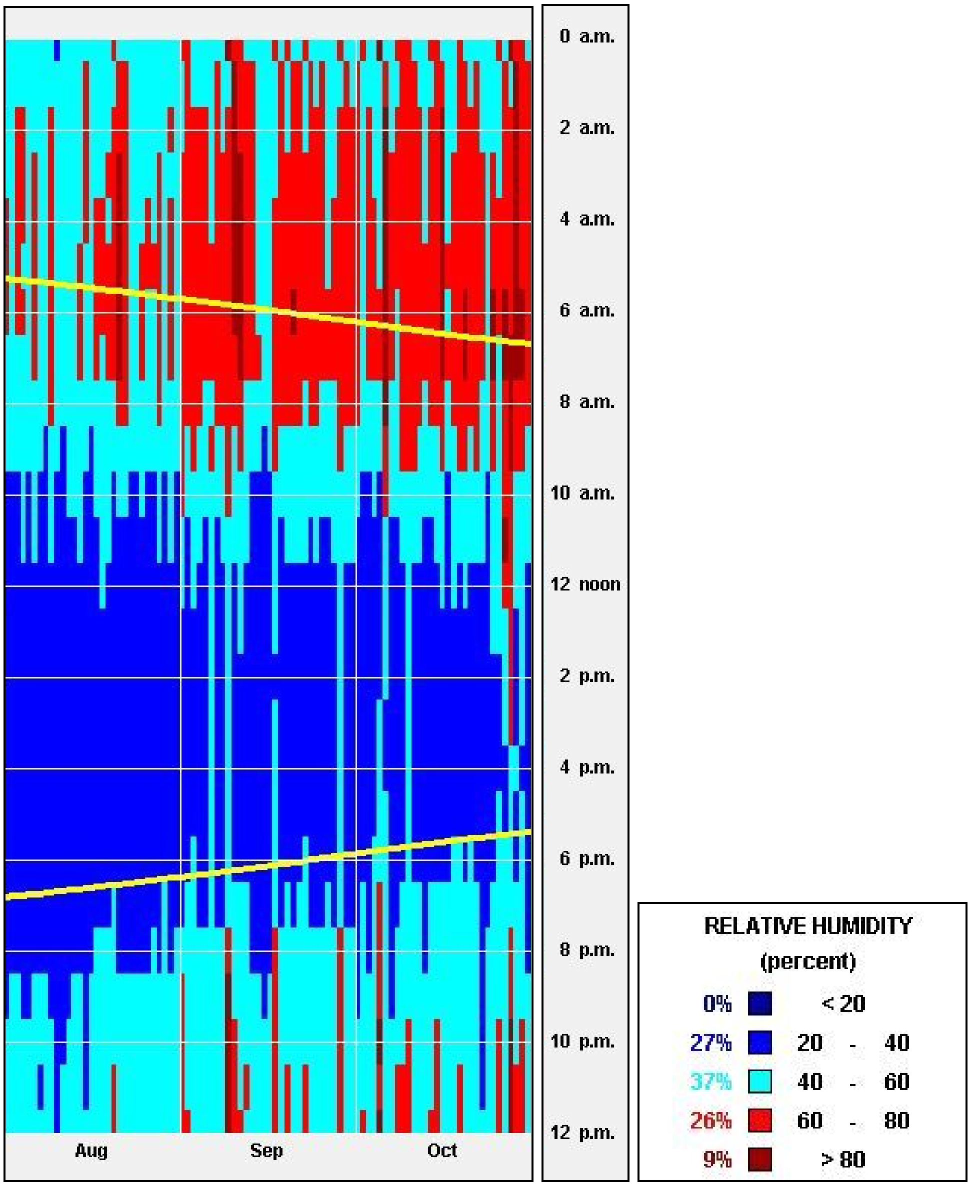
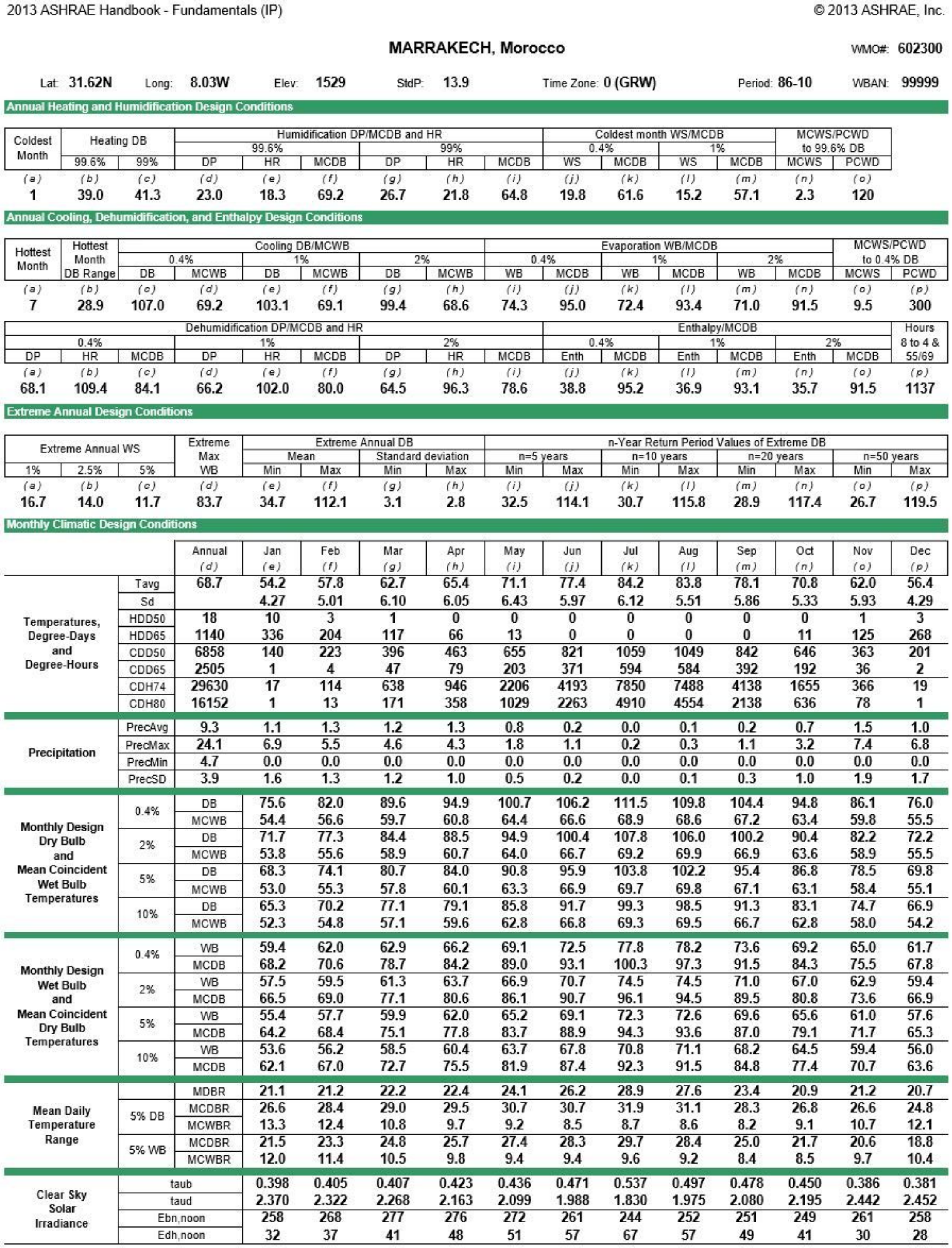


Figure B-05: Climate Consultant 6.0 timetable plot for relative humidity data for Ben Guerir, Morocco.



2013 ASHRAE Handbook - Fundamentals (IP) © 2013 ASHRAE, Inc.

MARRAKECH, Morocco WMO#: **602300**

Lat: **31.62N** Long: **8.03W** Elev: **1529** StdP: **13.9** Time Zone: **0 (GRW)** Period: **86-10** WBAN: **99999**

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)
1	39.0	41.3	23.0	18.3	69.2	26.7	21.8	64.8	19.8	61.6	15.2	57.1	2.3	120

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
7	28.9	107.0	69.2	103.1	69.1	99.4	68.6	74.3	95.0	72.4	93.4	71.0	91.5	9.5	300

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 55/69
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
68.1	109.4	84.1	66.2	102.0	80.0	64.5	96.3	78.6	38.8	95.2	36.9	93.1	35.7	91.5	1137

Extreme Annual Design Conditions

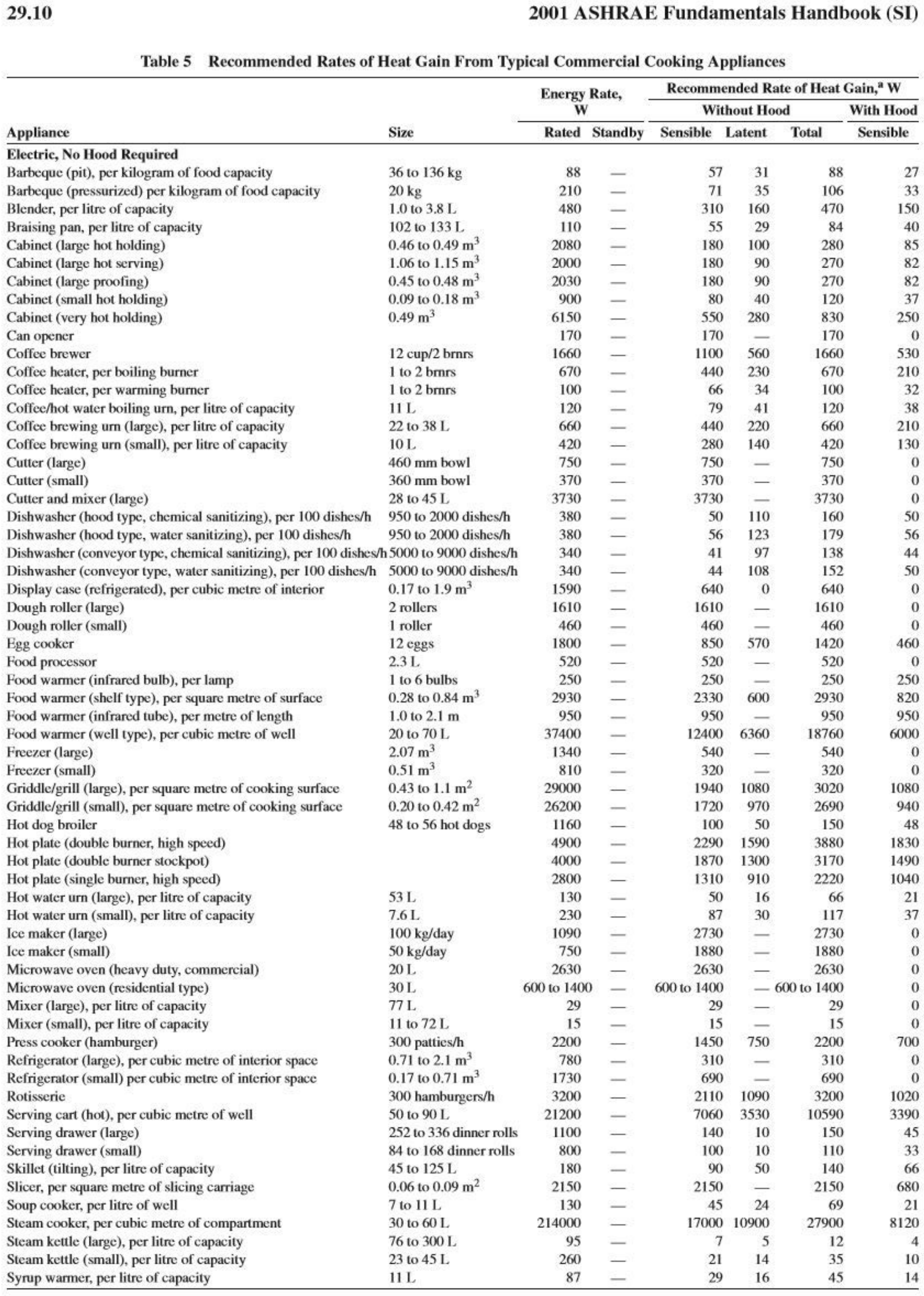
Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
16.7	14.0	11.7	83.7	34.7	112.1	3.1	2.8	32.5	114.1	30.7	115.8	28.9	117.4	26.7	119.5

Monthly Climatic Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
			(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
Temperatures, Degree-Days and Degree-Hours		Tavg	68.7	54.2	57.8	62.7	65.4	71.1	77.4	84.2	83.8	78.1	70.8	62.0	56.4
		Sd		4.27	5.01	6.10	6.05	6.43	5.97	6.12	5.51	5.86	5.33	5.93	4.29
		HDD50	18	10	3	1	0	0	0	0	0	0	0	1	3
		HDD65	1140	336	204	117	66	13	0	0	0	0	11	125	268
		CDD50	6858	140	223	396	463	655	821	1059	1049	842	646	363	201
		CDD65	2505	1	4	47	79	203	371	594	584	392	192	36	2
		CDH74	29630	17	114	638	946	2206	4193	7850	7488	4138	1655	366	19
		CDH80	16152	1	13	171	358	1029	2263	4910	4554	2138	636	78	1
Precipitation		PrecAvg	9.3	1.1	1.3	1.2	1.3	0.8	0.2	0.0	0.1	0.2	0.7	1.5	1.0
		PrecMax	24.1	6.9	5.5	4.6	4.3	1.8	1.1	0.2	0.3	1.1	3.2	7.4	6.8
		PrecMin	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		PrecSD	3.9	1.6	1.3	1.2	1.0	0.5	0.2	0.0	0.1	0.3	1.0	1.9	1.7
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	0.4%	DB		75.6	82.0	89.6	94.9	100.7	106.2	111.5	109.8	104.4	94.8	86.1	76.0
		MCWB		54.4	56.6	59.7	60.8	64.4	66.6	68.9	68.6	67.2	63.4	59.8	55.5
	2%	DB		71.7	77.3	84.4	88.5	94.9	100.4	107.8	106.0	100.2	90.4	82.2	72.2
		MCWB		53.8	55.6	58.9	60.7	64.0	66.7	69.2	69.9	66.9	63.6	58.9	55.5
	5%	DB		68.3	74.1	80.7	84.0	90.8	95.9	103.8	102.2	95.4	86.8	78.5	69.8
		MCWB		53.0	55.3	57.8	60.1	63.3	66.9	69.7	69.8	67.1	63.1	58.4	55.1
	10%	DB		65.3	70.2	77.1	79.1	85.8	91.7	99.3	98.5	91.3	83.1	74.7	66.9
		MCWB		52.3	54.8	57.1	59.6	62.8	66.8	69.3	69.5	66.7	62.8	58.0	54.2
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	0.4%	WB		59.4	62.0	62.9	66.2	69.1	72.5	77.8	78.2	73.6	69.2	65.0	61.7
		MCDB		68.2	70.6	78.7	84.2	89.0	93.1	100.3	97.3	91.5	84.3	75.5	67.8
	2%	WB		57.5	59.5	61.3	63.7	66.9	70.7	74.5	74.5	71.0	67.0	62.9	59.4
		MCDB		66.5	69.0	77.1	80.6	86.1	90.7	96.1	94.5	89.5	80.8	73.6	66.9
	5%	WB		55.4	57.7	59.9	62.0	65.2	69.1	72.3	72.6	69.6	65.6	61.0	57.6
		MCDB		64.2	68.4	75.1	77.8	83.7	88.9	94.3	93.6	87.0	79.1	71.7	65.3
	10%	WB		53.6	56.2	58.5	60.4	63.7	67.8	70.8	71.1	68.2	64.5	59.4	56.0
		MCDB		62.1	67.0	72.7	75.5	81.9	87.4	92.3	91.5	84.8	77.4	70.7	63.6
Mean Daily Temperature Range		MDBR		21.1	21.2	22.2	22.4	24.1	26.2	28.9	27.6	23.4	20.9	21.2	20.7
	5% DB	MCDBR		26.6	28.4	29.0	29.5	30.7	30.7	31.9	31.1	28.3	26.8	26.6	24.8
		MCWBR		13.3	12.4	10.8	9.7	9.2	8.5	8.7	8.6	8.2	9.1	10.7	12.1
	5% WB	MCDBR		21.5	23.3	24.8	25.7	27.4	28.3	29.7	28.4	25.0	21.7	20.6	18.8
		MCWBR		12.0	11.4	10.5	9.8	9.4	9.4	9.6	9.2	8.4	8.5	9.7	10.4
Clear Sky Solar Irradiance		taub		0.398	0.405	0.407	0.423	0.436	0.471	0.537	0.497	0.478	0.450	0.386	0.381
		taud		2.370	2.322	2.268	2.163	2.099	1.988	1.830	1.975	2.080	2.195	2.442	2.452
		Ebn,noon		258	268	277	276	272	261	244	252	251	249	261	258
		Edh,noon		32	37	41	48	51	57	67	57	49	41	30	28

Figure B-06: ASHRAE weather data for Marrakech, Morocco (American Society of Heating, Refrigeration, & Air-conditioning Engineers, 2013).

Appendix C

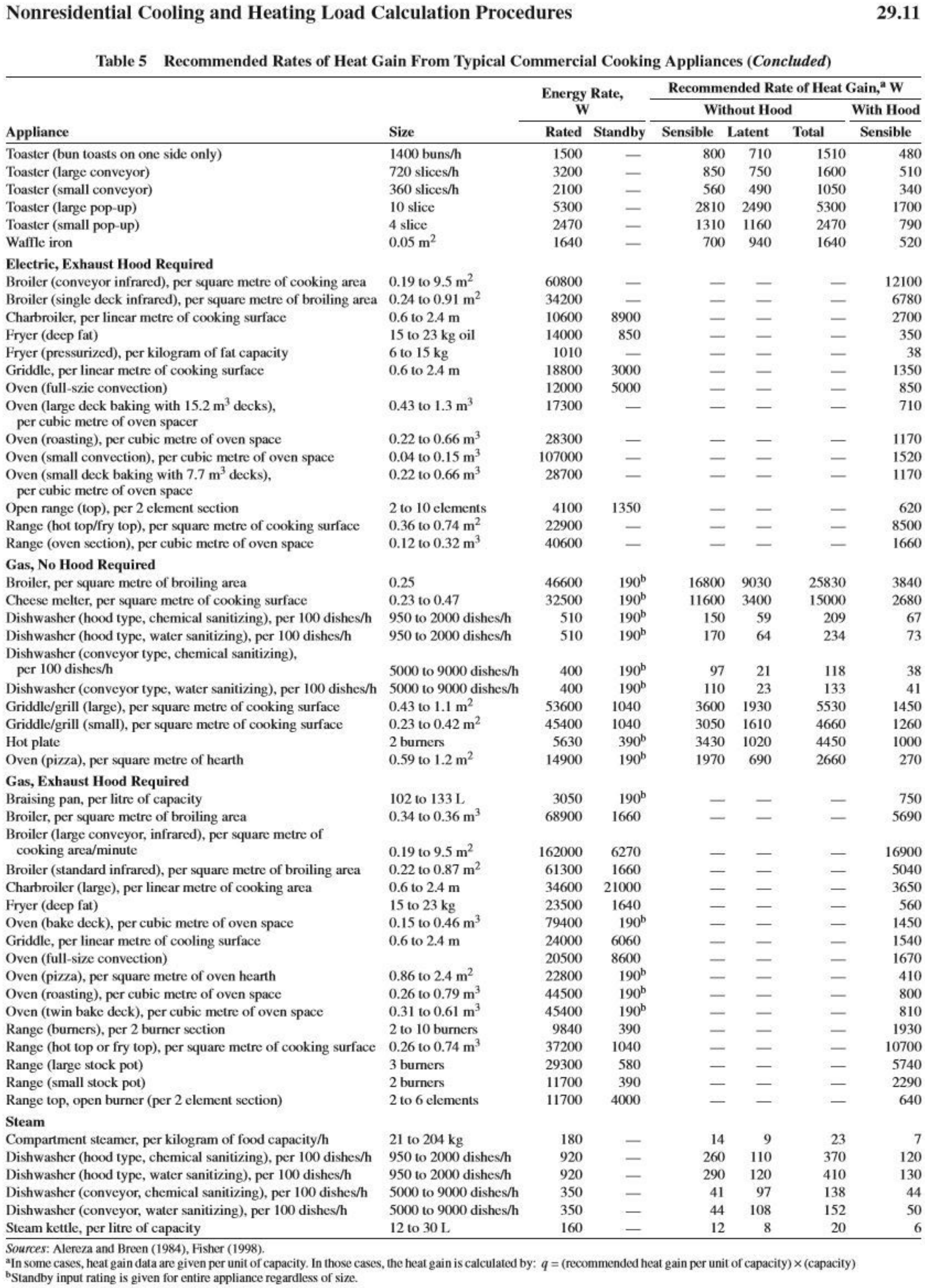


29.10 **2001 ASHRAE Fundamentals Handbook (SI)**

Table 5 Recommended Rates of Heat Gain From Typical Commercial Cooking Appliances

		Energy Rate, W		Recommended Rate of Heat Gain,[a] W			
				Without Hood			With Hood
Appliance	**Size**	**Rated**	**Standby**	**Sensible**	**Latent**	**Total**	**Sensible**
Electric, No Hood Required							
Barbeque (pit), per kilogram of food capacity	36 to 136 kg	88	—	57	31	88	27
Barbeque (pressurized) per kilogram of food capacity	20 kg	210	—	71	35	106	33
Blender, per litre of capacity	1.0 to 3.8 L	480	—	310	160	470	150
Braising pan, per litre of capacity	102 to 133 L	110	—	55	29	84	40
Cabinet (large hot holding)	0.46 to 0.49 m^3	2080	—	180	100	280	85
Cabinet (large hot serving)	1.06 to 1.15 m^3	2000	—	180	90	270	82
Cabinet (large proofing)	0.45 to 0.48 m^3	2030	—	180	90	270	82
Cabinet (small hot holding)	0.09 to 0.18 m^3	900	—	80	40	120	37
Cabinet (very hot holding)	0.49 m^3	6150	—	550	280	830	250
Can opener		170	—	170	—	170	0
Coffee brewer	12 cup/2 brnrs	1660	—	1100	560	1660	530
Coffee heater, per boiling burner	1 to 2 brnrs	670	—	440	230	670	210
Coffee heater, per warming burner	1 to 2 brnrs	100	—	66	34	100	32
Coffee/hot water boiling urn, per litre of capacity	11 L	120	—	79	41	120	38
Coffee brewing urn (large), per litre of capacity	22 to 38 L	660	—	440	220	660	210
Coffee brewing urn (small), per litre of capacity	10 L	420	—	280	140	420	130
Cutter (large)	460 mm bowl	750	—	750	—	750	0
Cutter (small)	360 mm bowl	370	—	370	—	370	0
Cutter and mixer (large)	28 to 45 L	3730	—	3730	—	3730	0
Dishwasher (hood type, chemical sanitizing), per 100 dishes/h	950 to 2000 dishes/h	380	—	50	110	160	50
Dishwasher (hood type, water sanitizing), per 100 dishes/h	950 to 2000 dishes/h	380	—	56	123	179	56
Dishwasher (conveyor type, chemical sanitizing), per 100 dishes/h	5000 to 9000 dishes/h	340	—	41	97	138	44
Dishwasher (conveyor type, water sanitizing), per 100 dishes/h	5000 to 9000 dishes/h	340	—	44	108	152	50
Display case (refrigerated), per cubic metre of interior	0.17 to 1.9 m^3	1590	—	640	0	640	0
Dough roller (large)	2 rollers	1610	—	1610	—	1610	0
Dough roller (small)	1 roller	460	—	460	—	460	0
Egg cooker	12 eggs	1800	—	850	570	1420	460
Food processor	2.3 L	520	—	520	—	520	0
Food warmer (infrared bulb), per lamp	1 to 6 bulbs	250	—	250	—	250	250
Food warmer (shelf type), per square metre of surface	0.28 to 0.84 m^3	2930	—	2330	600	2930	820
Food warmer (infrared tube), per metre of length	1.0 to 2.1 m	950	—	950	—	950	950
Food warmer (well type), per cubic metre of well	20 to 70 L	37400	—	12400	6360	18760	6000
Freezer (large)	2.07 m^3	1340	—	540	—	540	0
Freezer (small)	0.51 m^3	810	—	320	—	320	0
Griddle/grill (large), per square metre of cooking surface	0.43 to 1.1 m^2	29000	—	1940	1080	3020	1080
Griddle/grill (small), per square metre of cooking surface	0.20 to 0.42 m^2	26200	—	1720	970	2690	940
Hot dog broiler	48 to 56 hot dogs	1160	—	100	50	150	48
Hot plate (double burner, high speed)		4900	—	2290	1590	3880	1830
Hot plate (double burner stockpot)		4000	—	1870	1300	3170	1490
Hot plate (single burner, high speed)		2800	—	1310	910	2220	1040
Hot water urn (large), per litre of capacity	53 L	130	—	50	16	66	21
Hot water urn (small), per litre of capacity	7.6 L	230	—	87	30	117	37
Ice maker (large)	100 kg/day	1090	—	2730	—	2730	0
Ice maker (small)	50 kg/day	750	—	1880	—	1880	0
Microwave oven (heavy duty, commercial)	20 L	2630	—	2630	—	2630	0
Microwave oven (residential type)	30 L	600 to 1400	—	600 to 1400	—	600 to 1400	0
Mixer (large), per litre of capacity	77 L	29	—	29	—	29	0
Mixer (small), per litre of capacity	11 to 72 L	15	—	15	—	15	0
Press cooker (hamburger)	300 patties/h	2200	—	1450	750	2200	700
Refrigerator (large), per cubic metre of interior space	0.71 to 2.1 m^3	780	—	310	—	310	0
Refrigerator (small) per cubic metre of interior space	0.17 to 0.71 m^3	1730	—	690	—	690	0
Rotisserie	300 hamburgers/h	3200	—	2110	1090	3200	1020
Serving cart (hot), per cubic metre of well	50 to 90 L	21200	—	7060	3530	10590	3390
Serving drawer (large)	252 to 336 dinner rolls	1100	—	140	10	150	45
Serving drawer (small)	84 to 168 dinner rolls	800	—	100	10	110	33
Skillet (tilting), per litre of capacity	45 to 125 L	180	—	90	50	140	66
Slicer, per square metre of slicing carriage	0.06 to 0.09 m^2	2150	—	2150	—	2150	680
Soup cooker, per litre of well	7 to 11 L	130	—	45	24	69	21
Steam cooker, per cubic metre of compartment	30 to 60 L	214000	—	17000	10900	27900	8120
Steam kettle (large), per litre of capacity	76 to 300 L	95	—	7	5	12	4
Steam kettle (small), per litre of capacity	23 to 45 L	260	—	21	14	35	10
Syrup warmer, per litre of capacity	11 L	87	—	29	16	45	14

Figure C-01: ASHRAE table of heat gains from typical cooking appliances (American Society of Heating, Refrigeration, & Air-conditioning Engineers, 2001).



Nonresidential Cooling and Heating Load Calculation Procedures **29.11**

Table 5 Recommended Rates of Heat Gain From Typical Commercial Cooking Appliances (*Concluded*)

		Energy Rate, W		Recommended Rate of Heat Gain,[a] W			
				Without Hood			With Hood
Appliance	**Size**	**Rated**	**Standby**	**Sensible**	**Latent**	**Total**	**Sensible**
Toaster (bun toasts on one side only)	1400 buns/h	1500	—	800	710	1510	480
Toaster (large conveyor)	720 slices/h	3200	—	850	750	1600	510
Toaster (small conveyor)	360 slices/h	2100	—	560	490	1050	340
Toaster (large pop-up)	10 slice	5300	—	2810	2490	5300	1700
Toaster (small pop-up)	4 slice	2470	—	1310	1160	2470	790
Waffle iron	0.05 m^2	1640	—	700	940	1640	520
Electric, Exhaust Hood Required							
Broiler (conveyor infrared), per square metre of cooking area	0.19 to 9.5 m^2	60800	—	—	—	—	12100
Broiler (single deck infrared), per square metre of broiling area	0.24 to 0.91 m^2	34200	—	—	—	—	6780
Charbroiler, per linear metre of cooking surface	0.6 to 2.4 m	10600	8900	—	—	—	2700
Fryer (deep fat)	15 to 23 kg oil	14000	850	—	—	—	350
Fryer (pressurized), per kilogram of fat capacity	6 to 15 kg	1010	—	—	—	—	38
Griddle, per linear metre of cooking surface	0.6 to 2.4 m	18800	3000	—	—	—	1350
Oven (full-szie convection)		12000	5000	—	—	—	850
Oven (large deck baking with 15.2 m^3 decks), per cubic metre of oven spacer	0.43 to 1.3 m^3	17300	—	—	—	—	710
Oven (roasting), per cubic metre of oven space	0.22 to 0.66 m^3	28300	—	—	—	—	1170
Oven (small convection), per cubic metre of oven space	0.04 to 0.15 m^3	107000	—	—	—	—	1520
Oven (small deck baking with 7.7 m^3 decks), per cubic metre of oven space	0.22 to 0.66 m^3	28700	—	—	—	—	1170
Open range (top), per 2 element section	2 to 10 elements	4100	1350	—	—	—	620
Range (hot top/fry top), per square metre of cooking surface	0.36 to 0.74 m^2	22900	—	—	—	—	8500
Range (oven section), per cubic metre of oven space	0.12 to 0.32 m^3	40600	—	—	—	—	1660
Gas, No Hood Required							
Broiler, per square metre of broiling area	0.25	46600	190[b]	16800	9030	25830	3840
Cheese melter, per square metre of cooking surface	0.23 to 0.47	32500	190[b]	11600	3400	15000	2680
Dishwasher (hood type, chemical sanitizing), per 100 dishes/h	950 to 2000 dishes/h	510	190[b]	150	59	209	67
Dishwasher (hood type, water sanitizing), per 100 dishes/h	950 to 2000 dishes/h	510	190[b]	170	64	234	73
Dishwasher (conveyor type, chemical sanitizing), per 100 dishes/h	5000 to 9000 dishes/h	400	190[b]	97	21	118	38
Dishwasher (conveyor type, water sanitizing), per 100 dishes/h	5000 to 9000 dishes/h	400	190[b]	110	23	133	41
Griddle/grill (large), per square metre of cooking surface	0.43 to 1.1 m^2	53600	1040	3600	1930	5530	1450
Griddle/grill (small), per square metre of cooking surface	0.23 to 0.42 m^2	45400	1040	3050	1610	4660	1260
Hot plate	2 burners	5630	390[b]	3430	1020	4450	1000
Oven (pizza), per square metre of hearth	0.59 to 1.2 m^2	14900	190[b]	1970	690	2660	270
Gas, Exhaust Hood Required							
Braising pan, per litre of capacity	102 to 133 L	3050	190[b]	—	—	—	750
Broiler, per square metre of broiling area	0.34 to 0.36 m^3	68900	1660	—	—	—	5690
Broiler (large conveyor, infrared), per square metre of cooking area/minute	0.19 to 9.5 m^2	162000	6270	—	—	—	16900
Broiler (standard infrared), per square metre of broiling area	0.22 to 0.87 m^2	61300	1660	—	—	—	5040
Charbroiler (large), per linear metre of cooking area	0.6 to 2.4 m	34600	21000	—	—	—	3650
Fryer (deep fat)	15 to 23 kg	23500	1640	—	—	—	560
Oven (bake deck), per cubic metre of oven space	0.15 to 0.46 m^3	79400	190[b]	—	—	—	1450
Griddle, per linear metre of cooling surface	0.6 to 2.4 m	24000	6060	—	—	—	1540
Oven (full-size convection)		20500	8600	—	—	—	1670
Oven (pizza), per square metre of oven hearth	0.86 to 2.4 m^2	22800	190[b]	—	—	—	410
Oven (roasting), per cubic metre of oven space	0.26 to 0.79 m^3	44500	190[b]	—	—	—	800
Oven (twin bake deck), per cubic metre of oven space	0.31 to 0.61 m^3	45400	190[b]	—	—	—	810
Range (burners), per 2 burner section	2 to 10 burners	9840	390	—	—	—	1930
Range (hot top or fry top), per square metre of cooking surface	0.26 to 0.74 m^3	37200	1040	—	—	—	10700
Range (large stock pot)	3 burners	29300	580	—	—	—	5740
Range (small stock pot)	2 burners	11700	390	—	—	—	2290
Range top, open burner (per 2 element section)	2 to 6 elements	11700	4000	—	—	—	640
Steam							
Compartment steamer, per kilogram of food capacity/h	21 to 204 kg	180	—	14	9	23	7
Dishwasher (hood type, chemical sanitizing), per 100 dishes/h	950 to 2000 dishes/h	920	—	260	110	370	120
Dishwasher (hood type, water sanitizing), per 100 dishes/h	950 to 2000 dishes/h	920	—	290	120	410	130
Dishwasher (conveyor, chemical sanitizing), per 100 dishes/h	5000 to 9000 dishes/h	350	—	41	97	138	44
Dishwasher (conveyor, water sanitizing), per 100 dishes/h	5000 to 9000 dishes/h	350	—	44	108	152	50
Steam kettle, per litre of capacity	12 to 30 L	160	—	12	8	20	6

Sources: Alereza and Breen (1984), Fisher (1998).

[a] In some cases, heat gain data are given per unit of capacity. In those cases, the heat gain is calculated by: q = (recommended heat gain per unit of capacity) × (capacity)

[b] Standby input rating is given for entire appliance regardless of size.

Figure C-02: ASHRAE table of heat gains from typical cooking appliances, continued (American Society of Heating, Refrigeration, & Air-conditioning Engineers, 2001).

Peak OSA Temp for --
32 Degrees N. Lat
CLF: Light Construction
Wall Hieght (ft) 13
R-35

Summer

	Roof Type	10	
	Susp'd Ceil'g?	0	(1=Y, 0=No)
F	Indoor Temp	72	50% RH 58.38 gr/lb
F	Daily Range	30	
F	Outdoor Temp	108	70% RH 265.05 gr/lb

48.67 <-- 1.2m radius
845 <-- 5m radius

K	0.83
Tin corr	6
Tout corr	8

Color adjustment factor

	K	
dark	medium	light
1	0.83	0.65

		Wall	Wall	Wall	Wall	Glass	Glass	Glass						Wall	Wall	Wall		Glass	Glass		Glass	Glass	Roof/Floor	Roof/Floor	Transmn	Wall	Roof
	Orientation	Wall Length	Area	Group	U-Value	Area	U	SC	Roof/Floor Area	Roof/Floor U-Value	Peak Month	Peak Hour	Total S & T BTUH	Table CLTD	CLTD	BTUH	SHGF	CLF	Table CLTD	CLTD	Glass Solar BTUH	Glass Trans BTUH	Table CLTD	BTUH	Heat Loss	LM Corr	LM Corr
Roof						48.67	0.57	1.00	796.33	0.03	9	14	10,950				244	0.74	14	28	8,788	777	51	1,385	2,162		-5
1	N	13	169	E	0.03	0	0.65	0.88			9	20	121	22	24	121	33	0.84	14	28	-	-			121	-3	
2	NE	13	169	E	0.03	0	0.65	0.88			9	16	133	26	26	133	103	0.51	14	28	-	-			133	-4	
3	E	13	169	E	0.03	0	0.65	0.88			9	13	192	38	38	192	215	0.57	14	28	-	-			192	-2	
4	SE	13	169	E	0.03	0	0.65	0.88			9	15	209	37	41	209	218	0.63	14	28	-	-			209	3	
5	S	13	169	E	0.03	0	0.65	0.88			9	17	213	34	42	213	171	0.65	14	28	-	-			213	7	
6	SW	13	169	E	0.03	0	0.65	0.88			9	19	243	45	48	243	218	0.66	14	28	-	-			243	3	
7	W	13	169	E	0.03	0	0.65	0.88			9	20	238	49	47	238	215	0.64	14	28	-	-			238	-2	
8	NW	13	169	E	0.03	0	0.65	0.88			9	20	184	38	36	184	103	0.60	14	28	-	-			184	-4	
Floor Slab									845	0.05			1,521											1,521	1,521		

wall total S & T 1,532

SKIN TOTAL:	14,003	BTUH	sensible
	1.17	TONS	

TOTAL COOL Sens	21,502
TOTAL COOL Lat	9,112
TOTAL COOL LOAD (BTUH)	30,614
(TONS)	2.55

Internals

	ASHRAE Data Classification	BTUH(s)	BTUH(l)	W	Size	Quantity	Usage Factor (hrs of op/24 hrs day)	Total BTUH(s)	Total BTUH(l)
Lights									
Mino 2.5 Curve (r=118", 90		940	0	275	1	3	1.0	2820	0
LED pendant		62	0	18	1	2	1.0	124	0
People	walking, standing (drug store, bank)	250	250		1	4	0.5	500	500
Appliances									
Refrigerator (10 ft^3)	small, per 10 ft^3 of space	665			1	1	1.0	665	0
*Hot Plate	18x20x13, 2 heating units	5300	3600		1	1	0.1	530	360
Oven (~5 ft^3	small convection, per ft^3 of space	147			5	1	0.1	73.5	0
	hood type, water sanitizing, per 100 dishes/hour	190	420		1	1	0.1	19	42
Equipment									
Water Heater	(compressor)	4200			1	1	0.2	840	0

TOTAL INTERNAL HEAT GAIN (BTUH)	5572	902
	sensible	latent

ASHRAE Residential Infiltration

Basic Model Stack Coeff (Cs)	0.0150	(single story home)		
Shelter Class	1	2	3	
Basic Model Wind Coeff (Cw)	0.0119	0.0092	0.0065	
Effective Leakage Area (in^2)	30			
Temp Difference (F)	30	(daily range)		
Avg. Wind Speed (mph)	10	(from ClimateConsultant, Sept)		
Airflow Rate, Q (cfm)	38			
Bathroom Exhaust	20			
INFILTRATION HEAT GAIN	1268	(Temp Diff = sensible	5399	latent
BATHROOM EXHAUST HEAT GAIN	660	sensible	2811	latent

Figure C-03: Our CLTD Cooling Load Calculation.

Appendix D

This is our first mechanical layout concept. This concept featured a steel frame which used the weight of the water heater to cantilever the indoor HVAC unit beyond the edge of the floor slab.

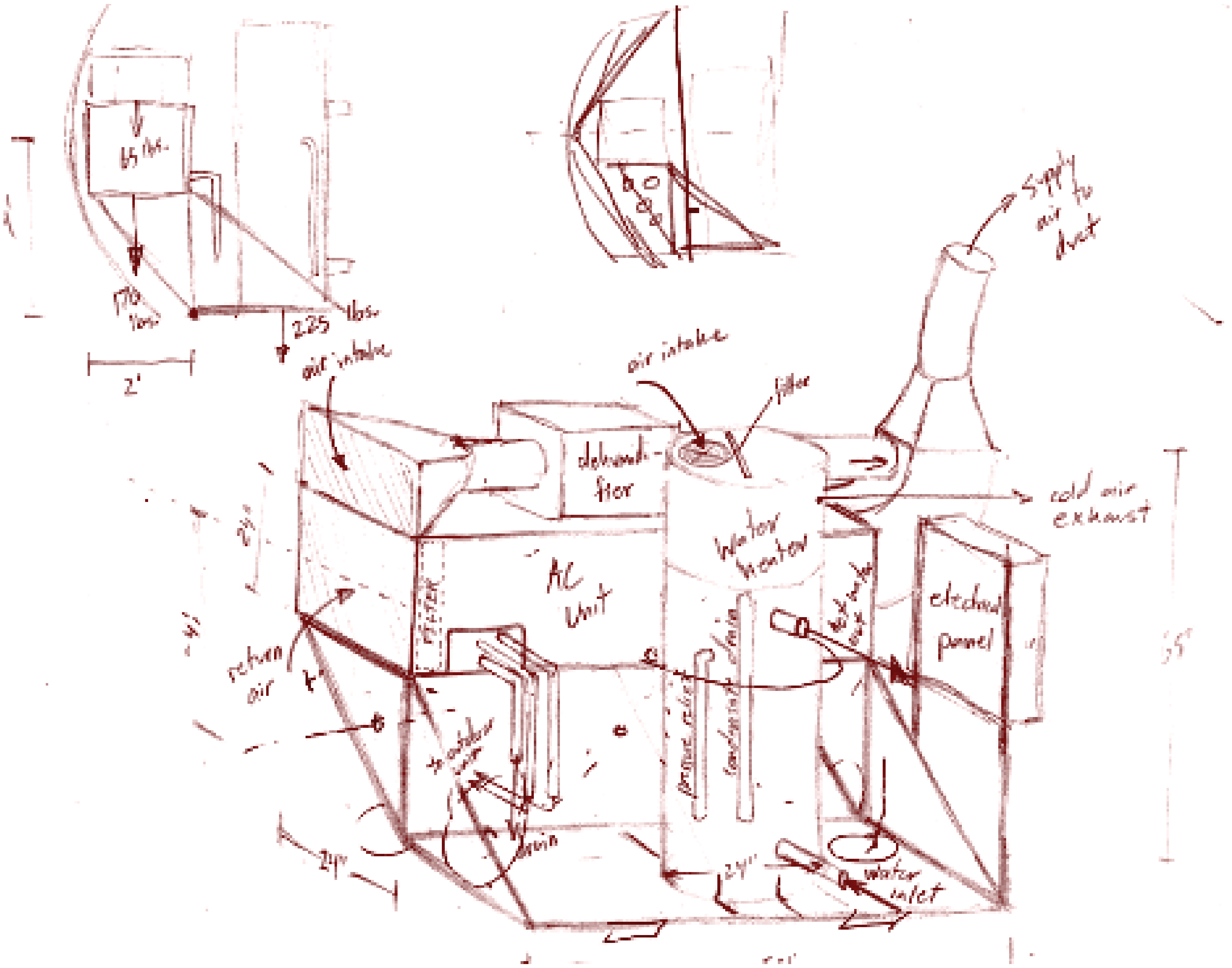


Figure D-01: First mechanical configuration concept drawings.

This is the second mechanical layout concept. This concept aimed to arrange all appliances around the perimeter of the house.

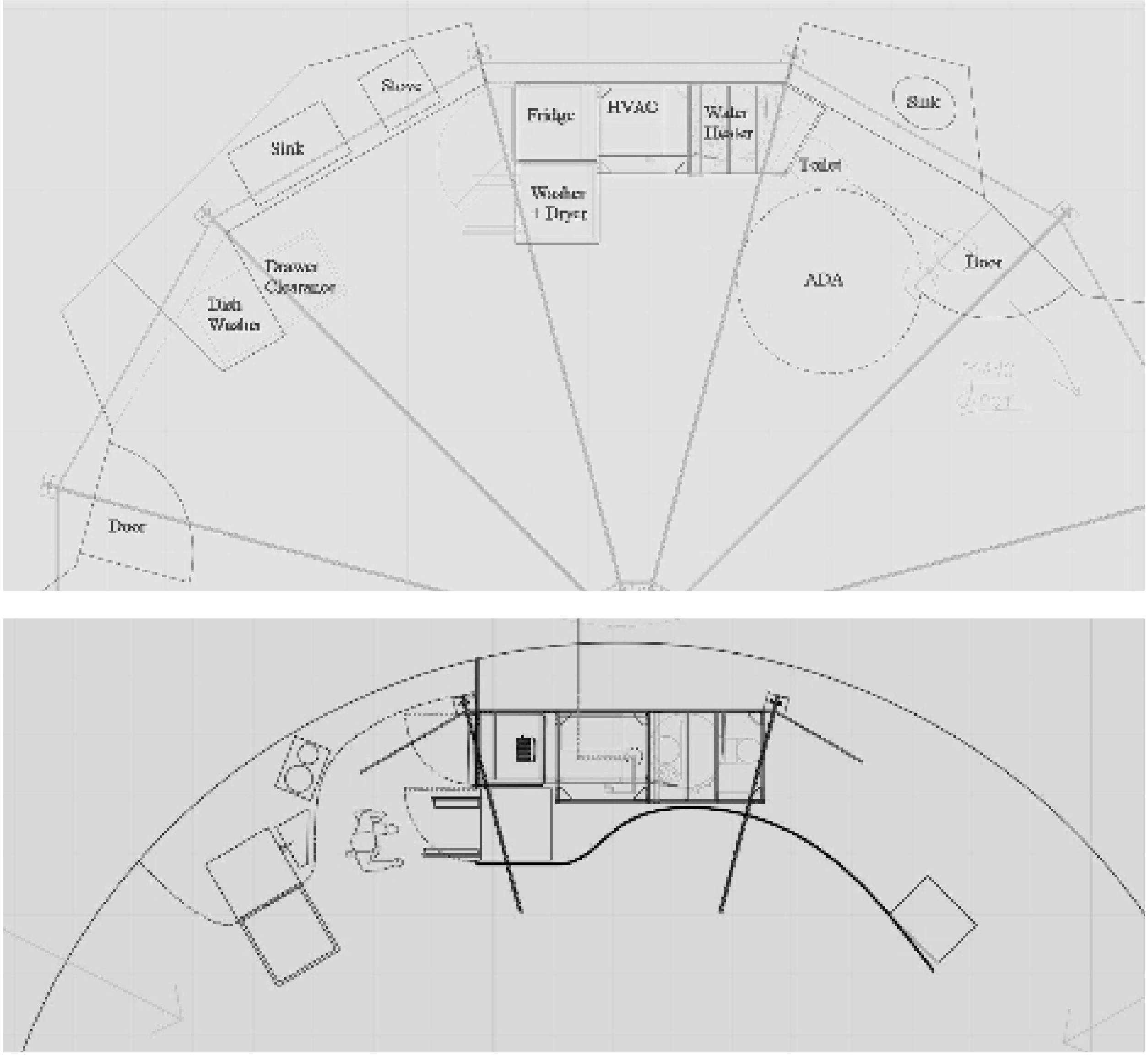
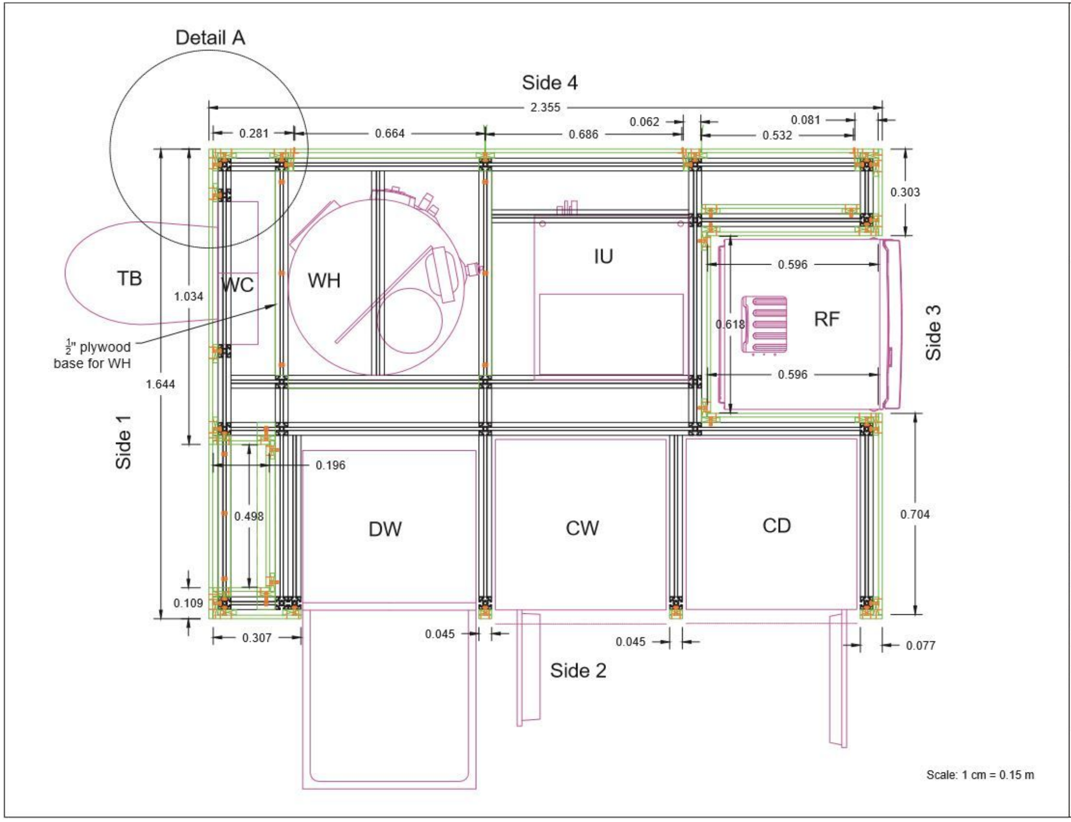


Figure D-02: Second mechanical configuration concept drawings.

Appendix E

A full drawing set for the mechanical unit can be found starting on the next page.



Scale: 1 cm = 0.15 m

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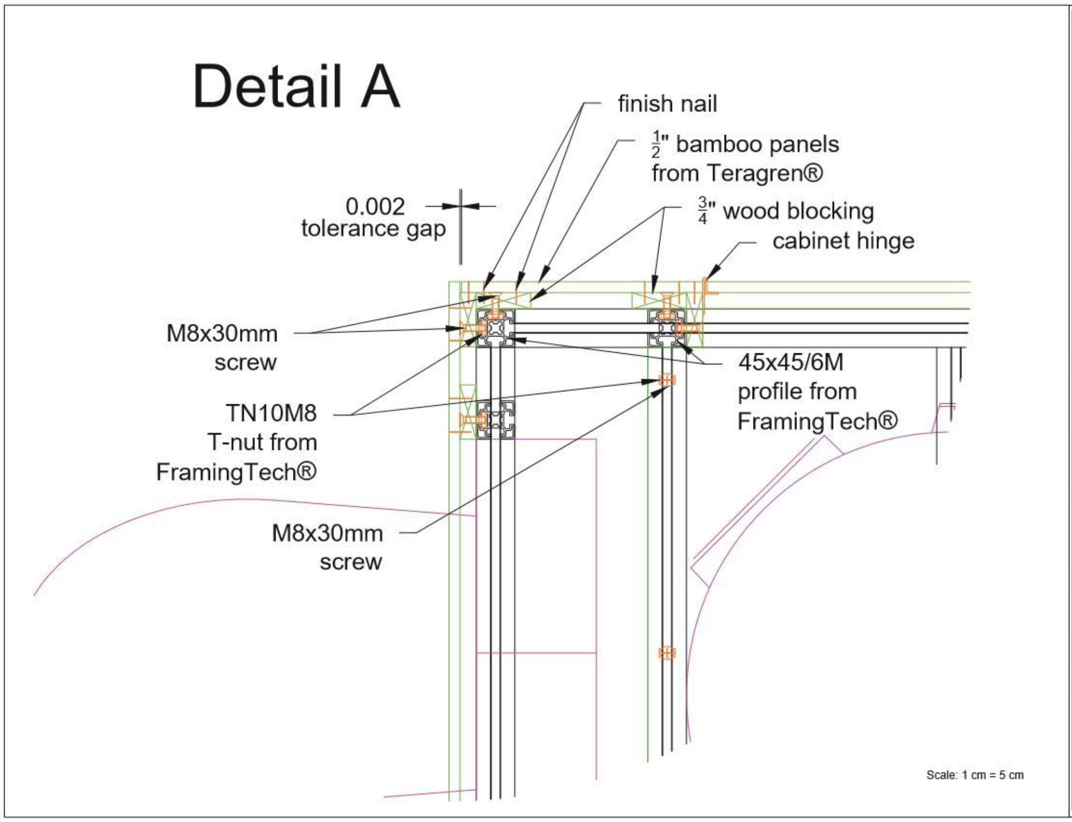
SHEET TITLE:
Mechanical Module - Plan View (below countertop)



Scale: 1 cm = 5 cm

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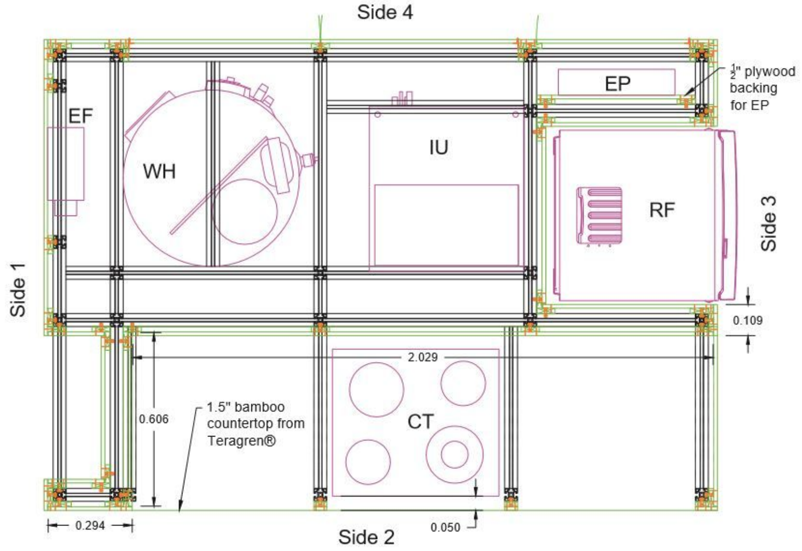

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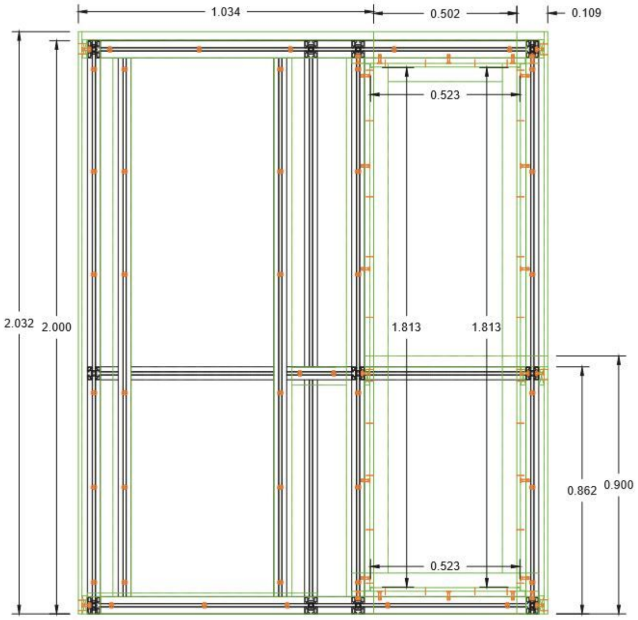
Mechanical Module - Plan View (above countertop)



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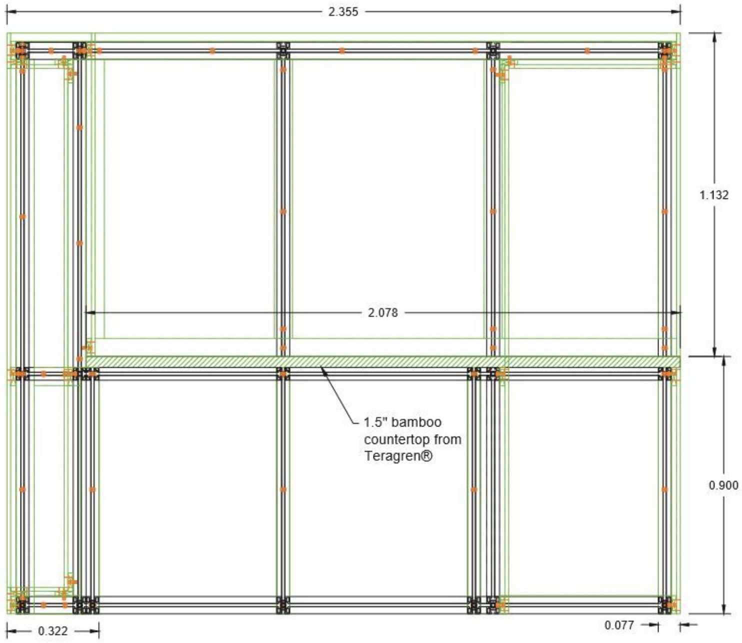

1.5" bamboo countertop from Teragren®

Scale: 1 cm = 0.15 m

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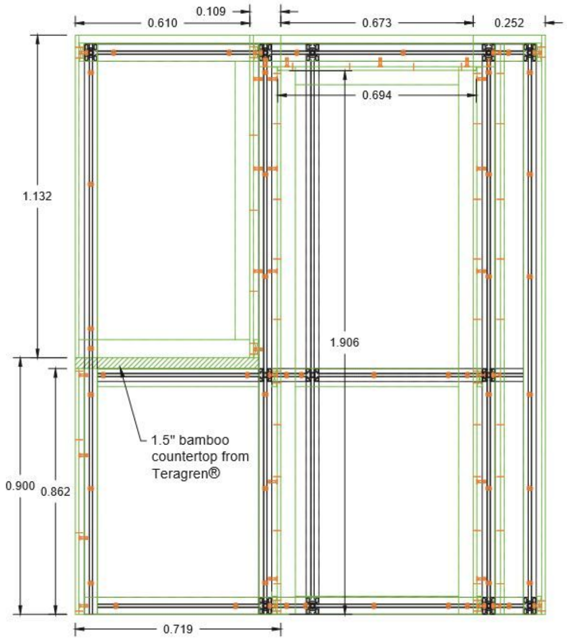
Mechanical Module - Side 2 Section



1.5" bamboo countertop from Teragren®

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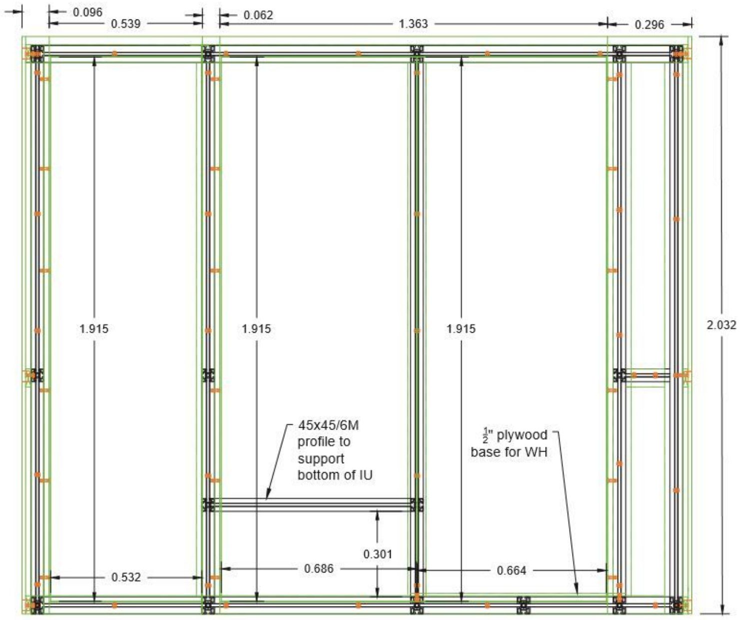
SHEET TITLE:
Mechanical Module - Side 3 Section



Scale: 1 cm = 0.15 m

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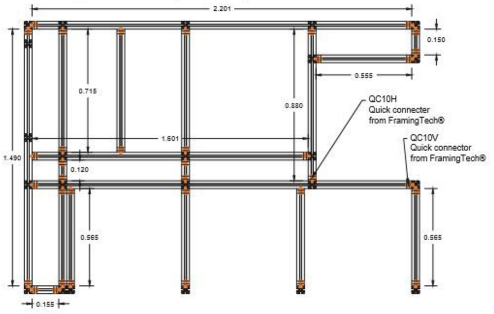
SHEET TITLE:
Mechanical Module - Side 4 Section

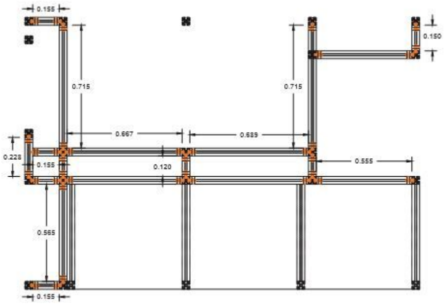
Base (45x60/6M profiles)

Scale: 1 cm = 0.25 m



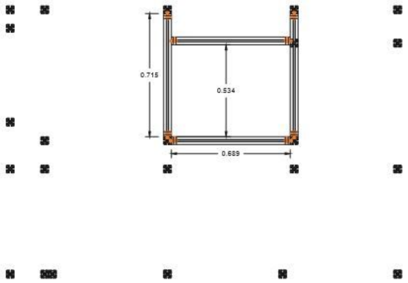
At countertop (45x45/6M profiles)

Scale: 1 cm = 0.25 m



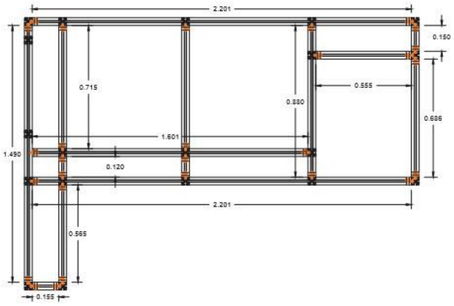
At bottom of HVAC unit (45x45/6M profiles)

Scale: 1 cm = 0.25 m



Top (45x60/6M profiles)

Scale: 1 cm = 0.25 m



All vertical members of the frame are 45x45/6M profiles

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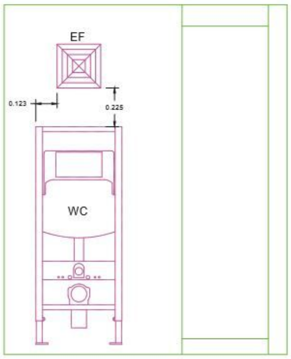

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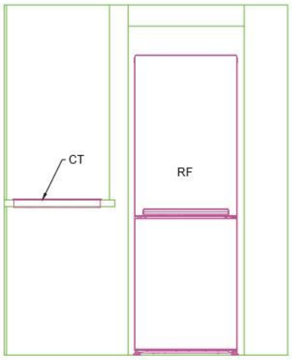

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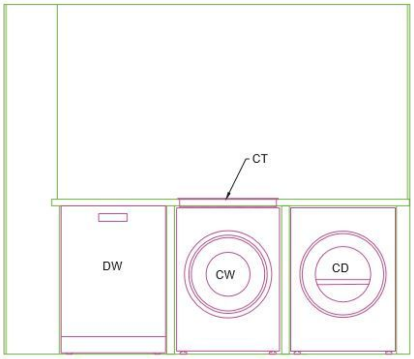

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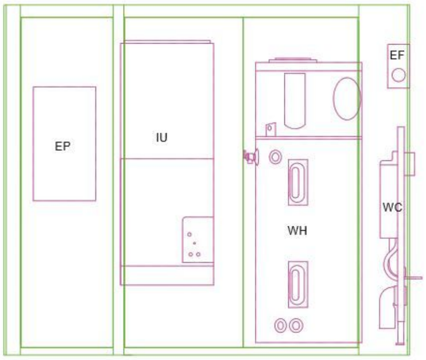

Scale: 1 cm = 0.25 m

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Appendix F

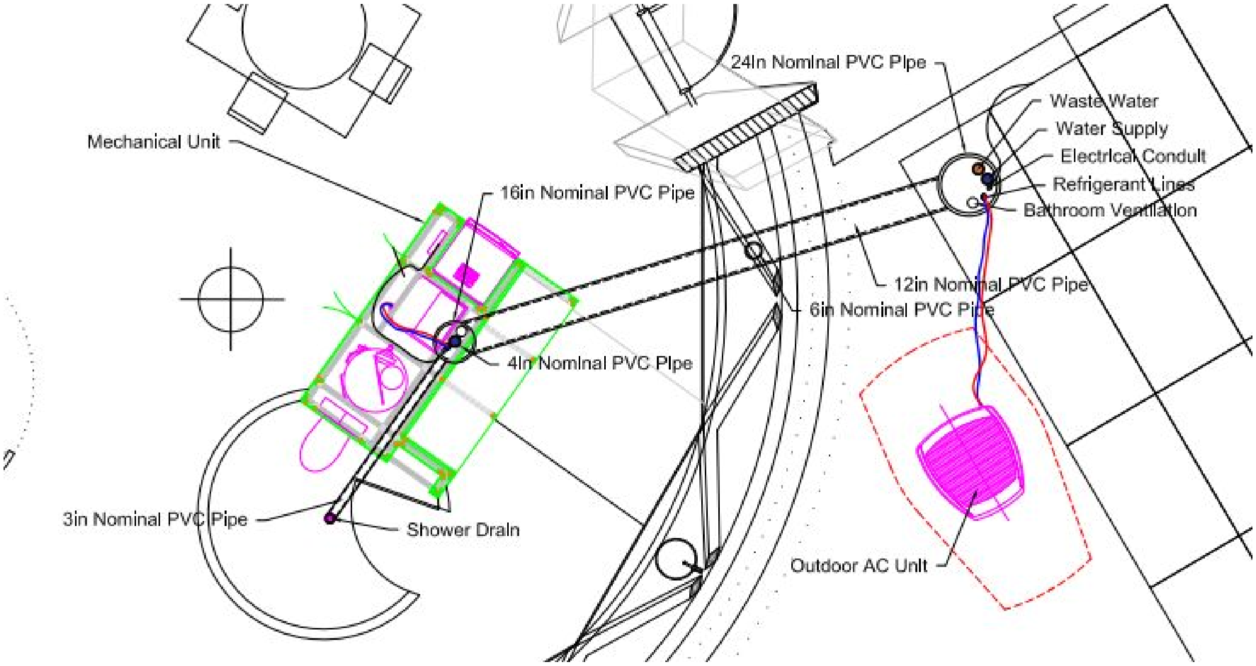


Figure F-01: Mechanical connection tunnel plan view.

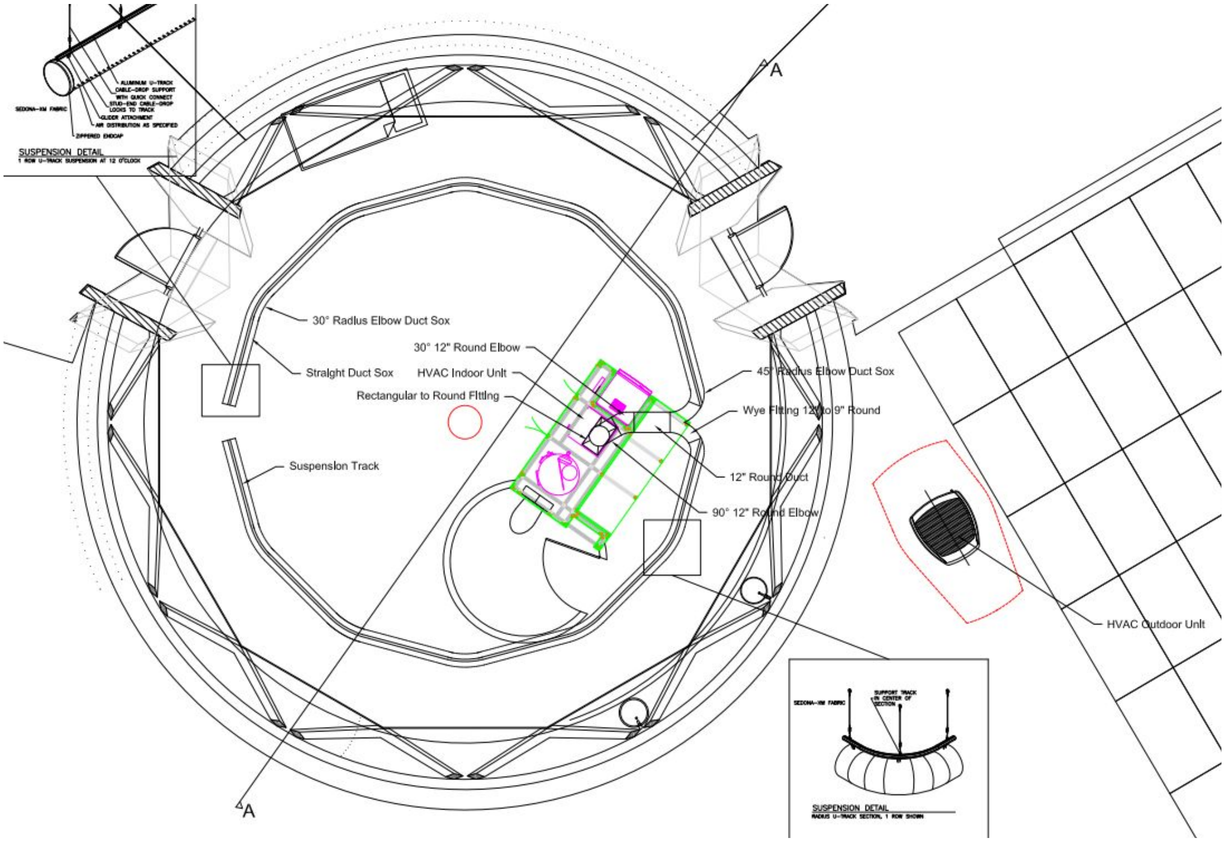


Figure F-02: Proposed duct layout plan view.

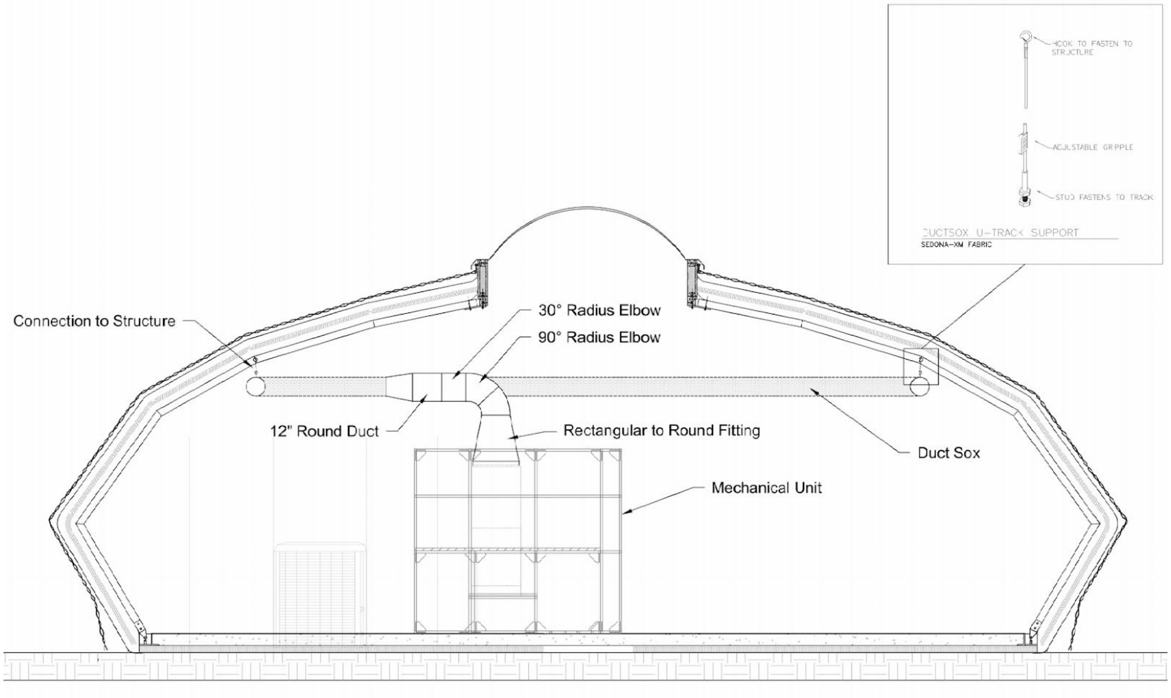


Figure F-03: Proposed duct layout section view.

Appendix G

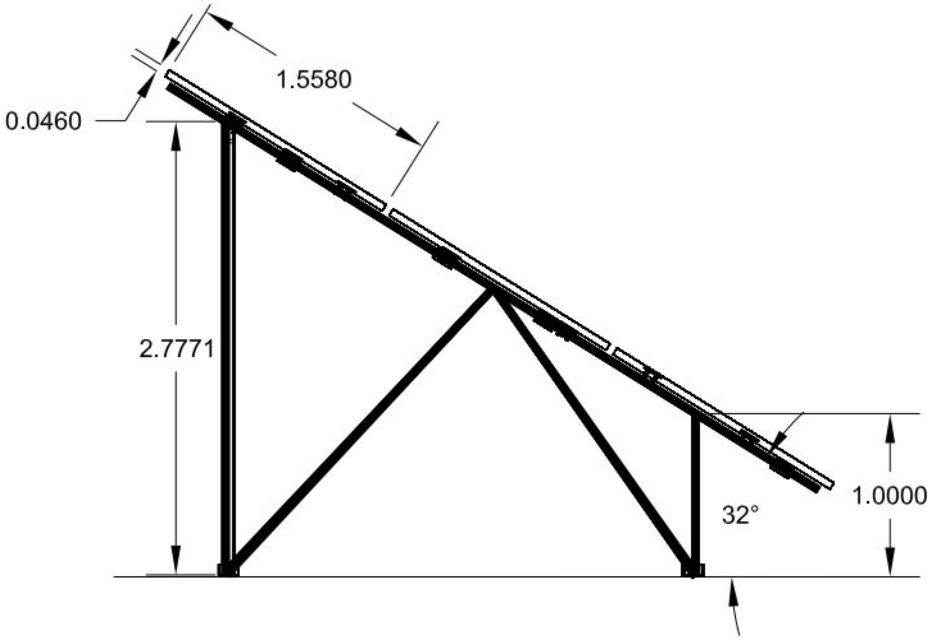


Figure G-01: Side view of the solar panel frame with dimensions.

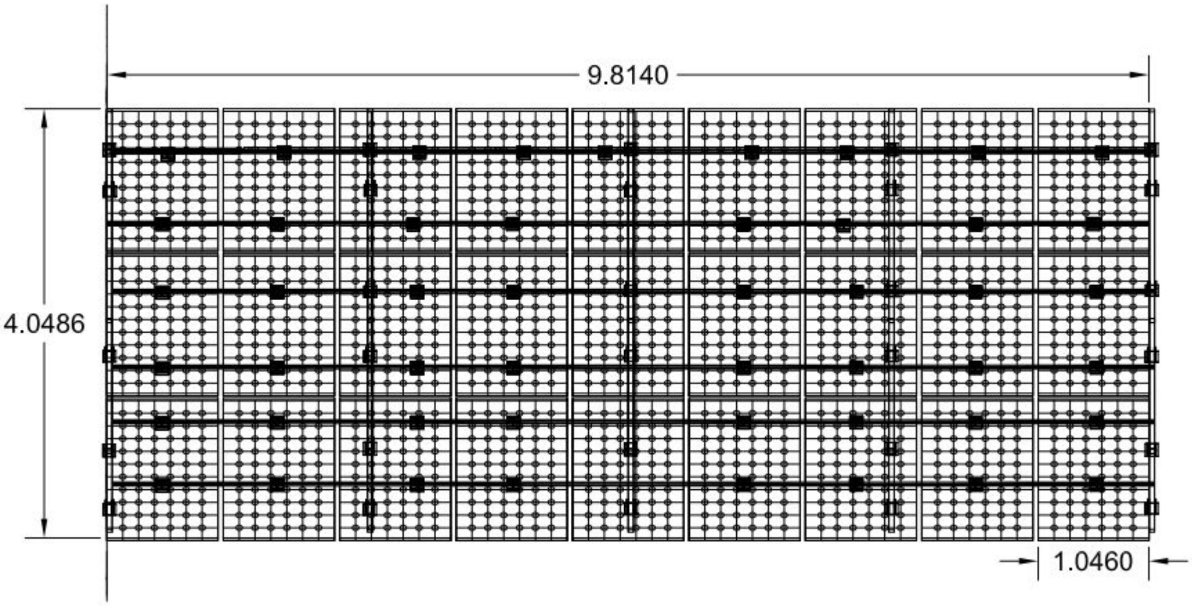


Figure G-02: Top view of solar panel frame with dimensions and number of panels.

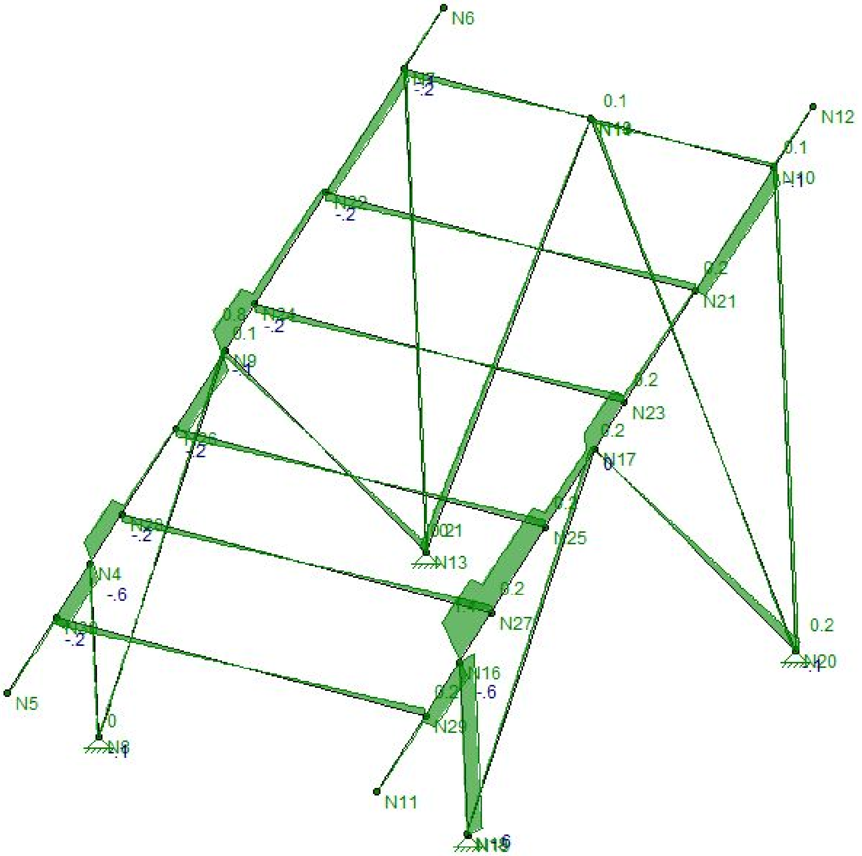


Figure G-03: Shear force on the y-axis of the members.

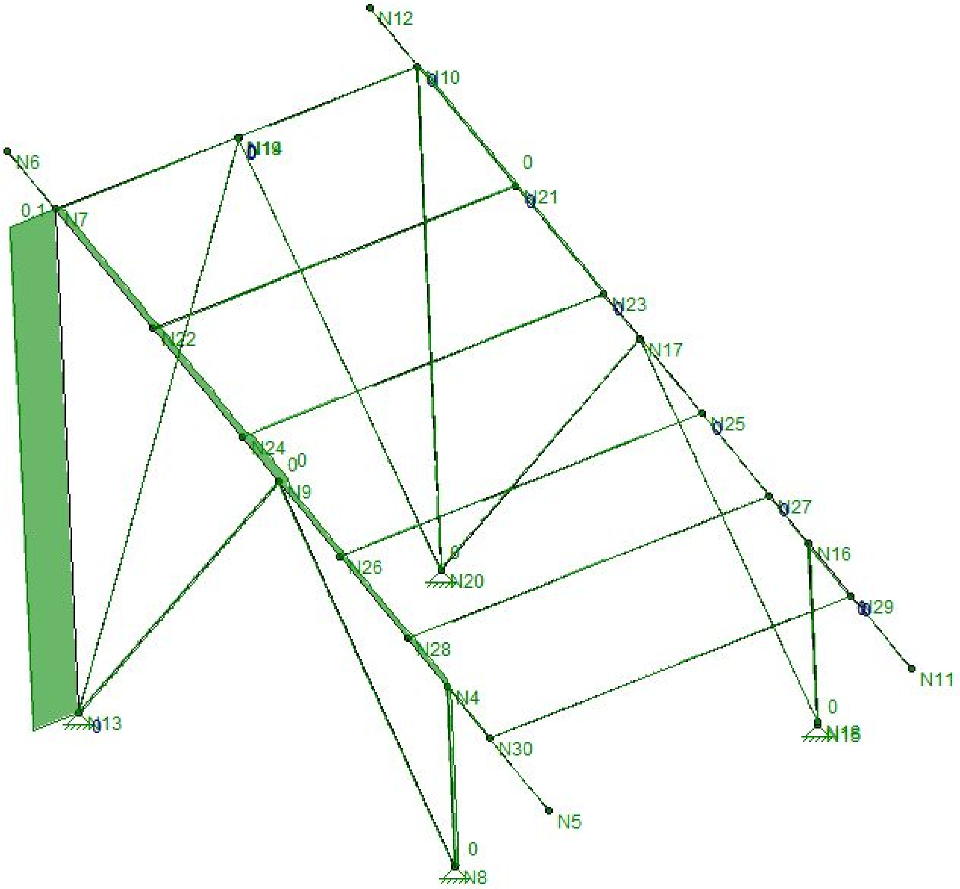


Figure G-04: Shear force on the z-axis of the members.

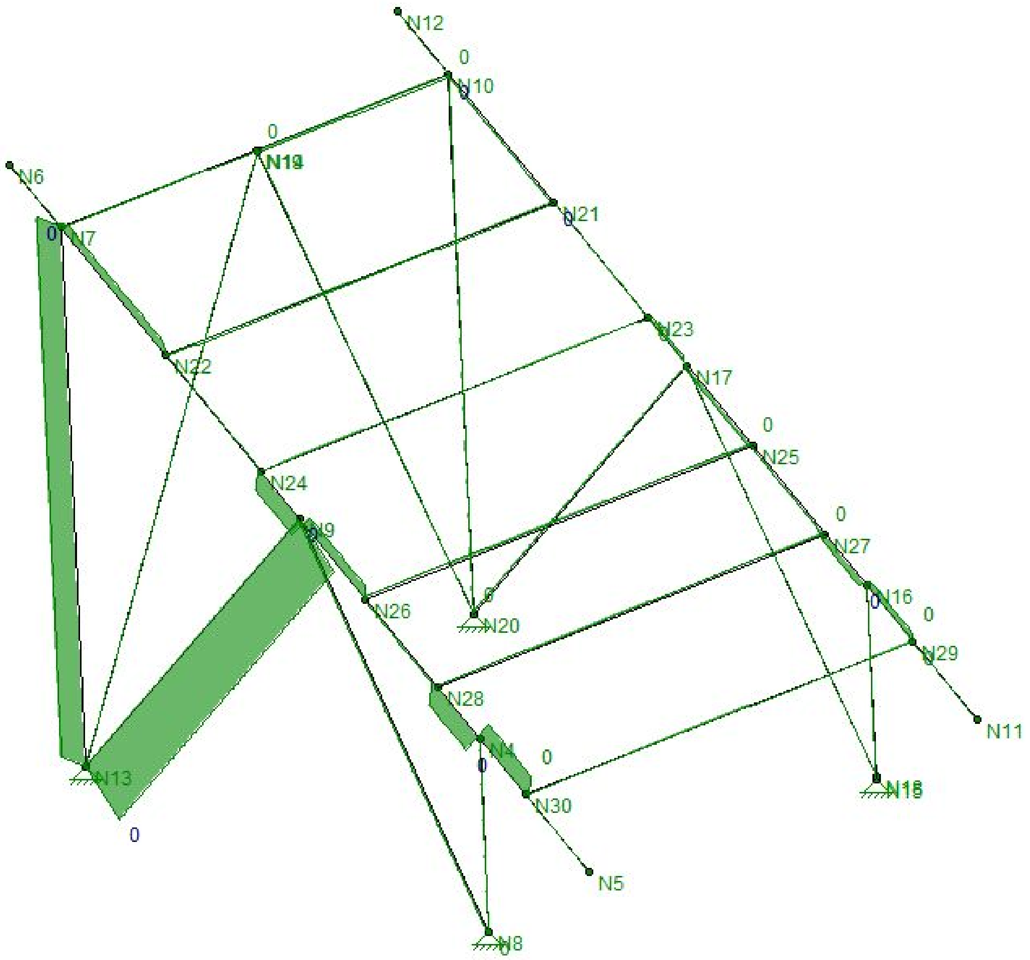


Figure G-05: Torque on the members of the solar panel frame.

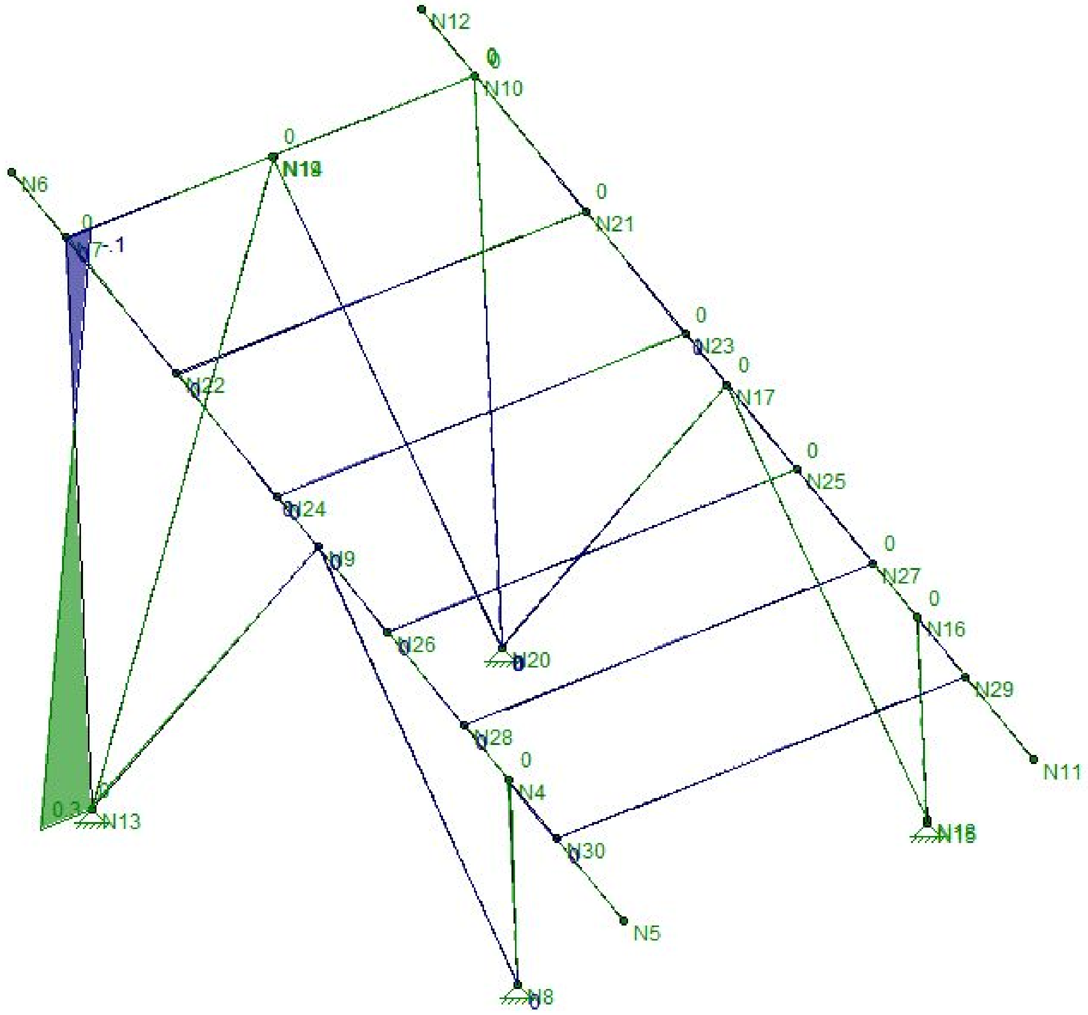


Figure G-06: Moment of the members on the y-axis.

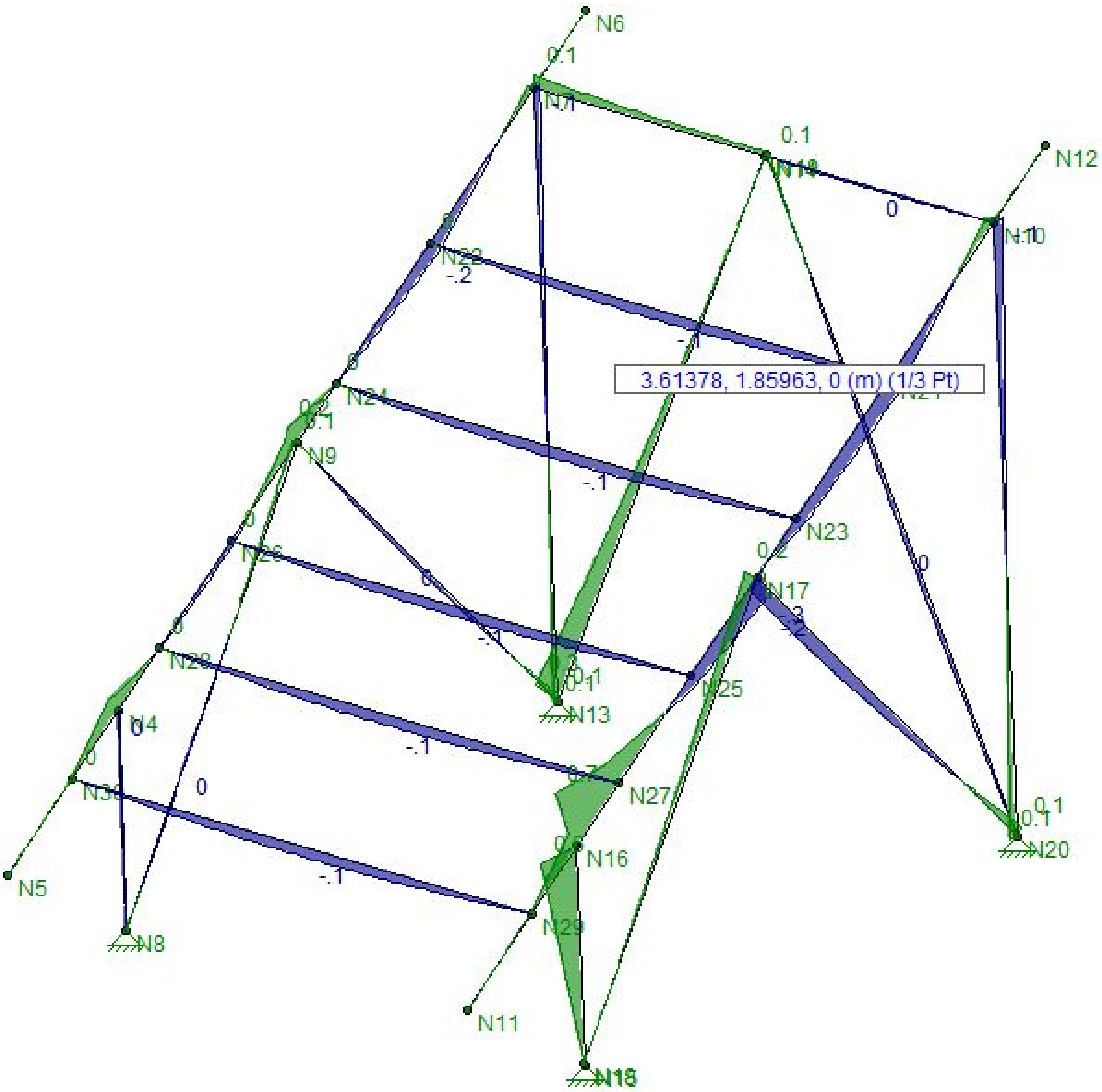
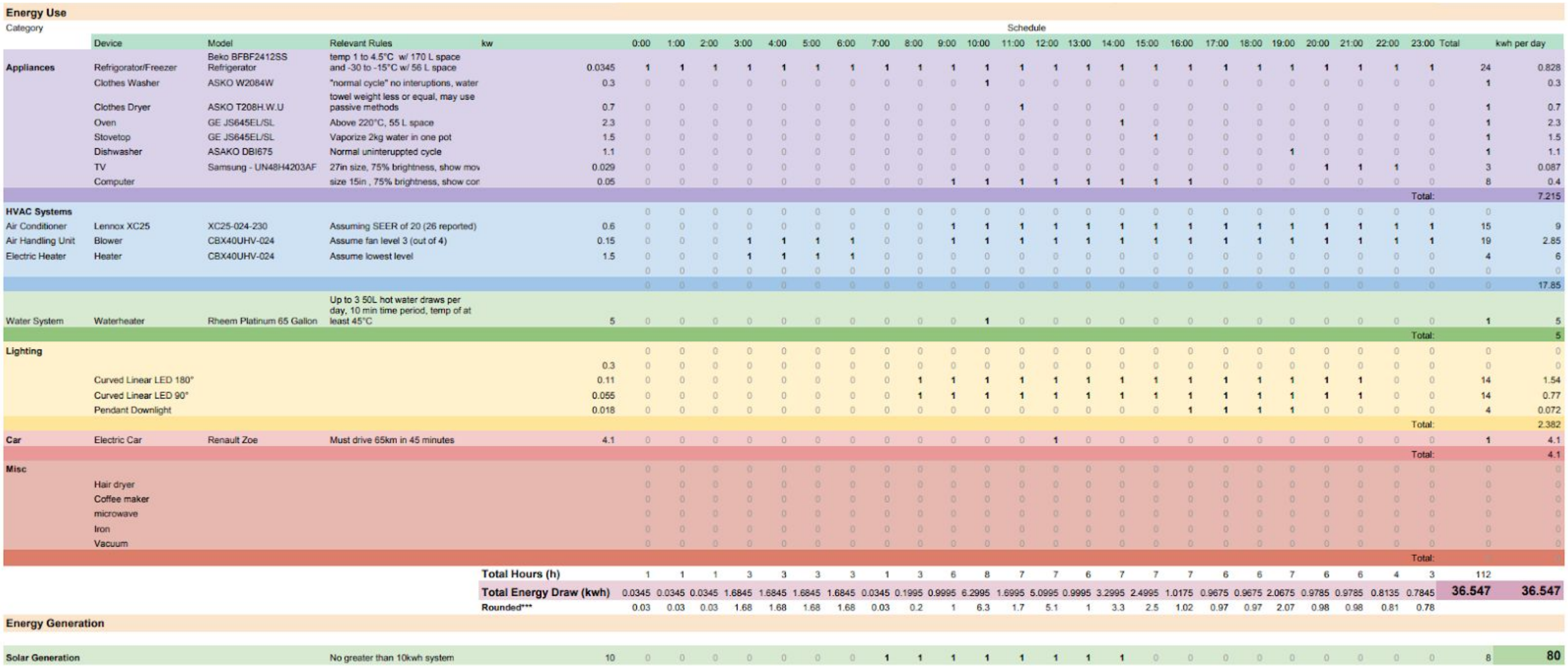


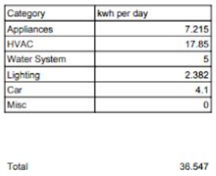
Figure G-07: Moment of the members on the z-axis.

Appendix H



Energy Use

Category	Device	Model	Relevant Rules	kw	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total	kwh per day
Appliances	Refrigorator/Freezer	Beko BFBF2412SS Refrigerator	temp 1 to 4.5°C w/ 170 L space and -30 to -15°C w/ 56 L space	0.0345	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24	0.828
	Clothes Washer	ASKO W2084W	"normal cycle" no interuptions, water	0.3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3
	Clothes Dryer	ASKO T208H.W.U	towel weight less or equal, may use passive methods	0.7	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
	Oven	GE JS645EL/SL	Above 220°C, 55 L space	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	2.3
	Stovetop	GE JS645EL/SL	Vaporize 2kg water in one pot	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1.5
	Dishwasher	ASAKO DBI675	Normal uninteruppted cycle	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1.1
	TV	Samsung - UN48H4203AF	27in size, 75% brightness, show mov	0.029	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	3	0.087
	Computer		size 15in , 75% brightness, show cor	0.05	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	8	0.4
																													Total:	7.215
HVAC Systems					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Air Conditioner	Lennox XC25	XC25-024-230	Assuming SEER of 20 (26 reported)	0.6	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15	9
Air Handling Unit	Blower	CBX40UHV-024	Assume fan level 3 (out of 4)	0.15	0	0	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	19	2.85
Electric Heater	Heater	CBX40UHV-024	Assume lowest level	1.5	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6
					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17.85
Water System	Waterheater	Rheem Platinum 65 Gallon	Up to 3 50L hot water draws per day, 10 min time period, temp of at least 45°C	5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5
																													Total:	5
Lighting					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Curved Linear LED 180°			0.11	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	14	1.54
	Curved Linear LED 90°			0.055	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	14	0.77
	Pendant Downlight			0.018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	4	0.072
																													Total:	2.382
Car	Electric Car	Renault Zoe	Must drive 65km in 45 minutes	4.1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	4.1
																													Total:	4.1
Misc					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hair dryer				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Coffee maker				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	microwave				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Iron				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Vacuum				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																													Total:	0
				Total Hours (h)	1	1	1	3	3	3	3	1	3	6	8	7	7	6	7	7	7	6	6	7	6	6	4	3	112	
				Total Energy Draw (kwh)	0.0345	0.0345	0.0345	1.6845	1.6845	1.6845	1.6845	0.0345	0.1995	0.9995	6.2995	1.6995	5.0995	0.9995	3.2995	2.4995	1.0175	0.9675	0.9675	2.0675	0.9785	0.9785	0.8135	0.7845	**36.547**	**36.547**
				Rounded***	0.03	0.03	0.03	1.68	1.68	1.68	1.68	0.03	0.2	1	6.3	1.7	5.1	1	3.3	2.5	1.02	0.97	0.97	2.07	0.98	0.98	0.81	0.78		
Energy Generation																														
Solar Generation			No greater than 10kwh system	10	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	8	**80**



Category	kwh per day
Appliances	7.215
HVAC	17.85
Water System	5
Lighting	2.382
Car	4.1
Misc	0

Total 36.547

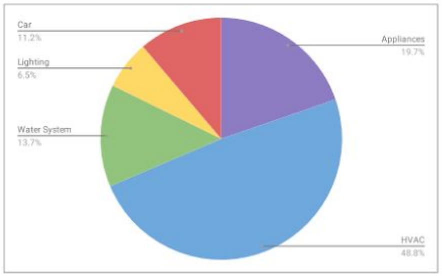


Figure H-01: Daily energy consumption and generation estimates.