Collaborative Sustainable Campus Design for Macaneta Beach, Mozambique

A Major Qualifying Project
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Abstract

In recent years, Mozambique has suffered from nationwide inequalities in education and infrastructure. To combat these inequalities, local leaders in the town of Macaneta sought assistance designing a university campus that will increase access to education while promoting sustainability and maintaining affordability. This project, developed as a capstone for the Architectural Engineering department at Worcester Polytechnic Institute, provides designs and recommendations for two initial buildings at the Macaneta Beach campus, including mechanical and structural analyses of shipping containers to be used as modular building components. This use of shipping containers helps achieve sustainability and affordability for campus development, and these initial plans will provide the necessary starting point for the mission created by Mozambican partners, allowing this project to be expanded upon in the future.

MQP Design Statement

The Major Qualifying Project (MQP) Requirement for the Architectural Engineering Program at Worcester Polytechnic Institute requires that all students participate in a culminating project that brings together knowledge learned from courses throughout their time at the institution. To meet this requirement, we created an architectural design proposal and engineering recommendations for a new university campus in Macaneta Beach, Mozambique. The project integrated multiple engineering disciplines, including architectural, structural, and mechanical, to develop a strategic building plan and initial design phase of the project that incorporates the environmental sustainability and innovation desired by stakeholders.

This project also satisfies the Capstone Project requirement set by the Accreditation Board for Engineering and Technology (ABET). The team consisted of four architectural engineering majors: three with design concentrations in building structural systems and one with a design concentration in building mechanical systems. All student contributors utilized a variety of coursework to show design competence in their selected curriculum areas. The team also communicated and collaborated with faculty advisors, local proponents of the project, local leaders, and other project proponents throughout the design process. This was accomplished through weekly advisory meetings, bi-weekly progress meetings with local partners, online file sharing, and constant communication between students, faculty advisors, and project partners.

Architectural design aspects of the project include the conceptual designs for an initial administration building and initial on-campus housing building at the university, as well as programming, floor plans, finishing suggestions, and sustainability strategies.

Structural design aspects of the project include the analysis of a 40-foot high-cube container that meets the International Organization for Standardization (ISO) criteria. Team members with a structural concentration developed a realistic model using RISA-3D 19.0 software to test the ability of these containers to be used as a structural block in campus buildings, both to verify structural capacity of a container and to provide limitations and recommendations for the removal and reinforcement of container sections. Loading requirements and deflection limits used in this analysis come from and adhere to the International Building Code (IBC) and the American Society of Civil Engineers (ASCE) code requirements.

Mechanical design aspects of the project include thermal load calculations and design recommendations for both a passive and active mechanical system. Calculations and designs were based on the requirements of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55 to provide an appropriate level of comfort for people in Mozambique.

Students also considered other factors including sustainability, feasibility, economics, and ethics in developing a campus plan and design for the initial campus buildings with shipping container modular construction.

Sustainability

One of the main goals of and concepts for this project was the incorporation of sustainable design and constructions strategies for the new campus. The use of refurbished shipping containers as a structural and design component contributed to this goal. So too did the inclusion and investigation of environmentally sustainable building and campus design strategies, technical solutions, and recommended behaviors. This project recognizes the importance of integrating sustainable design into the built environment as the impacts of climate change continue to increase around the world.

Feasibility

The team considered feasibility throughout the selection and implementation of materials in the specific region that the Macaneta Beach Campus is intended for. The lack of infrastructure and potential lack of skilled construction labor in Macaneta Beach, Mozambique posed a unique challenge to the design team in that local, easily transportable materials and simplified construction methods were preferred. Students created a Revit model to show architectural designs and details of initial buildings and outlined recommendations for the most feasible sustainability and construction strategies at the site.

Economics

The costs of materials and of sustainability aspects were considered by the design team to reduce construction expenses and help with the development of a future project budget. Economic planning will also be important for phased planning of campus expansion and implementation of different departments at the university following construction of the team's initially proposed designs. Finally, design proposals from this project will be used in applications for a government grant for the project.

Ethics

Professional engineers assume responsibility for the health, safety, and well-being of the public when designing building systems. In this specific project, consideration of ethics and social norms in different cultures was imperative to the creation of a successful campus design that would benefit the local community. The team made design decisions after discussions with local project proponents and stakeholders while keeping ethical considerations ever in mind.

Professional License Statement

Professional licensure is a demanding, yet critical process for engineers. The professional licensure program was developed to ensure that designs are subject to examination and verification from certified Professional Engineers, minimizing risks to the public.

In the United States the professional licensure process varies by state, but the general process is outlined by the National Council of Examiners for Engineering and Surveying (NCEES) (How, n.d.). This process includes four steps, the first of which is the successful completion of a Bachelor of Science degree in engineering from an Accreditation Board for Engineers and Technology (ABET) accredited program. Following the receival of this degree, aspiring Professional Engineers must pass the Fundamentals of Engineering (FE) Exam conducted by the NCEES. After passing the FE, the aspiring Professional Engineer becomes an Engineer in Training (E.I.T) and must complete three to five years of work experience under the supervision of a Professional Engineer. The length of the work experience varies by state and may be shortened based on different factors including the completion of a master's degree. After completing the work experience, the E.I.T. is eligible to sit for the discipline specific Professional Engineering (PE) exam. After passing the PE exam, the aspiring Professional Engineer can apply for a license in their desired state of practice.

In Mozambique, the Mozambican Order of Engineers (OEM) is the professional engineering governance (How, 2020). Individuals must follow the rules put in place by the OEM's Law No. 16/2002 that were created to impose a regulated and uniform professional engineering system. Under the OEM, the title Engineer is awarded to registered members that hold a degree, or legal equivalent, in engineering and understand the level of responsibility required in the application of technical sciences in their desired field. Application requirements include the completion of an application form, a certified identification document, an authorized Bachelor's Degree in Engineering, payment of the registration fee, a photograph of the applicant, and a Curriculum Vitae. Due to these constraints, the review and approval of the project drawings, specifications, and recommendations by a Professional Engineer in the country of construction must occur before proceeding with construction.

Executive Summary

Education can act as an equalizer. When children are given the opportunity to learn, they are provided access to a quality of life better than that of prior generations. The availability of education is supported by an ‘inclusive growth process,’ focusing agricultural productivity, development of a more diversified economy, and investment in individuals. This project promotes the creation of an affordable, sustainable, and accessible campus in Macaneta Beach, which will serve as an investment in the people and economy by local leaders.

Background

Mozambique suffers from nationwide inequalities in education and infrastructure. Currently, a small percentage of Mozambique’s population can enroll and participate in higher education, and the distribution of modern infrastructure is scattered, limiting access to electricity, clean water, and sanitation practices. To combat these inequalities, a tribal leader in Macaneta Beach, Mozambique dedicated land to the creation of a sustainable university. The vision for this university is to contribute to the development of Mozambique by bringing world class education to disadvantaged populations, inspiring both local and international communities while remaining sustainable and affordable.

To develop a design that accomplishes this mission, Mozambican project leaders partnered with a team of Architectural Engineering students from Worcester Polytechnic Institute (WPI) in the United States. WPI students designed an administrative building for the campus and an on-campus housing complex, utilizing shipping containers as affordable and sustainable modular construction elements. Moving forward, Mozambican leaders will use these initial designs to excite the community and promote further investment in the project.

Architectural Design

The team familiarized themselves with the site at Macaneta Beach to ensure feasibility of accomplishing the goals of innovation and simplified construction put in place by the project’s stakeholders. Studies were conducted to analyze rainfall, windspeeds, seismic events, topography, and soil data; all indicated that humidity and cyclones posed the largest concerns for any infrastructure in the area. The team then performed a solar study, showing that the northern facades and roofs will be exposed to the most direct sunlight and heat during hours of operation.

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The administrative building was designed as a place for students and faculty to interact, work, learn, and foster innovation. The final design of the administrative building houses office and classrooms and is accented by rooftop and outdoor collaborative gathering areas.

Exterior Render of the Administrative Building

The team also designed a modular housing complex with staggered 20-foot high-cube shipping containers. The initial design is a three-story complex with the capacity to house 98 students or faculty in doubles and singles. Occupants will have access to shared bathrooms and outdoor workspaces.

Exterior Render of the On-Campus Housing Complex

Structural Analysis

The team reviewed shipping container standards, previous research, and case studies, to investigate the use of shipping containers as structurally sound building components. This hypothesis was confirmed through structural testing using RISA 3-D 19.0. After multiple iterations, the team created a model with acceptable load transfers and deflections. The team referenced the International Building Code (IBC) to determine applicable loads for building use and acceptable deflection limits for the container members. The model withstood applicable loads and did not exceed deflection and stress limits, confirming research findings. Different configurations were then tested to represent common design elements, including stacking and spanning the containers. The team applied the worst-case load and resistance factor design (LRFD) scenario to these configurations and applied bracing where necessary. Finally, the team provided recommendations and sample calculations for a pier foundation based on building loads and poor soil quality at the site.

Mechanical Analysis

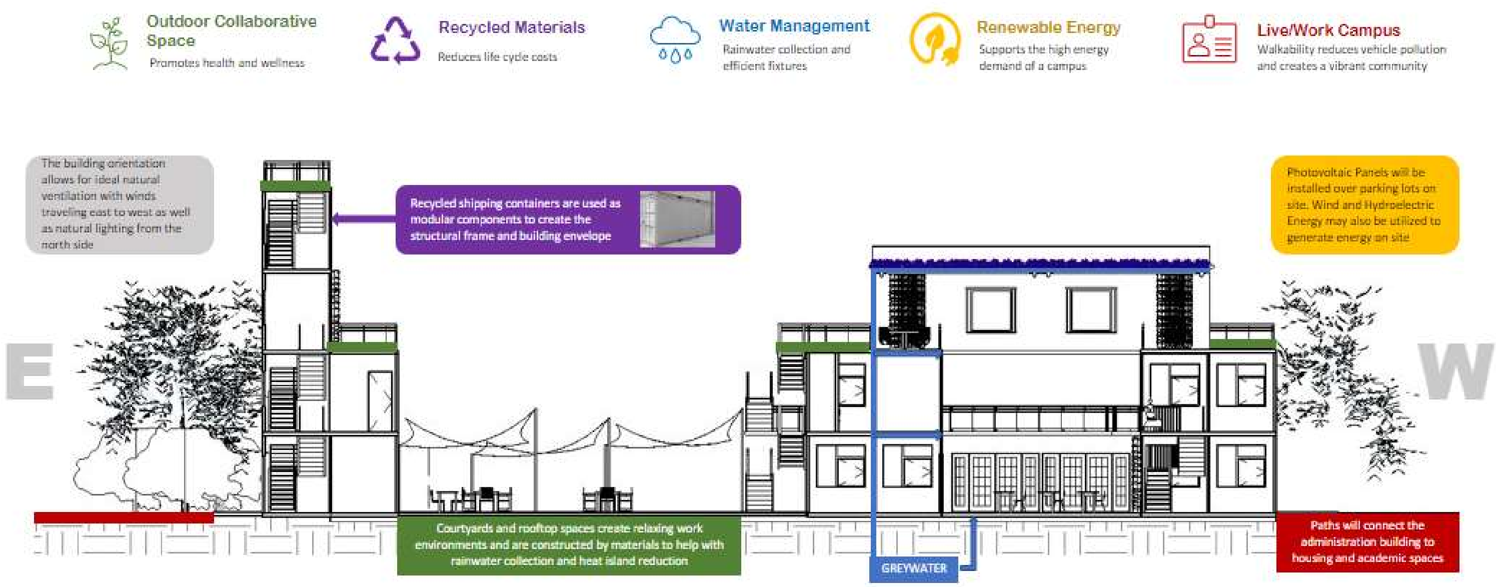
Climate studies showed that active or passive design strategies can be used to supplement the moderate temperatures and high humidity at the site. The team calculated peak mechanical, lighting, and equipment loads produced by a single container. Insulation recommendations were based on a container's thermal performance throughout the year. A similar analysis was performed for different configurations of containers as they appear in the building designs. From these analyses, the team recommended using cotton insulation to significantly reduce heating and cooling loads in all configurations. The heating and cooling loads using insulation and single-glazed windows were acceptable and decreased construction costs, earning the team's preference. However, the team suggests double-hung windows where passive design strategies are used for comfort control. Lastly, annual energy consumption was considered on a monthly basis to size the heating, ventilation, and cooling system. The team recommends the use of one 8,000 BTUH split air-conditioning unit for each container that requires conditioning, and passive design strategies in areas that do not require close indoor air quality control.

Building Envelope

Specific selection of roofing and finishing elements will protect shipping container building components from water damage and corrosion. The installation of a sloped, shed style roof supported by a lightweight truss to protect the containers, provide shading, and collect rainwater is recommended. Further durability, paint, and insulation recommendations were defined as well. Plywood flooring should be used in interior spaces because it is lightweight, low-cost, and can be modified or enhanced easily in the future. Finally, the use of polycarbonate sheeting is recommended for large openings meant to provide daylight because it is more cost effective and durable than glass.

Sustainability

To meet project sustainability goals, the team considered strategies that were affordable and realistic based on accessible resources for the Macaneta Beach campus. Recommendations were formatted into four categories: campus, building, technology, and behavior. Behavioral actions of the campus community are particularly important because they significantly affect campus performance and longevity. The team believes the sustainability goals will be achieved when green strategies are utilized conjunctively. Furthermore, the incorporation of sustainable elements will familiarize campus visitors with their uses and benefits, as well as setting a positive precedent for future community development.



Key Sustainable Features of the Administration Building

Future Recommendations

The final designs for the future campus should follow guidelines put in place by Mozambique's Ministry of Public Works and Housing and the provisions of the International Building Code (IBC) and the International Fire Code (IFC) to ensure safety and accessibility. The buildings designed by the team provide the necessary spaces to start a campus, however the creation of a campus plan outlining stages and goals for infrastructure development is still needed. Finally, construction at the campus will require a project management team working with university leaders to determine goals, develop a budget and project schedule, and maintain communication with contractors, architects, and engineers throughout construction.

Conclusion

The creation of a University in Macaneta Beach, Mozambique will provide access to higher education, lift standards of living for local communities, promote infrastructure development in the area, and benefit the local economy by drawing tourism and international influence. Additionally, the sustainability goals of the campus aim to protect the environment while also modeling sustainable strategies for future development. While this project requires further work, it provides a basis for the Macaneta Beach campus, allowing Mozambican project partners to continue working towards the project mission in the coming years.

Authorship

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Executive Summary	Ranieri	All
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2.0 Background	Bielawski, Correia, Ranieri	Cohn
3.0 Architectural Design	Bielawski, Ranieri	Cohn
4.0 Structural Analysis	Bielawski, Cohn, Ranieri	Correia
5.0 Mechanical Analysis	Correia	Cohn, Ranieri
6.0 Building Envelope Design	Cohn	Bielawski, Ranieri
7.0 Sustainable Design	Correia, Ranieri	Bielawski, Cohn
8.0 Campus Planning & Future Recommendations	Cohn, Correia	Bielawski, Ranieri
9.0 Conclusion	Bielawski	Cohn, Correia

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1. Introduction

Education acts as an equalizer. When children are given the opportunity to learn, they are provided access to a quality of life better than that of prior generations. However, this works only if there is a labor market to support the skills they learn. In Southern Africa, there is a disconnect between educational offerings and jobs, and these countries realize the disconnect between skills that people possess and the labor market. In Mozambique, this is one factor that has increased inequalities amongst the population since the end of the Civil War in 1992 ("Mozambique Economic Update," 2018). To combat these inequalities, international organizations including the World Bank are pushing for an "inclusive growth process" throughout the country. This process focuses on increasing agricultural productivity, developing a more diversified economy, and investing in individuals.

In order to combat the growing inequalities in his community, a tribal leader in Macaneta Beach, Mozambique dedicated a large portion of land to realize something novel: a university built on sustainable design principles to provide a well-rounded education as well as training to meet the economy's needs. This would then allow students of the university to find or create a job locally upon graduation. His vision also includes the creation of a space that brings world-class education, research, and innovation to disadvantaged populations. By serving these purposes, the university in Macaneta Beach would largely contribute to the inclusive growth process of the nation: boosting the economy, investing in students, and perhaps even working to improve agricultural innovation.

With this vision for a sustainable university underway, the challenge for tribal leaders became developing designs and functionality for the campus site. The design of these spaces would have to inspire the surrounding and international communities to join their mission, while addressing practical implications such as sustainability and affordability. In order to brainstorm and develop an initial campus design, the tribal leader and his colleagues turned to a team of Architectural Engineering students in the United States. Over the course of nine months, students and faculty from both the United States and Mozambique partook in meetings and design charrettes to determine an initial design proposal.

The finalized initial design utilized shipping containers for sustainable and affordable modular construction. With help from international partners and advisors, the student team developed initial designs for an administrative building and on-campus housing. During the development of these designs, the team performed mechanical and structural analyses on the shipping containers and their configurations to ensure safety and comfort in shipping container buildings throughout the university campus. The team also provided recommendations for sustainability strategies to minimize the impact of development on the surrounding environment and reduce operation costs. In the end, presentation of recommended engineering, architectural, and sustainable design strategies by the Worcester Polytechnical Institute team to the tribal leaders and project partners provides a starting point for further development of the Macaneta Beach campus vision. With this proposal, Mozambican partners can excite the community, engage local professionals for further development of the project, and move one step closer to their goal of reducing educational inequality in their community.

2. Background

This chapter provides the background information necessary to understand the need for an innovative and sustainable university in Macaneta Beach, Mozambique. Included in this discussion are the historical events that have led to economic inequalities throughout Mozambique, followed by the economic hardships in Mozambique and how they may be combated with improved access to education and infrastructure to reduce inequalities. Next, an explanation of the inspiration and background for this project is provided. Finally, the need for sustainable design of the campus and the corresponding use of modular shipping container construction provides the reasoning behind the team's architectural design proposals.

2.1. History of Mozambique

From 1752 until 1975, the land mass called Mozambique was colonized by and remained under Portuguese control ("Mozambique country profile," 2020). In 1977, two years after gaining independence as the People's Republic of Mozambique, a civil war broke out between the Mozambique Liberation Front (FRELIMO) and the Mozambique National Resistance (RENAMO). This conflict ended in 1990 when supplies and supporters on both sides ran out (Momodu, 2018). The Mozambican government formed a new constitution and signed a peace accord to allow the United Nations (UN) entrance into the country. The entrance of the UN exposed the plethora of political, social, economic, infrastructure, and environmental issues that grew over the hundreds of years of conflict. Despite these issues, the presence of the UN also showed that there was definite potential to improve national stability.

2.2. Combating Economic Inequality in Mozambique

Among the issues facing current-day Mozambique, the economy sits front and center. The economic problems that plague Mozambique trickle down and create problems elsewhere in the nation. In order to mend these economic hardships, the country's growth must become more inclusive.

2.2.1. Inequality

The UN Development Program reports that 46.1% of Mozambique's population of 28 million people live below the poverty line ("About Mozambique," n.d.). In 2019, the GDP per capita in Mozambique was 503.57

USD, less than one percent of the United States' 65297.52 USD GDP per capita, less than ten percent of neighboring South Africa's 6,001.40 USD GDP, and just over one third of neighboring Zimbabwe's 1,463.99 USD.

Widespread poverty across the country has prevented the reform of the corrupt government because there are not enough resources to create a proper system of checks and balances (Jett, 2020). Foreign efforts to provide aid to the country are valiant, however under the rule of the corrupt FRELIMO party, they are not always used as directed. This corrupt government structure is enabled by the weaknesses that exist throughout civil society.

Since the early 2000s, Mozambique has made some economic gains. However, these economic gains have not been evenly distributed amongst the urban and rural populations of the country ("Mozambique Economic Update," 2018). According to the World Bank, 80% of Mozambique's rural population is considered financially poor. As economic gains continue unevenly, the gap between the bottom 40% and top 20% grows larger. To reach its full potential as a coastal land full of agriculture and natural resources, Mozambique must work to shrink this gap. A uniform economy will provide the resources needed for governmental reform and relocation of funds to focus on industries and innovative solutions that address the country's other issues.

To minimize Mozambique's economic gap, the World Bank believes that focus is required in three main areas including: raising agricultural productivity, building a more diversified economy, and investing in people. This investment in people is the main focus of many organizations because investing in individuals puts them in a position to receive more opportunities, pushing them closer to people in the top 20%. According to the World Bank, the best way to invest in these individual people is to provide them with improved education and infrastructure that matches or exceeds the standards of what their top 20% counterparts receive.

2.2.2. Education

Mozambique's National System of Education (SNE) was developed in 1983 following the country's liberation from Portugal ("Mozambique education," n.d.). The system is organized into three levels: primary, secondary, and higher education (*"*Mozambique National*,"* 2018). Primary school is the only mandatory level of schooling in Mozambique, and students are required to enroll at the age of six. In recent years, the Mozambican government abolished school fees and provided more support to schools at the primary level ("Education situation," n.d.). This level of schooling is further divided into lower and upper subdivisions which last a total of seven years, encompassing grades one through seven. Once primary schooling is complete, students may choose to continue onto secondary school. Similar to primary, secondary is divided into a lower and upper subdivision. Altogether, secondary school lasts five years, covering grades eight through twelve. Once upper secondary school is complete, a small fraction of these students may choose to continue to higher education. This higher education typically includes attendance at a vocational school or a university.

While all these levels of education are established in Mozambique, a very small percentage make it through every stage. Similar to the economic system of Mozambique, inequalities exist within the educational system as well. In 2011, the Education Policy and Data Center (EPDC) reported that 11% of youth aged 15 to 24 had no education, while 48% had not completed primary schooling (*"*Mozambique National*,"* 2018). Wealthy communities saw only a 5% withdrawal rate at the primary level, while those in poverty saw a 37% rate. As the level of schooling increases, the wealthy populations experience a 15% withdrawal rate compared to a 57% rate for their poor counterparts among secondary educations. Many students are forced to leave school early to go to work to provide financial assistance for their families. Of the students that do complete secondary schooling, only 7% continue on to higher education, meaning that the other 93% withdraw. This large 93% withdrawal rate is a result of the lack of opportunities available in Mozambique as well as the financial responsibilities that come with enrolling in higher education.

There are fourteen higher education universities in Mozambique (Glavin, 2019). Of the fourteen institutions, more than half are privately run. Whether private or public, the higher education sector in Mozambique is very closed off to the general public. Entrance exam requirements close off applications to the top tiers of the population. Privately run schools face scrutiny for their possible financial or religious ulterior motives, while public schools are often forced to turn away applicants because they do not have enough available spaces. In order to combat the 93% withdrawal rate that occurs at the end of secondary education, Mozambicans must be given better access to higher education. If more people have the opportunity to receive a higher education, the gap between the top 20% and bottom 40% of the population will continue to shrink.

2.2.3. Infrastructure

Another key component to investing in individuals, is ensuring that everyone has access to the same infrastructure. In this context, buildings, roadways, structures, and access to utilities are all considered pieces of infrastructure. The three main threats to infrastructure availability in Mozambique include natural disasters, inequality, and climate change.

Mozambique ranks second out of all African nations for a high level of geographical exposure to the elements ("In-depth Mozambique," n.d.). These elements include floods, cyclones, droughts, fires, and earthquakes. As a result of these events, nearly 25% of the country's population faces high mortality risks. The root cause of a lot of these casualties is the failure of existing infrastructure when placed in these high stress situations. In order to minimize the effects of the natural disasters, new construction should include the creation of durable infrastructure and should be accompanied by the rehabilitation and strengthening of pre-existing elements to reduce vulnerability.

Another area of infrastructure failure exists at the gap between urban and rural access to utilities. These utilities include electricity, water, and sanitation. According to the World Bank's 2019 Economic Update, "reducing the growing infrastructure disparities between urban and rural areas is crucial for more inclusive and sustainable growth" (2019). In 2018, roughly 31.1% of Mozambicans had access to electricity. Among urban populations, this percentage was 72.2% while rural populations saw just under 8% ("Access to electricity," n.d.). Limited access to electricity leads to unsanitary conditions for food preparation and storage, which results in many health complications. When looking at water access in Mozambique, about 61% of the population has access to improved water sources ("Water, sanitation, and hygiene," n.d.). Geographically, 88% of urban residents have improved access while only 49% of rural residents can say the same. Similar to water issues, sanitation is also a source of inequality among rural and urban communities. Roughly three quarters of the Mozambican population lacks improved sanitation facilities. In rural areas, only 12% of residents have access to improved sanitation compared to 47% in urban areas. This lack of clean water access combined with limited sanitation use leads to a host of health problems and diseases. Although the minimization of the gap in infrastructure to different communities requires a large capital investment, it also requires an understanding amongst the people of how to use these resources and why they are important. Once communities are provided with improved infrastructure, the closing of the gap will occur faster if communities understand how to use and maintain them.

Mozambique sits among the top ten nations in the world affected by climate change mainly due to disruptions in economic productivity (Karombo, 2021). Disruptions in economic productivity occur when natural disasters pause day to day activities and require economic attention, and the frequency of these natural disasters has increased as a result of climate change. Although their consumptions and emissions are minimal compared to many other nations, electricity consumption in Mozambique has risen 2378% since 1990, and is paired with a 447% increase in CO_2 emissions. To offset these growths, environmentally sustainable elements must be implemented into poverty reduction strategies focused on infrastructure and economic growth. This pairing will not only benefit the environment but also utilize natural resources available to Mozambique in order to minimize costs and increase access, reducing the gap between the wealthy and poor.

2.3. Creation of a University at Macaneta Beach

In order to increase opportunity for higher education and thereby improve existing economic inequalities in Southern Mozambique, traditional leadership in Macaneta

Beach, Mozambique proposed the creation of a new university on traditionally owned land. The chief of the region offered two adjacent plots of pristine coastline, totaling almost 125 acres (50 ha), where the university can be constructed. Their vision is the creation of "a new-type of Global Social Entrepreneurial University to deliver world-class high-level research, education and innovation to [mostly] low-income countries worldwide," (P. Langa, personal communication, September 23rd, 2020). The university campus will also provide economic opportunities for local communities and drive the creation of reliable infrastructure in this region.

Foreign developers have expressed interest in developing this land into a resort for increased tourism. However, development of the proposed land for this purpose would not only disturb the natural ecosystem, but also undermine opportunities for indigenous people in the area. When land is sold to investors for foreign tourism, various rights are often exchanged, and local people are often left without opportunities to work for a foreign firm on the same land they once owned. Therefore, while investors may offer a large sum for this beachfront property, traditional leadership sought an alternative use for the land that would truly benefit their people and the nation. An accessible university built by and for the local community on this site would provide access to higher education, lift the standard of living for the local community, and benefit the local economy. Furthermore, a local university could act as a local gathering center, supporting a marketspace and access to natural recreational space.

2.4. Sustainable Campus Design

The creation of a University in Macaneta Beach not only provides opportunities for economic improvement, but also to model a more sustainable method of development. Every year, combined building and construction sectors account for 39% of total carbon emissions worldwide. From this 39%, 28% results from operational emissions, including energy used to heat, cool and light buildings, while the remaining 11% results from upfront carbon emissions of materials and construction processes (WGBC, 2021). This is a staggering contribution of the built environment to carbon emissions and climate change. However, alternative methods of design and construction can help reduce this carbon footprint. Campus design strategies, including use of renewable energy, wastewater management, and sustainable landscaping can harness natural resources from the existing environment to reduce the campus's carbon footprint while also protecting native flora and fauna. Building design strategies, such as natural ventilation, living green walls, and locally sourced, low emitting, and thermally efficient materials, can greatly reduce the carbon footprint of individual buildings while simultaneously creating a cleaner, healthier living environment for users. Technological strategies, such as high efficiency HVAC, energy and water efficient appliances and individual controls reduce energy usage, bringing the campus closer to net-zero. Finally, behavioral strategies, including commissioning and submetering, maintenance strategies, waste management, and reduced motor vehicle traffic, continue to reduce the impact of the campus on the environment while it is under construction and when it is finally in use.

In Mozambique, environmental concerns of deforestation, access to water resources, air pollution, and excessive waste are on the rise. Since the turn of the century, the country has lost over 7,400,000 acres (3,000,000 ha), or 10%, of their forests due to lumber and charcoal industries and illegal exploitation of forestry (Farge, 2018). Mozambique is also vulnerable to problems with water, sanitation and hygiene, as many regions of the country lack access to clean water resources and sanitation facilities. This is largely due to inadequate finances and large geographical separation (Findings, 2018). Furthermore, motor vehicle and industry emissions in more urban regions of the country have greatly increased air pollution in recent years ("Mozambique Air," 2015). These urban regions also experience problems with waste. In Maputo, Mozambique, an estimated 985 tons (1,000 metric tons) of waste is generated daily, but only 40-50% of this waste is collected and properly disposed of, leading to trash pileup and increased air and groundwater pollution from improper disposal ("Mozambique Waste Management," n.d.). These issues require present action to improve living conditions for Mozambique's people and reduce ever-pressing impacts of climate change throughout the country.

Considering the current environmental issues Mozambique faces, it is essential that the new campus in Macaneta Beach addresses these in both design and implementation. Ideally, the campus will model sustainable design strategies for other development of this kind. Its purpose as a hub for education also allows it the unique opportunity to further educate the campus and local community on sustainable living and future eco-friendly campus maintenance and construction.

2.5. Modular Shipping Container Construction

One of the most sustainable options for new construction is the reuse or repurpose of existing structures and materials. In Sub-Saharan Africa, container shipping has become so dominant that about 80% of containers that arrive at the ports either must leave empty or be reused. With the high cost of shipping the containers back out of the ports, many countries in Africa have turned to repurposing the containers as houses, stores, and warehouses (Brown, 2016). Maputo, the capital of Mozambique, is a port city that similarly has an excess of shipping containers and has been adapting them for use as offices, banks, and service stations (da Silva, 2019). Maputo's proximity to the campus site in Macaneta makes recycled shipping container construction a sustainable and feasible option for the project team.

Not only does recycling shipping containers offer a sustainable repurposing of resources, but shipping containers also offer many traits that make them beneficial for construction. These include their strength, stacking ability, and modularity. Shipping containers can be configured in a variety of ways to create larger buildings and campus spaces, offering flexibility for campus design and expansion. Size limitations of the containers can provide challenges during design, as containers are only available in specific dimensions. However, these limitations also allow for modulation of construction, which will increase speed of construction on the site and allow initial buildings on the campus to be occupied long before more traditional buildings (Giriunas, 2021). As modifications are made to the shipping containers for aesthetic and comfort purposes, they often must be reinforced with additional steel members and analyzed for changes in structural stability. However, these modifications to container structures can be completed prior to construction, and simply assembled on site with the use of a crane and welded connections (Giriunas, 2021).

Overall, the use of recycled shipping containers offers both environmental and logistical advantages for architectural design and construction, especially in the context of the Macaneta Beach Campus. Their use in the design of buildings for the initial phase of this campus informed architectural, structural, and mechanical decisions as described in the following chapters.

3. Architectural Design

The architectural goal of this project was to establish methods of design and construction for an initial phase of a university campus. Initial buildings include spaces that foster innovation in a campus setting, while simplifying construction with modular shipping containers. The team decided to use shipping containers prior to intensive design, seeing benefits for campus sustainability, cost, and speed of construction, and these containers helped dictate the form and layout of the final proposals. However, the team intended container construction to provide a starting point, allowing future campus expansion to include other construction methods. Proposals for an initial administration building, as well as an on-campus housing complex, were created and consider immediate needs of the new campus. Different requirements and considerations for the uses of each building, needs and desires expressed by partners in Mozambique for the campus, and available site information governed the designs.

3.1. Site Analysis

The site provided for the campus is located at Macaneta Beach, Mozambique, approximately 19 miles (30 km) north and 10 miles (16 km) east of Maputo. The local tribe in this region owns 124 acres (50 ha) of land, divided into two adjacent plots (one measuring 50 acres (20 ha) in area and one measuring 74 acres (30 ha)). The location of the site along the coastline offers a large and beautiful landscape that has not yet been developed. Unpaved access roads run parallel to the coastline and one bridge connects the area to the city of Maputo. Paths also exist within the site that connect to exterior access roads. However, it should be noted that sandy soil at the site makes it difficult to drive through the existing paths.

In order to further analyze conditions at the site, the team conducted initial research on climate and topography. The findings for site analysis served a critical role by informing architectural design decisions and should be continually considered in future designs as the campus expands.

3.1.1. Site Climate Considerations

Prior to starting architectural design of the campus, the team investigated typical climate conditions, storm risk, and wind patterns. Mozambique has a tropical climate, with a hot yet rainy season between November and March, and a dry season between May and October each year. The dry season also includes a cooler period from mid-May to mid-August (World Climate Guide, n.d.). Average temperatures in Maputo range from 79 °F (26 °C) in January to 67 °F (19 °C) in July. The maximum temperature in the warmest months (January and February) is typically comfortable, around 86 °F (30 °C). However, it can sometimes get uncomfortably hot, up to 104 °F (40 °C). Also, from May to August, the temperature at night can drop to around 50 °F (10 °C) (World Climate Guide, n.d.). Average monthly humidity in Maputo ranges from 63.5% to 71% (Yu Media Group, n.d.). While this humidity is relatively high for indoor comfort, partners in Mozambique confirmed they are very used to these humidity conditions. Based on these averages for temperature and humidity at the site, the team concluded that temperature will be generally comfortable in all seasons, and humidity can be reduced with passive design strategies.

Average rainfall in Maputo is 32 inches (815 mm) per year, with the majority of rainfall occurring from November to March (World Climate Guide, n.d.). The site will therefore receive minimal rain for most of the year, but during the rainy season, it will receive heavy rainfall in a short time span, which may result in flooding. Therefore, buildings on the campus shall be designed to divert heavy rain, but water collection methods will also be highly beneficial for seasons when rain is scarce. Cyclones also pose a risk of high wind and rainfall at the site; however, these storms will generally impact central Mozambique more than the site in Macaneta Beach.

Wind speeds in Maputo typically range from 5.0 miles per hour (5 kph) to 18.0 miles per hour (29 kph) and wind direction is typically north to south or south to north (WeatherSpark, n.d.). This is displayed in the wind rose diagram for Maputo (Figure 3.1). Based on this information, buildings and roofing on this site should be designed to withstand adequate wind speeds in the north and south direction. Furthermore, for buildings to utilize natural ventilation, windows shall be placed on the north and south facing walls of the structure.

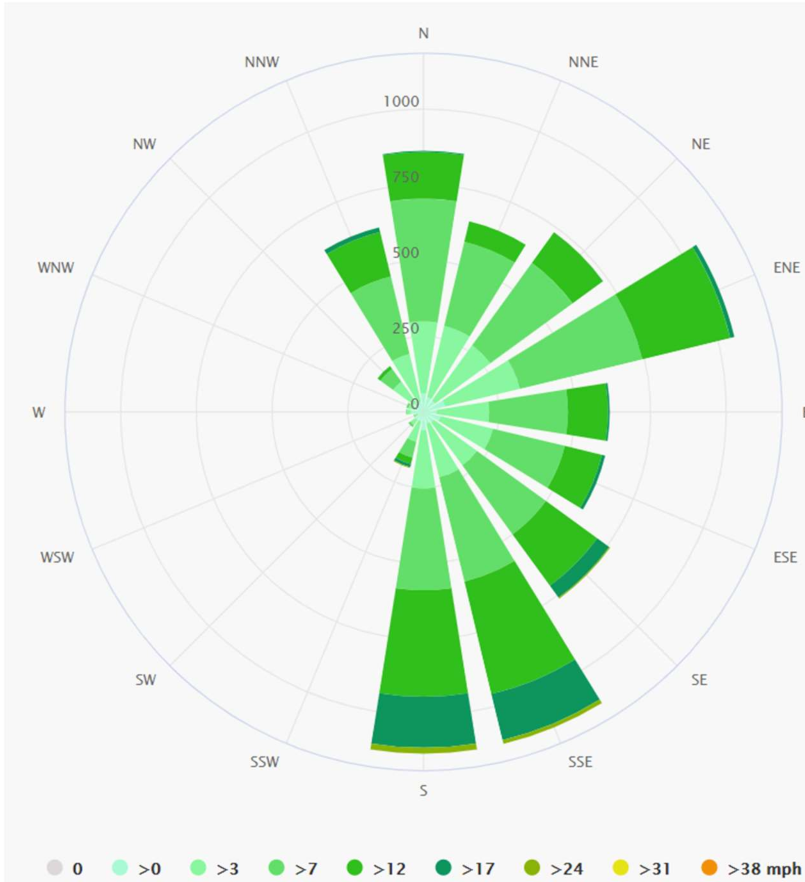


Figure 3.1: Wind Rose for Maputo, Mozambique (Milotlamicha, 2021)

3.1.2. Site Topography Considerations

Upon initial investigation, there was concern that rising sea levels along the coastline near the site may lead to drastic flooding in the coming years. The site location lies just east of floodplains from the Incomati River and about 3000 feet (910 m) west of the coast. Floodplains in this region of Mozambique pose a moderate to high risk of drought as well as a moderate to high risk of flooding, and climate change predictions state the sea level could rise one foot (30 cm) to 16.4 feet (5 m) by 2100 (INGC, 2009). However, through a topographical study in Google Earth (Figure 3.2), the team concluded the lowest site elevation to be 26.3 feet (8 m), which is high enough that flooding will not occur even in the current worst possible climate change scenario. This topographical study also confirms that elevation change throughout the site is minimal, though these elevations based on Google Maps should be verified through surveys.

Figure 3.2: Elevation of Topography from Google Earth

Macaneta beach also experiences moderate tides of about 6.6 to 13.1 feet (2 to 4 m), but this will not impact water at the site (INGC, 2009). Inland and coastal soil fertility is generally low. Soils in most of this region of Mozambique are largely infertile, and the agriculture capacity is low because of fine-grained, homogeneous, grey, siliceous, sands. This is a result of slash and burn methods used by locals and should be considered in agricultural plans for the campus (Massingue, 2019). Soil fertility is higher in nearby floodplains; however, floodplains are at a moderate to high risk of wind erosion and salinity, which still presents problems for agricultural use (INGC, 2009).

Seismic activity is not a large concern for the site, however moderate shaking and light damage may be experienced and were considered in structural analysis. Similarly, the site is only at a medium risk for tsunamis. These topographical considerations for the site further informed the architectural design and context of buildings for the campus.

3.2. Concept

The use of outdoor space and repurposing of shipping containers into building components inspired the architectural designs for the initial campus administration building and on-campus housing complex. The site of the campus in Mozambique offers a beautiful landscape, with natural vegetation, views of the ocean, and the Maputo city skyline in the distance. Designs for the initial buildings aim to integrate this landscape with the campus and take full advantage of its beauty. The use of sustainable design and construction principles will also protect the natural landscape, allowing students, faculty, and any community members visiting the campus to experience the buildings in harmony with nature. While the appearance of a singular shipping container may be industrial and unnatural, creative use of container configurations and finishes still allow for a natural appearance, where buildings are meant to blend in and the divide between nature and campus are blurred. This concept is exemplified in the green and brown earthy tones chosen for the façade of the on-campus housing proposal.

However, the versatility of shipping container construction and finishes will also allow certain buildings to stand out, creating an effective contrast with nature. This concept is exemplified in the minimalistic whites and greys chosen for the façade of the initial campus administration building. These color schemes were chosen in partnership with the Mozambican partners, with potential color schemes also including coastal cool blues and vibrant colors representing the culture of the region. Finally, the team drew inspiration from case studies of existing shipping container buildings, markets, and campuses around the world to create the following designs. The figures in this section provide an idea of what the proposed designs for the initial administration building and on-campus housing would look like in-person. The team created these visualizations with rendering capabilities in Revit and post-rendering adjustments in Adobe Photoshop.

3.2.1. Initial Administration Building Design

For the initial administration building, referred to throughout the paper as the administration building, the team proposes a two-part design integrating enclosed offices with open-air classroom and multipurpose spaces. This building will serve as a place for students and faculty to interact, work, and learn. The partners in Mozambique provided their requirements for the administration building design, including (1) ample office space for professors and faculty, (2) a university president's office, (3) a large classroom, (4) a tower to view the surrounding area, (5) sustainability features, and (6) iconic design elements to draw visitors to the campus. These requirements, in addition to aesthetic preferences, and site, climate, and structural considerations, informed the design.

Figure 3.3: Exterior Render of the Administration Building

The east structure of the administration building will be constructed from six 40-foot high-cube shipping containers and six 20-foot high-cube shipping containers (Figure 3.3). To clarify, shipping containers are referred to and named using length in feet, therefore metric conversions will not be provided for each instance. The interior spaces created by the shipping containers will provide private, quiet, and climate-controlled office space. Between the containers exists 960 square feet (89 m^2) classroom space, partially covered and shaded by spanning containers on the third level (Figure 3.4).

Figure 3.4: Interior Render of the Classroom

The roofs of shipping containers at the third level will be utilized as rooftop decks to provide more access to outdoor study or collaboration space, as well as additional rooftop offices. Since the site location receives direct sunlight for the majority of the day, rooftop decks and outdoor study spaces are equipped with lightweight overhead pergolas. These pergolas will be constructed with inexpensive steel tubes to provide shading for occupant comfort while remaining lightweight (Figure 3.5).

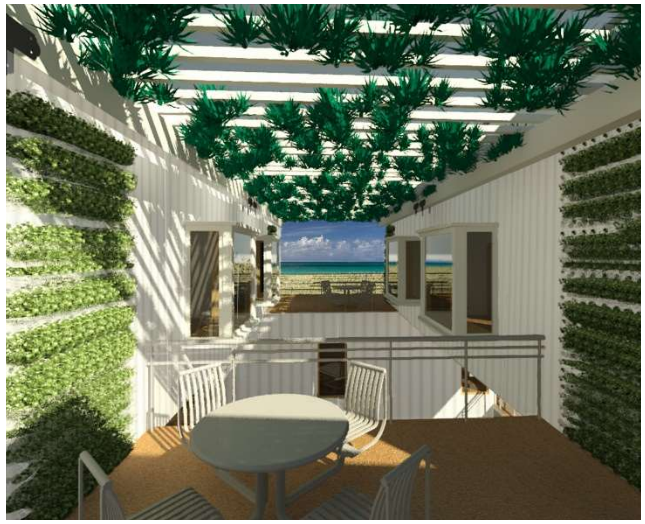


Figure 3.5: Exterior Render of the Rooftop Deck and Shading

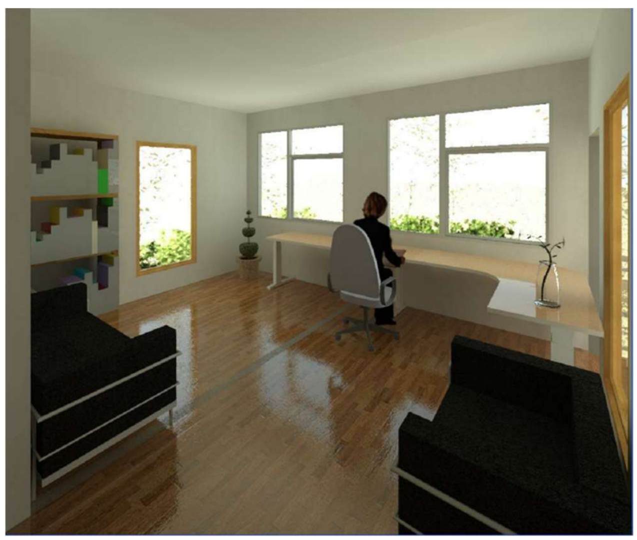


Figure 3.6: Interior Render of an Administrative Office

The west structure of the administration building (Figure 3.3) will be constructed from two 40-foot high-cube shipping containers and six 20-foot high-cube shipping containers, four of which will be stacked to create a lookout tower. This tower will serve as a distinctive element of the campus. The tower's rooftop deck will provide views of the ocean and landscape and the height of the tower will allow it to serve as a reference point throughout the campus (Figure 3.7). Interior spaces on the first and second floors will provide administrative office space (Figure 3.6), and a third story rooftop deck will provide more open-air work and gathering space for students and faculty. Lightweight pergolas on this third-story deck will also provide shading similar to the east structure.


Figure 3.7: Exterior Render of the Tower Deck

Finally, the space between the east and west structures of the initial administration building will serve as an outdoor multipurpose space (Figure 3.8). Adjustable seating and workspaces can be used for outdoor classroom space, student use, collaboration space between students and faculty, or for community engagement events. Tensile fabric connected between the east and west structures will provide shading and divert rainwater. Orientation of the east and west structures will also provide a natural breeze through this central space to combat warmer temperatures. Finally, the addition of green walls in this space will also provide a sustainable and aesthetically pleasing design element.


Figure 3.8: Exterior Render of the Outdoor Multipurpose Space

3.2.2. On-campus Housing Building Design

For initial on-campus housing, the team proposes a modular complex with dorm rooms housed by staggered 20-foot high-cube shipping containers and shaded outdoor communal spaces. The decision to design housing was inspired by conversations with stakeholders and their desire for a "campus citadel" where students and faculty could live and work. Due to the remote site location and desire to immediately grow the initial campus, a simple housing complex will be a necessity in the first stage of development. Aesthetic preferences and site, climate and structural considerations informed the overall design as shown in Figures 3.9.

Figure 3.9: Exterior Render of the Housing Complex from Interior Courtyard

This initial design is capable of housing 98 students and/or faculty, assuming 10 rooms are reserved as singles (Figure 3.10) with the remaining functioning as doubles (Figure 3.11). This three-story design is the maximum height recommended by the design team, however, the design allows for the complex to be built in levels, so one- or two-story complexes will also be applicable. In the application of a multi-story complex, the first level rooms shall be handicap accessible, but the upper stories will not be unless a lift or elevator is installed.

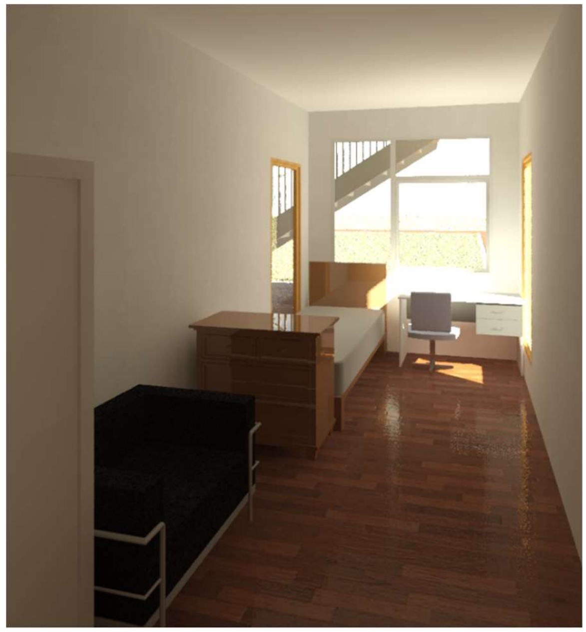


Figure 3.10: Interior Render of a Single Dorm Room

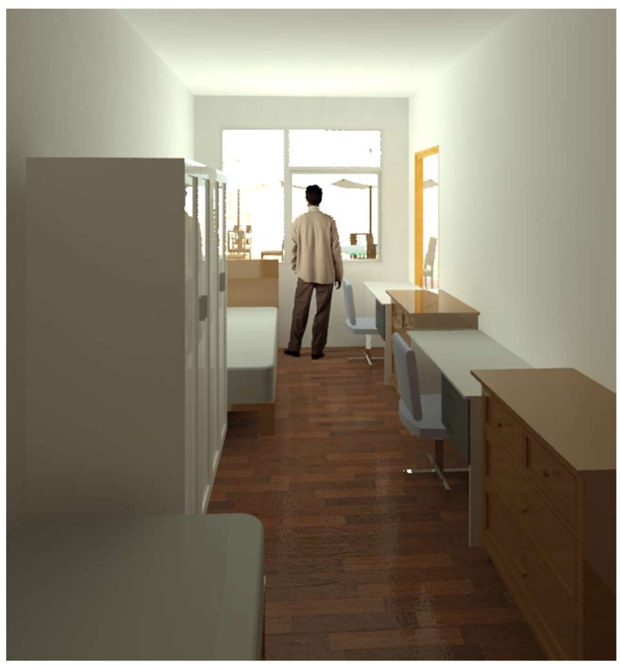


Figure 3.11: Interior Render of a Double Dorm Room

Each room will have shaded outdoor space at the entrance. Roof overhangs along all outdoor walkways will provide shading and divert rainwater to gutters for water collection. The shape and orientation of the complex will also provide shading for the majority of the day in the interior courtyard space, and a central section between staggered containers in the building's layout will provide an outdoor communal space on each level, as well as access to communal restrooms (Figure 3.12).

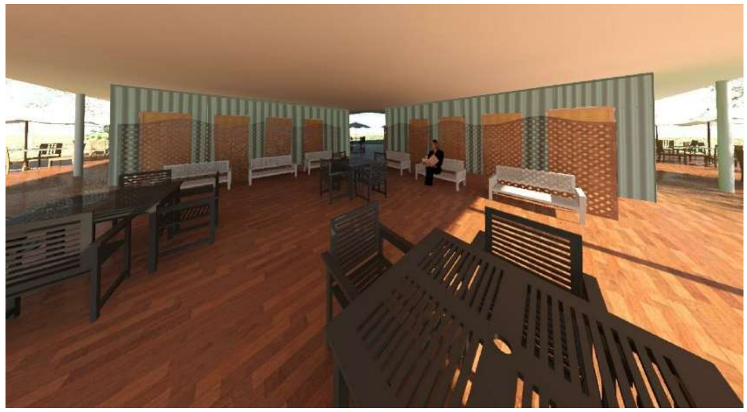


Figure 3.12: Exterior Render of the Outdoor Communal Space

3.3. Solar Study

Before the team made any decisions about the building orientation or solar shading used in the design, students developed an understanding of the sun's behavior at Macaneta Beach. This process began with an analysis of the effects of Macaneta Beach's global position at a latitude of 25.7719 ºS ("Praia de Macaneta," n.d.). This location in the Southern Hemisphere indicates that the sun passes through the sky on the northern side as it travels east to west each day. This also indicates that the summer solstice occurs on December 21st, when an average daylight period of 13 hours and 43 minutes is observed ("Sunshine & daylight," n.d.). Opposite this, the winter solstice occurs on June 21st, when an average daylight period of 10 hours and 32 minutes is observed. In addition to their significance as the longest and shortest days of the year, the solstices mark the days on which the sun is at its highest and lowest peak in the sky. In order to determine the altitude of the sun on different dates, the team generated a sun path diagram based on the given coordinates for the site (Figure 3.13) ("UO solar radiation," n.d.). On December 21st, the sun reaches an altitude as high as 87.8º while on June 21st its apex sits at 40.7º. The sun is the strongest on December 21st and continues this trend through March, forming a four-month long summer season in Macaneta Beach. Overall, the Macaneta Beach area sees sunny conditions during 62.7% of its daylight hours, while hazy or cloudy conditions occur for the remaining 37.3% of the time.

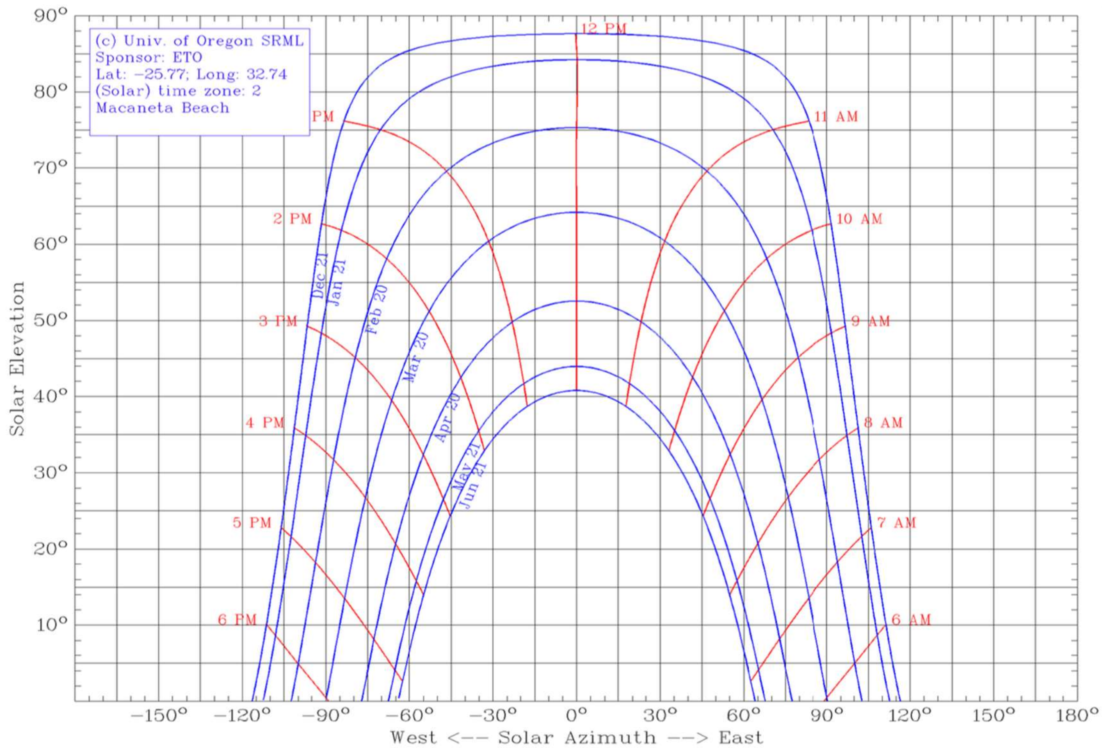


Figure 3.13: Sun Path Diagram for Macaneta Beach

Once data about the sun's pattern at Macaneta Beach was collected, the team determined orientation of the buildings on the site. In order to gain the best natural lighting during the daytime, the team decided to orient the administration building so that its longitudinal axis faced north. This configuration allows for optimal amounts of daylighting during peak hours of operation for the administration building. Furthermore, this positioning allowed more surface area to place living green walls on the facade of the administration building that faces the northern sky. Unlike the administration building, the on-campus housing building will benefit the most from an orientation that allows it to be easily shaded. Many of the spaces in the administration building will be thermally conditioned, while the units in the on-campus housing will rely on passive heating and cooling. For these reasons, the on-campus housing structure was oriented along the northeast to southwest axis. This orientation allows the walkways incorporated in the building's design to provide shading to the units beneath them and allows the building to shade the courtyard adjacent to it. The selection of these orientations for the two campus buildings will lead to optimal building performance and occupant comfort.

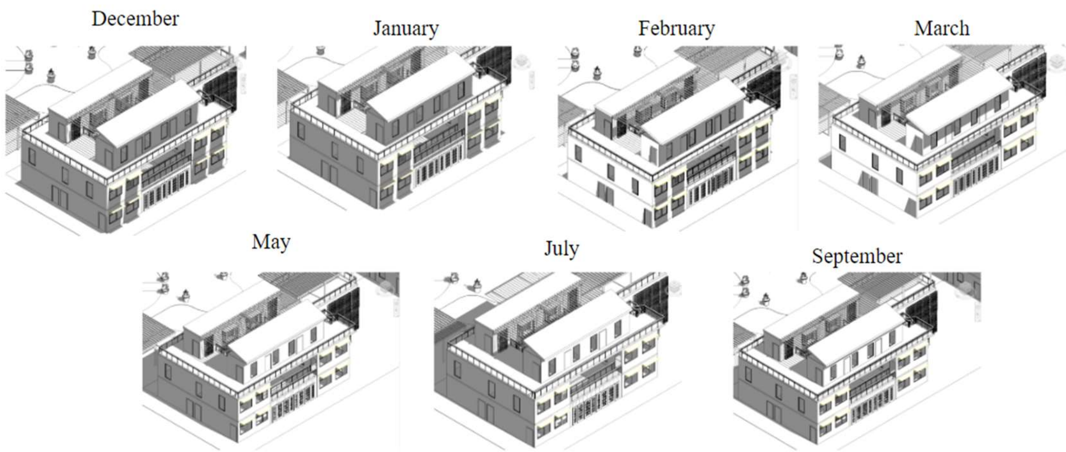


Figure 3.14: Solar Study of Administration Building East Structure Throughout the Year

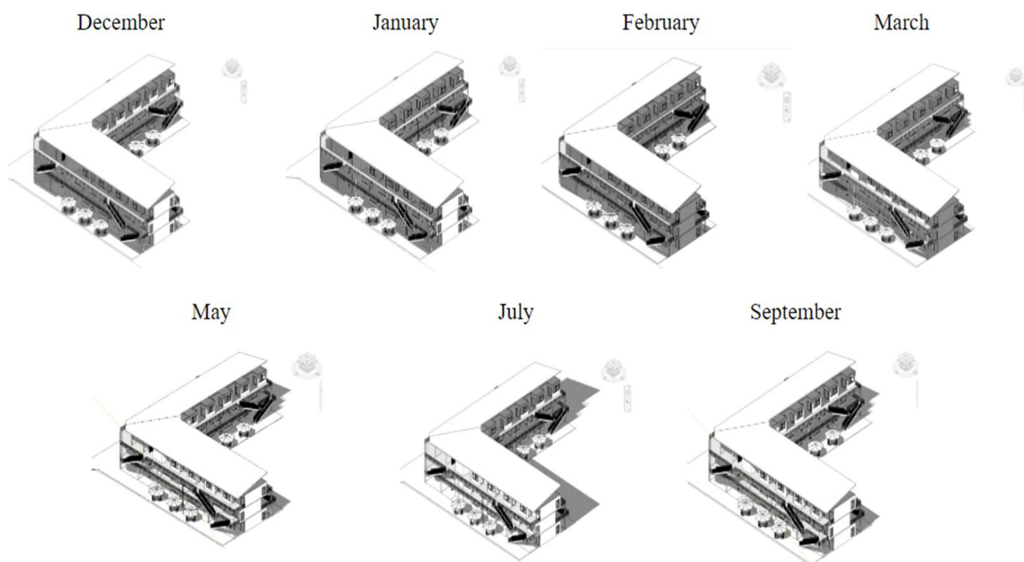


Figure 3.15: Solar Study of On-campus Housing Building throughout the year

In order to strengthen the effects of the building orientation strategies, the team also created a plan for solar shading on portions of each building's facade. This plan focused on shading strategies that would block the sun during the warm months of December through March but allow sun at other times (Figure 3.14, Figure 3.15). For the administration building, the team decided that solar shading was only necessary on the north facing facade. Although the east and west sides of the building are also exposed to sunlight as the sun rises and sets, this exposure occurs for short periods of time. As the sun moves through the sky, these sides become shaded for most of the day. In order to shade individual windows on the north side of the building, window awnings were utilized. These shading devices can be created through the repurposing of the corrugated steel cut out for window openings. To secure the awnings to the building, a multi-stage locking function arm should be attached at one end to the top face of the awning and to the building at the other end. This will cause the awning to behave similar to a top hung outward opening window, allowing the awnings to fold flush to the building's exterior in the event of a natural disaster as shown in Figure 3.16.

Figure 3.16: Solar Shading for Campus Administration Building North Side

Based on the size of the windows and their position on the building, it was determined that the awnings should be the same width as the windows. The awnings should extend 1'-9" (53.3 cm) outward from the exterior face of the wall and be installed so that their bottom face sits 0'-6" (15.24 cm) above the top of the window ("Overhang," n.d.). To test these determinations, the team added awnings to the Revit model of the administration building. The solar path and shadow tools were used to analyze the shadows produced by the awnings year-round. The results showed that the awnings provided adequate shading in the warm months while allowing sun in the cooler months. In addition to these window awnings, the third floor of the eastern structure of the administration building requires a roof overhang to provide shading. The team began with a starting point of a 1'-9" (53.3 cm) overhang, similar to the awnings. Since the windows in this portion of the building are larger, the 1'-9" (53.3 cm) overhang was not sufficient. Using the sun path and shadow tools in Revit, the team was able to conclude that a 2'-6" (72.6 cm) overhang would be needed to provide shading from December to March on this part of the building.

Looking at shading techniques for the on-campus housing, the team decided that the best strategy was to use the slope and overhang of the roof to shade the third-floor units. This allows seamless incorporation into the roof design and rainwater collection. The windows on the third floor of the on-campus housing are the same size as those on the northern side of the administration building and are located in the same position. Because of these similarities, the team decided to start with a roof overhang of 1’-9” (53.3 cm). Using the sun path and shadow tools in Revit, the team was able to conclude that a roof overhang of this size provided adequate shading in the summer months, while allowing sunlight exposure in the cooler months (Figure 3.15).

3.4. Architectural Program and Floor Plans

During the completion of this project, total occupancy of the initial administration building, and on-campus housing complex were still uncertain. Architectural programs for the designs were therefore based on conversations with stakeholders and generalization of occupancy to allow for changes in the future.

3.4.1. Initial Administration Building

With the concept of the initial administration building to be used by both students and faculty in an educational, administrative, and collaborative manner, the team paid attention to creating a variety of spaces with versatile uses. The following program shows the breakdown of general classification of spaces throughout the building. Figures 3.17 and 3.18 show more detailed layouts of building occupancies for each floor plan.

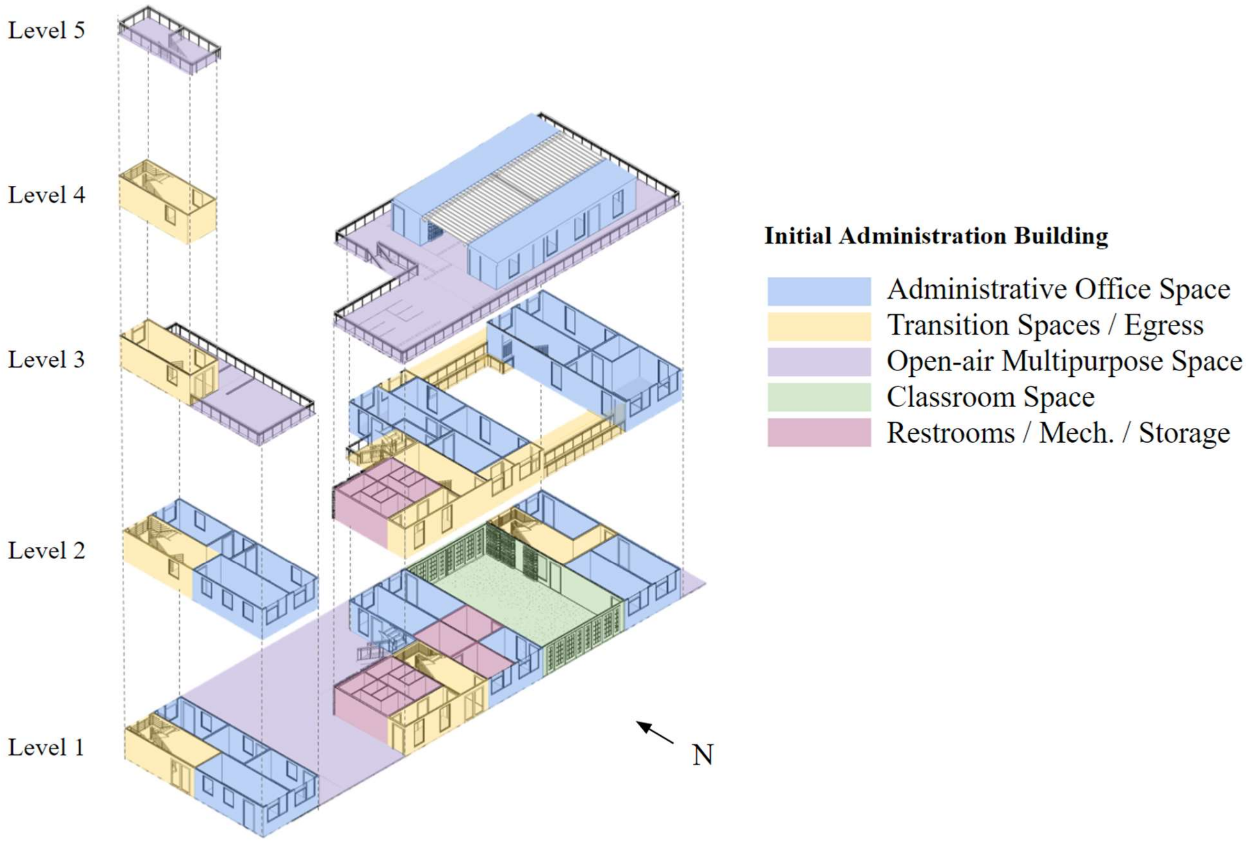


Figure 3.17: General Program for the Initial Administration Building

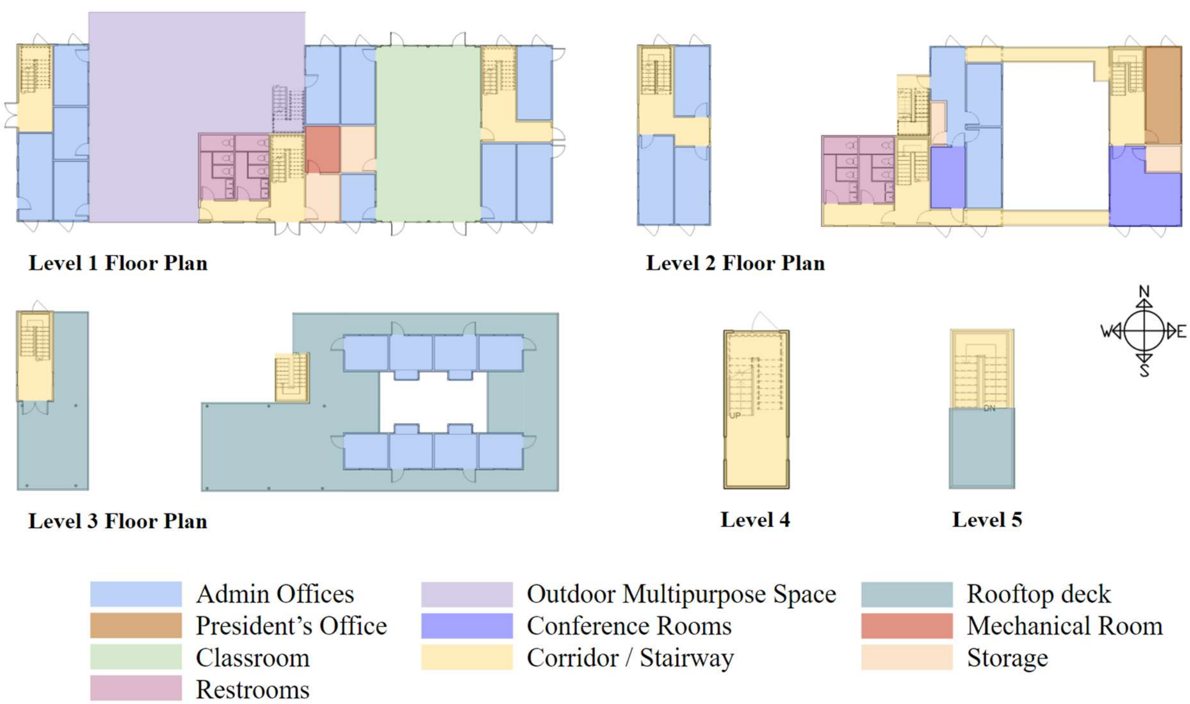


Figure 3.18: Distribution of Administration Building Architectural Program by Floor Plan

3.4.2. On-campus Housing Complex

The modular layout of the initial on-campus housing complex is defined by repetitive floor plan layouts with mirrored overhangs between different levels. The following floor plan provides a typical program for each level (Figure 3.19). The initial design is sized to house a maximum of 36 people on each floor. However, this layout can be extended in the future to accommodate more people.

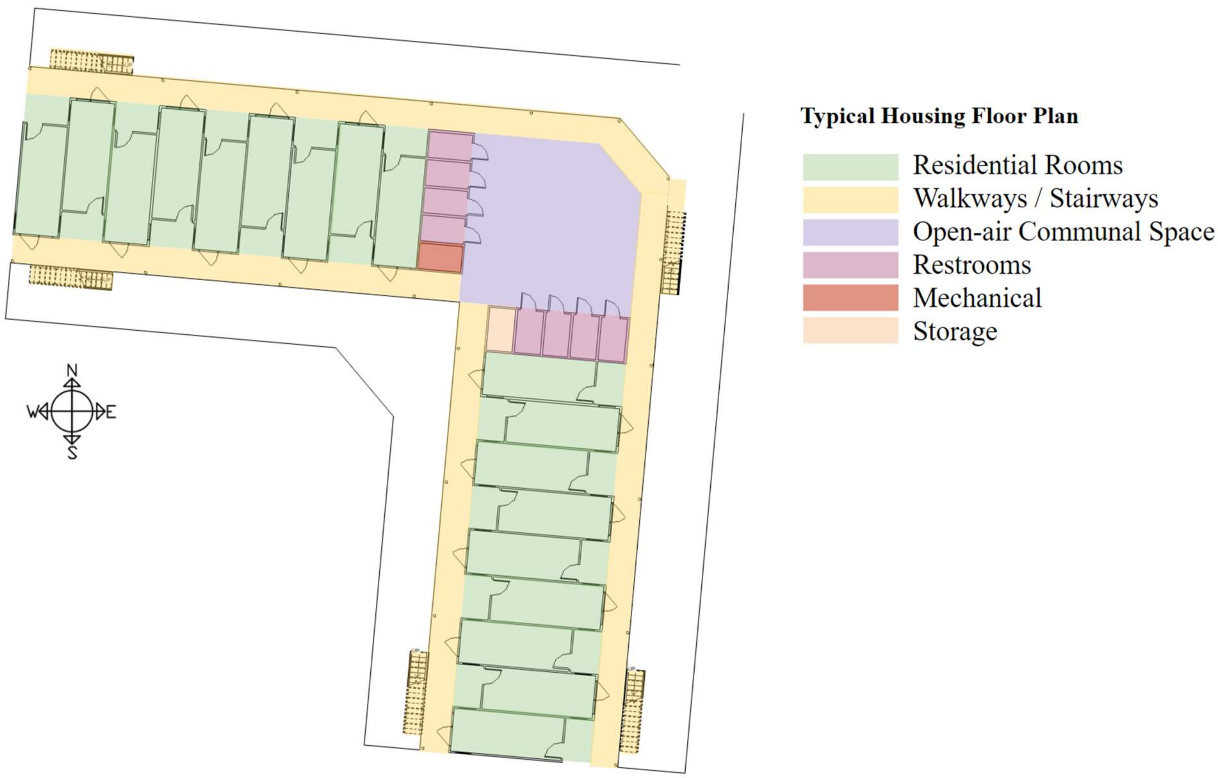


Figure 3.19: Typical Distribution of Architectural Program by Floor for on-campus housing

4. Structural Analysis of Modular Shipping Containers

Shipping containers provide a sustainable option for modular construction and are also advantageous when used as building blocks due to their structural strength. This section outlines the team's process of testing an individual shipping container unit for necessary loading scenarios using structural analysis software and provides limitations and conclusions for modifying shipping containers.

4.1. Structural Guidance from the International Organization for Standardization

The structural limitations for shipping containers used for carrying cargo are outlined in the International Organization for Standardization (ISO) 1496-1. In this publication, the ISO outlines the series of tests that the shipping containers must undergo before they are certified for use. These tests include the application of vertical and lateral loads acting on the corner connections and posts of the containers (Figure 4.1).

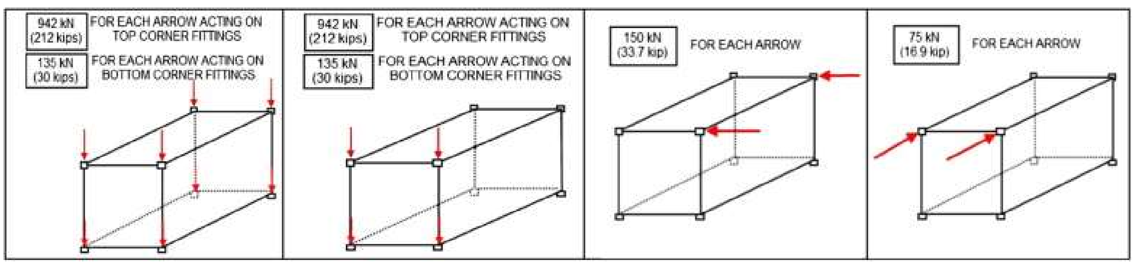


Figure 4.1: ISO Shipping Container Structural Tests Diagram

When used in their traditional sense, these shipping containers are loaded seven or eight stories high, resisting the weight of the containers surrounding them *(Series, 2013)*. High-cube containers, or shipping containers with a height of 9'-6" (2.9 m), have a standard tare weight of 8,470 pounds (3841.9 kg) and a maximum payload weight of 58,730 pounds (26639.5 kg) *(Series, 2013)*. Due to the high stress loading scenarios endured on cargo ships, and the intense weather conditions experienced at sea, many assume that the shipping containers are suitable modular building materials that will be able to withstand common building loads. The application of ISO loads shown above in Figure 4.1, incorporate loads that greatly exceed the values of equivalent loads that would be experienced as part of a typical building's structural system.

4.2. Structural Guidance from the International Building Code

Section 3115 of the 2021 International Building Code (IBC) released by the International Code Council (ICC) outlines general guidance for the construction of buildings using Intermodal Shipping Containers. In this section, the code recommends that shipping containers fit for construction must be in good condition, free of dents, notches in the rails and castings, or other defects. When manipulating the containers for design, the code states that the total linear length of all openings on the side or end walls is limited to 50% of the wall's length (Figure 4.2).

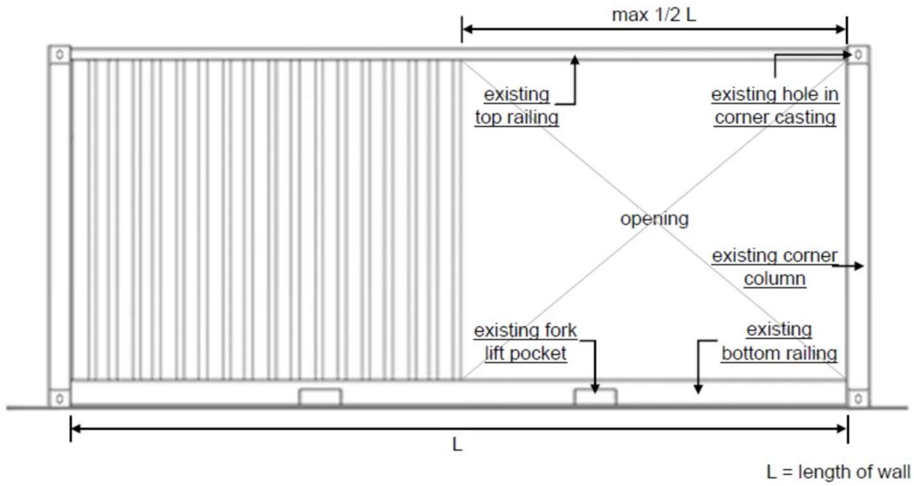


Figure 4.2: Figure 3115.8.5.3(1) Bracing Unit Distribution - Maximum Shear Length from IBC 2021

If additional reinforcements are required, new steel elements must have a cross section that is greater than or equal to that of the removed portion including welds or connections. When considering wind or seismic effects, the team looked at Table 3115.8.5.3 in the same IBC chapter which outlines that a high-cube 40-foot shipping container (IEEE) has a side wall allowable shear value of 75 pounds per foot (111.6 kg/m) and an end wall allowable shear value of 843 pounds per foot (1254.5 kg/m). This information from the IBC was considered in combination with the information from the ISO as the team looked at prior research on structural analyses of shipping containers and worked to create their own structural model and building design.

4.3. Structural Guidance from Prior Structural Analyses of Shipping Containers

The papers referenced by the team all outlined structural analyses of shipping containers using various computer modeling software. The most utilized softwares were Hypermesh and Abaqus/CAE (Giriunas, 2021) (Ntumi, 2018). In several of the papers, researchers stressed the importance in understanding the components of the structural frame, specifically their dimensions and materials. These details about the dimensions and materials of the structural components greatly impact the accuracy of the structural model that is generated.

Although the papers the team analyzed took varied approaches to their structural analyses, the team was able to draw some conclusions from the readings. The first paper outlined the analysis of an original unmodified container as well as seven various container configurations (Figure 4.3).

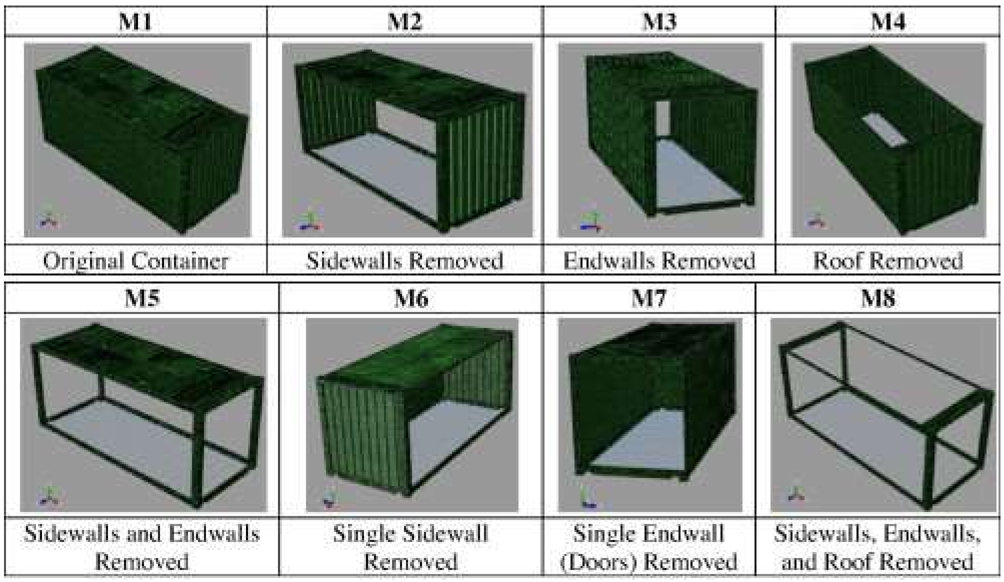


Figure 4.3: Abaqus/CAE Structural Analysis Models Used in Paper 1

Using these models, the researchers applied the same yielding forces tested by the ISO (Figure 4.4) to the reshaped containers.

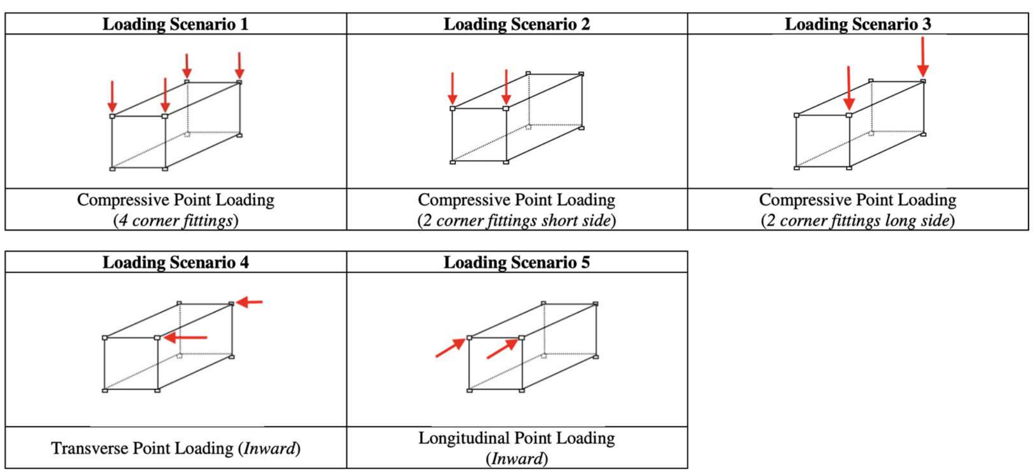


Figure 4.4: Load Scenarios Applied During Structural Analyses Outlined in Paper 1

After running the analyses in Abaqus/CAE, the researchers concluded several things:

1. For all loading scenarios, the calculated maximum elastic load for the complete model (M1) reached or exceeded the corresponding loads specified in ISO 1496-1.
2. The maximum resisting load for almost all the modified containers was either close or less than the ISO 1496-1 specified loads. Therefore, it is likely that yielding may occur in modified containers before reaching the capacity required in ISO 1496-1.
3. All the container models yielded at the door header component when subjected to four vertical point loads (Loading Scenario 1). The end walls under Loading Scenario 1 are the most critical load resisting components and were more effective at carrying the loads than the sidewalls.
4. The roof did not have any significant structural contribution when subjected to vertical point loads (Loading Scenarios 1, 2, and 3).
5. For axial/vertical loads applied on the top corner fittings, end walls were generally the strongest load resisting components, the sidewalls were the next strongest load resisting components, and the roof typically did not have any structural contribution.
6. For transverse lateral loads applied on the top corner fittings, the end walls were the strongest load resisting components. For longitudinal lateral loads applied on the top corner fittings, the sidewalls were the strongest load resisting components. The roof generally did not have any structural contribution for lateral loads.

   The findings of this paper confirm what the team had hypothesized. These hypotheses include:

   1. The shipping container will be the strongest if it remains unmodified.
   2. The structural frame made up of corner posts, corner connections, top rails, side rails, and end rails are critical to the structural integrity of the frame.
   3. The corner posts and connections carry vertical loads through the structure.
   4. The roof prevents the top chord of the sidewall from buckling but is not capable of supporting heavy loads placed on top of it.

These hypotheses and findings from the referenced paper were tested as the team created their own structural model.

The second paper that the team analyzed as part of their initial research analyzed the use of a simplified beam model to analyze the stresses placed on a 20-foot shipping container (Ntumi, 2018). Although this paper used a different size container, the team believed that the information would aid their understanding of how to create a simplified model and if it were even practical. When creating the simplified beam model, the researcher took into consideration the moment of inertia, modulus of elasticity, and modulus of rigidity of the original shipping container members to create similar simplified members (Ntumi, 2018). The researcher also paid close attention to the connections that were formed between the members, using rigid connections at the corner and ties that allowed equal movement in all degrees of freedom in the middle. Identical loads were applied to the complex Abaqus/CAE model and the simplified beam model, and the results showed that the simplified model responded within 10% accuracy for displacement and 15% accuracy for stress. Some limitations of the simplified model were the inability to mimic the stiffness of the corrugated walls with complete accuracy.

Knowing this information, the team concluded that using RISA-3D 19.0 and supplementing it with information obtained from the sources mentioned above would provide a detailed understanding of how the shipping containers will perform as building units. Although this type of model is not as precise as a model made from Hypermesh and/or Abaqus, the team believed that using new software to analyze a structure that they had little background knowledge on may lead to inaccurate results. The team used data collected from the models created in RISA-3D 19.0 to make general recommendations to their Mozambican partners. Future research should also be done by local engineers in Mozambique to verify these results as they occur in the finalized building design.

4.4. Strength Assessment of a Shipping Container Unit using RISA-3D-19.0

In order to assess the structural strength of a shipping container when repurposed as an architectural building component, the team had to create an accurate model of a singular container that could reasonably predict the structural behavior of an International Organization for Standardization (ISO) cargo shipping container according to ISO standards. The team used RISA-3D 19.0 design software to develop computer models for both a 40-foot high-cube container and a 20-foot high-cube container. These models were analyzed with the loading conditions for dead load, live load, wind load, and seismic load. Standards for maximum loading of the container, materials, and sizing for container components were based on the ISO standards 1496, 668, and 6346.

Since the team used RISA-3D 19.0 instead of the more popular Abaqus/CAE or Hypermesh, it was critical to ensure that the final model was behaving accordingly. The team began with a model of the shipping container's structural frame (Appendix A). This model included the bottom cross members, corner posts, door frame, end rails, and side rails and allowed the team to test the importance of the side and ends walls to the stability of the frame. After placing the loads on the frame, the team found that the model did not accurately represent the expected reactions because the shear was not being transferred correctly. This signaled that the corrugated end and side walls play critical roles in the transfer of shear.

In order to represent the corrugated side and panels, the team explored a different strategy using two-dimensional models. These two-dimensional models began with the insertion of vertical members that took the properties of corrugated steel and were spaced to match the corrugation dimensions (Appendix A). While this model was an improvement, the reactions in the corner posts and side rails and the overall deflections still did not meet the team's predictions. With the help of their advisor, the team decided to add diagonal members in tension to the model to aid in the transfer of the shear load (Appendix A). Along with the addition of these diagonals, the team switched out the two pinned supports at the bottom corners of the truss for a pinned support and a roller support. This model showed promise, as the axial distribution from the top rail through the side rail to the bottom wall was corrected, but the deflection values remained high. The next model that the team created took advantage of RISA-3D 19.0's wall panel tool. A steel wall panel was inserted that connected all four members of the structural frame (Appendix A). This steel wall panel was assigned the same properties and thickness of the corrugated Corten A steel. With this model the team saw that the axial distribution remained correct, and the resulting deflections were minimized to fall within the acceptable limits. The team decided to move forward with this concept and create a three-dimensional model using steel wall panels as the side and end walls. More information on the draft models that were critical in the formation of the final model can be found in Appendix A.

The three-dimensional model that resulted included the structural frame connected on three sides by steel wall panels and supported at two corners by pins and two corners by rollers. This model assumes that the shipping containers act as a large I-beam. The top rails, bottom rails, and side rails carry most of the loads while the corrugated steel provides stiffness and a means of transporting these loads.

4.4.1. Shipping Container Components

The components of a standard ISO shipping container can be seen in Figure 4.5 below.

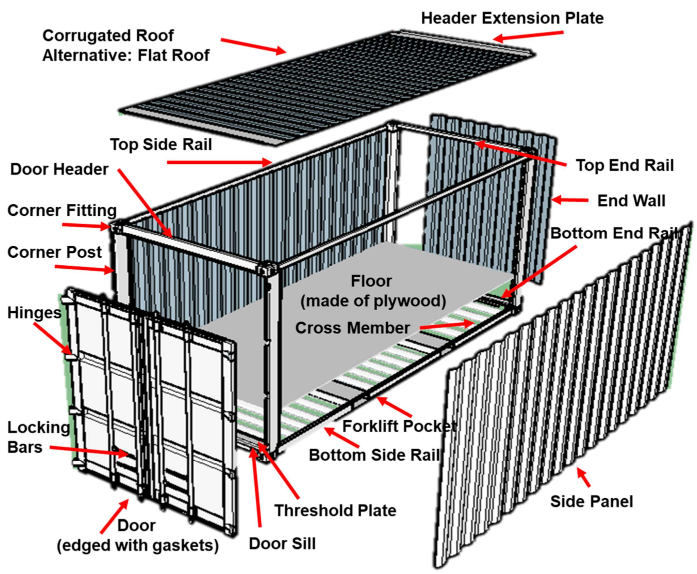


Figure 4.5: Structural Components of a Standard ISO Shipping Container

During the structural analysis in RISA-3D 19.0, the team focused on the members that create the frame of the container and provide its structural integrity. These components include the bottom cross member, bottom end rail, bottom side rail, corner post, door header, door sill, top end rail, and top side rail. The standard sizes of these components can be found in Table 4.1 and were based on technical specifications for containers manufactured by Steinecker Containerhandel (*Technical*, n.d.). Member sizes in the table are standardized, eliminating the need for conversions.

Table 4.1: Standard Frame Sizes of a 40-foot High-cube ISO Shipping Container

Component	Member Size	Shape	Quantity
Base Frame			
Small Bottom Cross Member	122 x 45 x 40 x 4.0 mm	"C" section	25
Large Bottom Cross Member	122 x 75 x 40 x 4.0 mm	"C" section	3
Bottom Side Rail	152 x 48 x 30 x 4.5 mm	Channel section	2
Front End			
Corner Post	113 x 40 x 12 mm	Hot Rolled Steel Section	2
Front Header	60 x 60 x 3.0 mm	Rectangular Tube	1
Front Rail	60 x 60 x 3.0 mm	Rectangular Tube	1
Rear End			
Corner Post	113 x 40 x 12 mm	Hot Rolled Steel Section	2
Horizontal Door Member	150 x 50 x 3.2 mm	Rectangular Tube	1
Vertical Door Member	150 x 50 x 3.0 mm	Channel Section	1
Side Wall			
Top Side Rail	60 x 60 x 3.0 mm	Rectangular Tube	2

A traditional ISO shipping container is constructed with fully vertical-corrugated steel sides and front wall, horizontal-corrugated steel double doors, and a die-stamped steel roof. Due to the limitations from the RISA-3D 19.0

software, the team was unable to model these corrugations. Instead, the team inserted steel wall panels on the two side walls and end wall of the model that matched the thicknesses of the corresponding corrugated steel (Figures 4.6, 4.7, 4.8). Since these wall panels do not allow for the inclusion of the corrugations, the model that resulted was conservative but acceptable.

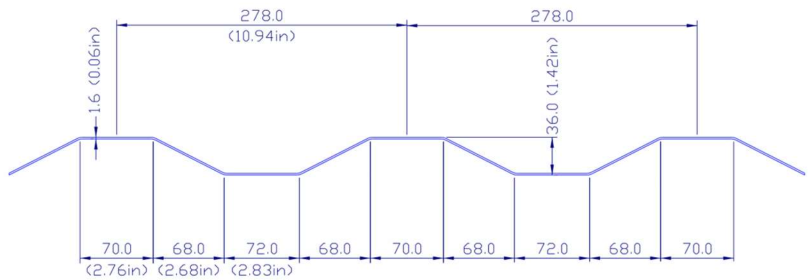


Figure 4.6: Side Wall Corrugation Dimensions

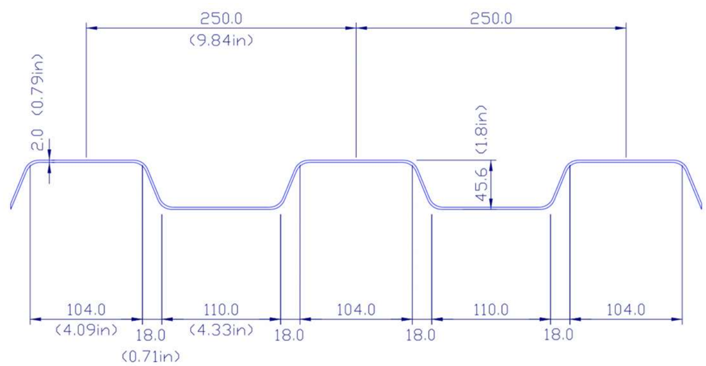


Figure 4.7: End Wall Corrugation Dimensions

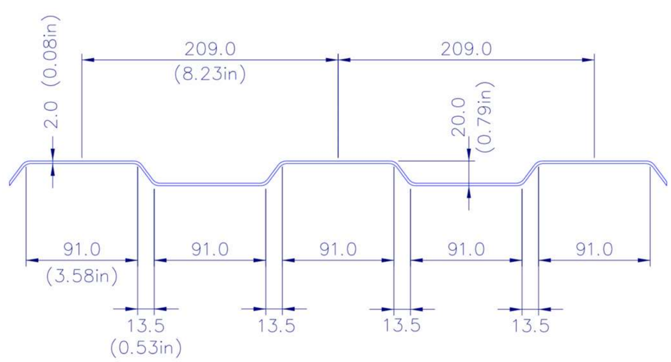


Figure 4.8: Roof Corrugation Dimensions

In addition to replicating the dimensions of the shipping container members, the team also ensured that the material properties of the members were identical. According to the Steinecker specifications, Corten A steel is used as the primary material for the front end, base, rear end, and floor assemblies (*Technical*, n.d.). The properties of Corten A steel that were provided in the specifications and inputted into RISA-3D 19.0 can be found in Table 4.2.

Table 4.2: Properties of Corten A ("Weathering") Steel

Property	Imperial Value	Metric Value
Elastic Modulus	200 GPa	29000 ksi
Poisson's Ratio	0.29	0.29
Shear Modulus	77.2 GPa	11200 ksi
Coefficient of Thermal Expansion	-17.8 1/°C	0.0000722 1/°F
Uniform Density	7849 kg/m ^{3}	0.49 k/ft^3
Yield Stress	0.227 GPa	33 ksi
Ultimate Tensile Stress	0.310 GPa	45 ksi

When modeling the frame and support members in RISA-3D 19.0, the team took advantage of the member creation tool, which enabled the creation of members of the exact size and material needed. The team also ensured that all the connections between the members were applied accordingly, using moment connections at the corrugated steel posts and pins and rollers at the bottom corners of the frame. The first general model created by the team may be seen in Figures 4.9 and 4.10.

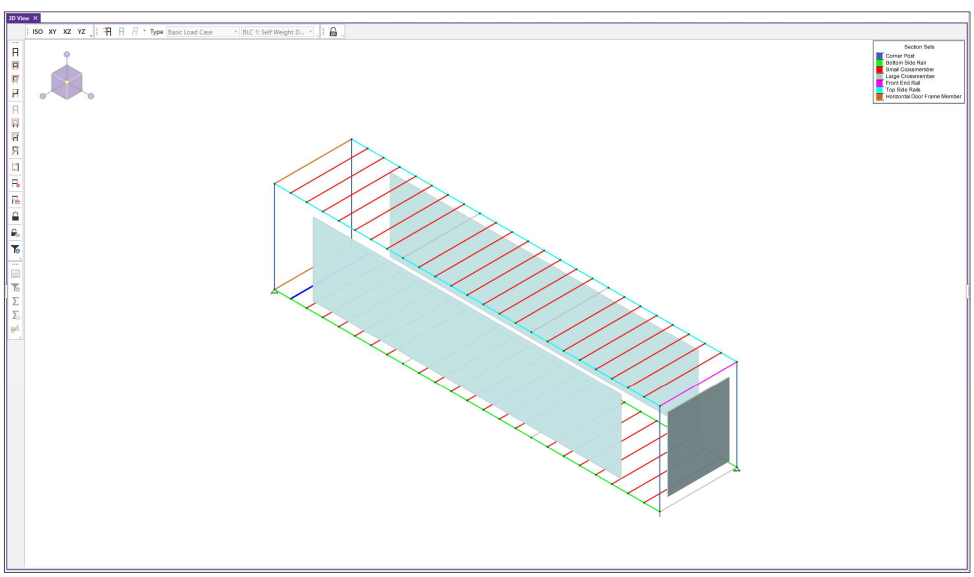


Figure 4.9: RISA-3D 19.0 Model of a 40-foot High-cube Shipping Container with Member Types

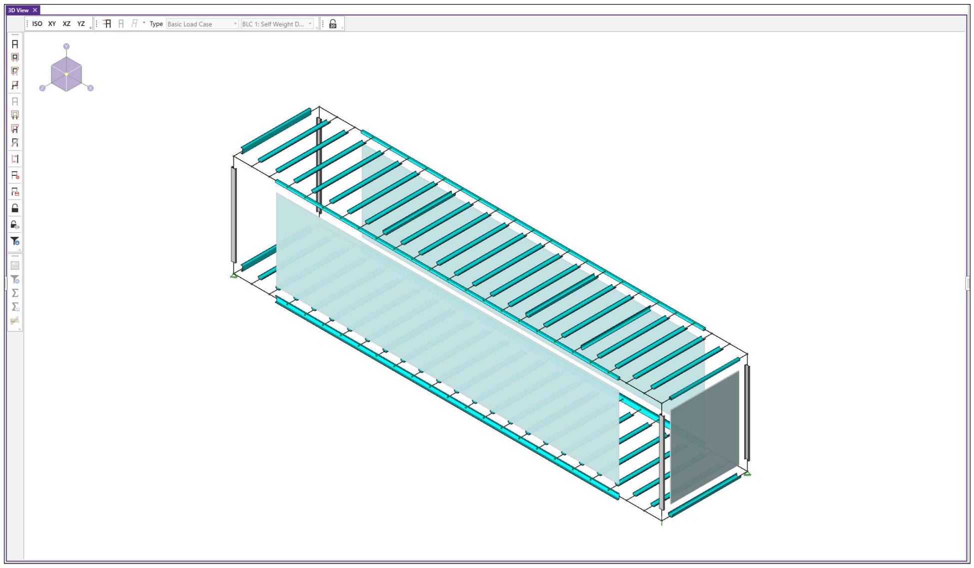


Figure 4.10: RISA-3D 19.0 Model of a 40-foot High-cube Shipping Container with Rendered Members

4.4.2. Container loads

Following the construction of the structural frame and supporting members of an ISO shipping container, the team began the application of various load types to analyze their effects on the container.

4.4.2.1. Dead Load

The analysis of the shipping container's loading capabilities began with a confirmation that the containers could be stacked on top of each other. The construction of the ISO shipping container forces the weight of any containers stacked on top of it to be distributed down through the four corner posts. With this in mind, the team applied point loads of 2.1 kips (952.5 kg) on each of the four corner posts to represent the 8.4-kip (3810.2 kg) weight of a 40-foot high-cube shipping container (Figure 4.11) (Appendix B). The information that results from this analysis will help the team determine how many containers may be stacked on top of each other and provide insight into what support will be needed for the building's foundation.

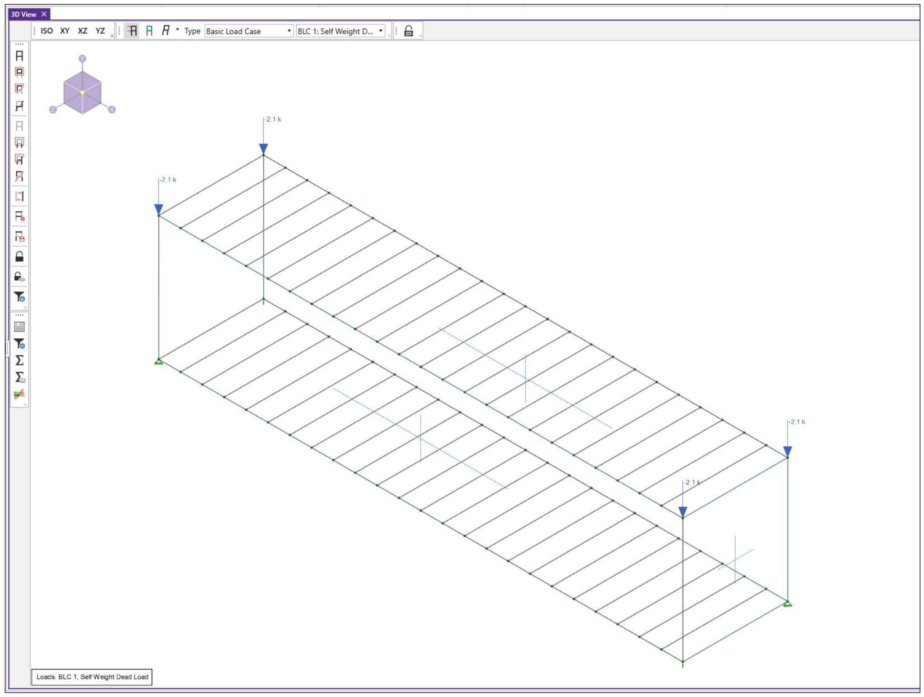


Figure 4.11: Self-Weight Dead Load Application on the Model in RISA-3D 19.0

In addition to the dead load of an empty shipping container, the team also considered dead loads applied to the structure as a result of the incorporation of a roof terrace. The team included a roof terrace in the design of the administration building. The load of this roof terrace will include the weight of the chosen decking material as well as the shading mechanisms. Typical roof construction yields an applied dead load of 15 pounds per square foot (73.2 kg/m^2). Since the roof terrace design will likely incorporate heavier materials the team used a more conservative 27 pounds per square foot (131.8 kg/m^2) based on the general weights of common building materials. Given that the area of the roof of a shipping container is 320 ft^2 (29.7 m^2) this would mean the applied dead load on the roof is 8.64 kips (3919 kg). This load would be applied to the top rails of the structure since the corrugations on the roof do not add to its structural integrity. Since the top rails have a combined linear length of 96 feet (29.3 m), the equivalent uniform load equals 0.90 kips/foot (13398.4 kg/m) (Figure 4.12) (Appendix B).

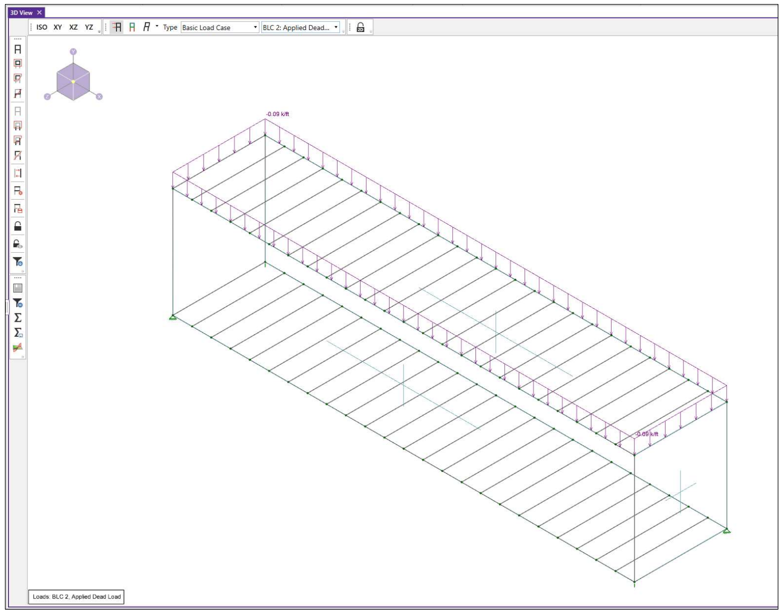


Figure 4.12: Applied Dead Load Application on the Model in RISA-3D 19.0

4.4.2.2. Live Load

After analyzing the effects of the dead loads on a shipping container, the team began the application of various live loads based on the anticipated use of the space. The live loads applied were taken from Table 1607.1 in Chapter 16 of the International Building Code (IBC) 2021 Edition. The program of the spaces designed by the team mainly consists of assemblies with movable seating, classrooms, computer labs, offices, and roofs subject to maintenance. The loads for these scenarios called for in the IBC are listed in Table 4.3.

Table 4.3: Minimum Live Load Requirements

Live Load	Uniformly Distributed Load	Concentrated Load
Assembly with movable seating	100 psf (488.2 kg/m^2)	--
Classrooms	40 psf (195.3 kg/m^2)	1000 lbs (4882.4 kg/m^2)
Computer Lab	100 psf (488.2 kg/m^2)	2000 lbs (9746.9 kg/m^2)
Offices	50 psf	2000 lbs

	(244.1 kg/m^2)	(9746.9 kg/m^2)
Residential - Private rooms and corridors serving them	40 psf (195.3 kg/m^2)	--
Roof subject to maintenance	--	300 lbs (1464.7 kg/m^2)

The team chose to analyze the application of an assembly live load, since this is a common load that would be applied in the administration building and is the most conservative. The team applied this load as a uniformly distributed load on the top side rails of the container. This assumes that the roof does not contribute significantly to the container's structural integrity and that the live load is transferred evenly to the two top side rails based on their tributary areas (Figure 4.13) (Appendix B).

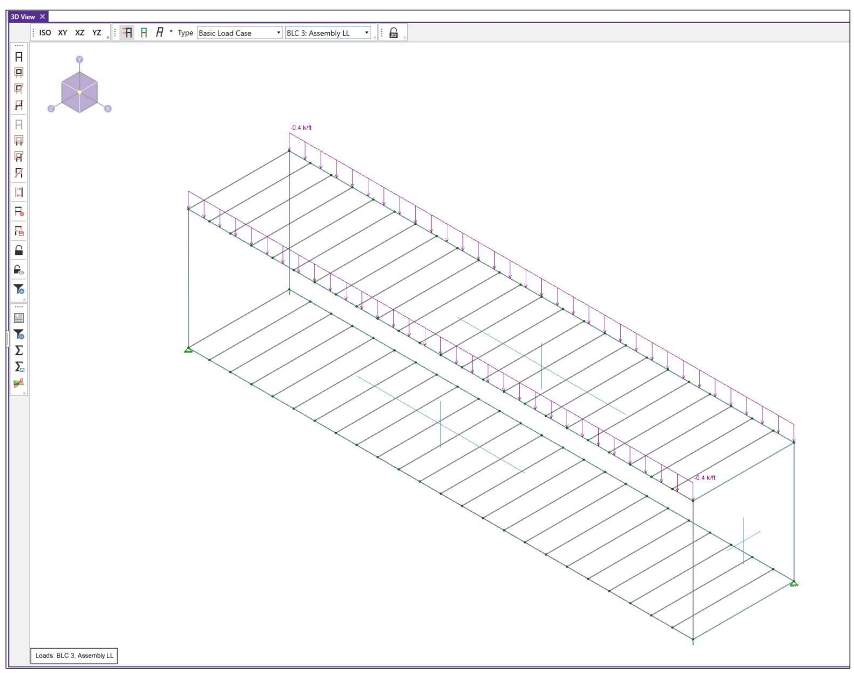


Figure 4.13: Assembly Live Load Application on the Model in RISA-3D 19.0

4.4.2.3. Wind Load

The location of the project near the shore of Indian Ocean in Macaneta Beach led to the initial concern that structures there would be subject to strong coastal winds. Upon further investigation, the team found that the winds in this area are not as strong as anticipated. Reports indicate that the region experiences the strongest winds in September at about 24-30 miles per hour (38-48 kph) maximum. This was confirmed with a check of the wind data in 2019 and 2020 which verified that over the past two years the strongest winds in the area occurred in the month of September within those ranges. Using this information, the team was able to use Equations 1 (Appendix B) to determine a probable wind load of 0.0022 kips per square foot (10.7kg/m^2) applied as a uniform sheet load (Figures 4.14 and 4.15).

Although the site is not susceptible to strong winds on a day-to-day basis, it is at higher risk for natural disasters that bring in stronger winds. To account for these high-wind events, the team included the wind load in the application of LRFD worst case scenario loads to the design configurations outlined in Section 4.6.

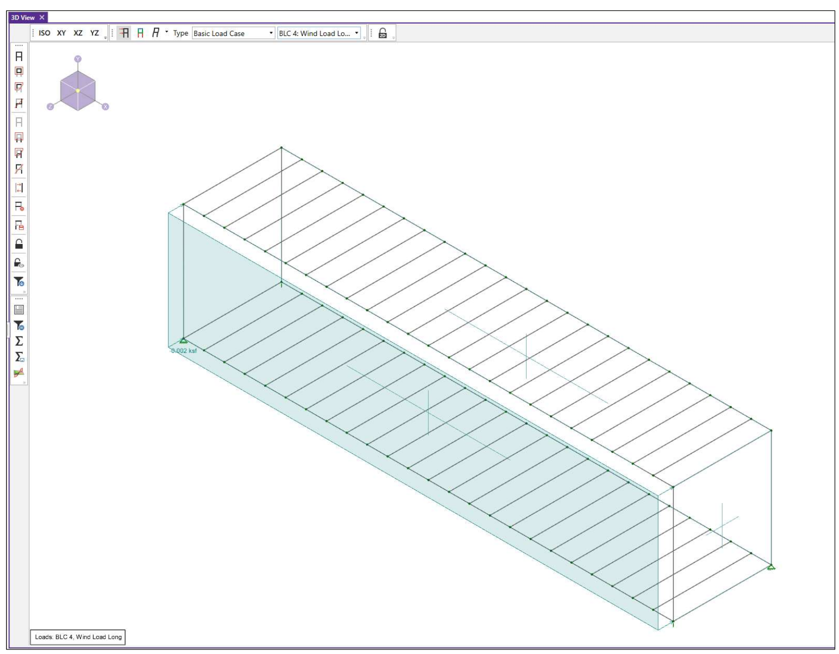


Figure 4.14: Wind Load Application to the Side Wall of the Model in RISA-3D 19.0

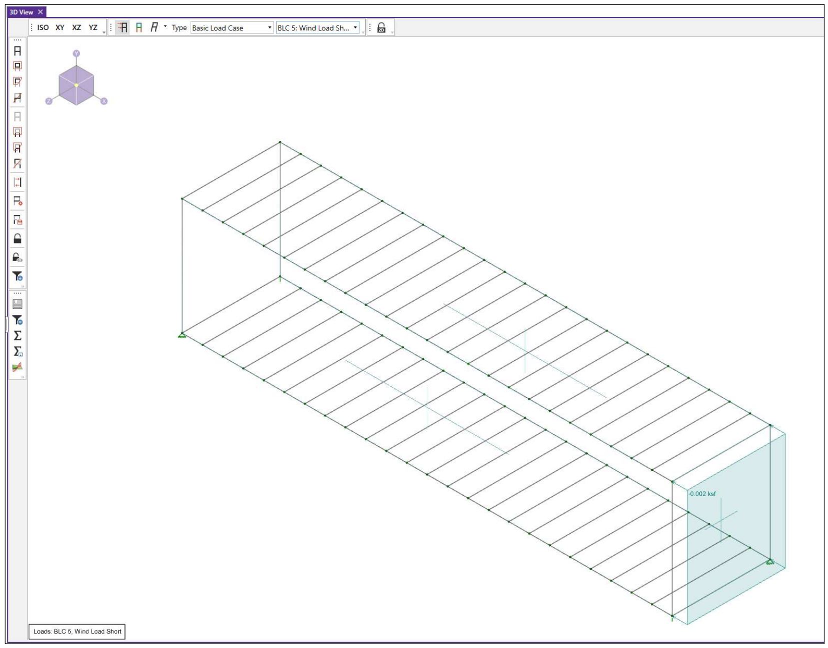


Figure 4.15: Wind Load Application to the End Wall of the Model in RISA-3D 19.0

4.4.2.4. Seismic Load

The first step in determining the seismic criteria for the buildings on our site was determining the categorization from Chapter 16 of the 2021 IBC. Although the initial campus buildings may be smaller, the team chose to use Occupancy Risk Category III which includes adult or higher education buildings with occupancy loads greater than 500 people. This structural design choice allows for expansion in the future without substantial structural changes. An Occupancy Risk Category III yields a Seismic Use Group II. The location of the site near Maputo, Mozambique yields a Mapped Short Period Acceleration Parameter (s_s) of 0.00137 pounds (0.62g) and a Mapped Long Period Acceleration Parameter (s_l) of 0.000617 pounds (0.28g) (UFC 3-310-03A Table 3-3) Additionally, the location of the project on a site with soft clay soil, provides a site classification of E (ASCE 7-10 Table 20.3-1). Using this information, the Short Period Site Coefficient (F_a) was determined to be 1.2 and the Long Period Site Coefficient (F_v) was determined to be 2.4 (ASCE 7-10 Tables 11.4-1 & 11.4-2). From here, the Design Short Period Spectral Acceleration Parameter (s_{DS}) and Design Long Period Spectral

Acceleration Parameter (s_{DI}) were calculated using Equations 2 & 3 in Appendix B and found that s_{DS}=0.496 and s_{DI}=0.448. These numbers could then be used to find the Seismic Design Category in Tables 1613.2.5(1) and 1613.2.5(2) of the 2018 IBC, yielding a Design Category D. Design Category D is described as "buildings and structures in areas expected to experience severe and destructive ground shaking But NOT located close to a major fault. Sites with poor soils are a good example". Furthermore, the ranking of Seismic Design Category D forbids the use of ordinary concrete or masonry bearing wall systems and ordinary concentric steel brace systems in a structure with a height of 35 feet (10.67 m) or more according to ASCE 7-10.

When looking at the seismic forces that will be applied to the RISA-3D 19.0 model, there will be a base shear force (V) that is equal to the summation of the seismic lateral forces felt at each level of the structure. The equations for these forces can be found in Appendix B and take into consideration the site characteristics and building properties to determine lateral seismic forces. The base shear force changes from level to level of a structure. Given the conditions at Macaneta Beach, the calculated total base shear force shall be 0.651 kips (295.3 kg). For a three-story building, the seismic lateral forces are as follows: F_{S1}= 0.1087 kips (49.31 kg), F_{S2}= 0.2168 kips (98.34 kg), and F_{S3}= 0.3225 kips (146.3 kg). For a four-story configuration, the seismic lateral forces are adjusted to: F_{S1}= 0.0651 kips (29.5 kg), F_{S2}= 0.1302 kips (59.06 kg), F_{S3}= 0.1953 kips (88.6 kg), and F_{S4}= 0.2604 kips (118.12 kg). Figure 4.16 shows the application of this load to the container assuming that the container is the first story of the building.

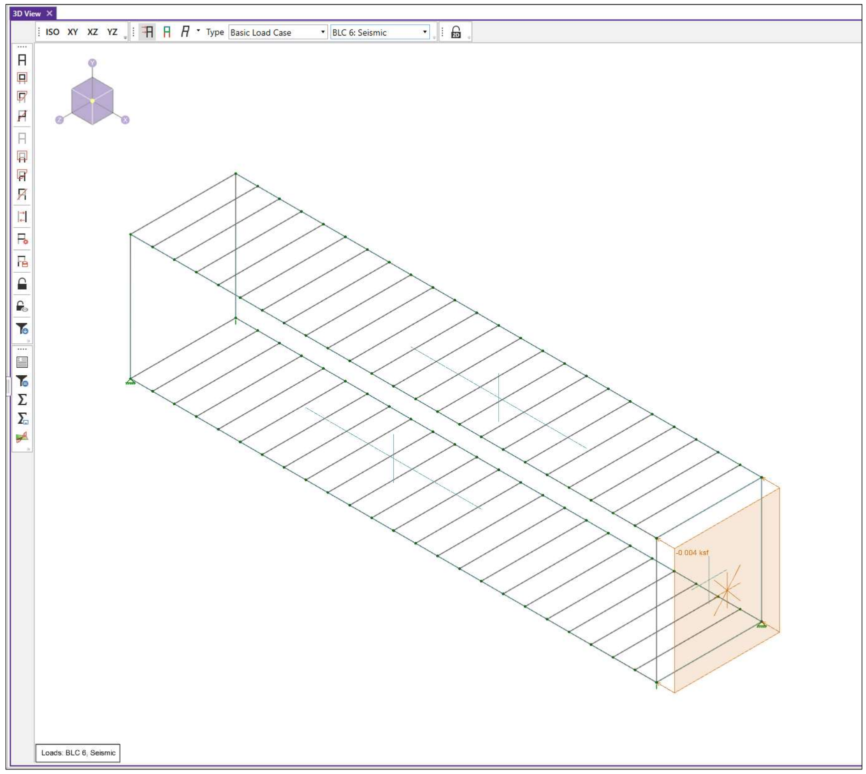


Figure 4.16: Lateral Seismic Load Application on the Model in RISA-3D 19.0

4.4.3. Container deflection limitations

After applying the necessary loads and load combinations to the shipping container, the team was able to access the structural capability of the structure through a comparison of the resulting deflections to the deflection limitations listed in Table 1604.3 in Chapter 16 of the IBC 2021 Version (*International,* 2020).

Table 4.4: Deflection Limitations from IBC Table 1604.3

Construction	L or L_r	S or W	D+L
Roof Members			
Supporting plaster or stucco ceiling	l/360	l/360	l/240
Supporting non plaster ceiling	l/240	l/240	l/180
Not supporting ceiling	l/180	l/180	l/120
Floor Members	l/360	--	l/240
Exterior Walls			
With plaster or stucco finishes	--	l/360	--
With other brittle finishes	--	l/240	--

With flexible finishes	--	l/120	--
Interior Partitions With plaster or stucco finishes With other brittle finishes With flexible finishes	 l/360 l/240 l/120	 -- -- --	 -- -- --

When looking at the frame that was created in RISA-3D 19.0, the top end rail and top side rails were analyzed under the deflection limitations of roof members supporting a non-plaster ceiling, bottom end rail and bottom side rail under the limitations of floor members, and corner posts and door components under the limitations of exterior partitions with other brittle finishes. Deflection of any of these members above the given limits under the applied loadings signaled the need for additional structural bracing of the frame.

4.4.4. Conclusions

After identifying the loads that the shipping container frame must withstand, these loads were applied to the model created in RISA-3D 19.0. The application of these loads on the model allows the team to assess if additional structural support is needed. When placed under loading conditions, the team also observed the functionality of the structural frame, and which members contribute the most to its integrity.

4.5. Shipping Container Loading Results and Recommendations

After applying the loads outlined in the above section to the shipping container model in RISA-3D 19.0, there were signs of deflection on the structural frame. Once the loads were applied to the frame, RISA-3D 19.0 produced a visual representation of the deformation that occurred. This visual was used to determine where deflections were occurring, leading to further investigation into the amount of member deflection. In places where the member deflection exceeded acceptable deflection limits, the addition of structural steel support was considered.

4.5.1. Unmodified Individual Shipping Container

The applications of the self-weight dead load, applied dead load, wind load, and seismic lateral load yielded no visual deformation (Figure 4.17, Figure 4.18, Figure 4.19, Figure 4.20, Figure 4.21). The member deflection table was then referenced to confirm that minimal to no deflection was present under these load cases (Table 4.5)

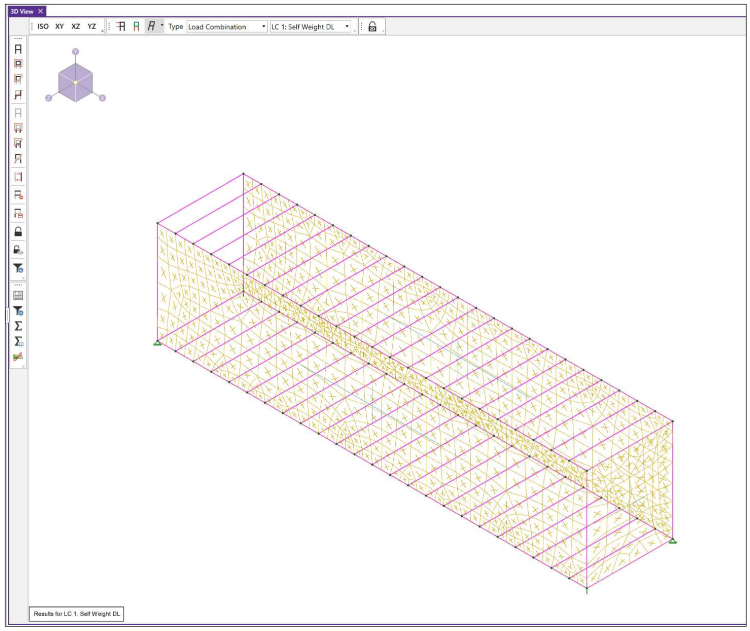


Figure 4.17: Individual Container Deflection from Self-Weight Dead Load

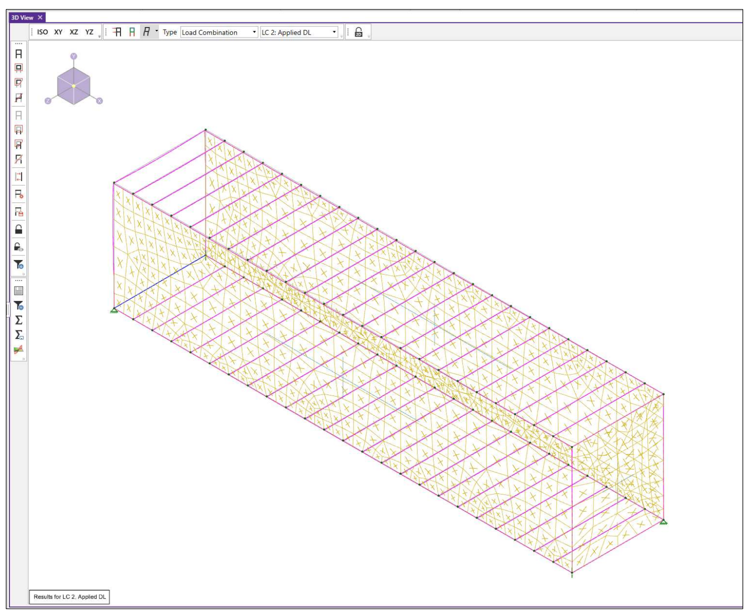


Figure 4.18: Individual Container Deflection from Applied Dead Load

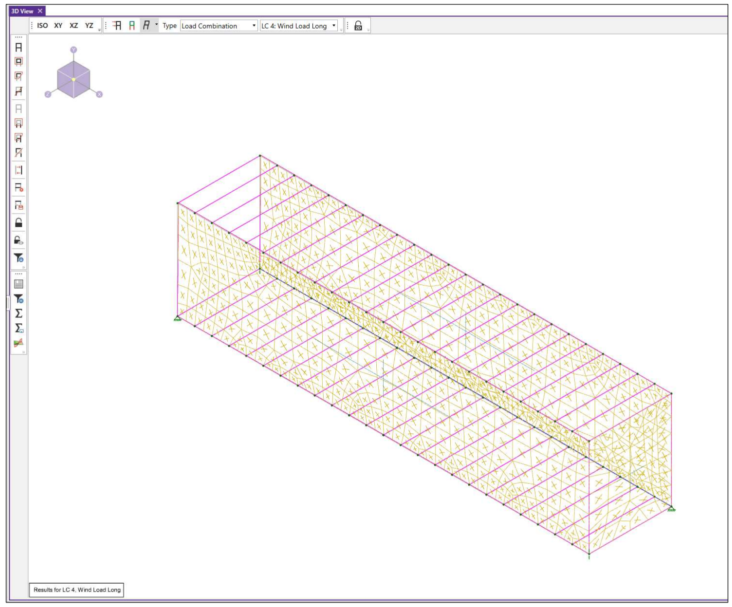


Figure 4.19: Individual Container Deflection from Wind Load Along 40’-0” Side Wall

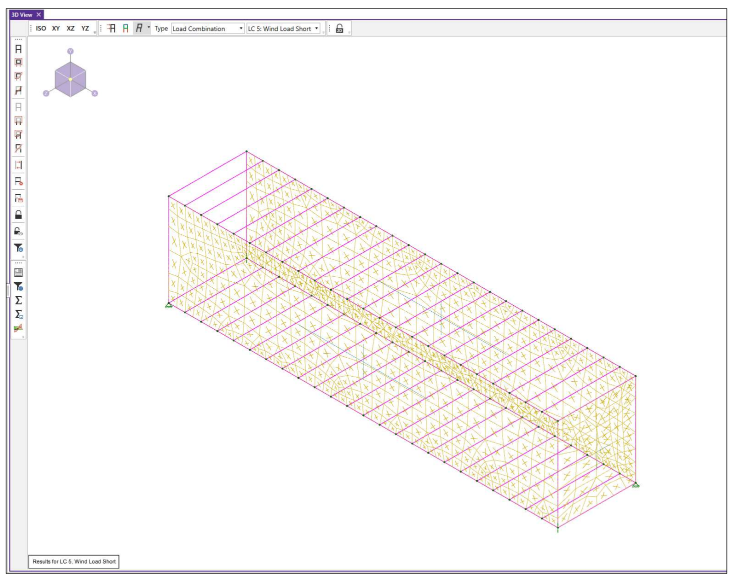


Figure 4.20: Individual Container Deflection from Wind Load on 8’-0” End Wall

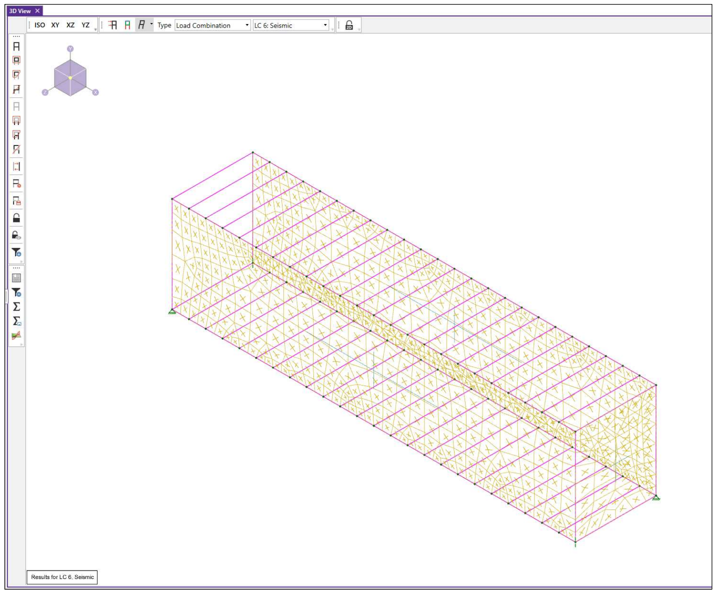


Figure 4.21: Individual Container Deflection from Seismic Lateral Load

Under the application of the assembly live load, there was visible deformation (Figure 4.22). The visible deformation occurs mainly in the top side rails and door frame of the container. When creating the model, the team assumed that the shipping container door does not contribute to the structural integrity of the frame since it can open and close without causing disruptions. As a result, the door end of the container is hollow and is experiencing deflection as the top side rails react to the assembly load and push down on the door frame. After confirming that the visible deflections match the predicted actions, the team checked the member deflection table (Table 4.5) to see if any of the deflections exceed the limits. The member deflection table showed that there was deflection present but none that exceeded the acceptable limits outlined in the IBC. Member deflections will not be converted into meters because containers are measured in feet, therefore calculations were kept to feet and inches.

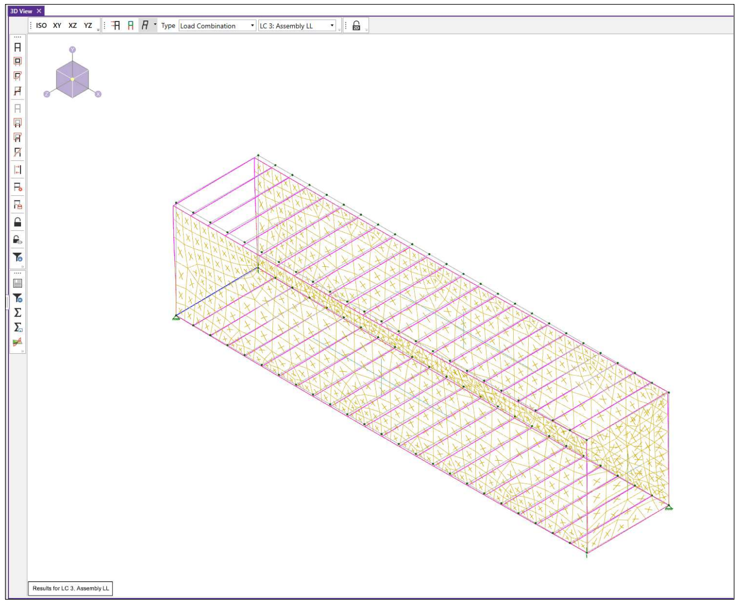


Figure 4.22: Individual Container Deflection from Assembly Live Load

Table 4.5: Individual Container Deflection Limitations vs. Actual Deflections

Load	Member	Size	Limit	Actual
Self-Weight DL	Roof w/ Non-Plaster Ceiling	8’0” 40’0”	0.533” 2.670”	0.000” 0.003”
Self-Weight DL	Floor Member	8’0” 40’0”	0.400” 2.000”	0.000” 0.001”
Applied DL	Roof w/ Non-Plaster Ceiling	8’0” 40’0”	0.533” 2.670”	0.034” 0.025”
Applied DL	Floor Member	8’0” 40’0”	0.400” 2.000”	0.009” 0.015”
Assembly LL	Roof w/ Non-Plaster Ceiling	8’0” 40’0”	0.400” 2.000”	0.039” 0.069”
Assembly LL	Floor Member	8’0” 40’0”	0.267” 1.333”	0.037” 0.065”
Wind Load on 40’-0” side wall	Roof w/ Non-Plaster Ceiling	8’0” 40’0”	0.400” 2.000”	0.031” 0.031”

Wind Load on 40'-0" side wall	Exterior w/ Brittle Finish	9'6" 40'0"	0.475" 2.000"	0.031" 0.015"
Wind Load on 8'-0" end wall	Roof w/ Non-Plaster Ceiling	8'0" 40'0"	0.400" 2.000"	0.002" 0.000"
Wind Load on 8'-0" end wall	Exterior w/ Brittle Finish	9'6" 40'0"	0.475" 2.000"	0.000" 0.000"
Seismic Load on 8'-0" end wall	Roof w/ Non-Plaster Ceiling	8'0" 40'0"	0.400" 2.000	0.008" 0.000"
Seismic Load on 8'-0" end wall	Exterior w/ Brittle Finish	9'6" 40'0"	0.475" 2.000"	0.000" 0.000"

4.5.1.1. Conclusions

Following the application of the loadings to the model of an unmodified individual shipping container, the container was able to withstand all the loadings, so no additional bracing is necessary. Additionally, some of the results and hypotheses formulated in Section 4.3 were confirmed. The first research paper that the team looked at stated that when the Abaqus/CAE model was subject to vertical loadings, the end walls portrayed greater structural stability than the side walls. This can be seen in our model under the applications of the Self-Weight and Applied Dead Loads that resulted in slightly greater deflections in end wall members than side wall members. Likewise, the research team reported that under the application of transverse lateral loads the end walls were the strongest but under the application of longitudinal lateral loads the sidewalls were the strongest. The wind load applied to the sidewall of the shipping container exemplifies the application of a transverse lateral load because it is applied in the direction of the shorter axis. Under the application of the wind load on the sidewall, there was greater deformation experienced by the sidewalls than end walls, confirming that they are more resistant than the sidewalls in this scenario. The application of the wind load along the end wall of the shipping container is an example of a longitudinal lateral load because it is acting in the direction of the longer axis of the container. Under the application of the wind load on the end wall, there was some deflection present in the end walls, while the side walls remained unchanged. The differences in the deflections for the side walls versus end walls in these cases were often very minimal due to the strong nature of the shipping container to resist building loads. Despite their minimal differences, these results still confirm the hypothesis formed by the team based on prior research. In order to further test these behaviors in the future, loads of larger magnitudes could be applied to the RISA-3D 19.0 model.

Although the model created by the team matches the behavior of the hypothesis, it should be taken as a conservative model. The omittance of corrugations in the wall panels signals that these features may not be as strong as the corrugated panels they were made to represent. The use of a conservative model for this project is acceptable because the work of the team provides a base starting point that will need to be confirmed as the project continues.

4.6. Analysis of Various Shipping Container Configurations

After performing an analysis of the structural integrity of an individual shipping container, the team looked to apply the collected information to the building design. Designs for the administration building and on-campus housing buildings utilize three notable container configurations: four story stack, bridge, and cantilever. The team completed structural analysis on each of these configurations to gain an understanding of where additional supports are required and where segments of the containers may be safely removed. This information will provide a supplement to the engineering team in Mozambique who will be verifying the work.

4.6.1. Four Story Stack of 20-foot High-cube Shipping Containers

The first configuration that the team tested is representative of the tower portion of the administrative building. In order to test this structure, the team created a new RISA-3D 19.0 model to match the dimensions of the shorter container. The length of the sidewalls was adjusted to 20’-0” (6.1 m), while the dimensions of members making up the structural frame remained the same. When creating the stack, the individual container models were placed on top of each other four high and connected at the corners by moment connections (Figure 4.23).

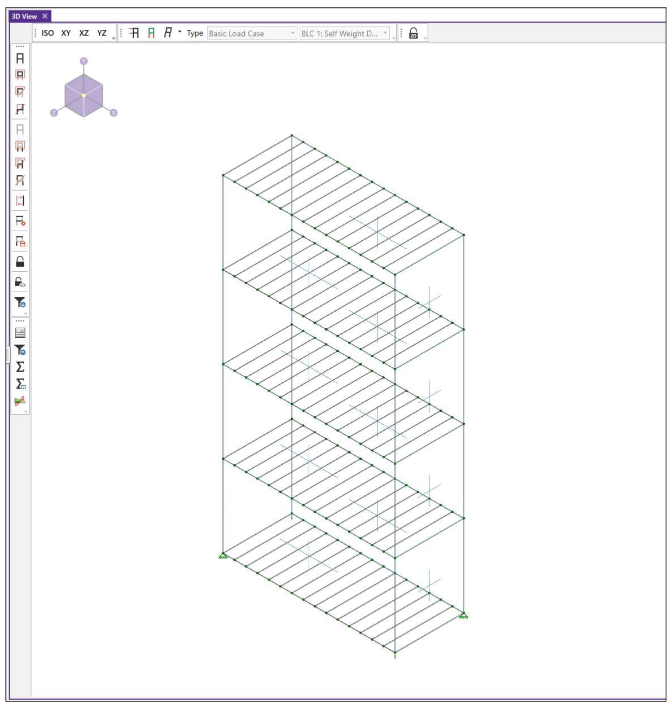


Figure 4.23: Four Story Stack of 20-foot High-cube Shipping Containers

Once the model was configured, the team applied the worst-case load and resistance factor design (LRFD) scenario to the stack to determine its structural integrity. The team used the equation 1.2D + 1.6L + 0.8W to represent the worst-case scenario because the site is very prone to high wind natural disasters. This equation applies load factors to the loads previously outlined in Section 4.4.2. A factor of 1.2 is applied to the self-weight and applied dead loads, a factor of 1.6 is applied to the assembly live load, and a factor of 0.8 is applied to the wind loads. The resulting deflections from this load scenario can be seen in Figure 4.24.

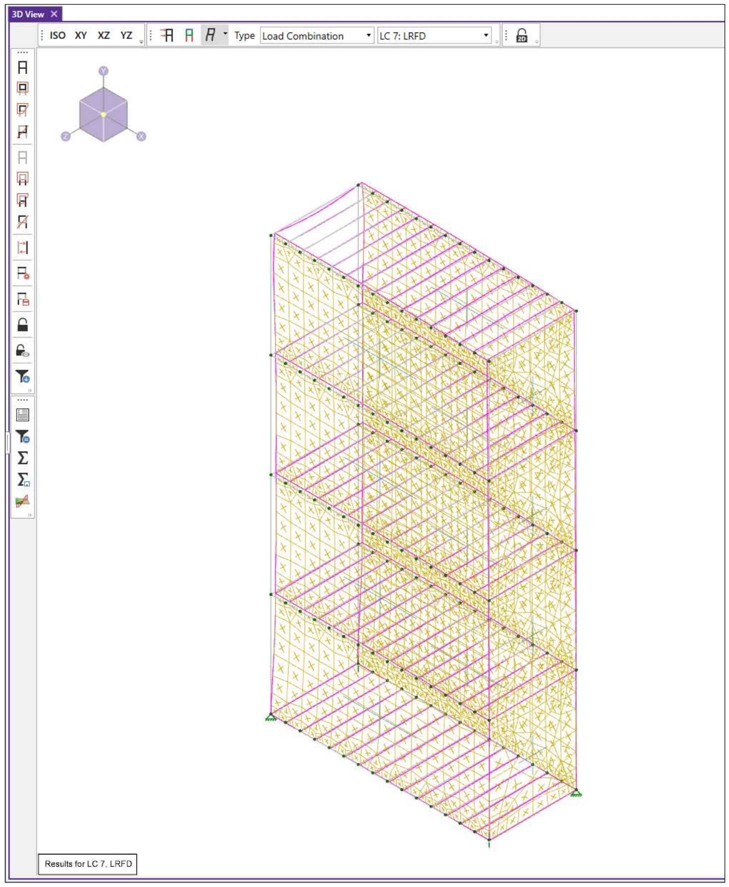


Figure 4.24: Four Story 20-Foot Shipping Container Stack LRFD Deflection

Like the individual 40-foot high-cube shipping container model, the weakest part of this stack is in the door frame open end. Although there is visible deflection present, none of the values in the member deflection table exceed the acceptable limits.

The next step in testing this configuration, was to create cutouts in the model that match the openings needed for the doors, windows, and staircase included in this part of the design. The model that resulted from these cutouts can be seen in Figure 4.25, and includes a 6'-0" x 7'-0" (182.9 cm x 213.2 cm) opening for a double wide door, three 3'-0" x 7'-0" (91.44 cm x 213.2 cm) openings for windows on every story above ground level, and a 8'-0" x 10'-0" (243.8 cm x 304.8 cm) shaft for the stairs.

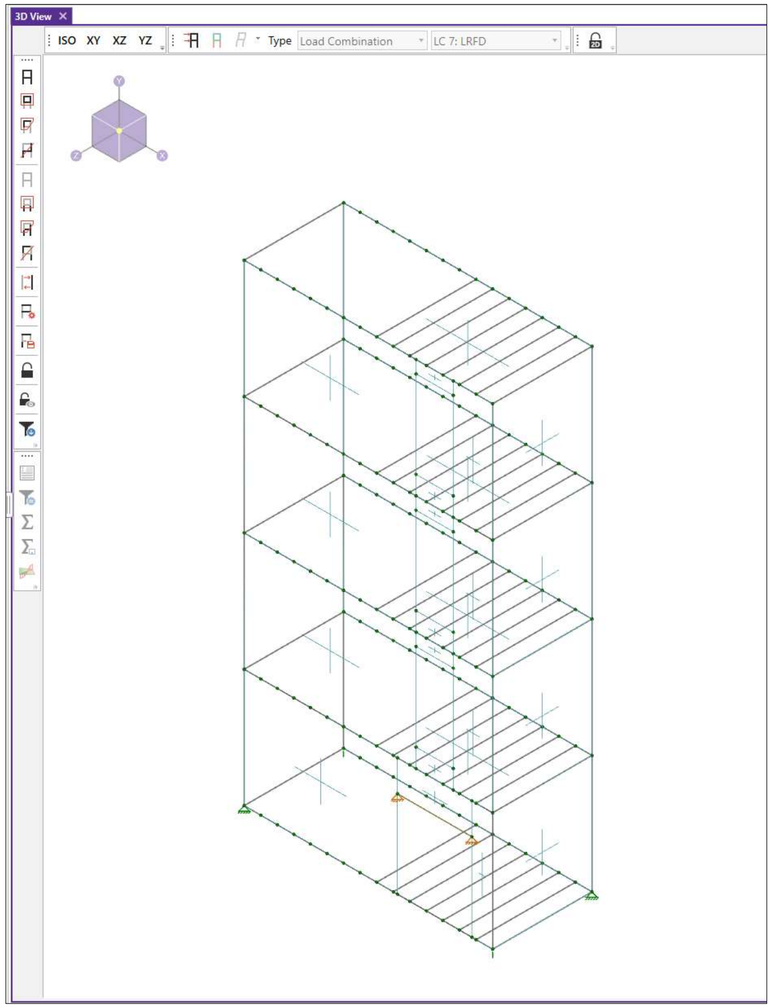


Figure 4.25: Four Story 20-Foot Shipping Container Stack with Cutouts

The worst-case scenario 1.2D + 1.6L + 0.8W was applied again to this model with the cutouts and the resulting deflections can be seen in Figure 4.26.

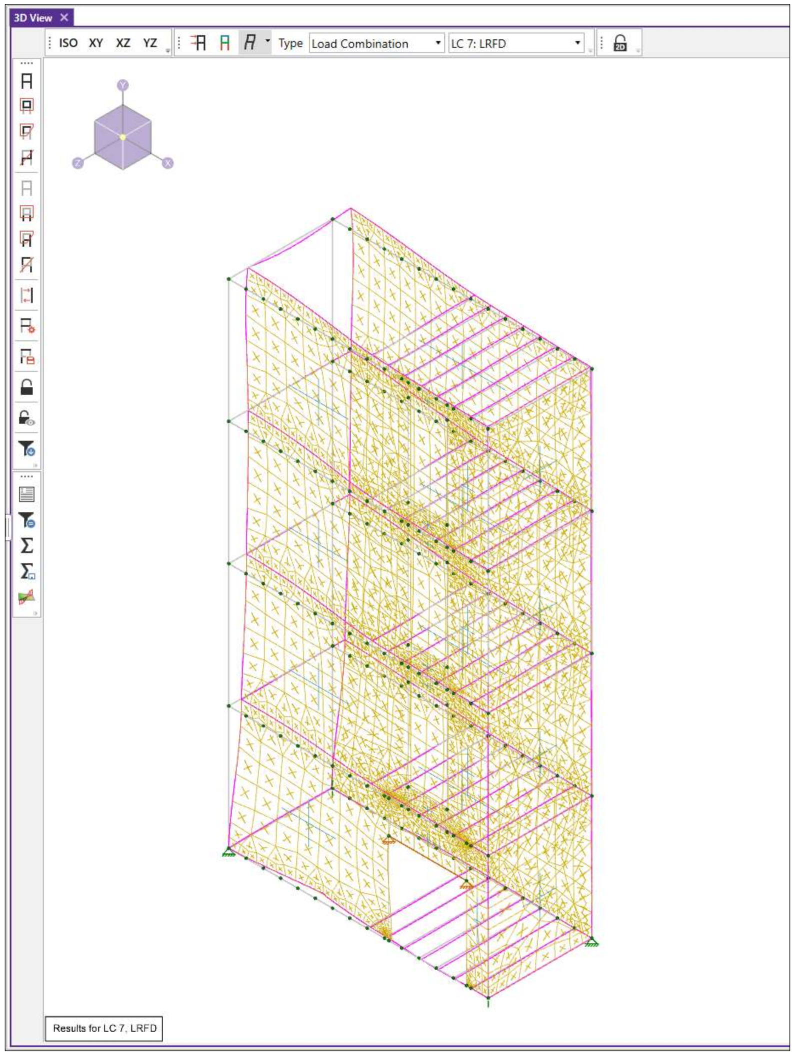


Figure 4.26: Four Story 20-Foot Shipping Container Stack with Cutouts LRFD Deflection

In this scenario, the combination of the open-door frame with the large openings for the stairway shaft resulted in large deformations that exceed the acceptable limits under the application of the load case. This signaled to the team that additional bracing would need to be provided in order to accommodate the design. To create the bracing, the team inserted hot rolled steel tubing HSS 2x2x1/4 X braces into the open-door frame ends. The cross section of these steel tubes is larger than that of the removed floor cross members, following guidance the guidance provided by the IBC that was discussed in Section 4.2. With the X braces in place, the team once again applied the worst case LRFD 1.2D + 1.6L + 0.8W load to the model. The new deflections that resulted are much smaller than those of the unbraced model and fall within the acceptable deflection limits

(Figure 4.27). These deflections may be minimized even farther when the foundation supports outlined in Section 4.7 are added to the bottom of the frame.

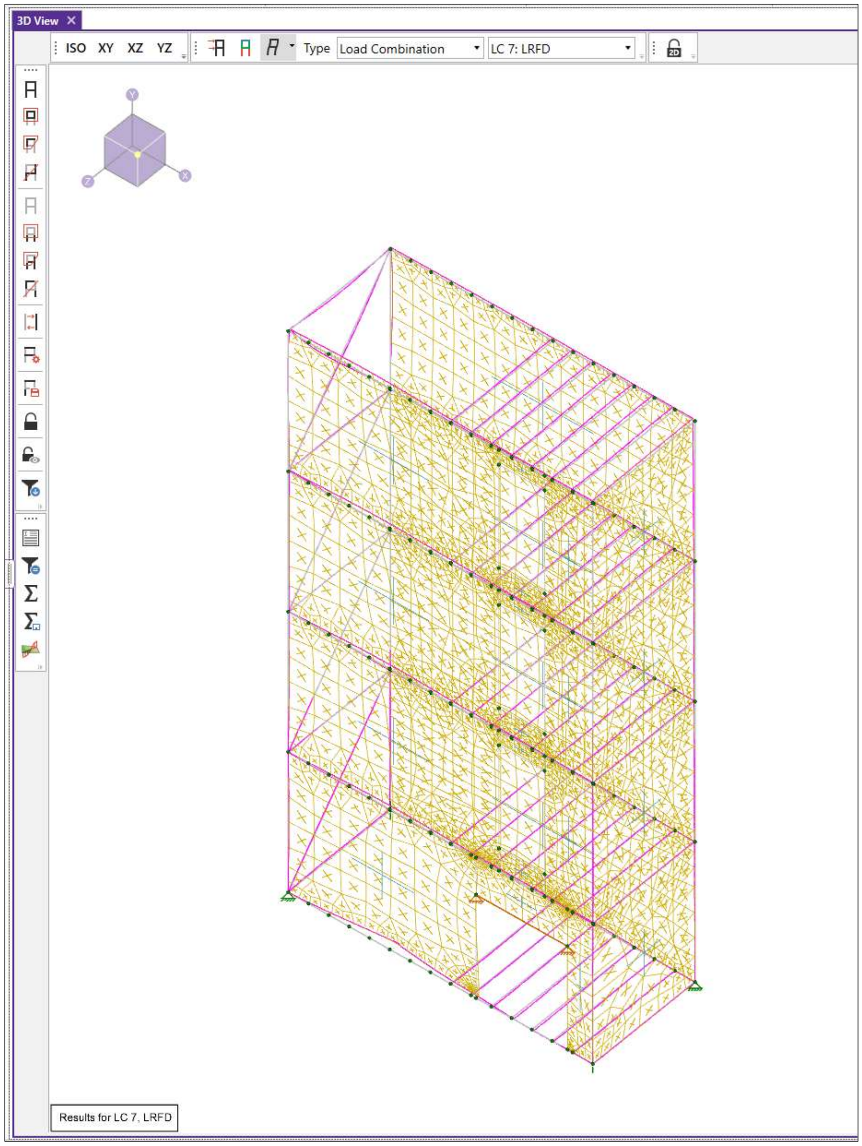


Figure 4.27: Four Story 20-Foot Shipping Container Stack with Cutouts and Bracing LRFD Deflection

These results reassure the team that with proper bracing, this four-story stack of 20-foot high-cube containers will be structurally sound and able to function as a means of egress and lookout point.

4.6.2. Bridge Container Configuration

The second configuration analyzed by the team in RISA-3D 19.0, referred to throughout this chapter as the bridge, models the span of a 40-foot high-cube shipping container across a 24-foot gap (731.5 cm). The span container is supported by two stacks of two 40-foot high-cube containers, as shown in Figure 4.28, to create a large open space below the span. The use of this configuration in the team's initial design for the administration building creates a large open air classroom space and extra offices on the third story roof deck.

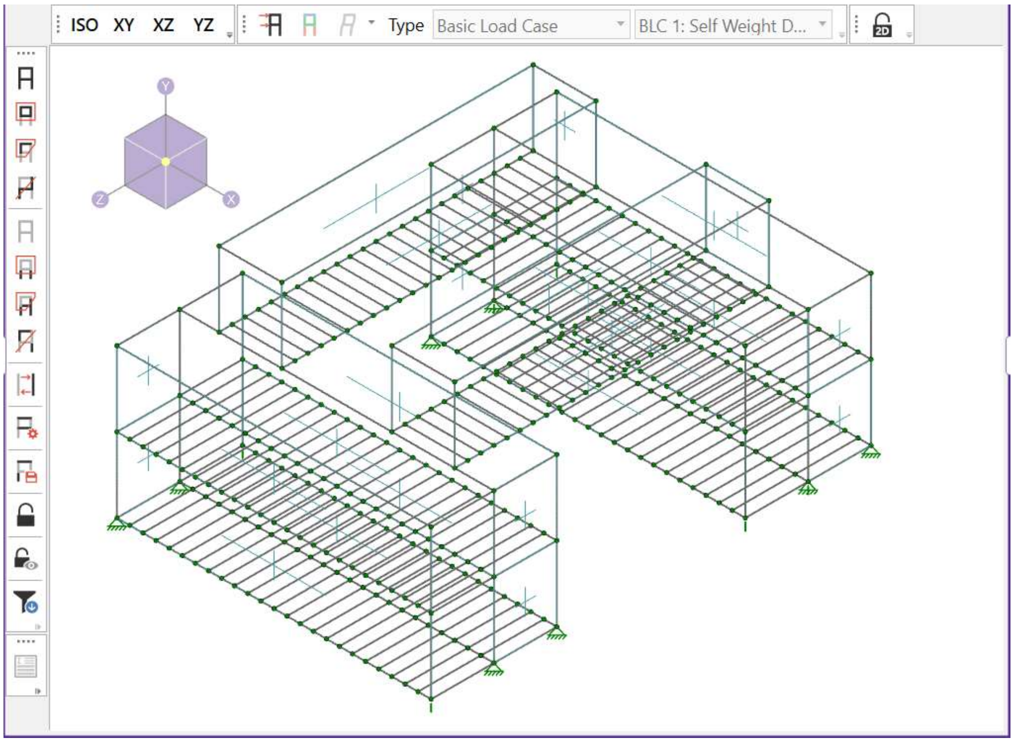


Figure 4.28: RISA-3D 19.0 Model of a Bridge Container Configuration

To test this structure in RISA-3D 19.0, eight iterations of the original 40-foot high-cube container model were stacked to create two supporting structures, and two additional iterations of the 40-foot high-cube model were rotated and stacked on the third level to form the bridge (Figure 4.28). All corner connections between containers were set as moment connections. Adjustments were also made to loading conditions outlined in Section 4.4.2 to align with occupancy requirements for this configuration. Since third level span containers are only intended for office use, the team reduced the floor Live Load in third level containers from 100 to 50 pounds per square foot (488.2 to 244.1 kg/m^2). Similarly, since roofs of third level containers will not be occupied, the team reduced the Applied Dead Load on these containers from 27 to 15 pounds per square foot (131.8 to 73.2 kg/m^2) to account for the addition of roofing and shading materials but no occupied roof deck.

Once the model was configured, the team applied the worst-case load and resistance factor design (LRFD) scenario to the bridge using the same method as described for the four-story stack: 1.2D + 1.6L + 0.8W. The resulting deflections from this load scenario can be seen in Figure 4.29.

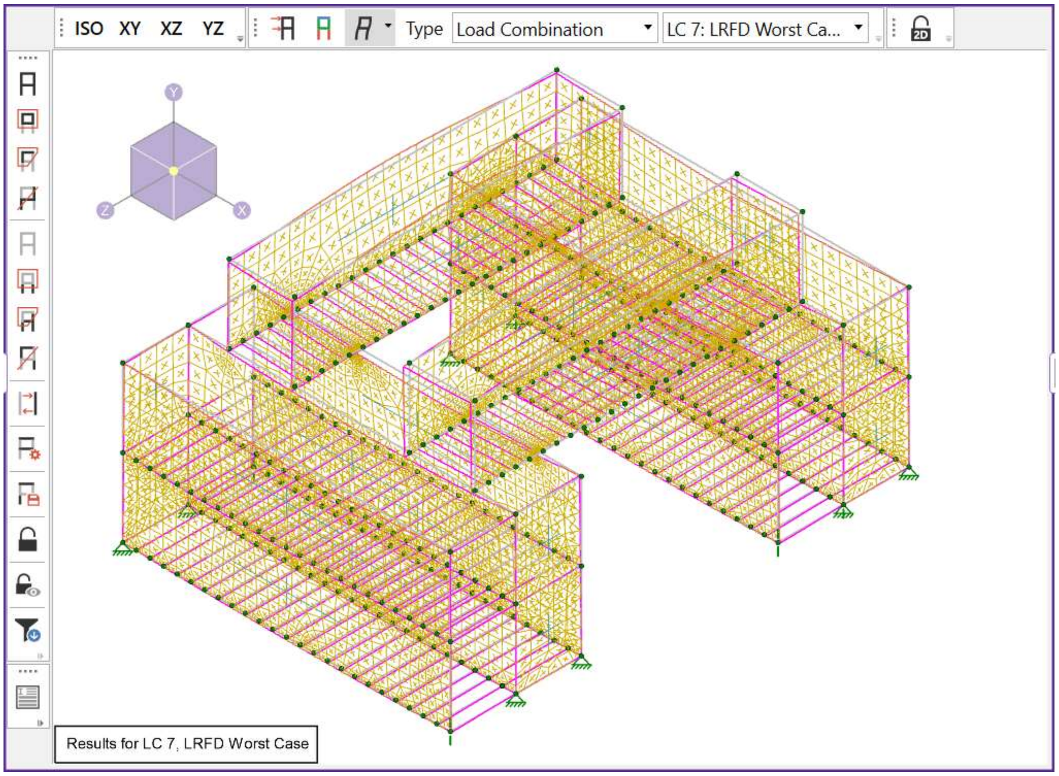


Figure 4.29: Bridge Container Configuration LRFD Deflection

The team noted deflections from this worst-case loading scenario in the top rails of supporting and span containers, and in the frame of the container door. However, review of maximum deflections for all visibly deflected members proved that none of the deflections exceed the acceptable limits.

Once the team had verified the bridge could maintain structural integrity without additional bracing, they next had to verify structural integrity once the containers were modified. The team made cutouts in the model to match the openings needed for the doors and windows in this configuration as specified in the design. The model that resulted from these cutouts can be seen in Figure 4.30. Openings made for doorways measured 3’-0” x 7’-0” (91.44 cm x 213.36 cm) and openings for windows measured either 3’-0” x 6’-0” (91.44 cm x 182.88 cm) or

4’-0” x 4’-0” (121.92 cm x 121.92 cm) to match elements included in the architectural design.

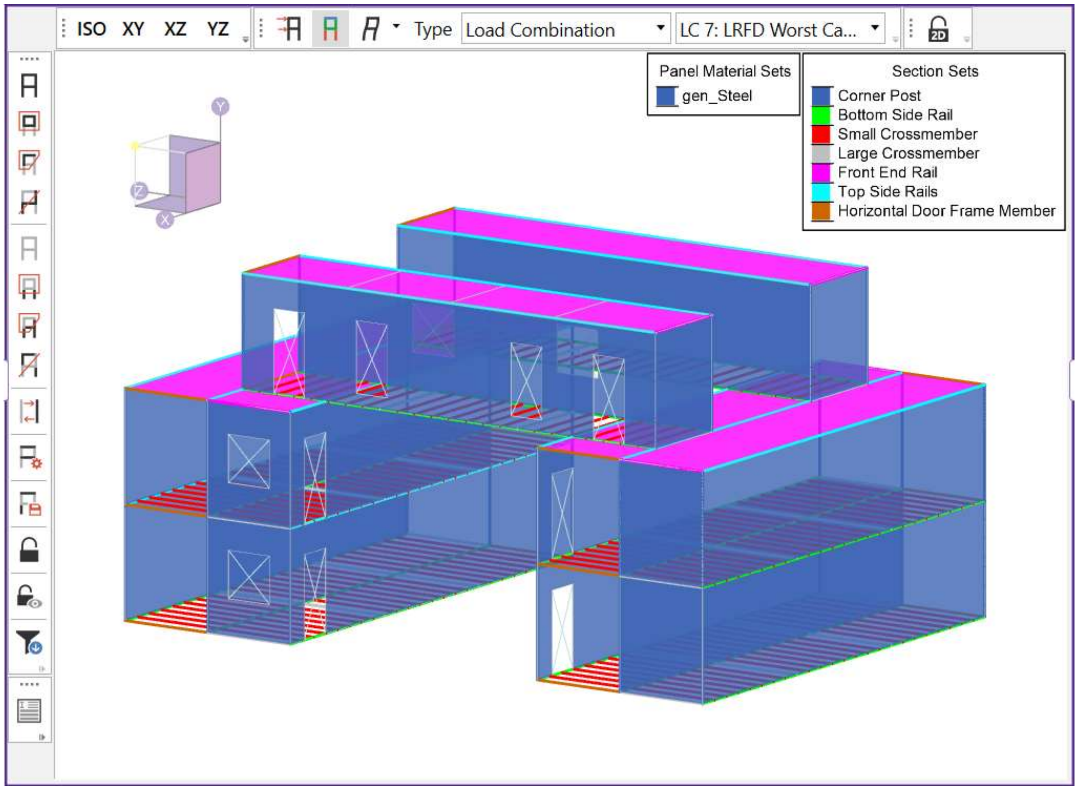


Figure 4.30: Bridge Container Configuration Model with Cutouts

The model only contains necessary cutouts on one side of the configuration to allow for comparison with the other span container once loading was applied. Once complete, the worst-case scenario 1.2D + 1.6L + 0.8W was applied to this model with cutouts to produce the resulting deflections (Figure 4.31).

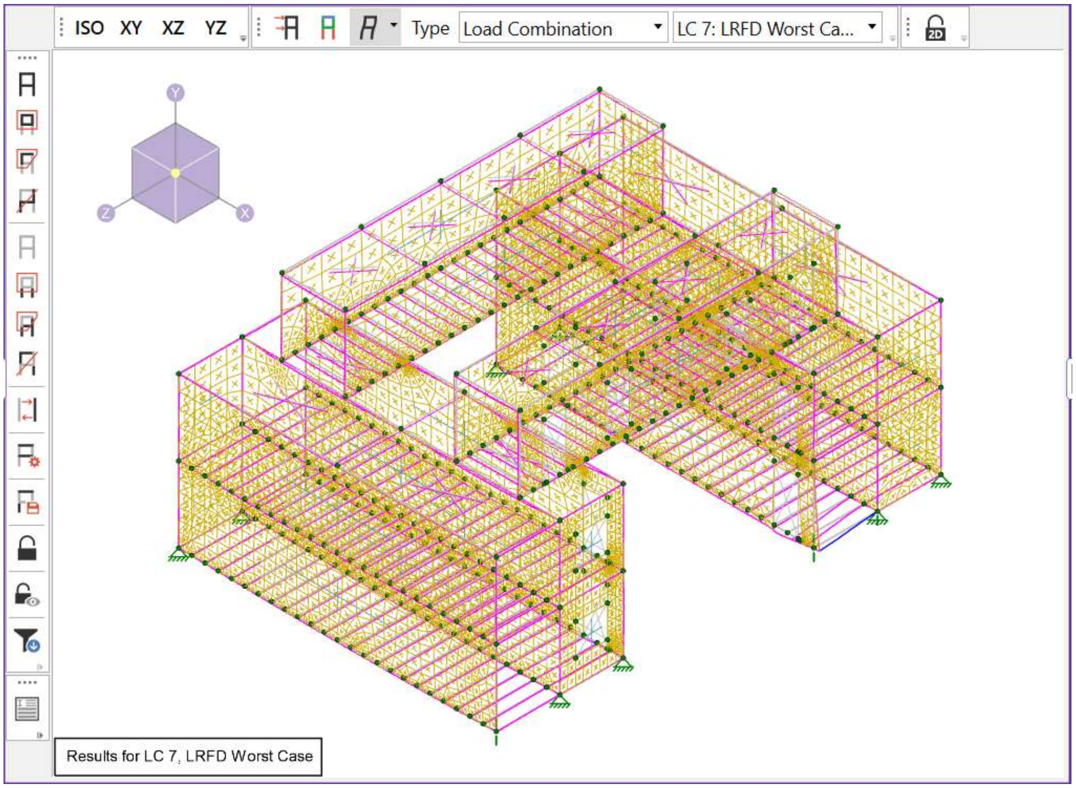


Figure 4.31: Bridge Container Configuration with Cutouts LRFD Deflection

After adding cutouts to the model, the team noticed greater lateral deflections of the top rails in the third level span containers under the worst-case loading scenario, but still very little sagging in top or bottom rails. All visible deflections fell within acceptable limits, confirming the team's hypothesis that40-foot containers could support loading across a span. These results are not surprising because when 40-foot high-cube containers are transported using a crane, they are secured at the corners of the container and lifted to reveal no notable deflection across the length. However, if future designs require greater sections of container walls to be removed for window or door openings, this configuration should be reanalyzed as lateral deflection and sagging will likely increase. Deflection of the 40'-0" (1.219 m) top and bottom rails of span and supporting containers may not exceed 0.4 inches (1.016 cm). Containers will require structural reinforcement if this is the case, likely across the ceiling of span containers to minimize lateral deflection.

These results reassure the team that with welded moment connections between containers and few wall openings, the bridge configuration of 40-foot high-cube containers will be structurally sound and able to function as an inhabited space for the administration building.

Based on results from this investigation and further wall removals in the bridge configuration model, the team provides the following recommendations to partners in Mozambique for further investigation. These recommendations are made with assumptions that 40-foot high-cube shipping containers are stacked and welded so that moment connections exist between the corners of the third level span container and the supporting container roof side rails. This also assumes the use of third level span container use for office space and lightweight roofing. Changes to initial design of the administration building should be verified by local engineers to ensure the following recommendations still stand.

1. A 40-foot high-cube container with a 24-foot span length and intended doors and window cutouts will not require additional bracing.
2. Floor to ceiling wall section removals of more than 10 feet along the span will require the addition of structural reinforcement. This reinforcement meets IBC standards and the Mozambican equivalent of AISC Steel Construction standards.
3. Floor to ceiling wall section removals at the center of the span, where maximum moment occurs, is not advised, as it would require the most additional reinforcement.
4. Removal of wall sections in the 8’ x 19’ (243.84 x 579.12 cm) wall area for supporting containers directly beneath the span container is not advised. If necessary, this section may require additional reinforcement.
5. If additional structural reinforcement becomes necessary, lateral bracing on the ceiling of containers or knee bracing under the span will provide the least limitations for the architectural design.

The next section provides analysis and recommendations for the team’s third container configuration, which appears in the initial design for on-housing housing buildings.

4.6.3. Cantilever

The cantilever structural analysis was performed to assess the strength of the on-campus dorm design. In this design, the length of the sidewalls is 20’-0” (609.6 cm), while the dimensions of members making up the structural frame remained the same as the initial single container analysis. A RISA-3D 19.0 model was created to represent the stacking of three containers, with the middle container offset by five feet. In the team’s initial design, the dorm building consists of containers stacked no more than three high, creating a building with alternating container offsets, and two cantilevered containers in a three-container stack. Given that this configuration is incorporated into the team’s on-campus housing design the live load was adjusted to be a residential live load of 40 pounds per square foot (195.3 kg/m^2) following the guidance outlined in the IBC (Giriunas, 2012). With this configuration, the team tested the model’s behavior under the same loads outlined in Section 4.2.2. Figure 4.32 shows the formation of the cantilever container stack in RISA-3D 19.0 with the member types.

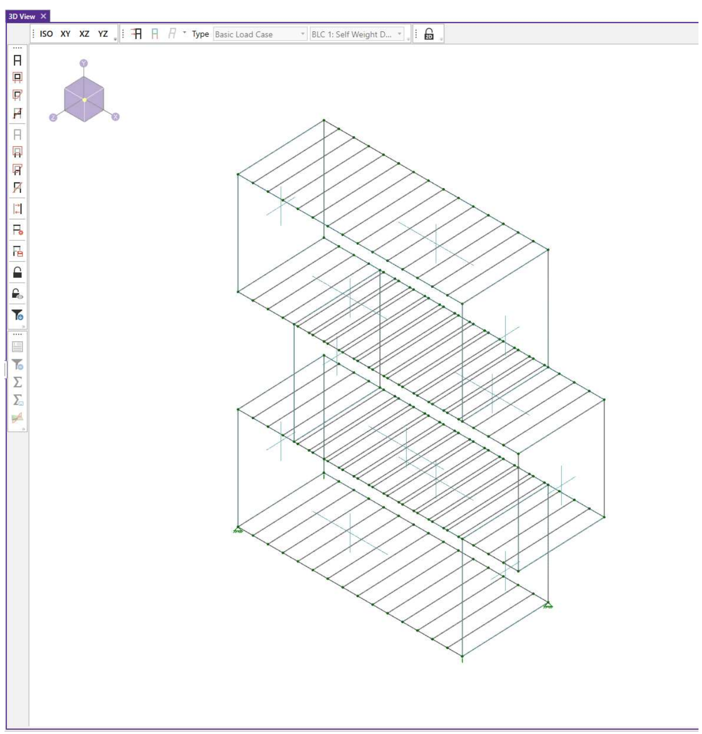


Figure 4.32: RISA-3D 19.0 Model of a Cantilevered Shipping Container Stack

The worst-case load and resistance factor design (LRFD) scenario was applied to the stack to determine its structural integrity. The team used the equation 1.2D + 1.6L + 0.8W to represent the worst-case scenario because the site is very prone to natural disasters with high-speed winds. This equation applies load factors to the loads outlined in Section 4.4.2. A factor of 1.2 is applied to the self-weight and applied dead loads, a factor of 1.6 is applied to the residential live load, and a factor of 0.8 is applied to the wind loads.

The deflections are most similar to the deflections seen in the stack of four containers. However, the cantilever puts more stress on the container frame. After reinforcement was added, cutouts were made for windows and doors to match the architectural designs of the dorm building. This meant adding a window on the long side of the container, offset from the end, a large window on one end of the container, and a door opposing the large window, where the container typically opens. The window cutouts are 3’-0” by 4’-0” (91.44 cm x 121.92 cm) and 5’-0” by 6’-0” (152.4 cm x 182.88 cm), respectively, and the door is 3’-0” by 7’-0” (91.44 cm x 213.36 cm), slightly larger than the typical 3’-0” by 6’-8” (91.44 cm x 203.2 cm). The 3’-0” by 4’-0” (91.44 cm x 121.92 cm) would be 3’-0” (91.44 cm) offset from the base of the container and spaced 1’-0” (30 cm) away from the end rail. The door and large opposing window would be centered, but the window is at a height of 3’-0” (91.44 cm) offset from the base of the container (Figure 4.33).

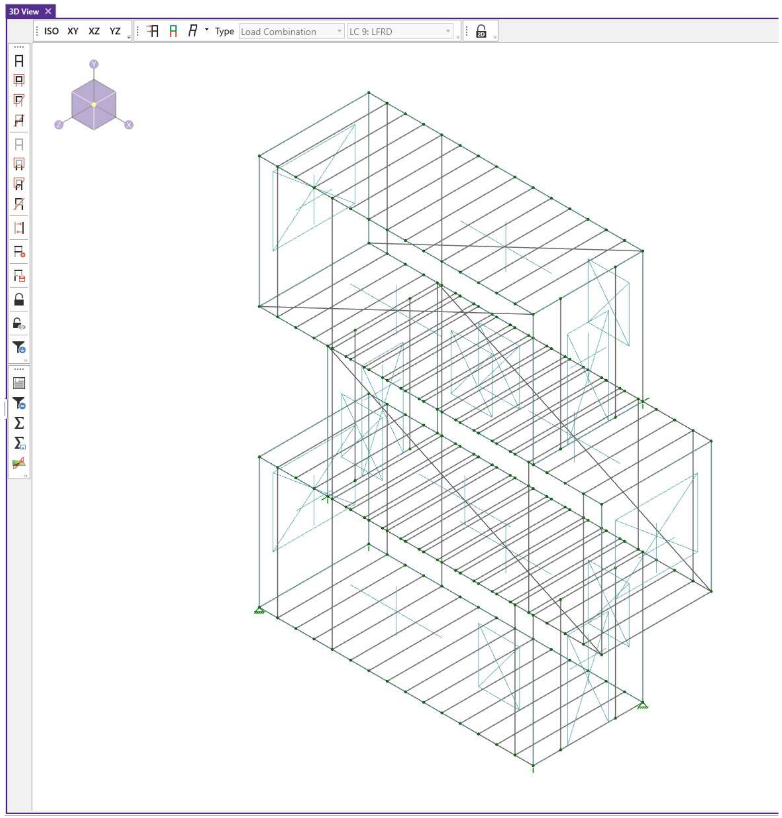


Figure 4.33: Cantilever Container Stack with Window and Door Cutouts

After applying the load combination scenarios to the cantilever stack of shipping containers, the team used the visuals and calculation tables produced by RISA-3D 19.0 to determine the deflections and their locations. The resulting deflections from this load scenario can be seen in Figure 4.34. The deflection that resulted caused concern on the end of the middle. Deflection occurred in the bottom rail on the end of every container, but only on one side of the stack. In this scenario the loads are transferred through the frame of the container, rather than directly from the floor to the roof of the container below, preventing buckling of the weaker parts of the container. Using a stress gradient revealed the need for additional support, all containers being yellow and red in problematic places, rather than green as desired. Bracing was added around the vulnerable end frame of the middle container. The additional reinforcement was added to reinforce these sections was added and is visible in Figure 4.35.

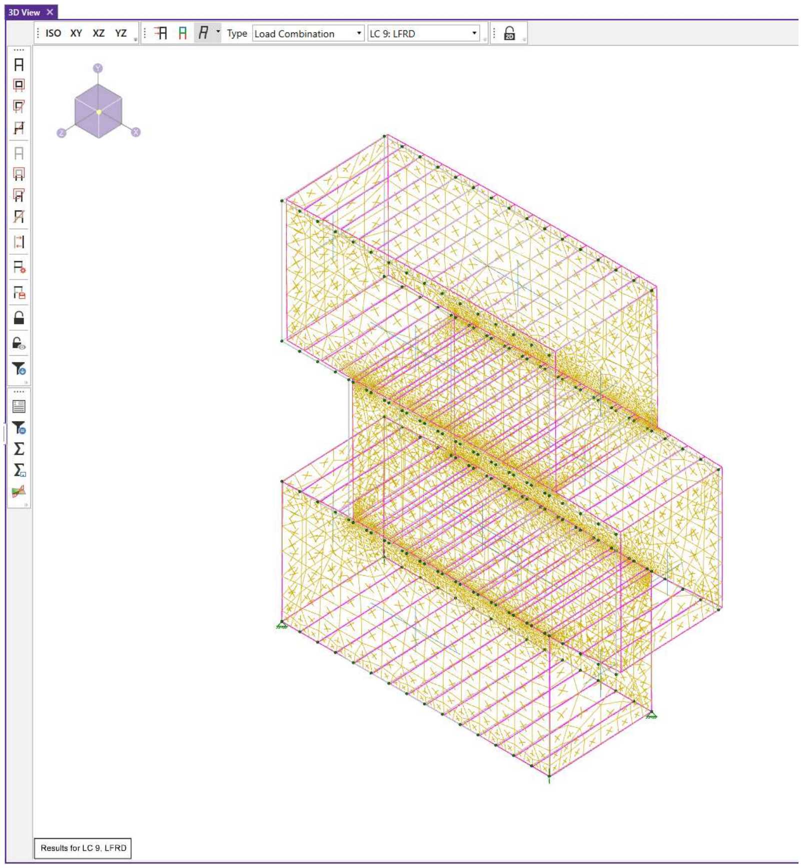


Figure 4.34: Load Combination Deflection for a Cantilever Shipping Container Stack

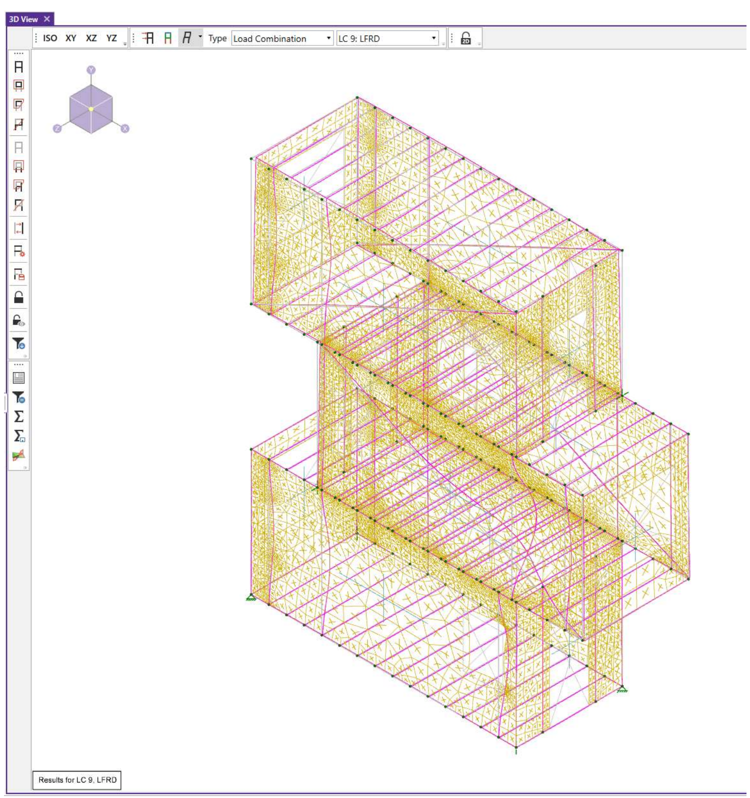


Figure 4.35: Bracing in Cantilever Container Stack

While some members in this model appear significantly warped in Figure 4.35, they do not exceed deflection limits, and only serve to be additional bracing. The warping is primarily due to wind loads, which are horizontal, rather than vertical, and these can be remedied when the containers are placed next to each other as they are in the on-campus housing design. The support from the adjacent containers will prevent toppling. The bracing allowed the containers to achieve the more acceptable green level of stress analysis, meaning low stress, with yellow in problematic places.

For the purposes of our design, the model we created only shows a segment of a building. This segment would be supported on either side by shipping containers arranged in the same configuration and adding more structural support and stability against the applied loads. Additional structural support could be provided by wall framing within the container meant to support insulation, plumbing, and electrical wiring. This would provide additional support to the structure and allow for more support for the floors and ceilings of the container decks. In addition, substitute flooring is needed to replace the chemically treated plywood that is standard for shipping. A stronger material could be selected in order to distribute the load evenly over the container and carry this load into the frame. This distribution of the load into the frame would relieve the stress felt by the middle of the container. Lastly, it is important to note that the RISA-3D 19.0 software utilized by the team does not display the deflections proportionally, exaggerating them to be more recognizable.

Through these analyses the team determined that the cantilever stack of containers is able to withstand residential use as a dorm. However, the team suggests that the chosen flooring is supported better than the traditional container flooring, a steel frame with plywood sheeting on top, to distribute the loads properly and be able to withstand anything a resident might need in their housing. Further recommendations include only removing the necessary amount of material from the containers to install doors and windows to prevent loss of structural integrity. Attaching these architectural/access elements to the container frame incorporates them into the body and reinforce the weakened structure.

4.7. Foundation

The most common types of foundations used to support shipping container structures use concrete slabs, with either concrete or timber footings. Engineers often use this style foundation when provided geotechnical data about the soil type at the site and for smaller commercial or residential buildings. Due to the unknown soil type at the site and likelihood of our need to support larger commercial and residential structures, our team has decided to recommend a conservative approach to supporting the shipping container structures based on assumptions and analysis outlined in this section.

4.7.1. Recommended Foundation

The team considered soil conditions at the site, cost, and feasibility when creating foundation recommendations. While specific information about soil conditions at the site was not known, the team assumed the soil was a mix of soft silt and sandy soil due to the proximity to the beach. To provide a stable foundation in this soil and reduce the cost of concrete, the team recommends a concrete pier foundation constructed with Sonotubes.

Construction of concrete piers, or cast-in-place concrete columns, would transfer the building load into the soil while also leaving some space under the containers for air flow and maintenance. The use of Sonotubes, or a local alternative, would ease the construction process, which is explained later in this section. The team recommends 30-inch (76.2 cm) diameter piers connected at the four corners of ground level containers, as well as other support points along the bottom side rails of ground level containers. The locations of these piers and the loads they must support are shown in Appendix B. Each pier will be capable of supporting applicable column loads for the four-story tower in the initial administration building design so long as the soil capacity is above 1,500 pounds per square foot (7323.6 kg/m^2) for vertical foundation pressure. Figure 4.36 shows the necessary setup for this foundation method.

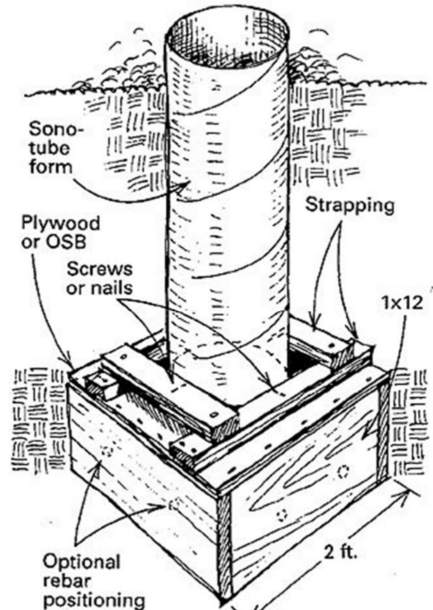


Figure 4.36: Pier Foundation using Sonotubes (Hausslein, n.d.)

To visualize the structural implications of this type of foundation, the team used appropriate boundary conditions in RISA-3D 19.0 where containers would be connected to foundation piers. In the RISA-3D 19.0 model, fixed supports were placed at the four corners of each ground level shipping container. Two additional fixed supports were added along each end bottom 40-foot side. Therefore, averagely loaded 40-foot containers at ground level will require eight concrete piers and 20-foot containers will require four piers. For the tower design specifically, two additional concrete piers were required at the center of each bottom rail for the 20-foot container supporting this increased load, as seen in the example calculations in Appendix C. The number of piers for other building designs and the soil capacity will need to be confirmed and explored in the future by local engineers.

4.7.1.1. Advantages of Pier Foundation

Concrete piers offer a relatively low cost, simple, and quick foundation for shipping container buildings. They do not require major excavation of the site, only holes for the piers, and do not require expensive specialized equipment for pile driving (*Series*, 2013). Sinking the piers deeper into the soil will also increase the ultimate bearing capacity and lateral loads that the building can withstand while decreasing the amount of settlement that occurs. The close proximity to the ocean leaves the site prone to moisture build up, and pier construction leaves the container building slightly elevated with a small air space underneath. This will protect the building from flooding and moisture, allow space for utilities and maintenance if necessary, and provide natural cooling from air flow under the containers.

4.7.1.2. Disadvantages of Pier Foundation

If soil at the site is particularly unstable, a pier foundation may not be adequate because building loads will need to be transferred to lower, more stable soil levels (*Series*, 2013). While the air space beneath the containers in a pier foundation provides benefits, it could also lead to rain accumulation under the container in the event of strong cyclones, which often occur at the site. Sagging of the floors is also a potential for large spans. Finally, while very affordable for small buildings, a pier foundation may be more expensive for larger construction as more support will be needed. The expected cost of labor and materials may be higher than other foundations because of the extensive use of steel and concrete (*Series*, 2013). Although these costs may be higher than possible alternatives, the use of a proper foundation from the start will prevent costly problems down the road that would occur with the use of an inadequate foundation.

4.7.2. Design and Analysis

With little information about soil conditions at the Macaneta Beach site, the team did not complete a full design of foundations for all initial designs. Instead, the team decided to provide an example design outlining the process necessary to size foundation elements under the tower structure. The tower was chosen as the design example due to its large load from the number of containers stacked and relatively small building footprint. The team made assumptions to govern conservative foundation design which are outlined as follows:

1. Load Bearing values for soil are assumed to be the minimum conditions described in IBC 2018 Table 1806.2 (Class of Materials: Clay, sandy clay,

silty clay, clayey silt, silt and sandy silt). Vertical Pressure = 1,500 pounds per square foot (7323.6 kg/m^2).

2. This load bearing capacity for soil includes a factor of safety for the strength of the soil and ensures that footing settlement will be within permissible limits.
3. A minimum compressive strength of 2,500 pounds per square foot (12206.07 kg/m^2) for concrete used in foundation elements assuming Condition 1 from IBC 2018 Table 1808.8.1.
4. Depth of piers will be determined appropriately by local geotechnical engineers once a soil investigation is complete.

Based on these assumptions and the team's knowledge of shipping container weights and building loads, required footing sizes were calculated for each concrete pier. From structural analysis outlined earlier in this chapter, the team knew that gravity loads for containers stacked corner to corner, as intended, would transfer down through the corner posts to ground level. With the corner posts of the containers acting as columns for the structure, the team located concrete piers under the corners of ground level containers, adding additional piers only when necessary, to more evenly distribute the load. These piers will then transfer column loads from the structure into the soil.

To size appropriate footings for each pier, the team calculated total load for each column in the structure. Loading was divided into three zones: the NW Tower stack made up of four 20-foot containers, the SW Office stack made up of two 20-foot containers, and the East Office stack made up of two 40-foot containers. Applicable dead and live loads were calculated for all zones as shown in Appendix B. Then, assuming a soil capacity of 1,500 pounds (680.4 kg), the total load on each pier was divided by this soil capacity to find the required footing size. All footings were rounded up to nominal size. These calculations yielded the following results.

Table 4.6: Concrete Footing Sizes for Tower Foundation

Loading Zone	**Required Footing**	**Number of Piers**

NW Tower, 20 feet (0.61 m)	12.5 $feet^2$ (1.16 m)	6
SW Offices, 20 feet (0.61 m)	8.0 $feet^2$ (0.743 m)	4
E Offices, 40 feet (12.2 m)	8.0 $feet^2$ (0.743 m)	8

4.7.3. Construction Process

Once sizes and locations for concrete piers are confirmed, holes must be dug for each pier. Assuming piers that are 30 inches (76.2 cm) in diameter, holes should be dug for 30-inch (76.2 cm) Sonotubes to the depth specified by the geotechnical engineer. Box molds for footings of the piers should then be placed at the bottom of each hole and Sonotube molds should be secured vertically on each footing. Concrete may then be mixed and poured into the Sonotube. Steel rebar reinforcement will then be driven into the concrete along the tubes and then tops of the pier should be leveled. For connections of shipping containers to the piers, a steel plate with welded anchors should be pressed into the wet concrete at the top of the pier before concrete is let to cure (*Series*, 2013). Condition 5 from IBC 2018 Table 1808.8.2 requires a minimum concrete cover of 1 inch. Curing of the concrete will take three to five days after the pour.

Temporary sunshades will also likely be needed at the site when concrete is poured, and cold water should be used since the climate conditions at the site are often high temperatures with direct sunlight (*Series*, 2013).

4.7.4. Conclusion

The foundation recommendations presented by our team in this section were developed with little knowledge about the soil conditions at the site. These recommendations for a concrete Sonotube pier foundation must be verified by an engineer in Mozambique who has access to more substantial information about the soil characteristics, including a geotechnical investigation as outlined in Section 1803 of the IBC 2018.

5. Mechanical System Analysis of Modular Shipping Containers

The use of an active or passive mechanical system was an important decision in the design of the campus. Compared to an active system, a passive mechanical system allows more cost and energy savings, therefore helping the campus achieve its sustainability goals. This section outlines the team's process of analyzing climate conditions, determining thermal comfort with active and passive design strategies, and performing thermal load calculations on a single shipping container.

5.1. Climate Conditions in Maputo

The climate in Maputo, Mozambique is classified as Aw by the Köppen-Geiger system (tropical savanna climate with dry-winter characteristics). This is comparable to the climate in Key West, Florida, United States ("Maputo Climate," n.d.). Table 5.1 below shows a summary of the relevant climate conditions when considering thermal comfort in the area (Lawrie & Crawley, 2019).

Table 5.1: Monthly Climate Conditions in Maputo, Mozambique

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg Temp (ºC)	26	26	25	23	21	19	19	19	21	22	23	25
Min Temp (ºC)	22	22	20	19	15	13	12	14	16	18	19	20
Max Temp (ºC)	30	31	30	29	27	25	25	26	27	28	29	30
Rel. Humidity (%)	77	80	77	73	74	65	67	76	75	70	79	75

When first investigating the climate in Maputo, the team hypothesized that while the temperatures would be comfortable, the humidity levels would be too high to also be considered comfortable by most people. If the outdoor environment were found comfortable to future building occupants, the team would be able to implement passive design strategies. More analysis was needed to determine which path of mechanical strategies would be acceptable.

5.2. Thermal Comfort

ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy outlines two different methods of determining thermal comfort for buildings. The first method uses design temperatures, relative humidity, clothing, and activity factors to determine the predicted mean vote (PMV) of the area. The PMV predicts the mean value of the thermal sensations votes of a large group of people on a sensation scale. This method provides a narrow comfort range for mechanically cooled buildings that use active design strategies. The second method, the adaptive model, relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters. The adaptive model assumes that representative occupants have metabolic rates ranging from 1.0 to 1.3 met and can take off or put on different layers of clothing to make themselves more comfortable. This method gives provisions for determining thermal comfort in occupant-controlled naturally conditioned spaces that use only passive design strategies. Since the adaptive model does not allow for mechanical cooling, the building only must comply with one of the two methods stated (*Standard 55*, 2017).

5.2.1. Active Design

Active design strategies were analyzed using Climate Consultant, a program that shows the effects of different design strategies on the thermal comfort of the climate conditions for a given location. The thermal comfort conditions are decided based on ASHRAE Standard 55. If active design strategies were to be used, the team wanted to minimize the amount of strategies in order to keep the energy use and cost down. Figure 5.1 shows the chosen design strategies, many of which are not very costly. Figure 5.2 also shows a year of climate data in Maputo from 8:00AM to 8:00PM every day (a standard university building schedule) plotted on a psychrometric chart (Liggett & Milne, 2020). The green data points are comfortable hours whereas the red data points are uncomfortable hours. Using mostly window shading and dehumidification for cooling strategies is not enough to make the building comfortable year-round.

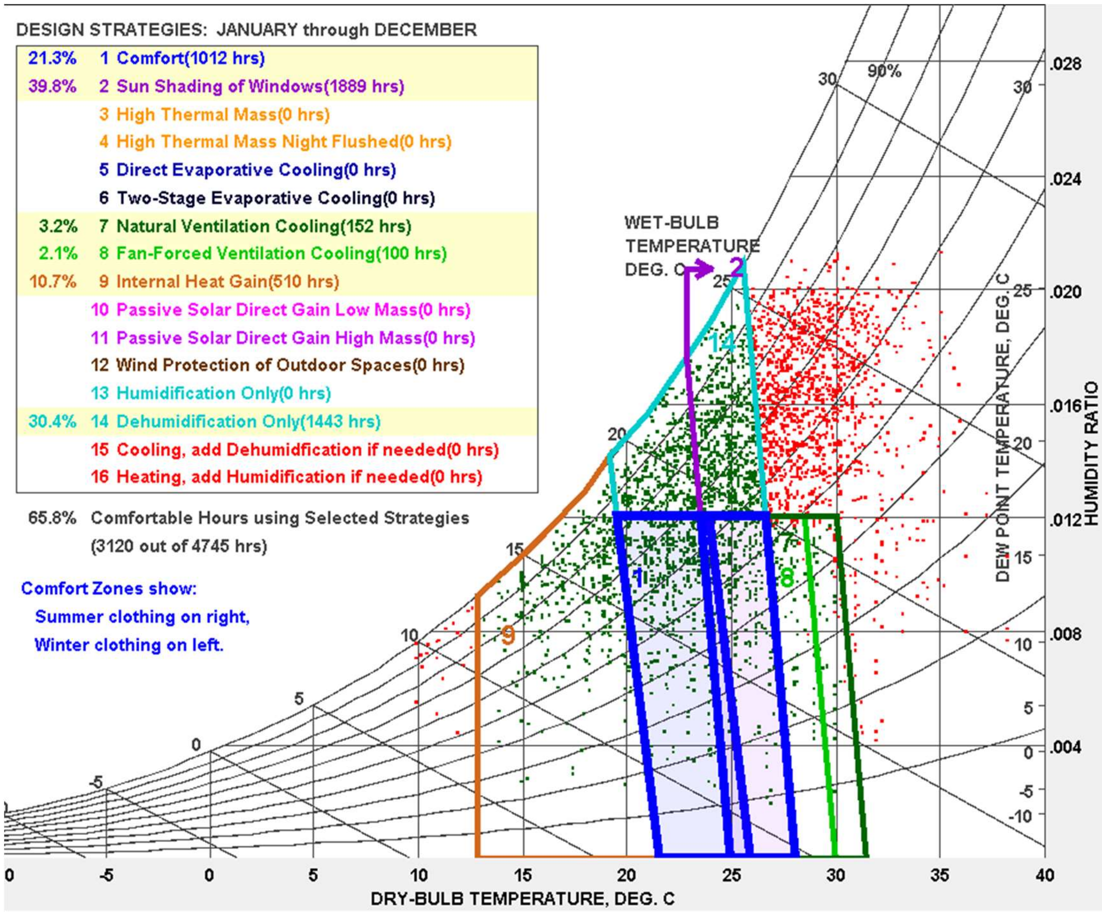


Figure 5.1: Partial Active Design Strategies

Figure 5.1 shows that adding a heating, ventilation, and air conditioning (HVAC) system will make the building comfortable year-round. The design strategies listed in Figure 5.2 would all be necessary if an active system were to be chosen.

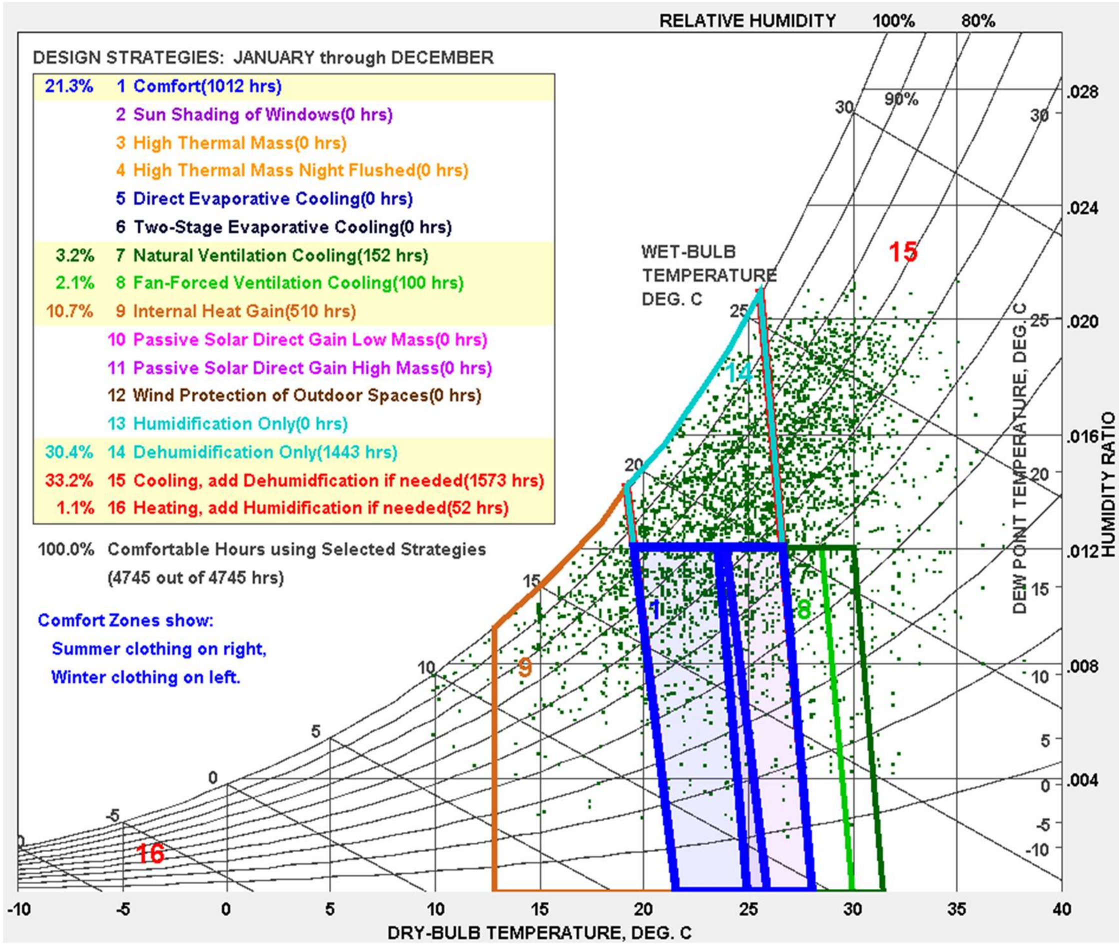


Figure 5.2: Necessary Active Design Strategies

5.2.2. Passive Design

To determine if passive design was possible, the CBE Thermal Comfort Tool was used to show temperature compliance (Tartarini et al., 2020). The thermal comfort acceptability limits are decided based on the ASHRAE Standard 55 adaptive model. For this analysis, the worst-case summer and winter temperatures were input to determine if the building would be within the acceptability limits. Figures 5.3 and 5.4 below show the results of the worst-case summer and winter temperature analysis, respectively.

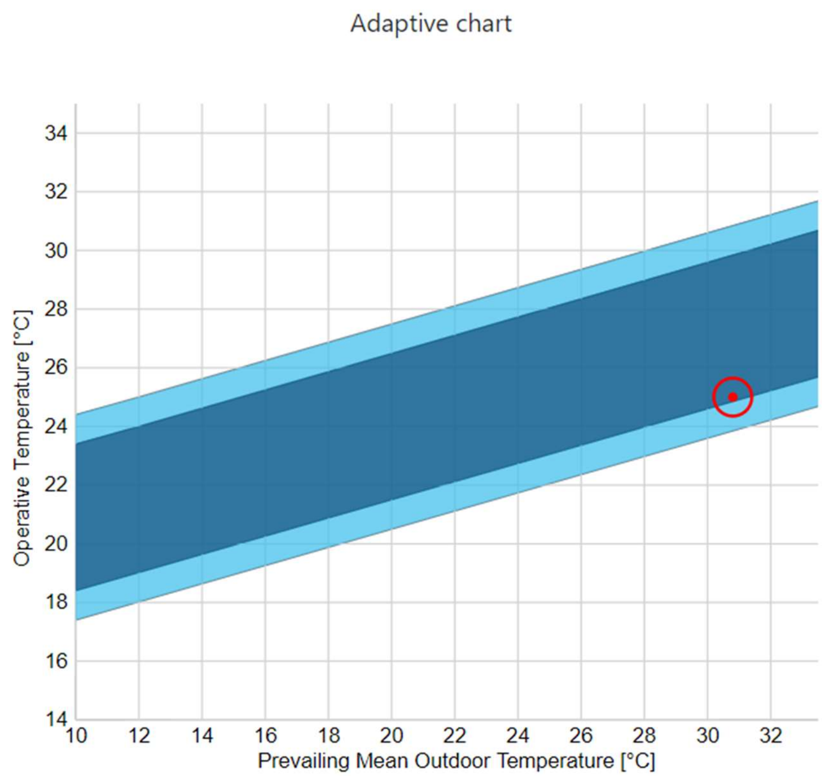


Figure 5.3: Worst Case Summer Temperature Adaptive Chart

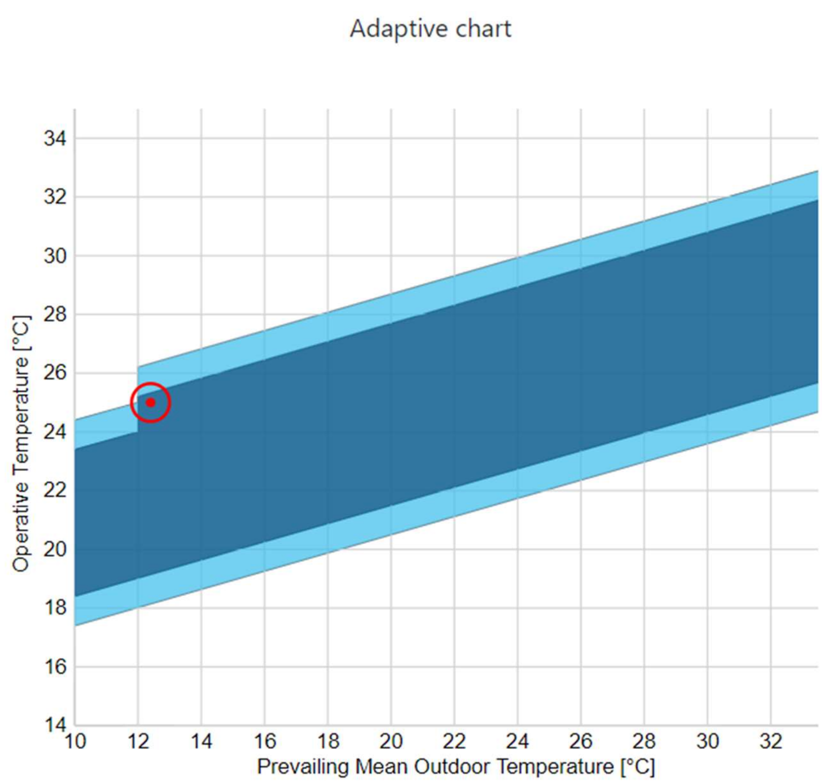


Figure 5.4: Worst Case Winter Temperature Adaptive Chart

The operative temperature used was 25 °C, which is the default value for this model. In the summer, the building is within 90% acceptability limits with an air speed of 0.98 feet per second (0.3 m/s), and in the winter the building is within 90% acceptability limits with an air speed of 1.97 feet per second (0.6 m/s). This indicates that the building will be compliant year-round with minimal air speeds. However, the ASHRAE Standard 55 adaptive model has no provisions for relative humidity. While the building may be compliant using the adaptive model, this standard only shows the minimum requirements for thermal comfort. The high humidity in Maputo is still a concerning factor in terms of thermal comfort and should be taken into consideration.

5.3. Peak Load Calculations on a Single Shipping Container

Peak load calculations were performed on a single shipping container for the hottest and coldest times of the year based on the Maputo climate information available in Table 5.1. The peak load values provide a good comparison for the different possible shipping container configurations that could be found in the buildings on this campus.

5.3.1. Peak Thermal Loads

Thermal load calculations were performed on a single 40-foot high-cube shipping container to provide a baseline for what the team could expect the thermal loads of an entire building to be before completing the architectural design of the building. For these calculations, it was assumed that the container has a roof and steel walls of specified thicknesses, with a plywood floor of a specific thickness. The calculations were performed for both an uninsulated scenario and an insulated scenario using cotton insulation. Heat loss was calculated using Equation 1 and heat gain was calculated using Equation 2.

$$Q = UA(Tin - Tout)$$

Equation 1: Heat Loss Equation

Where:

Q = heat loss (W)

U = overall heat transmission coefficient (W/m^{2}K)

A = area of exposed surface (m^2)

T_{in} = inside air temperature (°C)

T_{out} = outside air temperature (°C).

$$Q = UA * CLTD$$

Equation 2: Heat Gain Equation

Where:

Q = heat gain (W)

U = overall heat transmission coefficient (W/m^2K)

A = area of exposed surface (m^2)

$CLTD$ = cooling load temperature difference (°C).

Two different outdoor temperature measurements were taken into consideration: worst case and average case. It was necessary to be able to see both the maximum heat loss and heat gain as well as the average in order to make a comfortable design. Table 5.2 below shows a summary of the results of these calculations. Calculations were completed in metric units, as mechanical calculations often are, therefore conversions will not be shown. Detailed calculations can be found in Appendix D.

Table 5.2: Summary of Single Shipping Container Peak Thermal Load Calculations

	Heating				Cooling			
	Worst Case		Average Case		Worst Case		Average Case	
	W	W/m^2	W	W/m^2	W	W/m^2	W	W/m^2
With Insulation	415	14	222	7	1,493	50	1,398	47
Without Insulation	5,041	169	1,619	54	6,958	234	5,372	180

5.3.2. Lighting and Equipment Loads

In addition to calculating the thermal loads of the shipping container, the team evaluated the lighting and equipment loads that may be present in a single container. According to ASHRAE standards, the maximum lighting power density for an office building is 0.9 W/ft^2 (9.67 W/m^2) (DiLouie, 2011). The lighting power density is multiplied by the floor area of a single container to find the lighting load. The maximum lighting power density of an office building was chosen as a measure of evaluation because it is higher than that of a residential building and the team chose to create an in-depth design of the campus' administration building, which will host offices and assembly spaces. The lighting and equipment load for each container can be found in Table 5.3 ("Electrical usage," 2021).

Table 5.3: Lighting and Equipment Loads for a Single Shipping Container

Equipment	**Load (W)**
Lighting	288
Computers	600
Fans	150
Outlets	7,200

5.4. Analysis of Various Shipping Container Configurations

After analyzing the thermal loads of one shipping container, the team applied the calculations to various configurations of shipping containers that will likely be found throughout the campus buildings. The three configurations considered in this section are two side by side containers, four containers in a block configuration, and a single shipping container with glass windows. Similar to the single shipping container calculations, each configuration was considered with and without insulation for worst and average case temperatures. The information obtained from the analysis of the different configurations helped the team determine if insulation is needed and size the potential active system for a container.

5.4.1. Two Side by Side Containers

The team first analyzed a configuration of two side by side containers, shown below in Figure 5.5, which could be found in any single-story building.

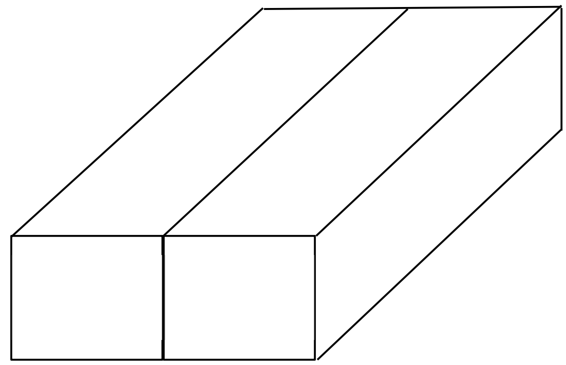


Figure 5.5: Two Side by Side Containers Configuration

This configuration assumes the same 40-foot high-cube containers and cotton insulation are being used. Additionally, it is assumed that the air gap between the containers will be sealed so that the interior wall acts like a partition wall and therefore causes minimal heat loss or heat gain across the wall. Table 5.4 below shows a summary of the results of these calculations. Detailed calculations can be found in Appendix D.

Table 5.4: Summary of Two Side by Side Containers Peak Thermal Load Calculations

	Heating				Cooling			
	Worst Case		Average Case		Worst Case		Average Case	
	W	W/m^2	W	W/m^2	W	W/m^2	W	W/m^2
With Insulation	331	11	176	7	1,403	47	1,337	45
Without Insulation	3,529	119	1,163	39	5,432	182	4,334	146

The results of the calculations show that the cotton insulation significantly reduces the heating and cooling loads. When compared to the single shipping container calculations, each of the shipping containers have slightly lower heating and cooling loads.

5.4.2. Four Containers Block Configuration

Next, the team analyzed four containers in a block configuration, shown below in Figure 5.6, which could be found in any two-story building.

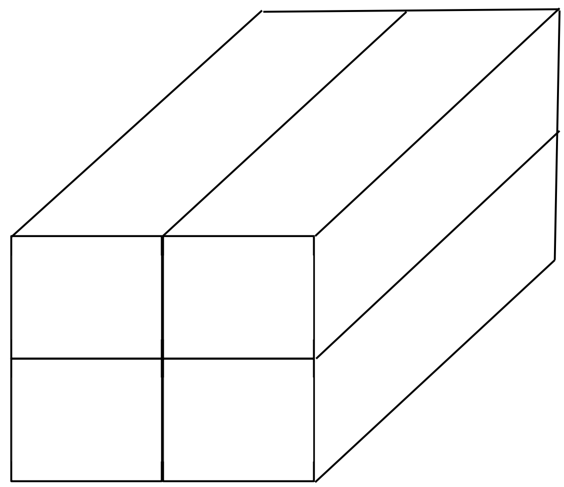


Figure 5.6: Four Containers Block Configuration

This configuration assumes the same 40-foot high-cube containers and cotton insulation are being used. Similar to the side-by-side configuration, it is assumed that the air gap between the containers will be sealed so that the interior wall acts like a partition wall and will therefore cause minimal heat loss or heat gain across the wall. Additionally, it is assumed that the air gap between the ceilings and floors of the containers will be sealed so that there will be minimal heat loss or heat gain across the ceiling/floor. Table 5.5 and Table 5.6 below show a summary of the results of these calculations. Detailed calculations can be found in Appendix D.

Table 5.5: Summary of Four Containers Block Configuration Peak Thermal Load Calculations With Insulation

Without Insulation	Heating (per Container)				Cooling (per Container)			
	Worst Case		Average Case		Worst Case		Average Case	
	W	W/m^2	W	W/m^2	W	W/m^2	W	W/m^2
Bottom Containers	260	9	175	6	1,317	44	1,25 0	42

Top Containers	192	6	58	2	1,769	59	1,48 0	50

Table 5.6: Summary of Four Containers Block Configuration Peak Thermal Load Calculations Without Insulation

Without Insulation	Heating (per Container)				Cooling (per Container)			
	Worst Case		Average Case		Worst Case		Average Case	
	W	W/m^2	W	W/m^2	W	W/m^2	W	W/m^2
Bottom Containers	2,258	76	779	26	3,817	128	2,809	94
Top Containers	3,391	114	1,024	34	5,798	195	4,478	150

The results of the calculations show that the cotton insulation significantly reduces the heating and cooling loads. Additionally, the top two containers in the configuration have slightly different loads than the bottom two because of the different surfaces that are exposed to the outside air. When compared to the single shipping container calculations, each of the shipping containers in this configuration generally have slightly lower heating and cooling loads.

5.4.3. Single Container with Glass

Lastly, the team analyzed a single shipping container with glass windows, shown below in Figure 5.7, which showed the effects of windows on the heating and cooling loads.

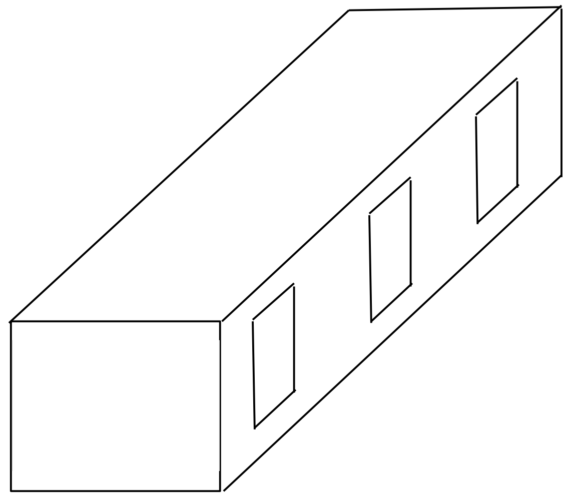


Figure 5.7: Single Container with Glass Configuration

This configuration assumes the same 40-foot high-cube containers and cotton insulation are being used. Additionally, it is assumed that there are three 4'-0" x 7'6" (1.2 m x 2.3 m) windows on each of the long sides of the container and the windows are facing north and south, respectively. The windows are assumed to have an awning type shading. The calculations were performed using both single glazing and double glazing to determine which type would be best. Table 5.7 and Table 5.8 below show a summary of the results of these calculations. Detailed calculations can be found in Appendix D.

Table 5.7: Summary of Single Container with Glass Peak Thermal Load Calculations Single Glass

Single Glass	Heating				Cooling			
	Worst Case		Average Case		Worst Case		Average Case	
	W	W/m^2	W	W/m^2	W	W/m^2	W	W/m^2
With Insulation	1,178	40	452	15	2,562	86	2,134	72
Without Insulation	5,129	172	1,646	55	7,349	247	5,646	190

Table 5.8: Summary of Single Container with Glass Peak Thermal Load Calculations Double Glass

Double Glass	Heating				Cooling			
	Worst Case		Average Case		Worst Case		Average Case	
	W	W/m^2	W	W/m^2	W	W/m^2	W	W/m^2
With Insulation	857	29	355	12	1,866	63	1,675	56
Without Insulation	4,808	162	1,549	52	6,653	224	5,187	174

The results of the calculations show that the cotton insulation significantly reduces the heating and cooling loads. When compared to the single shipping container calculations, each of the shipping containers with single glazing have higher heating and cooling loads while each container with double glazing has slightly higher or lower loads, depending on the insulation. Although using single glazing increases the loads more than double glazing, the heating and cooling loads with insulation are still acceptable.

5.4.4. Various Configuration Conclusions

The cooling loads calculated without insulation for each configuration are much higher than those with insulation, therefore insulation is necessary for the shipping containers. Since insulation is necessary, single glazing is sufficient based on the calculations provided above which will help reduce construction costs. Higher maintenance costs can be prevented through sustainable energy sourcing, as discussed in chapter 6.0 Sustainability. The heating loads with insulation for each configuration are minimal except for the worst-case winter with single glass scenario. In this case, a small heater may be necessary on the coldest days of the year to maintain optimal thermal comfort.

5.5. Annual Energy Consumption

After peak loads were calculated, the team used the same methodology to calculate an average monthly energy consumption for each shipping container configuration. Peak thermal loads only show the maximum consumption necessary at the worst times of the year. Since Maputo's climate is fairly comfortable for most of the year, a monthly weather analysis is more appropriate in determining the size of the HVAC system to save energy costs and to be more sustainable. The monthly thermal loads were multiplied by the number of hours during the month that the system would be in operation to find the energy consumption for each month. The team assumed a schedule of 8-hour workdays and 22 working days per month. Table 5.9 below shows a summary of the annual energy consumption for a single shipping container.

Table 5.9: Single Shipping Container Annual Energy Consumption

	Energy Consumption (kWh)	
	With Insulation	Without Insulation
January	246	945
February	246	945
March	232	709
April	232	709
May	5	90
June	30	284
July	44	298
August	44	298
September	34	119
October	218	472
November	232	709
December	232	709
Total	**1,794**	**6,286**

5.6. System Selection

When determining how to actively condition a single shipping container, the team drew a comparison to the air conditioning systems commonly found in construction trailers in the United States. The use of smaller individual cooling units allows the active systems to be applied more easily to different types of buildings that are designed as the campus plan develops. These air conditioning units are commonly 8,000 BTUH which is equivalent to about 2,345 watts. This is enough power to cool each individual shipping container provided in the calculations for all configurations if insulation is used. A common metric used for window air conditioning units is the CEER (Combined Energy Efficiency Ratio) which is a measure of how efficiently a cooling system will operate, taking into account the energy used while the air conditioner is running as well as the standby power used when the unit is not running but is powered on ("Air conditioner EER," 2021). The average CEER for an 8,000 BTUH unit is 11% which means the unit only uses 727 W to cool the total 2,345 W ("Understanding CEER," 2020). Additionally, a split air conditioning unit consists of an outdoor compressor and indoor air outlet units which eliminates the need for ductwork inside the building. This is an ideal system to use in the shipping containers because it consumes less space ("What is a Split," 2020). The team recommends the use of one 8,000 BTUH split air conditioning unit for each shipping container that needs to be conditioned.

5.7. Conclusion and Recommendations

From the above mechanical system analysis, it was determined that either active or passive strategies could be used for this location. If active design strategies are used, the economic and environmental costs associated with the HVAC system will be greater. If passive design strategies are selected, the buildings on campus may not reach ideal thermal comfort, particularly under humid conditions. The team recommends passive design for as much of the campus as this is applicable. For laboratory spaces or other enclosed spaces where active strategies may be necessary, the team provides recommendations for the implementation of these systems previously in this section. If both strategies are to be implemented in the initial campus, thermal comfort and energy usage should be monitored in these buildings for one year to determine which design strategy fits best for the needs of the community. If buildings that were originally intended to be passive need to be made active in the future, this is possible by making all building openings sealable and adding mechanical cooling.

6. Building Envelope

The building envelope separates the inside and outside of the building. More technically, it is the physical barrier between the regulated and unregulated environment of the building, according to the World Building Design Guide (WBDG) (Arnold, 2016). It resists the transfer of water, air, heat, light, and noise that could disturbed the internal environment. While the WBDG considers below grade structural elements to be included in the building envelope, the team decided it applied to the shell of the shipping containers for the context of this project, focusing on the unique properties of the containers and the spaces that will contain people.

This section details the roofing, wall makeup, insulation, flooring, windows and doors, and water management that the team selected to use within the buildings on campus, and the process for making these choices.

6.1. Roofing

The roof of the buildings is especially important to protect the containers from weather damage. While water can drain off the top of a single shipping container, multiple containers in line together may prevent drainage. The team decided to use a shed style roof, with a 3:12 pitch because it is simple to construct and could support solar panels if desired. Furthermore, a shed style roof uses less material than a gable roof, keeping the project costs down. Based on solar studies completed in Revit, the team determined that a 1'-9" (533.4 cm) overhang on the lower side of the container, and a 6" (15.24 cm) overhang on the higher side would be adequate protection. An overhang of 1'-9" (533.4 cm) feet to protect the walls of the buildings, without disturbing their visual appeal with a distracting roof. This would give the roof an area of 420.25 square inches (2711.3 cm^2), and a length along the 14.0° slope of 11'-6" (350.52 cm) feet for a single container. However, while the overhang does not change, the area of the roof varies in size depending on the building and configuration of the containers.

The team decided to use galvanized sheet metal for the roof for a few reasons: it is durable, it is widely available and already in use across Mozambique in housing construction, it is low cost, and it is visually similar to the containers. The galvanized steel sheets would be connected to the frame using purlins. The roof frame can be built from steel piping or wood, however the team selected to use 2" x 2" (5.08 cm x 5.08 cm) steel piping because it can be welded to the frame of the shipping containers. In addition, a galvanized steel frame would likely be lighter and withstand inclement weather better than a wood frame because it is not completely enclosed, instead open to the air. An image of the roof is below in Figure 6.1 labeled to show the galvanized sheets, purlins, frame, and gutters, and an isometric view of a roof frame over a 40-foot high-cube container. The frame is only partially covered by sheet metal to show the framing underneath.

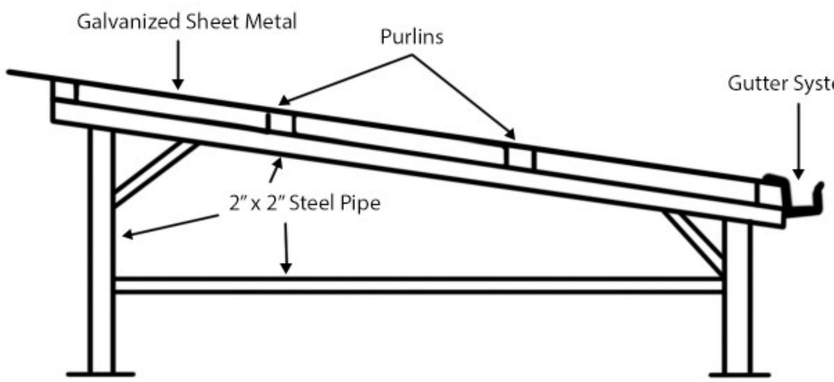


Figure 6.1: Labeled Side View of Roof Structure on Container Buildings

To prevent possible leaks and corrosion, the team chose to have a liquid rubber membrane spread over the top of all roofs. With possible ponding or wet materials lingering on the roof, a membrane provides a layer of protection from corrosion. In addition, the air gap between the container roof and the sheet metal roof allows for the evaporation of sitting water and can serve as a weak but extra layer of insulation.

The roof deck on the administration building will be a structural lightweight aggregate concrete that sits on top of the container roof. The deck would be applied to the shipping container surface after the roof of the container has had a liquid rubber membrane applied. The Constructor provides data on lightweight concrete in a 2019 article and compares it to normal concrete. Normal weight aggregate concrete is 150 pounds per cubic foot (2403.77 kg/m^3), while structural lightweight aggregate concrete is only 90 to 120 pounds per cubic foot (1441.66 kg/m^3 to 1922.22 kg/m^3). In addition, lightweight concrete can hold anywhere from 5 to 25% of its weight in water whereas normal concrete does not absorb anything significant, less than 2%. The downfall of lightweight concrete is that the drying time, where the concrete reaches a relative humidity of 75%, is anywhere from two to six months (Rahman, 2019). However, if the roof were to be applied during the dry season, this would not be a significant problem, and the sunlight would keep the drying time on the shorter side.

The walkways on the roof deck will be covered by the 5-foot (152.4 cm) roof overhang from the containers atop the large classroom space. Here the roof will slope away from the open-air space, overhang 5-feet (152.4 cm) to cover the deck, and meet column supports as shown in Figure 6.2 below.

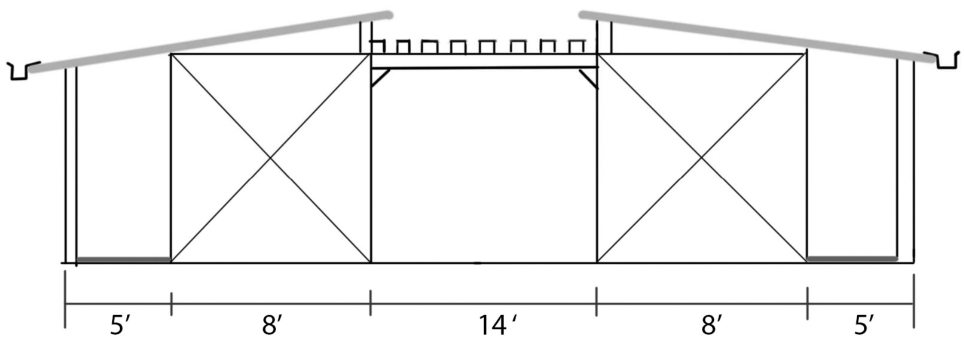


Figure 6.2: Cover Over the Administration Building Roof Deck

A CAD model of the roofing that the team wants to use is available in Figure 6.3. Various support types can be used to bind the sheet metal to the supporting structure, so long as they adequately attach to prevent blowing off in the wind. While this is a secondary cover on the spaces occupied by residents and users, attachments should be checked semi-regularly, especially due to the frequency of cyclones in the area.

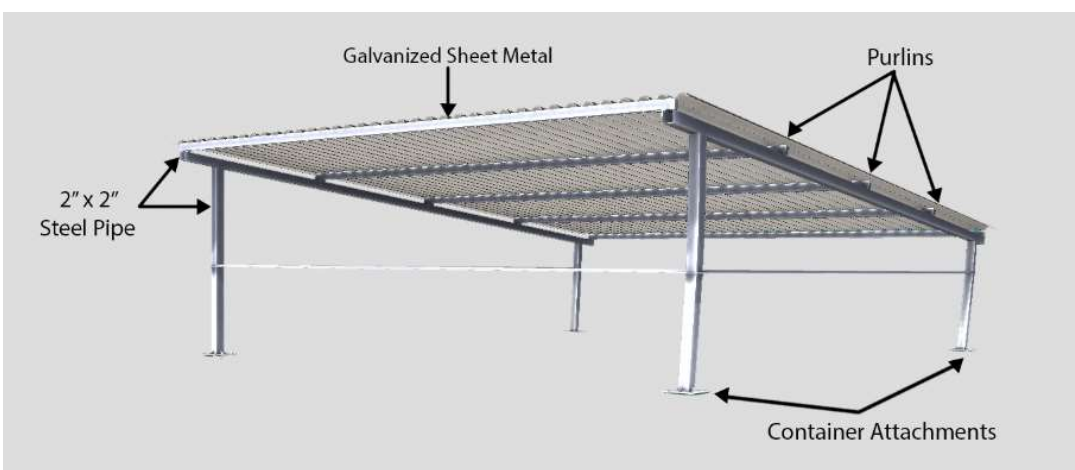


Figure 6.3: CAD Model of the Sheet Metal Roof Covering

Walls and Siding

The benefit of the shipping container is that the structure and sealed nature of the container prevents the need for external siding. The buildings on campus would not have extra siding beyond what would be used for artistic decoration. The walls of the container are corrugated steel, not the most visually appealing or insulating. Therefore, the team decided to add typical wall framing, which can be steel, wood, or aluminum, depending on availability around the site and the project budget. The team believes using wood 2” x 4” (2.08 cm x 10.16 cm) for framing is best when it comes to cost and included it in the design. There are multiple options for wall paneling, including drywall, sandalwood, plywood, aluminum, or steel sheets. The team decided to use drywall for the wall paneling because it is commonly used throughout buildings and should be familiar to work with. Drywall provides insulation against heat and noise transfer, and creates a polished, smooth appearance. The drywall can be painted whatever color the university decides fits their desired interior design.

Interior and exterior walls will be layered similarly; however, the interior walls have a thinner insulation layer and do not need a vapor barrier unless the container is housing a bathroom, washroom, or bathroom. The material order in the wall section from exterior to interior shall be container wall, cotton insulation, wood framing, vapor barrier, followed by drywall and paint.

Exterior container walls can be painted to match the campus color scheme using a zinc-rich paint, as those are best at preventing rust. The preparation process of painting the containers is important, as the walls need to be properly sandblasted and primed in order for paint to adhere. Metal is not as porous as other surfaces so paint will not stick to it as easily. There are rust-inhibiting primers that can be paired with rust-inhibiting paint. According to Business & Industry Connection Magazine, zinc-rich paints are somewhat “self-healing,” meaning that a protective layer from moisture will be formed by the zinc if a small break in the covering were to occur. While it is suggested to not build up a primer and paint thickness of more than 10 mils (0.254 mm), the paint should be checked annually to ensure no gapping is occurring (“World of zinc,” 2018). Paint is the most cost-effective measure of protection but Manufacturing Net lists epoxy or polyurethane coating to be the best long-term solutions, the latter of which lasting up to 10 years in harsh climates ("Understanding corrosion," 2015).

6.2. Insulation

The team chose to use cotton insulation, as stated in chapter 5.0 Mechanical Analysis, because it is more readily available in Mozambique and more ecologically friendly than other options. Insulation is put between the studs of the wall framing on the interior side of the buildings. The mild climate on site and watertight nature of the shipping containers prevents the need for multiple vapor barriers.

Interior walls do not need to be insulated to resist the transfer of water, air, heat, or light. Rather, they only need insulation against noise from elsewhere in the building. The air gaps between containers can act as a layer of air insulation to prevent heat transfer but may need to be filled with a material to prevent sound from travelling through so easily. In addition, any water that may penetrate the seals would be absorbed into the material and diverted away from the metal walls. Exterior walls would need insulation against all elements a building envelope protects from.

It is likely that noise will travel more easily in container buildings than traditional construction because metal reverberates energy rather than damping it, like wood tends to, because metals have a higher elastic capacity ("Why wood," n.d.). The cotton insulation that is being used to insulate external walls would be adequate to prevent sound from travelling and it would not need to be as thick. Ensuring walls and penetrations are properly sealed is important to preventing the passage of sound and vibrations through walls, ceilings, and floors.

6.3. Flooring

There are many flooring options available to the university depending on what interior design aesthetic they would prefer. Materials that are easy to clean and remove sand from would be beneficial given the environment the campus is placed in. For these reasons, the team is recommending the use of plywood as flooring in all the interior spaces. This type of wood flooring is lighter and cheaper than other methods and can be easily replaced or covered if desired in the future. As for the indoor-outdoor courtyard space in the administration building, the team recommends the placement of a concrete slab to provide easy cleaning flooring with simple water drainage.

6.4. Windows and Doors

It is advantageous to use the same windows and doors in one building, to simplify construction, ease maintenance, and lower the cost by buying in bulk. Different types of doors can be used for exterior and interior uses, however keeping windows the same size would prevent any mistakes when it comes to cutting holes in the container walls, because every window penetration would be the same size. Structural support and framing would need to be added and reinforced around penetrations to ensure they are strong enough. While the team conducted structural analysis of 3'-0" by 7'-0" (91.44 cm x 213.36 cm) door cutouts and 3'-0" by 5'-0" (91.44 cm x 152.4 cm) window cutouts.

The team selected to use single-hung windows, as discussed in Chapter 5.0 Mechanical Analysis. Functional windows in offices and dorm rooms can provide occupants with fresh air, sunlight, and temperature control. However, in places where windows are meant for design purposes, to let sunlight into large spaces but do not need to open, using polycarbonate sheeting instead of glass is more cost effective.

Window and door frames can be welded into the container walls and frame and sealed with expanding foam. A good construction job would ensure that the expanding foam is not visible beyond on the finished interior or exterior wall surfaces to prevent disturbing the visual appeal and impact of the building. Clear and colored liquid rubber can also be applied around more visible penetrations to create a fluid-tight barrier. It is available in cans and in spray forms.

6.5. Water Management

Water management is incredibly important to ecologically friendly campuses. The collection and reuse of water helps prevent overuse and pollution of water around and on site, in addition to reducing water usage. It is likely that the coastal location at Macaneta Beach does not have plumbing or a clean water source nearby. With the high frequency of cyclones, the heavy rain can be collected in greywater storage tanks and used in bathroom plumbing and irrigation during drier periods of the year.

The roof system employs the use of gutters at the lower end of the slope of the roof. The water would then be diverted through piping into storage tanks. Tanks can be buried underwater or hidden in other shipping containers. After filtration, the water from the tanks can be diverted back into the plumbing within the building or an irrigation system that is used all over campus. Gutters and diversion of water into a collection tank and away from the building structures and foundations will help protect the structural integrity of the buildings and prevent further water damage from ponding or excessive evaporation.

7. Sustainability Strategies

In September of 2015, the United Nations met at their headquarters in New York City, New York, United States to create the 2030 Agenda (Transforming, n.d.). The 2030 Agenda was created to outline a list of goals for the United Nations 139 member states to work towards over the next fifteen years. Although these goals did not all directly relate to environmental issues, the term “sustainability” was used to define them as an acknowledgement that environmental improvement cannot happen on its own. In addition to goals pertaining to the environment, other critical issues such as poverty, hunger, education, health care, economy, culture, and many more were addressed. A short list of 17 Sustainable Development Goals was included in the 2030 Agenda. The ninth goal on this list is to “build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation” (Transforming, n.d.).

Five years later in 2020, the United Nations released a review of Mozambique’s progress toward the 2030 Agenda (Mozambique, n.d.). In this report, the growth of Mozambique’s education system was noted as the Net Schooling Rate grew from 86.4% in 2016 to 93.5% by 2019. Another acknowledgment made by the report was the vulnerability of Mozambique to the effects of climate change and the need to focus on efforts on constructing resilient socioeconomic infrastructures to help lesson these impacts. The report also included a ten-year framework of the Mozambican government’s framework of programs on sustainable consumption and production patterns priorities. This ten-year framework included priorities addressing cleaner and more accessible transportation, energy efficiency, renewable energy, construction standards, and building operations. Designs for this project were created with these goals set forth by the United Nations and the Mozambican government in mind, to ensure the campus in Macaneta Beach can aid in these sustainability efforts.

Campuses began as smaller scale models of ecocities (Finlay & Massey, 2012). The significant infrastructure and energy requirements for higher education campuses make them clear targets when trying to minimize emissions. Furthermore, the application of sustainability strategies into these campuses provides many opportunities for learning and expansion of engagement among students and faculty. For campuses, primary sustainability targets include facilities management, emissions reduction, resource conservation, transportation, ecological restoration, and sustainable landscape. As the team determined the best strategies for implementing and enhancing sustainability at the Macaneta Beach Campus, the criteria outlined by all three of the previously mentioned organizations was considered. In this section, the team outlines recommendations for how to incorporate these strategies in the design of the campus and buildings, maintenance of these spaces, and behavior of the campus community.

To ease understanding, most numerical information will be provided in metric units, as is most common for calculations and general information, rather than imperial, unless it is vital to provide a conversion.

7.1. Campus Design Strategies

In order to develop a plethora of sustainability strategies to incorporate into the Macaneta Beach Campus, the team developed strategies with four different focuses. These focuses include campus level, building level, technological, and behavioral strategies. This section discusses the campus level methods, or strategies that should be developed and implemented uniformly throughout the infrastructure design of the entire campus. The strategies outlined in this section include renewable energy, water management, and sustainable landscape.

7.1.1. Renewable Energy

Renewable energy from natural resources has become an increasingly popular way to displace fossil fuels. This clean energy helps reduce carbon emissions and other pollutants that fossil fuels are notorious for emitting by being naturally occurring and constantly replenished. Some common forms of renewable energy are solar, wind, hydraulic, and biomass energy. While the first three forms are beneficial for the environment, biomass energy involves burning organic material which can produce just as many carbon emissions as fossil fuels, if not more (Shinn, 2018). Many developing countries, including Mozambique, use wood fuel inefficiently as an energy source, creating indoor air pollution. This pollution kills approximately 400,000 people per year in Sub-Saharan Africa alone (Cuvilas et al., 2010). Working towards increased use of clean, renewable energy in Mozambique will benefit the health and safety of the population.

According to the International Energy Agency, two policy initiatives for Mozambique are to promote the construction of electricity infrastructure that is resilient to climate change and to ensure sustainable and transparent management of the natural resources and the environment (“Africa Energy Outlook,” 2019). In

2009, Mozambique created the New and Renewable Energy Development Policy which aims to work towards initiatives such as those previously mentioned. Now, 88% of the country's energy sources are renewable and there is a total renewable potential of more than 23,000 gigawatts. This capacity is capable of providing for Mozambique's renewable energy demand as well as exports to neighboring countries (Jamaca, 2021).

7.1.1.1. Solar Energy

Overall, Mozambique is an ideal location for solar energy. The global horizontal irradiation varies between 1,785 and 2,206 kWh/m^2/year and currently, the country has 3 megawatts of solar potential already installed, 70 megawatts under construction, 300 megawatts under study, and a total solar potential of 23,000,0000 megawatts (Cloin, n.d.). Maputo province in particular has a high potential for grid-connected solar energy due to infrastructure in the area ("Renewable Energy Potential," n.d.). With this in mind, the team highly recommends using solar energy to help provide electricity to the campus. In order to provide air conditioning for a building on the campus with 10 shipping containers, about 18 310-watt solar panels are needed ("How many solar panels," 2021). This would cost approximately $15,680 USD or 1,157,811 in Mozambican metical (Matasci, 2021). Detailed calculations for these estimates are included in Appendix E.

7.1.1.2. Wind Energy

Mozambique overall has limited wind resources, but Maputo and Macaneta Beach offer greater potential for wind energy. Average wind speeds reach about 7 meters per second and the Renewable Energy Atlas of Mozambique reports that the country has a total wind energy potential of 4.5 gigawatts ("Renewable Energy Potential," n.d.). In 2020, construction began for the first wind power plant in Mozambique. Estimated at $280 million USD, this plant will produce approximately 120 megawatts of wind energy ("Wind energy in Mozambique," 2020). Since Mozambique is only beginning to explore potential for wind energy, the team recommends implementing this renewable option later in the campus expansion.

7.1.1.3. Hydroelectric Energy

As of 2016, Mozambique's hydroelectric potential was 12,500 megawatts, making it one of the largest hydroelectricity producers in Sub-Saharan Africa. The National Climate Change Adaptation and Mitigation Strategy has an initiative to improve the capacity for integrated water resources management including building climate resilient hydraulic infrastructures in Mozambique. The country currently houses six hydroelectric energy stations that connect to the national grid. As this renewable resource is continually explored and exploited, hydroelectric energy offers potential use of mini grids to help power smaller-scale projects and communities. Since much of Mozambique's hydroelectric power originates from the Zambezi River, located far from the campus site, the team recommends implementing this renewable option later in the campus expansion ("Country Profile: Mozambique," 2016).

7.1.1.4. Conclusion

In recent years, Mozambique has begun to explore natural, renewable resources that are readily available in the country. More work is still required to create more renewable energy plants throughout Mozambique to support the national grid. Considering that solar energy is currently the most supported renewable energy in the country and infrastructure near the site is favorable, the team recommends solar energy to be used at the initial campus. As the campus and renewable energy resources develop, a secondary analysis should be performed to analyze potential of wind or hydroelectric energy at the site. The use of renewable energy to power the campus will reduce energy costs as well as support the sustainable endeavors of the campus.

7.1.2. Water Management

The country of Mozambique is very vulnerable to problems with water, sanitation, and hygiene (WASH). This vulnerability is largely a result of inadequate finances and large geographical separation (*Findings*, 2018). In 2006, the Mozambican government, the United Nations International Children's Emergency Fund (UNICEF), and the Netherlands created a joint program nicknamed "One Million Initiative" to combat WASH problems in Mozambique (Water, n.d.). This program was active until 2013 with targets to bring safe drinking water to 1 million people in rural areas, rehabilitate the water sources of 200,000 people, educate 1.2 million people about appropriate hygiene practices, and partner with 400 primary schools serving 140,000 pupils (*Impact,* n.d.). This program greatly improved Mozambican infrastructure, but there is still more work needed. In 2017 after the initiative had ended, UNICEF reported that 61% of Mozambicans had access to improved water sources, but 76% of Mozambicans still did not have access to improved sanitation facilities (Water, n.d.). When looking at the gap between rural communities, this same report listed that 88% of people in urban areas had improved water sources while only 49% in rural areas could say the same. Likewise, 12% of people in rural areas reported having access and using improved sanitation while 47% reported the same in urban areas. The Macaneta Beach site is located within the Maputo Province is located within a semi-urban area in comparison to the rest of the country. In 2018, the World Bank reported that the Maputo Province was performing at high levels for improved water provision but still had large inconsistencies in access to improved sanitation. In order to combat these problems with WASH and financial and geographical inconsistencies, our team recommends the use of wells, rainwater collection, and stormwater management throughout the Macaneta Beach Campus.

7.1.2.1. Wells

Due to its location in a rather remote area with little prior municipal development, the team recommends the use of wells at the Macaneta Beach Campus to access potable water. A geotechnical report of the site will be needed to determine the type and placement of these wells throughout the sight. Organizations working to install wells in rural parts of Mozambique report that estimated costs range from $6,000 to $8,000

USD for drilling, installation, training, and oversight (Wells, n.d.). On average, one well can serve 2,000 people over the course of 20 years.

7.1.2.2. Rainwater Collection

As outlined in Section 6.6 Water Management, the implementation of a sloped steel roof and gutter system at the Macaneta Beach Campus will aid rainwater collection abilities. Given climate conditions in Macaneta Beach and the size of the roof systems, it is estimated that 118,850 gallons (449896.191 L) can be collected annually from the on-campus housing while 170,478 gallons (645329.43 L) can be provided by the administration building (Appendix E). Once the water is collected from the roof, pipes will redirect it to a submersible direct-pumped system. This type of system is placed in a shallow hole underground with a tank ranging in size from 264.2 to 5811.8 gallons (1,000 to 22,000 L) and an internal pump (Group, 2020). This water will then be run through a filter and pumped from the tank to the buildings to assist greywater appliances. These appliances include washers and toilets and will be further discussed in Section 7.3.3 Water Efficient Appliances.

7.1.2.3. Stormwater Management

During meetings with partners in Mozambique, the design team was continuously reminded that "when it rains it pours". The location of the campus on Macaneta Beach leaves it susceptible to strong tropical storms. These tropical storms will bring large amounts of water onto the site over short periods of time. In order to prevent small floods resulting from these storms, the team recommends the use of permeable surfaces and bioswales into landscape features (Denchak, 2020).

Permeable surfaces are sustainable alternatives to traditional asphalt or concrete surfaces (Soak, 2020). These surfaces come in the form of pavers, asphalt, or concrete, all with special properties that allow rainfall and water runoff to filter through into underlying soil and gravel (Figure 7.1). Permeable pavements can also help filter out pollutants that may have contaminated water before it is soaked back into the groundwater aquifers.

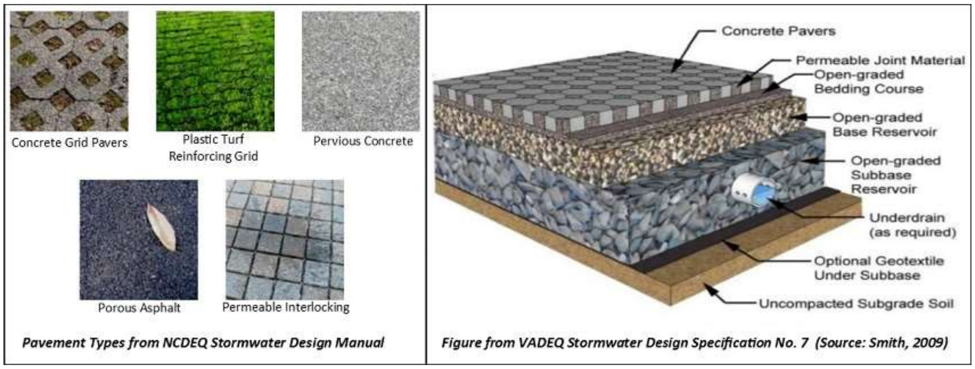


Figure 7.1: Permeable Surfaces and Installation ("NR pervious," n.d.)

Bioswales are long, deep channels of native plants and soils that serve as another strategy for water management (Denchack, 2020). These installations are often installed parallel to parking lots, roads, or sidewalks to absorb and retain water runoff (Figure 7.2). These systems can also help slow water runoff during high rain scenarios. Once the water is absorbed, it is filtered by the system before it returns to groundwater aquifers.

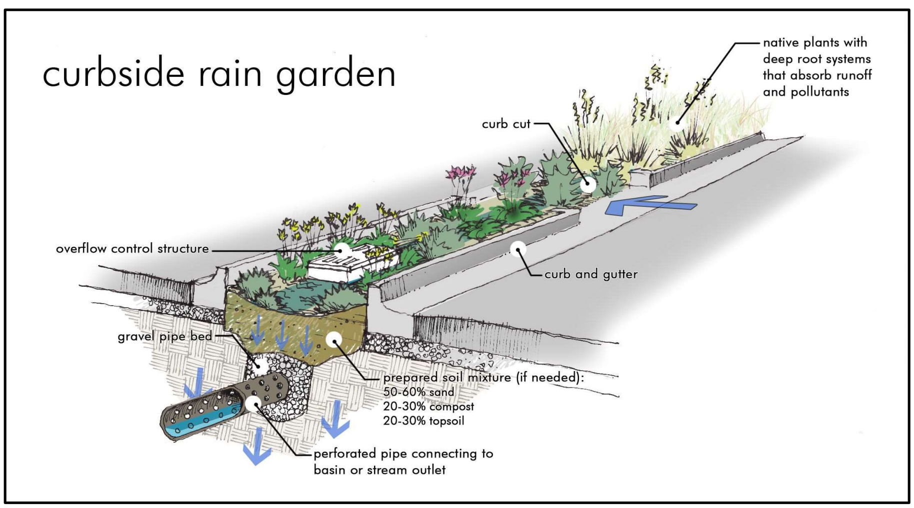


Figure 7.2: Bioswale Setup ("Curbside-rain-garden," n.d.)

7.1.2.4. Conclusion

The implementation of wells, rainwater collection, and stormwater management will help the Macaneta Beach Campus find clean and sustainable water sources in a country where water, sanitation, and hygiene are a large issue. Additionally, these strategies will help the campus survive the severe tropical storms that bring in heavy rainfalls to the area.

7.1.3. Sustainable Landscaping

This section outlines recommended landscape strategies to help minimize the strain placed on native ecology by infrastructure development. These recommendations were developed based on research of the region but should be further verified by site visits and site specific investigations of present biodiversity.

7.1.3.1. Protecting Natural Habitats

Conservation of Mozambican ecology has been a primary goal of various private and public organizations in recent years. From 2014 to 2019, the Mozambique Conservation Areas for Biodiversity and Development Project (MozBio) ran with goals to increase effective management of conservation areas and enhance living conditions of nearby communities (Mozambique, 2019). The efforts of the project aimed to achieve these goals through a strengthening of institutions to manage conservation, promotion of tourism to generate revenue, improvement of surveying and monitoring, and financial support of locals.

The diversity of the landscape at Macaneta Beach has led some individuals to call for increased conservation efforts in the area. Macaneta Beach provides a diverse landscape that offers the perfect habitat for roughly 291 different species of birds (Geldenhuys, 2020). The location of Macaneta Beach along with its landscape create a perfect place for birds to visit while migrating from other parts of Africa or Madagascar. These diverse populations create ideal birdwatching conditions in the area for bird watchers of all interests and abilities.

This information about the large bird population around the site is important to consider when choosing the layout of the campus and developing a construction plan. Before construction begins it is important to ensure that none of the birds in the area are actively breeding (*Dealing*, 2016). This can be determined with a specialized bird breeding survey of the site. The occurrence of construction while any of the birds are breeding may be highly disruptive and harmful to these populations. In order to prevent this, construction should be scheduled around breeding so that birds are not discouraged from creating breeding nests for the given season.

Once the campus is up and running, a program should be developed to help with conservation efforts. This program could include the development of a small research station or field laboratory to learn and study. The presence of these programs will help the campus attract birdwatchers, outside researchers, and tourists to the area, thereby attracting funding and publicity for the campus while simultaneously helping the birds.

7.1.3.2. Native Plants

The implementation of native plants in landscaping strategies of the Macaneta Beach Campus will reduce the amount of landscaping maintenance required. This reduction will help reach the campus's overall sustainability goals by saving money, time, and water resources, and allowing these to be allocated elsewhere.

Macaneta Beach is located within the coastal plain of the Maputaland coastal belt (Campbell, 2019). The Maputaland coastal belt consists of six ecologically unique vegetation types including: coastal grassland, savannah, woodland, miombo, forest, and dune forest. Based on footage of the site provided by partners in Mozambique, it is believed that the site at Macaneta Beach contains a mixture of coastal miombo woodlands (Figure 7.3) and coastal grasslands (Figure 7.4).


Figure 7.3: Coastal Miombo Woodlands on the Macaneta Beach Site


Figure 7.4: Coastal Grasslands on the Macaneta Beach Site

Coastal miombo woodlands located in areas with sandy dunes are characterized by thicket areas with trees that grow up to 45 feet (13.716 m) in height. Meanwhile, coastal grasslands are identified as areas where grasses are the dominant form of vegetation, though they are sometimes dotted with pockets of forests.

The most common species in the coastal miombo woodlands of Maputoland include *Julbernardia globiflora, Brachystegia spiciformis, Brachystegia torrei, and Androstachys jonsonnii. Julbernardia globiflora* is a species of tree that averages 15 to 45 feet (4.574 to 13.716 m) in height with fragrant flowers and large branches to provide shade (Figure 7.5) ("Julbernardia globiflora," n.d.).

Figure 7.5: Julbernardia globiflora (2004)

Brachystegia spiciformis is a tropical tree that averages 24 to 75 feet (7.315 to 22.86 m) in height with dark leaves, small flowers, and pods that contain seeds (Figure 7.6) (Brachystegia, n.d.).

Figure 7.6: Brachystegia spiciformis (Baumann, n.d.)

Brachystegia torrei is a common deciduous tree of sand forests and woodlands that can grow 30 to 54 feet (9.144 to 16.459 m) in height with a wide crown full of leaflets in pairs of six to 10 each (Figure 7.7) ("Brachystegia torrei Hoyle," n.d.).

Figure 7.7: Brachystegia torrei leaves (McCleland, 2015)

Finally, *Androstachys johnsonii* is a medium-size evergreen tree that can grow up to 100 feet (30.38 m) in height with distinct heart shaped flowers and flowers that produce three-lobed fruits (Figure 7.8) ("Androstachys johnsonii prain," n.d.).

Figure 7.8: Androstachys johnsonii fruit (2014)

The incorporation of these four species of trees into the landscape plan for the Macaneta Beach Campus, will provide texture and elevation to the landscape as well as shading devices for outdoor gathering spaces or nearby buildings.

The most dominant vegetation of the coastal grasslands is *Poaceae* grass. However, this is sometimes accompanied by *Cyperaceae* sedges and *Juncaceae* rushes as well. The difference between these kinds of vegetation is the type of flower they produce (Figure 7.9) ("Flower Terminology Part 3," n.d.).

Figure 7.9: Poaceae, Cyperaceae, Juncaceae Flowers

The inclusion of these plants into the Macaneta Beach Campus, will provide comfortable areas for students and faculty to sit and gather. It is important to note however, that this type of vegetation will likely require mowing and fertilization in order to prevent it from becoming overgrown.

In addition to the species that populate the coastal miombo and grasslands, there are also three species that are considered endemic in Coastal Maputaland. These species include *Cussonia arenicola, Dialium schlechteri, and Eugenia albanensis*. If the conditions at the site allow, these three plants should also be incorporated into the landscape in order to aid conservation efforts of these types of vegetation in their native habitats.

7.1.3.3. Heat Island Reduction

A heat island is formed when heat from the sun and buildings combine and become trapped in a highly developed area due to a lack of airflow. As warm air becomes trapped in the heat island, areas can experience temperature rises of 2 ºF to 10 ºF (absolute value of 16.67 ºC to 12.22 ºC). However, these effects can be minimized by ensuring that building density in an area does not become so high that hot air cannot easily escape. It is important to ensure adequate spacing between each building to create channels of ventilation. Additionally, finishes that are lighter in color will reflect heat instead of absorbing it like their darker counterparts. This means that vast expanses of pavement or sidewalks that are directly exposed to the sunlight should be avoided. If their installation is necessary, they should be accompanied by shading mechanisms to reduce their heat island contribution. Finally, installation of the vegetation outlined in the previous section will also help combat possible temperature increase across campus as they absorb light and heat energy during their biological processes.

7.1.3.4. Light Pollution

A commonly forgotten form of pollution created by areas of dense development is light pollution. Light pollution occurs when artificial light obstructs or brightens the natural nighttime sky. This can be damaging to nearby wildlife whose ecosystems are disrupted and can deter the visibility of stars in the sky. In order to prevent this phenomena, non-emergency lights should be turned off during hours outside of normal operation. The remaining required lighting fixtures should include some sort of shielding such as low angles or cutoffs that direct the light only toward the direction that is needed. These strategies will not only reduce light pollution, but also reduce the amount of energy consumed to light the campus.

7.2. Building Design Strategies

After developing strategies for the whole campus, the team explored building level alternatives. These alternatives will be implemented into the design of the building. Recommendations may vary based on the different uses and occupancies of campus facilities, but their implementation is critical to the achievement of sustainability goals. The strategies included in this section include natural ventilation, living green walls, locally sourced materials, low emitting materials, and thermally efficient materials.

7.2.1. Natural Ventilation

Natural ventilation has been used as a means to cool buildings without a mechanical system. This design strategy employs the use of pressure differentials between different building openings to maintain thermal comfort in the building. In recent years, natural ventilation has become popular as designers try to reduce energy usage and costs (Walker, 2016).

7.2.1.1. Benefits

The three goals of natural ventilation are to reduce energy consumption, maximize thermal comfort, and improve indoor air quality ("Basics of Natural Ventilation," 2021). The use of natural ventilation instead of mechanical air conditioning leads to an up to 25% reduction in building energy consumption and a 40% reduction in energy costs (Jones & West, 2001). Air conditioners use hydrofluorocarbons (HFCs) as cooling agents as well as release carbon dioxide, which act as greenhouse gases contributing to global warming (Schlossberg, 2016). By reducing the total energy consumption of a building and eliminating the production of greenhouse gases, natural ventilation is much better for the environment than mechanical cooling. Natural ventilation also requires little to no maintenance because the design strategy is fully implemented in the building envelope.

In addition to the environmental benefits that natural ventilation provides, there is increased occupant comfort. As discussed in Chapter 5 of this report, thermal comfort is a building measure regulated by ASHRAE Standard 55: Thermal Environmental Conditions for Human

Occupancy. Thermal comfort is essential for occupant satisfaction and productivity levels. While simply removing an air conditioning system would benefit the environmental impact of a building, the building would not be occupiable during warm months. Natural ventilation is able to provide cooling effects while increasing the indoor air quality of a space. Additionally, openings in the building envelope allow occupants to feel more in touch with nature and the environment around them (Jones & West, 2001).

7.2.1.2. Incorporation into Design

When designing buildings for the campus, the team took into consideration both active (mechanical cooling) and passive (natural ventilation) design strategies. While natural ventilation has many benefits, some areas of a campus, such as spaces with computers and laboratories, require the controlled environment that mechanical cooling provides. Where natural ventilation is possible, the shipping containers are advantageous because the short width of the containers provides better airflow. The team recommends placing the long side of any naturally vented container perpendicular to the summer winds, which are mostly North to South. The exhaust opening should be placed high above the supply opening to maximum the stack effect within the container. Additionally, ceiling fans are recommended to further reduce the effective temperature in the room (Walker, 2016).

7.2.1.3. Conclusions

The team recommends the use of natural ventilation as a cooling strategy wherever possible throughout the campus. Not only does this design strategy help reduce energy consumption and costs, but it also helps maintain thermal comfort in classroom and office settings which will increase productivity in students and faculty.

7.2.2. Living Green Walls

Nearly 80 years ago Professor Stanley Hart White of the University of Illinois developed and patented the design for a vegetation-bearing architectural structure and system (Reggev, 2020). At the time of their creation, these vegetation walls were not immediately popular. Eight decades later, under the rise of environmental issues, new technologies, and modernized design, these structures have finally gained attention under a new name, living green walls.

7.2.2.1. Benefits

The use of living green walls has risen notably in urban communities because of their proven benefits when installed both indoors and outdoors. When installed indoors, living green walls provide inhabitants many health benefits (Weinmaster, n.d.). On average, habitants of man-made buildings inhale up to 300 different types of pollutants each day. While this exposure may not be harmful at a small-scale level, studies have shown that humans spend over 90% of their lifetime indoors. Living green walls provide a way to minimize the exposure levels to these pollutants because the biological processes of the plants help filter them out of the air. In addition to their air purification capabilities, living green walls also help minimize the amount of ultraviolet radiation buildings are exposed to and have been linked to reduce other common health problems such as cough, fatigue, and irritable skin significantly (Reggev, 2020). Furthermore, the incorporation of plants into indoor spaces has also proven beneficial for the mental health of humans, reducing stress levels and improving focus, leading to greater overall productivity.

When installed outdoors, living green walls provide many benefits to a structure's building envelope. Living green walls can help with stormwater management, even purifying grey water. They can also help promote biodiversity and conservation, creating their own mini ecosystems. The plants themselves help regulate the building envelope's temperature fluctuation and help protect the surface from harmful ultraviolet radiation. In addition to these technical benefits, when installed on a building's exterior living green walls add to the aesthetic of a building and help promote a sustainable image.

7.2.2.2. Incorporation into Design

When looking at the team's architectural design, living green walls were incorporated into both interior and exterior spaces. For the purposes of this project, the team recommends the installation of a modular sheet media system because of its durability and longevity (Mustonen, 2017). Sheet media systems take advantage of a polyurethane patterned plastic sheet that is used to hold plants and water, requiring no soil and reducing the need for maintenance against bugs and mold. Figure 7.10 outlines the recommended installation for an exterior living green wall while figure 7.11 outlines that of an interior living green wall.

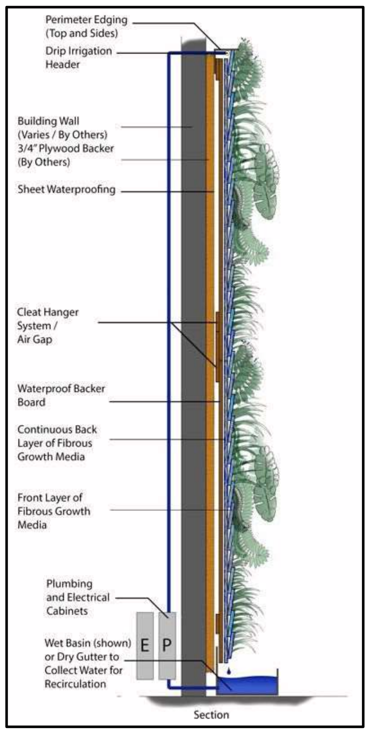


Figure 7.10: Exterior Green Wall Installation (Contreras, n.d.)

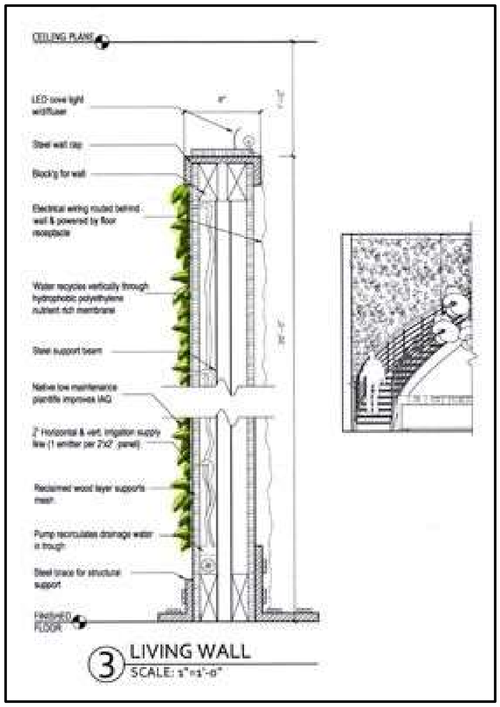


Figure 7.11: Interior Green Wall Installation ("Living Wall Detail," 2011)

Important components of the living green wall installation include waterproofing, structural support, and drainage. Lighting can also be added to contribute to the aesthetic of the walls.

7.2.2.3. Maintenance

Once living green walls are installed, they will require some regular maintenance ("How to Care for a Living Green Wall," 2020). Irrigation systems often include technology that will allow for scheduled watering. The amount of watering necessary depends on climate conditions and positioning. In addition to routine watering, seasonal maintenance is needed to verify functionality of the irrigation and structural systems. Depending on the plant species, this seasonal maintenance will also require pruning and fertilization.

7.2.2.4. Conclusions

The team recommends the use of living green walls for the interior and exterior of campus buildings to help promote biodiversity and conservation. In addition to these biological benefits, these living green walls will provide technical and health benefits to the campus buildings and their users. Additionally, the use of these walls will help the campus's overall aesthetic and promotion of sustainability.

7.2.3. Locally Sourced Materials

Selecting locally sourced materials for use in the design of a building offers many sustainable benefits. The use of local materials means shorter transportation distances, thereby reducing emissions. Furthermore, local material sourcing supports the local economy. The team evaluated the use of locally sourced materials for windows and wood accents, two prominent parts of the administration building and on-campus housing building designs.

7.2.3.1. Polycarbonate Sheeting

The designs drawn up by the team for the administration building and on-campus building designs incorporate large windows to allow an abundance of natural light. Traditional glass materials used for these components are expensive and are often imported from China or Germany. For these reasons, the team proposes the use of polycarbonate sheeting produced by Perpex, a South African company, in the place of glass windows ("Glaze," n.d.)

Polycarbonate sheeting is a lightweight material that is easy to cut and install. It can be formed into many different shapes and manufactured to be many different colors. These characteristics allow for a flexible building design. Figure 7.12 below illustrates the utilization of polycarbonate sheeting in two different ways. The sheeting used in the upper portion of the building is frosted, allowing for privacy, while that of the lower portion is transparent.

Figure 7.12: Polycarbonate Sheeting Incorporation into Building Design (“Cellular Polycarbonate Panel,” n.d.)

Furthermore, the thickest 2.36 inches (60 mm) polycarbonate sheeting is about 200 times more durable than glass, an ideal characteristic for materials in cyclone prone Macaneta Beach (Amerilux, n.d.). This higher strength means less need for structural supports. The flexibility and strength of this material also makes it 20% less expensive than glass to transport and install.

In addition to design and structural benefits, polycarbonate sheeting also provides environmental benefits. The plastic sheets are recyclable at the end of their life, and some are even manufactured from recycled materials (“Polycarbonate products,” 2017). Polycarbonate sheets also provide good thermal insulation, high visual light transmittance, and quality diffused light (Amerilux, n.d.). Overall, polycarbonate sheets can boost the overall energy efficiency of a building.

Due to the combination of design, economic, and environmental benefits presented by the use of polycarbonate sheeting, the team believes that sourcing this material from Perpex in South Africa will benefit the sustainability agenda of the Macaneta Beach Campus.

7.2.3.2. Wood

Since the turn of the century, Mozambique has fallen victim to severe deforestation, losing almost 7.5 million acres (3 million ha) or 10% of their forests (Farge, 2018). Deforestation of this magnitude is accompanied by the release of 200 million tons of carbon dioxide emissions. The rapidly changing landscape has also proved detrimental in the face of natural disasters. Forests that once acted as shields to slow winds and rains during cyclones no longer exist (Vleeschauwer, 2019). As a result, the seasonal cyclones that hit the Mozambique coast have generated much more severe impact over the past two decades.

Rapid deforestation throughout Mozambique has been aided by foreign bodies behind illegal exports of native woods. Mozambique serves as the tenth largest supplier of rosewoods to China (Farge, 2018). This system of exports to China has been largely corrupt and illegal. To make up for lost profits and land destruction, the Mozambique government has introduced forestry reforms and signed a memorandum of understanding with China. The World Bank also provided $47 USD million in loans, credits, and grants to help the fight against deforestation. While the effort has helped slow the problem, issues with regulation and surveillance remain.

Mozambique's charcoal industry also contributes to deforestation. Farmers who work in the charcoal industry have acknowledged detrimental effects on the environment but continue to view wood as a natural resource that they can exploit for their own profit (Vleeschauwer, 2019). The main problem is the inability to replace the trees that are cut down in a timely fashion. With reform and regulations, the charcoal industry could become more sustainable. However, this would be extremely difficult to enforce.

While the main material used in the initial design of the Macaneta Beach Campus is steel, there are some areas of the design where the team recommends the use of wood for structural or aesthetic reasons. Pine is the one of the most commonly used woods in Mozambican construction (Baloi, n.d.). Pine is native to the Manica province in the mid-western portion of the country. Logging and transportation of this wood to the site in Macaneta Beach is a viable option but may pose issues given the 683.5-mile (1100 km) distance between the two locations. Another possible option is the importation of pine from Southern Africa. In order to determine the best option, an analysis to determine the economic and environmental costs of each option would need to be performed.

In order to offset the removal of native trees resulting from the use of pine in the design, the team recommends that the campus partner with local preservation organizations. The African Conservation Foundation (ACF) has already begun a campaign to preserve and reforest the Nhamacoa Forest and the wildlife that call it home ("Tree nurseries," 2019). A partnership with the campus could begin with donations and eventually expand to include educational workshops or curriculums. Partnership with the ACF, or a similar organization, will allow the campus to communicate the negative effects of deforestation with the community, and provide helpful knowledge on how to combat and prevent deforestation in the future.

7.2.4. Low Emitting Materials

The United States Environmental Protection Agency reports indoor air pollution levels are two to five times higher than outdoor air. Much of this indoor air pollution comes from building materials, especially when they are first installed. The materials give off harmful chemicals in the gaseous form ("Indoor Air Quality," 2018). One way to increase indoor air quality is to choose low emitting materials in construction and finishing.

7.2.4.1. Benefits

The United States Green Building Council Leadership in Energy and Environmental Design highlights the following building features that contribute to indoor air pollution: interior paints, interior adhesives and sealants, flooring, composite wood, ceilings, walls, thermal and acoustic insulation, and furniture ("Low-Emitting Materials," 2021). These features often contain organic chemicals such as formaldehyde, benzene, acetaldehyde, and toluene. The chemicals are referred to as VOCs (Volatile Organic Compounds) because they easily release gases into the air. Exposure to VOCs over time can lead to eye, nose and throat irritation, headaches, and dizziness. Because of the effects of VOCs on building occupants, low-VOC and no-VOC, also called low-emitting, products are highly sought after. In addition to improving indoor air quality and occupant health, low-emitting materials reduce pollution of natural waterways (“Low Emitting Materials,” 2018). The cost of low-emitting materials is comparable to their conventional counterparts so using these materials will not drastically increase the cost of the project (“Selecting Low-Emitting Materials,” 2017).

7.2.4.2. Incorporation into Design

Low-emitting materials are often made of more natural or renewable materials compared to synthetic conventional materials. One example of a low-emitting material is bamboo plywood, which has much lower VOC levels than traditional plywood (Farooq, 2016). By replacing all of the shipping container floors with bamboo plywood, the containers would maintain structural integrity while also reducing indoor air pollution. Additionally, as mentioned in the following section, using recycled cotton as insulation can replace traditional fiberglass insulation and keep VOCs at a minimum. Lastly, low-VOC paints and other finishing materials should be used inside the shipping containers.

7.2.4.3. Conclusions

The team recommends using low-emitting materials wherever possible in the shipping containers and buildings on the campus. These materials will not incur a large additional cost to the project and will help the students and faculty remain healthy and focused over time.

7.2.5. Thermally Efficient Materials

When choosing building materials, it is important to also consider which materials will have a high thermal performance and therefore help reduce cooling and heating loads in the building. Many aspects of a building’s construction can make use of thermally efficient materials.

7.2.5.1. Recycled Steel

Steel is the most recycled material on the planet and does not lose its structural stability after being continuously recycled. According to the American Iron and Steel Institute, “Recycling a single refrigerator reduces the resulting greenhouse gas emissions by 215 pounds of CO_2. Through recycling, the steel industry saves enough energy to supply the annual electricity needs of more than 18 million homes” (“Sustainability in Steel Recycling,” 2020). In addition to being environmentally friendly, recycled steel is a very strong and weather resistant material as well as a good insulator for hot and cold temperatures (“8 best building materials,” 2021). The team’s use of recycled shipping containers in building designs will therefore contribute to the sustainability of the campus.

7.2.5.2. Cool Roof

Roofs with a coating of highly reflective paint are referred to as cool roofs because heat from the sun is reflected instead of absorbed into the building. This coating can be added to almost any roof style and remains up to about 50^{o}F (28^{o}C) cooler than a standard or dark roof. By reflecting the sun’s heat, cool roofs help lower the cooling load of the building in the summer months and can also reduce electricity demands (“Cool Roofs,” n.d.). The team recommends adding a cool roof coating to all shipping containers in the campus design.

7.2.5.3. Insulation Options

A major consideration when considering thermal efficiency of a building is insulation, because it helps keep heat in during the winter and out during the summer. Traditionally, fiberglass insulation is used in buildings. However, the team recommends more energy efficient insulation to be implemented at the Macenta Beach Campus. The first is spray foam insulation, which has a more accurate application method and does not distort over time. The ability of spray foam to fill small crevices makes it more thermally efficient than traditional insulation. Plant-based polyurethane foam is another type of insulation that has out-performed fiberglass insulation. Besides its ability to insulate a building well, plant-based polyurethane foam is made from materials such as hemp, bamboo, and kelp which have very low VOCs (Volatile Organic Compounds) as opposed to fiberglass insulation. As mentioned in the previous section, this means that the plant-based foam will not pollute the indoor air (Farooq, 2016). A third type of insulation is cotton insulation, which is made from recycled clothing which often goes to waste. Similar to plant-based polyurethane foam, cotton is a natural material and therefore has a low VOC (Roberts, 2020). While the other insulation types slightly out-perform cotton insulation, recycled cotton is more readily available in Mozambique than the other materials mentioned in this section. Therefore, the team recommends using cotton insulation in all shipping containers to reduce the heating and cooling loads.

7.2.5.4. Low-Emissivity Glass

The United States Department of Energy estimates that about 25% to 30% of a building's heating and cooling loads is due to the windows ("Update or Replace Windows," n.d.). Similar to the cool roof, low-emissivity glass has a thin reflective coating on it to reflect the sun's infrared and ultraviolet radiation while allowing visible light to pass through. This allows the interior of the building to stay cool and protects furniture and fabrics from harmful ultraviolet radiation ("What is Low-E glass," 2017). The team recommends using low-emissivity glass wherever possible for the shipping container windows to improve the thermal efficiency of the building.

7.3. Technological Strategies

After strategizing the implementation of sustainable elements into the design of the campus and buildings, the team looked at different technological strategies. These do not directly affect design choices but have a large impact on the building's overall performance. Strategies recommended include high energy HVAC, energy efficient appliances, water efficient appliances, and individualized controls.

7.3.1. High Efficiency HVAC

A high efficiency HVAC system can greatly reduce energy consumption in a building. As discussed in Chapter 5 Mechanical Analysis, the mechanical system selected for active cooling design is an 8,000 BTUH split air conditioning unit for each shipping container. To understand the efficiency of a specific HVAC system, the Energy Efficiency Ratio (EER), Seasonal Energy Efficiency Ratio (SEER), or Combined Energy Efficiency Ratio (CEER) is listed in the product specifications. The EER of a system only shows how efficient the system will be at one specified indoor and outdoor design temperature, which only provides a small amount of information about the system. Like the EER, the SEER is a measure of energy efficiency using indoor and outdoor design temperatures over an entire season, which is often used for central air conditioning systems. The CEER, however, is often used for window air conditioning units and considers the energy efficiency when the system is running and when the system is using standby power. The higher the energy efficiency ratio is for an HVAC system, the more energy efficient the system will be (“Air conditioner EER,” 2021). Therefore, when designing the cooling system, the team chose a CEER of 11% for the air conditioning units to ensure that the system will save energy, thus being more sustainable (“Understanding CEER,” 2020).

7.3.2. Energy Efficient Appliances

The use of energy efficient appliances throughout the campus provides a simple and effective way to reduce energy consumption while saving costs. Three common energy efficient appliances that the design team recommends for this project are refrigerators/freezers, clothing dryers, and ceiling fans.

7.3.2.1. Refrigerators and Freezers

According to Energy Star, a program run by the United States Environmental Protection Agency and United States Department of Energy, refrigerators that are ten years or older can cost consumers $5.5 billion a year in energy costs (“Refrigerators,” n.d.). Now, a multitude of styles of refrigerators and freezers are being produced that are at least 9% more efficient than their standard counterparts (“8 best appliances,” 2019).

While energy efficient refrigerators may have a higher upfront cost, the savings in energy costs and greenhouse gas emissions over time are well worth the initial cost. The team recommends using energy efficient refrigerators and freezers across campus, including department buildings and laboratories.

7.3.2.2. Clothing Dryers

Clothing dryers often use the highest amount of energy out of all household appliances. The Natural Resources Defense Council reports that clothing dryers can consume as much energy as a refrigerator, clothing washer, and dishwasher combined ("What are the most energy efficient," 2019). Energy efficient clothing dryers use sensors to stop the appliance as soon as the clothes are dry, consuming about 20% less energy than their standard counterparts. Additionally, low heat settings while drying clothes helps use less energy in the long run ("Clothes Dryers," n.d.). Clothing dryers are not typically found in Mozambique because most Mozambicans dry their clothes on lines or racks outside. If a decision is made to incorporate student laundry services on the campus, the team recommends using energy efficient clothing washers and dryers to greatly reduce energy consumption.

7.3.2.3. Ceiling Fans

The use of ceiling fans in addition to mechanical cooling can help reduce energy consumption due to effective cooling. Although fans do not actually reduce the temperature in a room, the circulation of air and wind chill effect can reduce the effective temperature of a room by about 4 ºF (2 ºC). With a lower effective temperature, the temperature of the mechanical cooling system can be raised slightly without affecting thermal comfort, thereby saving energy. Additionally, energy efficient ceiling fans are available and use 20% less energy than a traditional ceiling fan ("8 best appliances," 2019). The team recommends energy efficient ceiling fans in all interior locations on campus, whether passive or active cooling is used.

7.3.3. Water Efficient Appliances

The implementation of campus level water management strategies outlined in section 7.1.3 will help the Macaneta Beach Campus address issues with water availability and stormwater management. Pairing water efficient appliances with wells, rainwater collection, and stormwater management will help further the economic and environmental efficiency of the campus's water system.

7.3.3.1. Faucets and Showerheads

The functionality of faucets and showerheads as well as how they are used have a large impact on water efficiency. Studies show that turning off the faucet while brushing your teeth can save an average of 3,000 gallons (11356.24 L) of water a year ("Bathroom faucets," 2020). Likewise, cutting back the time spent in the shower saves an average of 2 gallons of water per minute. Behavioral strategies for minimizing water use are best paired with more efficient appliances. Basic faucets and showerheads consume an average 2.2 gallons of water per minute (8.33 L/min). Technological advances in recent years have allowed for the creation of fixtures that only use 1.5 gallons of water per minute (5.68 L/min). The use of these more efficient appliances rather than their traditional counterparts reportedly saves nearly 175 gallons (662.45 L) of water per user per year.

7.3.3.2. Toilets

Toilets are another main contributor to water consumption in commercial and residential settings. In the United States, toilets account for nearly 24% of daily water consumption in households ("Indoor water," 2020). In order to reduce the strain that toilets place on the water system, the team proposes two possible options.

The first option is the use of water efficient western style sit down toilets. Basic types of these toilets consume 1.6 gallons of water per flush 6.06 L/flush), while their efficient counterparts use just under 1.3 gallons of water per flush (4.92 L/flush). This gap indicates a 20% reduction in water use which equates to about 3,250 gallons of water saved per user per year (12302.6 L/year).

The second option is the use of composting toilets. These toilets use virtually no water in comparison to Western sit-down toilets (Saner, 2019). The use of these toilets also creates a closed loop system as humans consume food, expel the food's waste, and this waste is then used to grow more food. The implementation of compostable toilets would require extensive maintenance and oversight to ensure that everything is being operated under sanitary conditions.

7.3.3.3. Dishwashers

Dishwashers are not commonly found in Mozambique; however their implementation may assist the strategy to create an internationally inclusive campus, and will certainly aid water conservation efforts. In the 1990's dishwashers were consuming an average of 10 gallons of water per cycle (37.9 L/cycle) (Alexander, 2019). This rate has been significantly reduced to just 2 gallons per cycle in the most water efficient dishwashers on the market today. This high level of efficiency means that dishwashers have become more sustainable than hand washing which can use up to 20 gallons of water ("Saving water," 2020). The use of these dishwashers in kitchens and labs where pots and pans or equipment needs to be frequently sanitized will greatly assist water conservation and provide a convenience to campus occupants and staff.

7.3.3.4. Washing Machines

Washing machines are another appliance that is not typically found in Mozambique. Most Mozambicans clean their clothes by soaking them in pails of water and letting them dry in the sun. If a decision is made to incorporate washing machines in the residential spaces of the campus, it is recommended that water efficient models be selected. Basic washing machines consume an average of 20 gallons per load of laundry (75.7 L/load) ("Clothes Washers," 2020). The water efficient alternatives consume just 14 gallons per load of laundry in comparison (53 L/load).

This equates to a savings of nearly 500 gallons of water per year (1892.71 L/year) for the average individual. Additionally, these models are often more energy efficient.

7.3.3.5. Greywater Use

The water collected from roofs of campus buildings during rainfall will be stored and used throughout the campus as greywater. Greywater is water that is not clean enough to drink or bathe in but can be used for other purposes (Rauch, 2020). In addition to collection from the roof, greywater can be sourced from washing machines, dryers, dishwashers, sinks, and air conditioning units. The water collected must be stored and used safely. It is commonly recommended that greywater should not come into contact with humans, should not be pooled where it is stored, and should be used within 24 hours of its collection. With this in mind, the greywater that is collected may be used by toilets, hot water heaters, and irrigation systems in low-contact outdoor areas. The implementation of a greywater system will require a separate storage tank or reservoir and plumbing routes.

7.3.4. Individualized Controls

Lighting and thermal controls in a building often cover large areas and are not highly adjustable. However, the use of individualized controls in buildings can maximize energy efficiency by only using what is necessary at any given time.

7.3.4.1. Lighting Controls

Individualized lighting controls often use sensing technologies to detect building conditions and adjust the lighting settings as needed. The two main types of sensing are occupancy sensing and ambient light sensing. Occupancy sensors use passive infrared technology to sense movement in the space, either when someone enters a room or when someone leaves a room, and most often change lighting between on and off settings. Ambient light sensors measure the amount of light in a room at a given time and adjust the electrical lighting, as necessary. This act of daylight harvesting makes maximum use of the natural light throughout the day and often changes the light settings by dimming. Benefits of using lighting sensors include significant energy savings and the fact that sensing systems are simple to install and not expensive ("Lighting control sensors," n.d.). Therefore, the use of individualized light sensing is highly recommended for the campus to save energy as many spaces will be intermittently occupied.

7.3.4.2. Thermal Controls

Like lighting controls, individualized thermal controls are useful in spaces that are intermittently occupied or may have varying levels of thermal comfort. Individualized thermal controls allow for an increased range of comfortable temperatures in a building and work very well with naturally ventilated spaces. In a traditional building, Variable Refrigerant Flow (VRF) zoning is used to control different areas of the building. VRF allows for the refrigerant to only reach the zones needed, therefore being able to even cool some zones while heating others. Because of the use of shipping containers in the design of the campus, the concept of VRF is applied to small split-ductless air conditioning systems ("Individual Comfort Control," 2011). A split air conditioning system consists of an outdoor compressor and indoor air outlet units. These systems not only save interior space by being ductless, but also allow for individualized thermal controls in each shipping container ("What is a Split," 2020). In shipping containers that have multiple rooms such as offices, the occupants can control their thermal comfort level, thereby saving energy by not assuming one baseline thermal comfort level. Additionally, since using a small split unit for each container is recommended, the units for containers that are not in use can be turned off and not affect the comfort level of the entire building. Overall, the use of individualized thermal controls will help reduce energy consumption across the campus.

7.4. Behavioral Strategies

Finally, the team developed a list of recommended behaviors for potential campus employees, students, and visitors. These strategies address how the community uses the spaces, and what actions will allow for the greatest efficiency and potential to be reached. Recommendations in this section include commissioning and submetering, building and campus maintenance, waste management, and motor vehicle traffic.

7.4.1. Commissioning & Submetering

When building construction is completed, it is essential to perform commissioning for the energy systems. According to the United States Department of Energy, commissioning is a quality-assurance process used to verify that a building performs according to the original design and intent and meets the needs of the owners and occupants. Usually commissioning of building systems and equipment by federal agencies is required for buildings of new construction ("Commissioning in Federal Buildings," n.d.). The team recommends hiring a company to perform commissioning services once the primary campus buildings are constructed and for any subsequent campus buildings.

Once the buildings are commissioned and ready for occupancy, submetering should take place. Just as utilities can be metered, individual equipment and other loads can be submetered to give a more precise measurement of energy uses in the building. This tool is often used by landlords in apartment buildings to accurately charge each tenant for their utilities. Submetering is essential to the sustainability of the building because the energy efficiency of the systems can be measured as well as how and where in the building energy is being consumed. Three main benefits of submetering include receiving real-time energy consumption data, being able to compare energy usage across multiple facilities, and making informed decisions to optimize energy performance (Brooks, n.d.). Because of these benefits, the Federal Energy Management Program reports that continuously submetering can result in 15% to 45% energy savings ("Submetering for Commercial," n.d.). The team highly recommends using submetering to monitor the energy usage throughout the campus in order to be more energy efficient and save costs.

7.4.2. Building & Campus Maintenance Plan

Building and site maintenance are critical to ensuring that designs continue to meet sustainability goals. The main focus of sustainable maintenance is the health, safety, comfort, and productivity of current and future users ("Optimize operational," 2018). This importance begins during the design and construction process with selection of materials that are durable and easy to maintain. Once the building or site are in use, it is important to analyze activities needed to maintain them (Hermans, n.d.). This analysis should consider energy consumption, waste generation, annoyance to occupants, and frequency of various tasks. This information will provide an understanding of which maintenance tasks have the largest impact, and therefore should receive priority in the implementation of sustainable alternatives.

Once these priorities are established, there are recommendations to enhance the maintenance process. At the site level, it is important that any fertilizers and pesticides needed to manage landscaping are non-toxic to humans or animals in the area. It is also critical that the maintenance strategies used are minimally disruptive to humans and animals. On the building level, traditional cleaning supplies should be replaced with alternatives that are resource-efficient, biodegradable, and safe for indoor air quality ("Optimize operational," 2018). Automated sensors and controls for energy, water, waste, temperature, moisture, and ventilation should also be checked regularly to ensure they are functioning correctly. Facilities managers and maintenance workers should be trained in the sustainable design principles and methods and made aware of campus wide goals.

The employment of sustainable maintenance in campus buildings and grounds will increase the lifecycle of these spaces. This increased life cycle ensures that less energy and resources are required to make repairs or replacements, and that generations to come will be able to enjoy these spaces.

7.4.3. Waste Management

Urban cities in Mozambique are plagued with waste collection problems. Some of these problems stem from a lack of organization within the municipality while others stem from a lack of cooperation from individuals. The city of Maputo operates its waste collection around the Hulene, an open-air waste dump which is the largest in the company. Municipality workers are dispatched every one to two days around the city to collect waste ("Policy Brief IV," n.d.). Many residents of Maputo claim that the workers are not consistent and are hard to identify. This leads residents to become impatient, leaving their waste in the streets or other public areas to remove it from their property. As a result, municipalities are only able to collect 40-50% of the estimated 1102.31 tons (1,000 MT) of waste generated city-wide each day. When waste does make it to Hulene, it is either burned, buried, or compacted, causing issues with groundwater and air pollution in the surrounding areas ("Mozambique Waste Management," n.d.). Another large issue the city faces is the lack of understanding of the importance of proper waste disposal throughout the community. This is problematic because city residents do not separate their organic, paper, and plastic waste when preparing it, leaving it all to be sent to the landfill. Of the estimated 1102.31 tons (1,000 MT) of waste generated daily, it is believed that 68% is organic, 12% are paper products, and 10% are plastics. Failing to separate these items means a loss of at least 22% or 242.51 tons (220 MT) a day of waste that could otherwise be recycled. Despite this large-scale gap in recycling, some individuals have found ways to recycle on smaller scales. Many city residents reuse bottles and cans for personal purposes. Some neighborhoods have taken the initiative to create their own informal waste management systems where they recycle, bury, and burn waste themselves. While the ideals behind this strategy are good, carrying out these processes in an uncontrolled area with no regulations can prove harmful for the surviving environment and population. With these issues in mind, there is a critical need to communicate the importance of proper waste management with the people of Mozambique.

Higher-education campuses are often viewed to be their own small municipalities, producing large amounts of waste on their own. In 2015, it was estimated that each individual student attending college in the United States produced an average of 640 pounds (290.3 kg) of solid waste annually ("Curbing the college," 2015). The most common types of waste produced on these campuses include food, paper, plastic, glass, cans, clothes, houseware, electronics, chemicals, maintenance, and biological products ("The 10 most," 2021). In order to combat this high level of waste production there are a number of strategies that should be implemented around campus. The first step is the establishment of campus waste management goals, followed by communication of these goals and strategies to achieve them with the community. Once this is done, waste management strategies that call for action may be implemented. One of these strategies is the limitation of non-recyclable or reusable materials. The campus may encourage this through "bring your own" campaigns in which the community is asked to bring their own bag or container or straw to limit daily waste. These campaigns can be paired with incentives such as discounts in order to motivate more participation. For the community members who decide not to bring their own products, the campus can still stick to using recyclable or compostable materials in common spaces to minimize solid waste. When disposing of waste, the campus should take advantage of waste separation stations where campus members place garbage in designated landfill, paper, plastic/glass/metal, or food bins. This separation allows easier distribution of the waste to its respective destination. These stations must be monitored and maintained regularly in order to succeed. In order to tackle wastes in the form of clothing or household objects, the campus could create its own thrift or trade store. For other waste items such as electronics, chemicals, maintenance, and biological products that may not be recycled as easily, it is important that the campus ensure proper disposal of these items to minimize health and environmental risks.

The implementation of these strategies at the Macaneta Beach Campus provides an opportunity to educate members of the community about the importance of waste management, hopefully aiding the larger problem that exists throughout Mozambique. In the early stages of development, it will be crucial to coordinate with the local municipality to ensure collection of construction materials and routinely generated waste. For recyclables and compost, there are many local companies and organizations that the campus may be able to partner with. Common private recycling companies include Moza Waste Paper (paper), Neoquimica (glass), Reclam (iron and glass), Valor Plastico (plastic) ("Recycling plastics," 2020; "Mozabique waste," n.d.). A local organization entitled Associacao Mocambicana de Reciclagem (AMOR, Mozambique Recycling Association), may also be a beneficial ally for the campus. The mission of the organization is to "promote and organize a social recycling of solid waste" ("The ecopoint network," n.d.). This mission is carried out through widespread education, recycling events, and waste collection throughout the network of Ecopoints located in various Mozambican cities. The Ecopoints manage paper, cardboard, plastic, glass, metal, and electronic waste. Looking towards the future as the Macaneta Campus becomes more developed, a self-sufficient recycling program may be integrated as part of the engineering and sustainability programs, or a self-sufficient composting program as a part of the agricultural school. Overall, the implementation of campus-wide sustainable waste management will minimize environmental and health hazards. It will also provide an opportunity for greater education on waste management which can then be shared and translated by campus members among the communities they came from.

7.4.4. Reduced Motor Vehicle Traffic

During the last decade, Mozambique has experienced a steady increase of motor vehicle imports. From 2013 to 2018, the nation experienced an average annual increase of 40,000 vehicles per year, bringing the total number from 542,000 to 782,000 (Arante, 2019). This growing motor vehicle presence has led to a surplus of problems for the nation. An increase in accidents, has put citizens in danger and created economic problems due to increased insurance claims. On top of these social and economic issues, the rise in motor vehicle use has also negatively impacted Mozambique's environment.

Motor vehicles continue to be a leading cause of air pollution in Mozambique (“Mozambique Air,” 2015). The primary sources of fuel in Mozambique are gasoline and diesel. On average, one gallon of gasoline produces 19.4 pounds (8.8 kg) of CO_2 emissions while one gallon of diesel produces 22.2 pounds (10.1 kg) of CO_2 emissions (Average Carbon Dioxide, n.d.). These emissions are a large contributor to global warming, as well as other environmental problems like smog and acid rain. To reduce the Macaneta Beach Campus’s contribution to this environmental destruction, our team has designed the initial campus to be motor vehicle free and encourage a continuation of this in future campus planning.

To create a motor vehicle free campus, patrons will be encouraged to park their car in main lots placed off the pre-existing road into the campus. Limited handicap accessible spaces will be available for those who need them closer to the campus. Premiums will also be provided for patrons driving environmentally friendly vehicles. This could include free charging or preferred parking. Deliveries made by motor vehicles will be allowed on campus but will be restricted to certain roads.

As previously mentioned, limiting motor vehicle use at the Macaneta Beach site will reduce negative environmental emissions, pushing the campus closer to sustainability goals. In addition, this strategy will provide economic and health benefits for the campus community. Minimization of motor vehicle use saves money on roadways and their maintenance. Furthermore, this strategy will lead to more time spent walking outdoors among the campus community, an activity that holds many health benefits (Steinhilber, 2020).

8. Future Recommendations

This section outlines suggested actions for the partners in Mozambique to further the work of the project. Future recommendations include: the reference of the International Building Code (IBC) and International Fire Code (IFC), staged expansion of the campus, and project management lead by university leaders.

8.1. Building Code

The building designs that the team created are still in the conceptual design phase and will require further development as the campus design continues. One aspect to consider when continuing with these designs is ensuring the buildings adhere to local and national building and fire codes in Mozambique. Building regulation in Mozambique is the responsibility of the Ministério das Obras Públicas e Habitação (Ministry of Public Works and Housing). The team also recommends following the provisions of the International Building Code (IBC) and the International Fire Code (IFC) in order to maintain proper life safety and property protection.

Although every building should be completely compliant with the applicable codes and standards in the region, two areas to focus on are egress and accessibility. The IBC has many provisions to ensure the safe egress of all occupants in the case of a fire event. For the means of egress to be code compliant, occupant load and exit capacity will need to be calculated, and exit access travel distance, common path of travel, and exit remoteness will need to be measured. Other means of egress requirements can be found in Chapter 10 of the IBC. Accessibility is also very important because this campus should be usable by all members of the community. Some key aspects of accessibility are adding elevators to each multi-story building, providing an accessible route in all buildings, and providing adequate width for all corridors and doorways. Other accessibility requirements can be found in Chapter 11 of the IBC. The IBC only provides minimal accessibility requirements, so the team recommends following more stringent codes in order to make the campus more inclusive.

8.2. Campus Expansion

The team focused this initial proposal on key buildings that would be necessary for the operations of a new campus: administration, housing, and some classroom space. However, as the campus attracts more students, faculty, and staff, more space and infrastructure will be necessary. This includes classroom, office, and lounge space, in addition to housing, parking, and operation space. This section discusses design elements for the campus that the team did not yet include in the design proposal but would like to see implemented in future campus plans.

The design team discussed initial campus maps and a potential phased plan for campus expansion, but ultimately did not have enough site data to solidify ideal starting locations for types of buildings proposed by project partners. Potential elements for campus expansion could include department buildings for various educational programs, further housing, outdoor classrooms, green spaces, agricultural fields, an athletic complex, a tourist center, and a marketplace open to outside vendors and local community members. The team envisioned the creation of a large green space, with local flora and fauna, that would allow people to take walks through nature and study outdoors. This could double as an agricultural space, allowing students to utilize the space to learn about agriculture in addition to growing crops and providing for the university citadel. In addition, the team imagined the creation of a reservoir and ponds to immerse residents in nature in addition to serving as holding spaces for collected greywater before reuse. To include the local community in the campus, stimulate the local economy, and introduce possible international students to local goods, the team envisioned a market space. This would allow people to sell goods and services in a central location with infrastructure to support their trades.

The modular nature of the shipping containers allows for buildings to be assembled to fit the specific needs of the campus. Individual containers can be placed as stand-alone rooms for temporary use while other buildings are being constructed, especially in the aforementioned market space. Individual containers around campus could also serve as coffee shops, cafes, or a school supplies store. Shipping container markets have been seen already in Europe and would fit with this campus well.

8.3. Project Management

The site of the campus is currently undeveloped, so initiating construction of the proposed buildings will require professional management. Construction at the campus will require a project management team working with university leaders to determine goals, develop a budget and project schedule, and maintain communication with contractors, architects, and engineers throughout construction. Construction of initial buildings at the site may also first require prior construction of infrastructure, as current conditions at the site will make transport of materials and equipment for construction very difficult. The team recommends the implementation of paved roads or wooden boardwalks that will allow the site, and later campus, to be more accessible before construction, or another temporary method of infrastructure.

Expansion of the campus will require careful thought to ensure as little disruption of natural species and landscape as possible, and so that the campus remains open and logical in design. The team recommends development plans be created so the incorporation of new elements is timely and works well with the campus layout. This would require creating a list of desires, which may include different department buildings, faculty housing, or recreational space, and adding them to a campus map that is displayed as a timeline. Seeing what the campus will look like in five, ten, then twenty years in the future can help people believe in the potential of this campus and attract investors. Creating a map of development and further designs of all buildings to be implemented will also provide vital cost information and a timeline of funding necessary for the ideal project schedule. This funding timeline should be considered alongside the projection of campus growth. Once construction commences, all costs and budget changes should be tracked by a project management team to ensure the project is as low cost as intended and remains on schedule.

Finally, utilizing student designs and knowledge could help to engage local students more closely in their campus and keep costs low. However, all designs and projections will need to be verified by certified architects and engineers in order to satisfy local laws and building codes. The team also recommends creating a global design competition for the project or for future building designs to engage global architects to generate unique and iconic designs for a low cost, ensure that designs for the campus meet international standards, and attract investors to the project.

9. Conclusion

This project began with a vision of an environmentally conscious, affordable, and accessible university that could not only provide a well-rounded education, but also lift standards of living for the local community in the town of Macaneta, Mozambique. This mission proves timely and necessary due to the current inequalities in education and infrastructure that Mozambique faces, and the global need for environmental action. While this Major Qualifying Project may not accomplish all goals set by the project mission and leaders, it provides a necessary starting point for initial building and campus development and recommendations to drive the project forward.

At the conclusion of their involvement in the project, the student team from Worcester Polytechnic Institute presented Mozambican partners with architectural designs for two buildings to be constructed in the initial phase of campus development: an administration building with a large classroom and an on-campus housing facility. Students also provided a model for structural analysis of shipping containers as building components, structural calculations and recommendations, and mechanical calculations and recommendations for individual shipping container building components and multiple configurations of containers. Sustainability and building envelope strategies used by the team will also provide guidance for future design and construction. Finally, the team provided architectural drawings sets and models to partners in Mozambique, as well as this report to support further development of the project by local engineers and architects. Moving forward, the team recommends review of local building codes to adhere to local building and accessibility standards, creation of a full, phased plan for campus development and layout, and inclusion of a project management team to facilitate future design and construction, as well as further building design, budgeting, and fundraising.

The student team recognizes importance of acknowledging the limitations of this project. All work was completed by students and advisors rather than professional engineers, preventing immediate progress on current designs. The lack of professional engineering licenses prevents approval for future construction by the Worcester Polytechnic Institute (WPI) team. Proposed architectural designs must be further analyzed by local professionals in Mozambique, and structural and mechanical analyses in this report must be verified by locally certified engineers. In addition, limited access to information about the campus site and limits of international communication presented obstacles that will need to be addressed in future project development. Slow information exchange and review of work delayed the initial MQP schedule and prevented further campus development from being completed as the student team had initially wanted. Without being able to visit the site or collect accurate climate and soil data, the team relied on available data from Maputo, local estimations, and other studies completed in the area. Therefore, assumptions of climate and soil conditions are generally conservative and require verification. The team believes further development of the project should be completed locally to avoid differences and delays in communication that will hinder the project schedule.

In addition to limitations, the student team wishes to address possible sources of error in calculations and modelling. The team had limited previous use of RISA-3D 19.0 and while the model was updated with the help of a professor proficient in the software, user error may have influenced the results that led to conclusions about deflections of container models.

In conclusion, this project can be utilized by our Mozambican partners to excite the community, engage local professionals, entice investors, and move one step closer to their goal of creating a sustainable and inclusive university in Macaneta, Mozambique. The team hopes that this campus can provide additional benefits to the surrounding area, such as promoting infrastructure development in the area, increasing tourism to the area, influencing behavior to be more environmentally friendly, and modeling sustainable design strategies. If the vision is brought to fruition, then the university campus will serve as a sustainable model for not only southern Mozambique, but for the world.

References

8 best building materials for energy-efficient houses. (2021, January 13). Retrieved March 18, 2021, from https://www.yourownarchitect.com/8-best-building-materials-for-energy-efficient-houses/

8 best building materials for energy-efficient houses. (2021, January 13). Retrieved March 18, 2021, from https://www.yourownarchitect.com/8-best-building-materials-for-energy-efficient-houses/

The 10 most common types of waste on a university campus. (2021, February 12). Retrieved March 8, 2021, from https://www.ercofusa.com/blog/common-types-university-waste/

[Photograph]. (2014, October). Retrieved March 8, 2021, from http://pza.sanbi.org/androstachys-johnsonii

About Mozambique. (n.d.). Retrieved March 14, 2021, from https://www.mz.undp.org/content/mozambique/en/home/countryinfo.html

Access to electricity, rural (% of rural population) - Mozambique. (n.d.). Retrieved March 14, 2021, from https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?locations=MZ

Africa Energy Outlook 2019. (2019, November). Retrieved March 18, 2021, from https://iea.blob.core.windows.net/assets/1d996108-18cc-41d7-9da3-55496cec6310/AEO2019_MOZAMBIQUE.pdf

Air conditioner EER, CEER, and SEER rating. (2021). Retrieved March 19, 2021, from https://products.geappliances.com/appliance/gea-support-search-content?contentId=19151

Alexander, G. (2019, June 13). 10 greenest Dishwashers. Retrieved March 4, 2021, from https://earth911.com/how-and-buy/10-greenest-dishwashers/

Allen, E., & Iano, J. (2012). *The Architect's Studio Companion: Rules of Thumb for Preliminary Design*. Hoboken, New Jersey: John Wiley & Sons.

Androstachys johnsonii prain. (n.d.). Retrieved March 13, 2021, from https://www.zimbabweflora.co.zw/speciesdata/species.php?species_id=134720

Arante, E. (2019, September 9). Number of vehicles on Mozambique's roads skyrocketed last year. Retrieved March 8, 2021, from https://clubofmozambique.com/news/number-of-vehicles-on-mozambiques-roads-skyrocketed-last-year-141445/

Arnold, C. (2016, August 11). *Building Envelope Design Guide.* Retrieved March 19, 2021, from https://www.wbdg.org/guides-specifications/building-envelope-design-guide/building-envelope-design-guide-introduction

Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel (pp. 1-2, Rep.). (n.d.). United States Environmental Protection Agency.

Baloi, D. (n.d.). *Feasibility Analysis of Timber Houses in Mozambique* (pp. 1-7, Rep.). Eduardo Mondlane University.

Basics of Natural Ventilation. (2021). Retrieved March 18, 2021, from http://coolvent.mit.edu/intro-to-natural-ventilation/basics-of-natural-ventilation/

Bathroom faucets. (2020, October 21). Retrieved March 4, 2021, from https://www.epa.gov/watersense/bathroom-faucets

Baumann, G. (n.d.). *Tree growing in native habitat* [Photograph found in African Plants - A photo guide]. Retrieved March 8, 2021, from http://tropical.theferns.info/viewtropical.php?id=Brachystegia+spiciformis

Brachystegia spiciformis. (n.d.). Retrieved March 13, 2021, from http://apps.worldagroforestry.org/treedb/AFTPDFS/Brachystegia_spiciformis

Brachystegia torrei Hoyle. (n.d.). Retrieved March 13, 2021, from https://www.zimbabweflora.co.zw/speciesdata/species.php?species_id=126680

Brooks, C. (n.d.). Energy Submetering: Benefits & Applications. Retrieved March 18, 2021, from https://www.setra.com/hubfs/Resources/Introduction_to_Submetering_Whitepaper.pdf

Brown, R. L. (2016, July 11). The second lives of shipping containers. Retrieved March 18, 2021, from https://www.usnews.com/news/best-countries/articles/2016-07-11/the-second-lives-of-shipping-containers

Campbell, E. (2019). *Ecological Assessment and Biogeography of Coastal Vegetation and Flora in Southern Mozambique* (Unpublished doctoral dissertation). Nelson Mandela University. Retrieved February 24, 2021.

Cellular Polycarbonate Panel. (n.d.). Retrieved March 8, 2021, from https://www.archiexpo.com/prod/rodeca-gmbh/product-56741-1414087.html

Cloin, J. (n.d.). Solar Energy Investment Opportunities in Mozambique. Retrieved March 18,

2021, from
https://www.solarpowereurope.org/wp-content/uploads/2018/09/Solar-Energy-investments-in-Mozambique.pdf

Clothes Dryers. (n.d.). Retrieved March 18, 2021, from https://www.energystar.gov/products/appliances/clothes_dryers

Clothes Washers. (n.d.). Retrieved March 4, 2021, from https://www.energystar.gov/products/appliances/clothes_washers

Cohn, N. (2021) *Professors quotes into inspirational quotes* [easter egg] Retrieved May 5, 2021, from https://vm.tiktok.com/ZMeVvBanP/

Commissioning in Federal Buildings. (n.d.). Retrieved March 18, 2021, from https://www.energy.gov/eere/femp/commissioning-federal-buildings

Contreras, R. (n.d.). *Agriculture Verticale*. Retrieved March 8, 2021, from https://www.pinterest.com/pin/562035228502460180/

Cool Roofs. (n.d.). Retrieved March 18, 2021, from https://www.energy.gov/energysaver/design/energy-efficient-home-design/cool-roofs

Country Profile: Mozambique. (2016, May). Retrieved March 18, 2021, from https://www.hydropower.org/country-profiles/mozambique

Curbing the college waste problem. (2015, May 11). Retrieved March 8, 2021, from https://www.planetaid.org/blog/curbing-the-college-waste-problem

Curbside-rain-garden. (n.d.). Retrieved March 8, 2021, from https://headwatersatthecomal.com/our-story/curbside-rain-garden/

Cuvilas, C. A., Jirjis, R., & Lucas, C. (2010, September). Energy Situation in Mozambique: A Review. Retrieved March 18, 2021, from https://doi.org/10.1016/j.rser.2010.02.002

Da Silva, R. (2019, July 29). From stores to offices: The various utilities of containers in Maputo. Retrieved March 18, 2021, from https://www.dw.com/pt-002/de-lojas-a-escrit%C3%B3rios-as-v%C3%A1rias-utilidades-dos-contentores-em-maputo/g-49785397

Dealing with Construction and Birds (pp. 1-3, Rep.). (2016). Scottish National Heritage.

Denchak, M. (2020, February 05). Green infrastructure: How to manage water in a sustainable way. Retrieved February 24, 2021, from https://www.nrdc.org/stories/green-infrastructure-how-manage-water-sustainable-way

DiLouie, C. (2011, April 18). ASHRAE Releases 90.1-2010–Part 1: Design, Scope, Administrative Requirements. Retrieved March 18, 2021, from http://lightingcontrolsassociation.org/2011/04/18/ashrae-releases-90-1-2010-part-1-design-scope-administrative-requirements/

The ecopoint network: Amor. (n.d.). Retrieved March 8, 2021, from https://www.associacao-mocambicana-reciclagem.org/the-ecopoint-network/

Education situation in Mozambique. (n.d.). Retrieved March 14, 2021, from https://www.unicef.org/mozambique/en/education

Electricity usage of a ceiling fan. (2021). Retrieved March 18, 2021, from https://energyusecalculator.com/electricity_ceilingfan.htm

Farge, E. (2018, July 26). Mozambique reforms timber sector to counter illegal logging. Retrieved February 28, 2021, from https://www.reuters.com/article/us-mozambique-forest-logging/mozambique-reforms-timber-sector-to-counter-illegal-logging-idUSKBN1KG1F8

Findings of the Mozambique Water Supply, Sanitation, and Hygiene Poverty Diagnostic (pp. 1-77, Publication). (2018). Washington, DC: World Bank Group.

Finlay, J., & Massey, J. (2012, April 06). Eco-campus: Applying the ecocity model to develop green university and college campuses. Retrieved February 22, 2021, from https://www.emerald.com/insight/content/doi/10.1108/14676371211211836/full/html?casa_token=OmgUN6naIV8AAAAA%3AgwQ89srUuIrZOP8ZRChV66ekWXfl_R_IpGJ-duI3owwe8ot2LB_-TS-jhiQsf5VchysLt9dA1dOUKktL1eEFrQ8DY6GSxqoSF29KgC5cdAWccS0bFJQ

Flower Terminology Part 3. (n.d.). Retrieved March 13, 2021, from https://www2.palomar.edu/users/warmstrong/termfl3.htm

Geldenhuys, C. (2020, December 4). Mozambique: First-ever sighting of rare bird in Macaneta. Retrieved February 24, 2021, from https://clubofmozambique.com/news/mozambique-first-ever-sightings-of-rare-bird-in-macaneta-179168/

Giriunas, K. (2012). *Evaluation, Modeling, and Analysis of Shipping Container Building Structures* (Unpublished master's thesis). The Ohio State University. Retrieved from https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=osu1323878208&dis

position=attachmentGlaze. (n.d.). Retrieved February 28, 2021, from https://www.perspex.co.za/glaze/#1548859836618-83ce1960-34e2

Glavin, C. (2019, March 13). Higher education in Mozambique. Retrieved March 14, 2021, from https://www.k12academics.com/Higher%20Education%20Worldwide/higher-education-mozambique

Group, G. (2020, March 24). What are the different types of rainwater harvesting systems? Retrieved February 24, 2021, from https://www.rainwatersolutions.co.uk/blog/what-are-the-different-types-of-rainwater-harvesting-systems/

Hermans, M. H. (n.d.). *Sustainable Building Maintenance* (Rep.). Retrieved March 7, 2021.

How many solar panels do I need? (2021). Retrieved March 18, 2021, from https://www.gogreensolar.com/pages/how-many-solar-panels-do-i-need

How to Care for a Living Wall. (2020, June 04). Retrieved February 28, 2021, from https://livewall.com/technical/maintenance/

How to Get Licensed. (n.d.). Retrieved December 9, 2020, from https://www.nspe.org/resources/licensure/how-get-licensed*Impact evaluation of drinking water supply and sanitation interventions in rural Mozambique* (pp. 22-133, Rep.). (n.d.). IOB and UNICEF.

How to register with Association of Engineers of Mozambique. (2020, December 04). Retrieved December 9, 2020, from https://constructionreviewonline.com/professional-associations
/how-to-register-with-association-of-engineers-of-mozambique/Indoor water use at home - direct water use and water footprints. (2020, May 28). Retrieved March 4, 2021, from https://www.watercalculator.org/footprint/indoor-water-use-at-home/

In-depth Mozambique. (n.d.). Retrieved March 14, 2021, from https://www.mz.undp.org/content/mozambique/en/home/ourwork/environmentandenergy/in_depth.html

Individual Comfort Control. (2011, May 26). Retrieved March 18, 2021, from http://seedengr.com/documents/IndividualComfortControl.pdf

Indoor Air Quality. (2018, July 16). Retrieved March 18, 2021, from https://www.epa.gov/report-environment/indoor-air-quality

INGC. 2009. Synthesis report. INGC Climate Change Report: Study on the impact of climate change on disaster risk in Mozambique. [van Logchem B and Brito R (ed.)]. INGC, Mozambique.

International building code. (2020). Falls Church, VA: International Code Council.Julbernardia globiflora. (n.d.). Retrieved March 14, 2021, from http://tropical.theferns.info/viewtropical.php?id=Julbernardia%2Bglobiflora

Jamaca, I. (2021). Renewable Energy in Mozambique. Retrieved March 18, 2021, from https://www.dlapiper.com/fr/africa/insights/publications/2019/11/africa-connected-issue-3/renewable-energy-in-mozambique/

Jett, D. (2020, March 07). Mozambique is a failed state. The West isn't helping it. Retrieved March 14, 2021, from https://foreignpolicy.com/2020/03/07/mozambique-is-a-failed-state-the-west-isnt-helping-it

Jones, J., & West, A. W. (2001, November). Natural Ventilation and Collaborative Design. Retrieved March 18, 2021, from https://search.proquest.com/openview/a6ca6e2306df48dd7da5d16a723d2d2a/1?pq-origsite=gscholar&cbl=41118

Karombo, T. (2021, January 27). These African countries are among the world's worst hit by climate change. Retrieved March 14, 2021, from https://qz.com/africa/1965013/mozambique-zimbabwe-malawi-worlds-worst-hit-by-climate-change/#:~:text=The%20Global%20Climate%20index%20ranks,the%20deaths%20of%20700%20Mozambicans

Langa, P. (2020, September 23). Personal interview [Virtual interview].

Lawrie, L. K., & Crawley, D. B. (2019). Development of Global Typical Meteorological Years (TMYx). Retrieved March 18, 2021, from http://climate.onebuilding.org/

Liggett, R., & Milne, M. (2020, January 23). Climate Consultant 6.0. Retrieved March 18, 2021, from http://www.energy-design-tools.aud.ucla.edu/

Lighting control sensors and their benefits. (n.d.). Retrieved March 18, 2021, from https://www.cmd-ltd.com/advice-centre/lighting-control-systems/lighting-control-sensors-and-their-benefits/#:~:text=Light%20sensors%20installed%20as%20part,no%20electric%20light%20is%20wasted

Living Wall Detail. (2011, March 1). Retrieved March 8, 2021, from https://ensigndesigns.wordpress.com/ciu-multi-cultural-center/comm-1-ciu-9-3/

Low Emitting Materials. (2018, June 28). Retrieved March 18, 2021, from https://www.scrantonproducts.com/low-emitting-materials/

Low-Emitting Materials. (2021). Retrieved March 18, 2021, from https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-healthc-178

Maputo Climate. (n.d.). Retrieved March 18, 2021, from https://en.climate-data.org/africa/mozambique/maputo/maputo-535/

Massingue, A. O. (2019). *Ecological Assessment and Biogeography of Coastal Vegetation and Flora in Southern Mozambique* (pp. 72-84, Tech.). Port Elizabeth, South Africa: South East Academic Libraries System (SEALS).

Matasci, S. (2021, February 4). The cost of solar panels in 2021: Are they worth it? Retrieved March 18, 2021, from https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/

McCleland, W. (2015, June). Brachystegia torrei [Photograph found in Inhassoro, Mozambique]. Retrieved March 8, 2021, from https://flickr.com/photos/25495229@N04/22748571685 (Originally photographed 2015, June 3)

Milotlamicha. (2021, March 09). Climate Maputo. Retrieved March 16, 2021, from https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/maputo_mozambique_1040652

Minimum Design Loads for Buildings and Other Structures. (2013). Reston, Virginia: American Society of Civil Engineers. doi:https://doi.org/10.1061/9780784412916

Momodu, S. (2018, July 4). The Mozambican Civil War (1977-1992). Retrieved March 14, 2021, from https://www.blackpast.org/global-african-history/the-mozambican-civil-war-1977-1992/

Mozambique Air Quality Policies (pp. 1-3, Rep.). (2015). UN Environment Programme.

Mozambique Conservation Areas for Biodiversity and Development (MozBio). (2019, January 31). Retrieved March 24, 2021, from https://www.arcgis.com/apps/MapJournal/index.html?appid=5a7c9b975d6041aabc95b70

9064b039a#:~:text=beginning%20of%20narrative-,Mozambique%20Conservation%20Areas%20for%20Biodiversity%20and%20Development%20(MozBio),Global%20Environment%20Facility%20financed%20project

Mozambique country profile. (2020, January 17). Retrieved March 14, 2021, from https://www.bbc.com/news/world-africa-13890416

Mozambique Economic Update: Less poverty, but more inequality. (2018, November 14). Retrieved March 14, 2021, from https://www.worldbank.org/en/country/mozambique/publication/mozambique-economic-update-less-poverty-but-more-inequality

Mozambique education fact sheet. (n.d.). Retrieved March 14, 2021, from http://www.sacmeq.org/?q=sacmeq-members%2Fmozambique%2Feducation-fact-sheet#:~:text=In%20Mozambique%20primary%20education%20is,into%20school%20is%206%20years

Mozambique National Education Profile 2018 Update (pp. 1-4, Rep.). (2018). Education Policy and Data Center.

Mozambique Waste Management (Rep.). (n.d.). Retrieved March 7, 2021, from United Nations Sustainable Development website.

Mozambique. (n.d.). Retrieved February 22, 2021, from https://sustainabledevelopment.un.org/memberstates/mozambique

Mustonen, T. (2018, January 29). What are green walls - the definition, benefits, design and greenery. Retrieved February 28, 2021, from https://www.naava.io/editorial/what-are-green-walls

NR pervious hardscape materials. (n.d.). Retrieved March 8, 2021, from http://greenmanual.rutgers.edu/nr-pervious-landscape-materials/

Ntumi, D. (2018). *A Simplified Structural Analysis Method for a 20-Foot Cargo Shipping Container* (Master's thesis, University of New Hampshire, Durham, 2018) (pp. 1-118). Durham: University of New Hampshire Scholars' Repository. Retrieved February 1, 2021, from https://scholars.unh.edu/cgi/viewcontent.cgi?article=2260&context=thesis.

Optimize operational and maintenance practices. (2018, August 03). Retrieved March 7, 2021, from https://www.wbdg.org/design-objectives/sustainable/optimize-operational-maintenance-practices#:~:text=Sustainable%20operations%20and%20maintenance%20(O%26M,reuse%20and%20recycle%20building%20components

Overhang Recommendations. (n.d.). Retrieved March 13, 2021, from https://susdesign.com/overhang_recs/index.php

[Photograph found in Fine Home Building]. (n.d.). In 1210746442 902293329 R. Hausslein (Author). Retrieved February 21, 2021, from https://www.finehomebuilding.com/1994/05/01/monolithic-column-forms*Policy Brief IV Solid Waste Management in Maputo, Mozambique* (4th ed., Vol. 14, pp. 1-4, Rep.). (n.d.). Bergen, Norway: Cities Alliance.

Polycarbonate products. (2017, September 05). Retrieved February 28, 2021, from https://solarinnovations.com/information/glazing/polycarbonate-products/

Praia da Macaneta. (n.d.). Retrieved March 13, 2021, from http://www.getamap.net/maps/mozambique/maputo/_praia_da_macaneta/

Rahman, F. U. (Ed.). (2019, January 24). Lightweight Aggregate Concrete . The Constructor. https://theconstructor.org/concrete/lightweight-aggregate-concrete/6734/.

Rauch, J. (2020, February 6). What is greywater? How to collect it & use it safely. Retrieved March 4, 2021, from https://blog.publicgoods.com/what-is-greywater-and-how-does-it-apply-to-you/

Recycling plastics in Mozambique. (2020, September 28). Retrieved March 8, 2021, from https://www.africanews.com/2020/09/28/recycling-plastics-in-mozambique//

Refrigerators. (n.d.). Retrieved March 18, 2021, from https://www.energystar.gov/products/appliances/refrigerators

Reggev, K. (2020, February 20). Living Green Walls 101: Their Benefits and How They're Made. Retrieved February 28, 2021, from https://www.dwell.com/article/living-green-walls-how-to-5fa86ae0

Renewable Energy Potential. (n.d.). Retrieved March 18, 2021, from https://www.get-invest.eu/market-information/mozambique/renewable-energy-potential/#:~:text=Mozambique%20has%20a%20total%20renewable,and%20geothermal%20(0.1%20GW)

Roberts, T. (2020, February 15). Cotton batt insulation - is it for you? Retrieved March 18, 2021, from https://www.buildwithrise.com/stories/cotton-batt-insulation-is-it-for-you

Saner, E. (2019, December 09). The no-flush movement: The unexpected rise of the composting toilet. Retrieved March 4, 2021, from https://www.theguardian.com/global/2019/dec/09/no-flush-movement-composting-toilet-clean-water-waste-fertiliser-eco-revolution

Saving water while washing the dishes. (2020, April 17). Retrieved March 4, 2021, from https://www.watercalculator.org/posts/dish-washing/

Schlossberg, T. (2016, August 09). How Bad is Your Air-Conditioner for the Planet? Retrieved March 18, 2021, from https://www.nytimes.com/2016/08/10/science/air-conditioner-global-warming.html

Selecting Low-Emitting Materials. (2017, August 23). Retrieved March 18, 2021, from https://santacruzarchitect.wordpress.com/2017/08/23/selecting-low-emitting-materials/

Series 1 freight containers - Specification and testing (Sixth ed.). (2013). Geneva, Switzerland: International Organization of Standards.

Shinn, L. (2018, June 15). Renewable Energy: The Clean Facts. Retrieved March 19, 2021, from https://www.nrdc.org/stories/renewable-energy-clean-facts

Shipping Container Home Foundations 101. (2020, October 01). Retrieved February 22, 2021, from https://www.discovercontainers.com/shipping-container-home-foundation-types/

Soak Up the Rain: Permeable Pavement. (2020, November 24). Retrieved February 24, 2021, from https://www.epa.gov/soakuptherain/soak-rain-permeable-pavement#:~:text=Soak%20Up%20the%20Rain%3A%20Permeable%20Pavement,-Alternatives%20to%20traditional&text=These%20alternative%20materials%20which%20include,layers%20of%20soil%20and%20gravel

Standard 55: Thermal Environmental Conditions for Human Occupancy. (2017). Atlanta, GA: ASHRAE.

Steinhilber, B. (2020, August 03). Why walking is the most underrated form of exercise. Retrieved March 8, 2021, from https://www.nbcnews.com/better/health/why-walking-most-underrated-form-exercise-ncna797271

Submetering for Commercial and Residential Properties. (n.d.). Retrieved March 18, 2021, from https://www.triacta.com/post/commercial-submetering-how-much-could-you-save-really#:~:text=But%20how%20much%20can%20you%20save%2C%20really%3F&text=But%20that%20was%20just%20the,15%25%20to%2045%25%20savings

Sunshine & daylight hours in Maputo, Mozambique. (n.d.). Retrieved March 13, 2021, from http://www.maputo.climatemps.com/sunlight.php

Sustainability in Steel Recycling. (2020). Retrieved March 18, 2021, from https://www.steel.org/wp-content/uploads/2020/09/Steel-Sustains-in-Recyclability-Fact-Sheet.pdf

Tartarini, F., Schiavon, S., Cheung, T., & Hoyt, T. (2020). CBE Thermal Comfort Tool. Retrieved March 18, 2021, from https://comfort.cbe.berkeley.edu/

Technical Specification for a typical 40' x 8' x 9'6" ISO Type Steel Dry Cargo Container "High-cube" (Tech.). (n.d.). Retrieved February 1, 2021, from Steinecker Container website: http://steinecker-container.de/container/Container2/Spez-Container/Spez_high%20cube40.pdf

The world of zinc primers just changed. (2018, June 05). Retrieved March 19, 2021, from https://www.bicmagazine.com/departments/maintenance-reliability/june-july-2018-the-world-of-zinc-primers-just-changed/

Transforming our world: The 2030 agenda for sustainable Development | Department of economic and social affairs. (n.d.). Retrieved February 22, 2021, from https://sdgs.un.org/2030agenda

Tree nurseries and reforestation, Mozambique. (2019, February 24). Retrieved March 2, 2021, from https://africanconservation.org/project/tree-nurseries-and-reforestation-mozambique/

UFC 3-310-03A Seismic Design for Buildings (3- Discipline-Specific Criteria 3-300: Structural and Seismic Design, pp. 1-829, Rep.). (2005). Virginia: United States of America Department of Defense. Retrieved from https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-3-310-03a.

Understanding CEER – what is a good CEER rating for AC? (2020, December 11). Retrieved March 18, 2021, from https://www.pickhvac.com/faq/what-is-ceer/

Understanding corrosion and how to protect against it. (2015, December 18). Retrieved March 19, 2021, from https://www.manufacturing.net/home/article/13217663/understanding-corrosion-and-how-to-protect-against-it

UO solar radiation monitoring laboratory. (n.d.). Retrieved March 13, 2021, from http://solardat.uoregon.edu/

Update or Replace Windows. (n.d.). Retrieved March 18, 2021, from https://www.energy.gov/energysaver/design/windows-doors-and-skylights/update-or-replace-windows

Vleeschauwer, B. (2019, April 25). How rampant Deforestation Made Mozambique more vulnerable to Cyclone idai. Retrieved March 2, 2021, from https://www.thenewhumanitarian.org/news-feature/2019/04/24/how-rampant-deforestation-made-mozambique-more-vulnerable-cyclone-idai

Walker, A. (2016, August 02). Natural Ventilation. Retrieved March 18, 2021, from https://www.wbdg.org/resources/natural-ventilation#:~:text=Natural%20ventilation%2C%20unlike%20fan%2Dforced,and%20to%20increase%20thermal%20comfort.

Water, sanitation and hygiene (wash). (n.d.). Retrieved February 24, 2021, from https://www.unicef.org/mozambique/en/water-sanitation-and-hygiene-wash

WeatherSpark. (n.d.). Average Weather in Maputo, Mozambique. Retrieved March 16, 2021, From https://weatherspark.com/y/97168/Average-Weather-in-Maputo-Mozambique-Year-Round

Weinmaster, M. (n.d.). Are Green Walls as "Green" as they Look? *Journal of Green Building, 4*(4), 3-18.

Wells for Africa: What's the Cost. (n.d.). Retrieved February 24, 2021, from https://waterwellsforafrica.org/whats-the-cost/

What are the most energy efficient appliances and are they worth it? (2019, January 2). Retrieved March 18, 2021, from https://www.energysage.com/energy-efficiency/costs-benefits/energy-star-rebates/

What is Low-E glass & does it make windows energy efficient? (2017, February 14). Retrieved March 18, 2021, from https://www.stanekwindows.com/what-is-low-e-glass-and-does-it-make-windows-more-energy-efficient.aspx

What is a Split Air Conditioner? (2020, December 18). Retrieved March 19, 2021, from https://modernize.com/hvac/central-air-conditioner-installation/split#:~:text=A%20split%20air%20conditioner%20consists,an%20inside%20air%20outlet%20unit.&text=One%20of%20the%20most%20common,conditioner%20system%20and%20here's%20why

Why does wood absorb vibration so well? (n.d.). Retrieved 2021, from https://www.montaukhardwoodbikes.com/why-does-wood-absorb-vibration-so-well

Wind energy in Mozambique: First wind farm to be set up. (2020, August 31). Retrieved March 18, 2021, from https://www.evwind.es/2020/08/31/wind-energy-in-mozambique-first-wind-farm-to-be-set-up/76909

World Climate Guide. (n.d.). Climate - Mozambique. Retrieved March 16, 2021, from https://www.climatestotravel.com/climate/mozambique

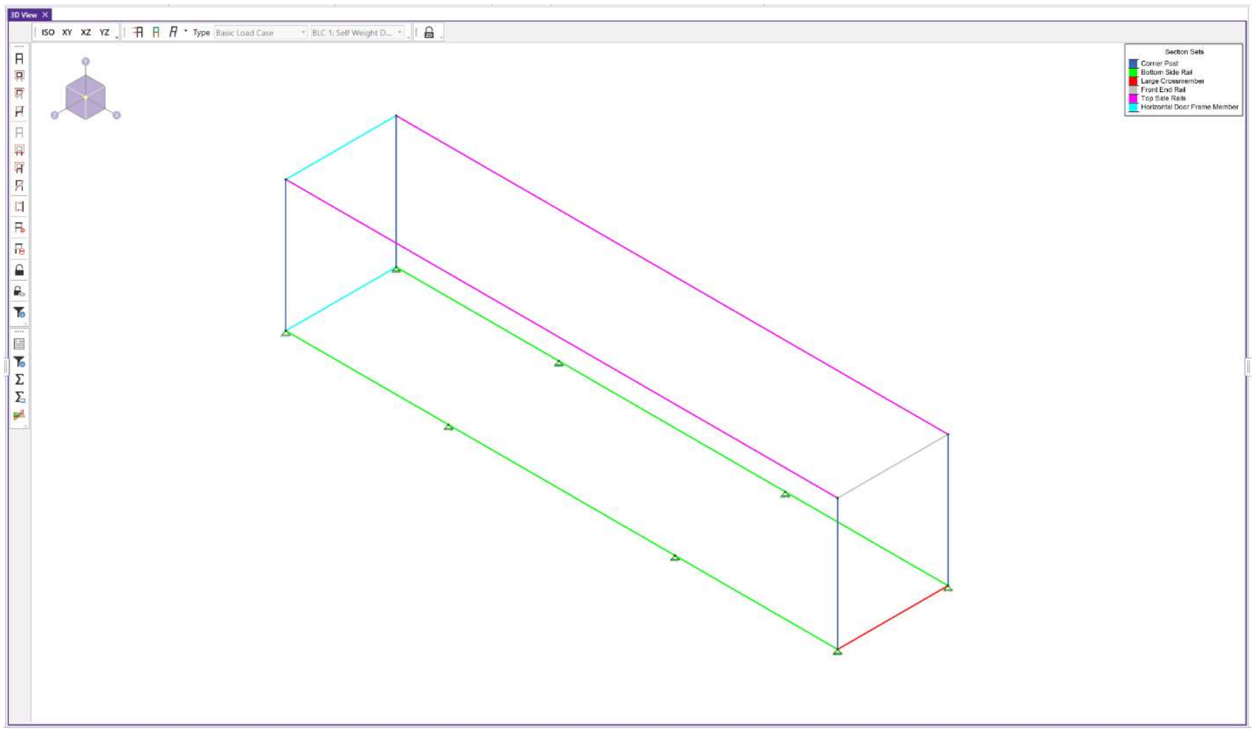
World Green Building Council (WGBC). (2021). New report: The building and construction sector can reach net zero carbon emissions by 2050. Retrieved March 16, 2021, from https://www.worldgbc.org/news-media/WorldGBC-embodied-carbon-report-published

Yu Media Group. (n.d.). Maputo, Mozambique - detailed climate information and Monthly weather forecast. Retrieved March 16, 2021, from https://www.weather-atlas.com/en/mozambique/maputo-climate

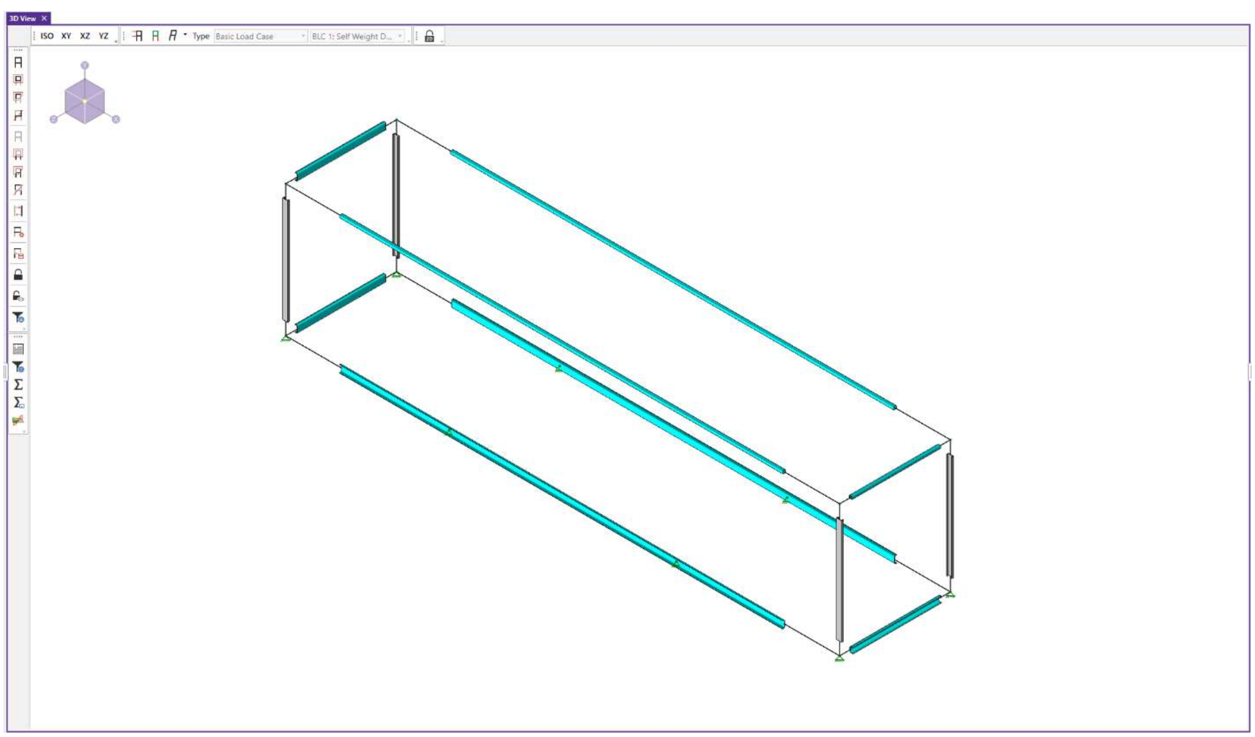
[Photograph found in Burma Valley, Zimbabwe]. (2004, August 15). Retrieved March 8, 2021, from https://www.zambiaflora.com/speciesdata/image-display.php?species_id=126770&image_id=1

Appendix A: RISA-3D 19.0 40-Foot High-cube Shipping Container Models

Model 1: Structural Frame



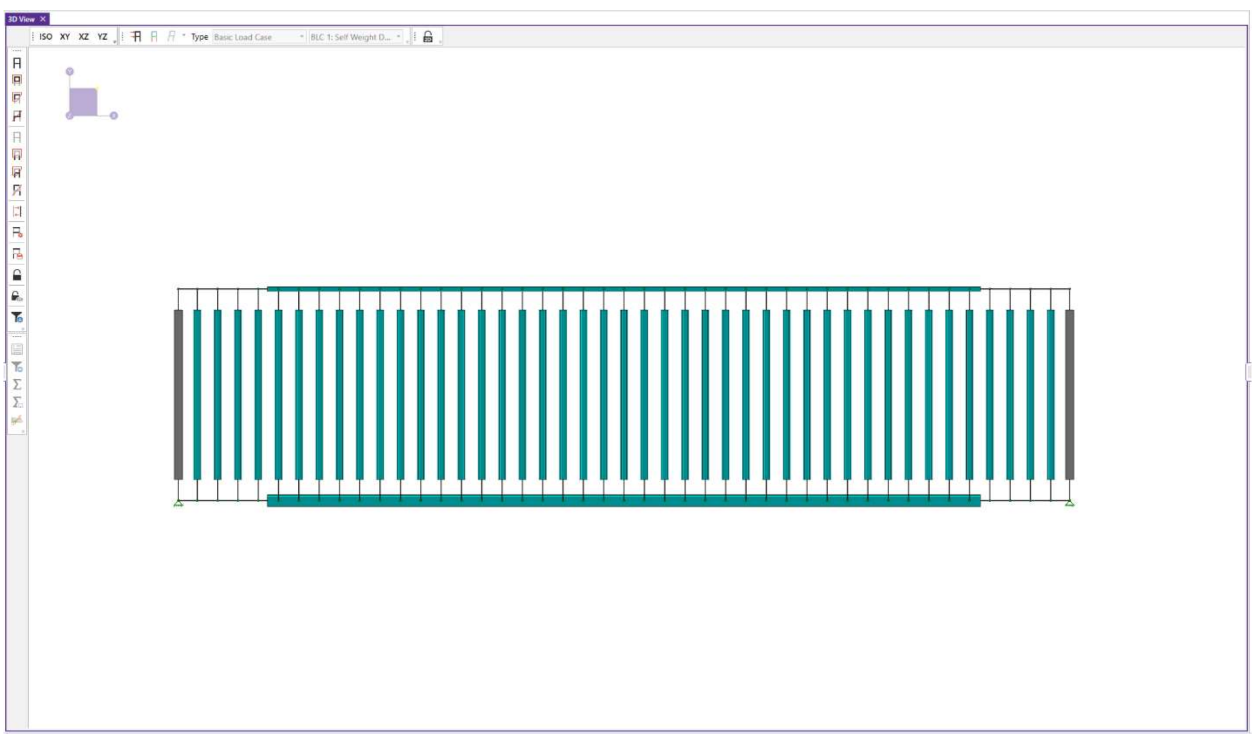
Model 1: Structural Frame of a 40-foot High-cube Shipping Container with Member Types



Model 1: Structural Frame of a 40-foot High-cube Shipping Container with Member Renders

Model 2: Structural Truss with Verticals

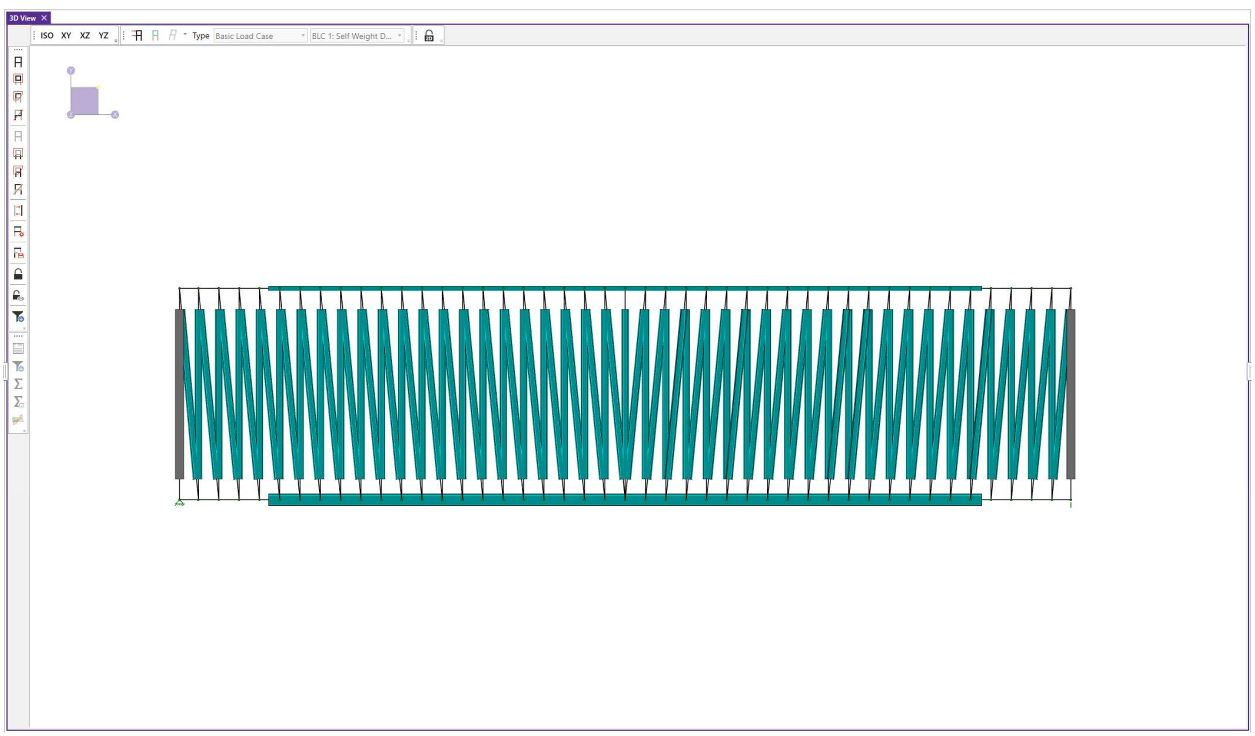
Model 2: Structural Truss with Verticals of a 40-foot High-cube Shipping Container with Member Types



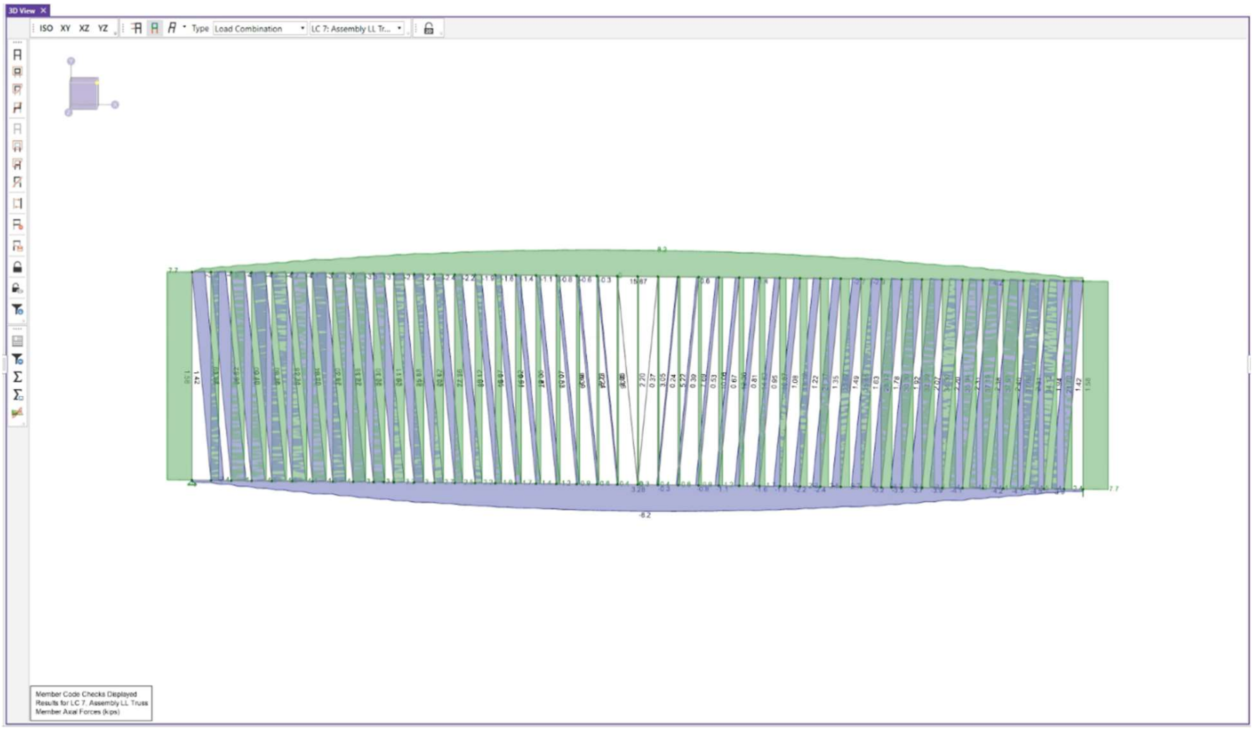
Model 2: Structural Truss with Verticals of a 40-foot High-cube Shipping Container with Member Renders

Model 3: Structural Truss with Verticals and Horizontals

Model 3: Structural Truss with Verticals and Horizontals of a 40-foot High-cube Shipping Container with Member Types

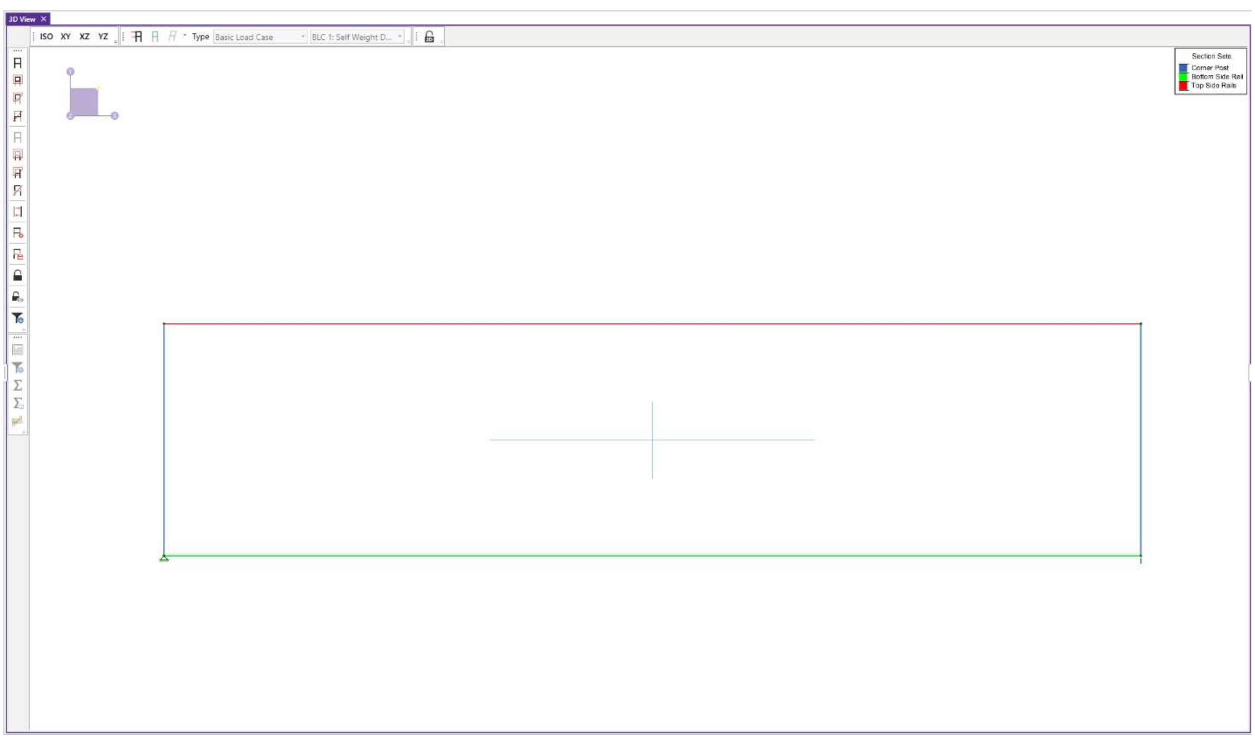


Model 3: Structural Truss with Verticals and Horizontals of a 40-foot High-cube Shipping Container with Member Renders



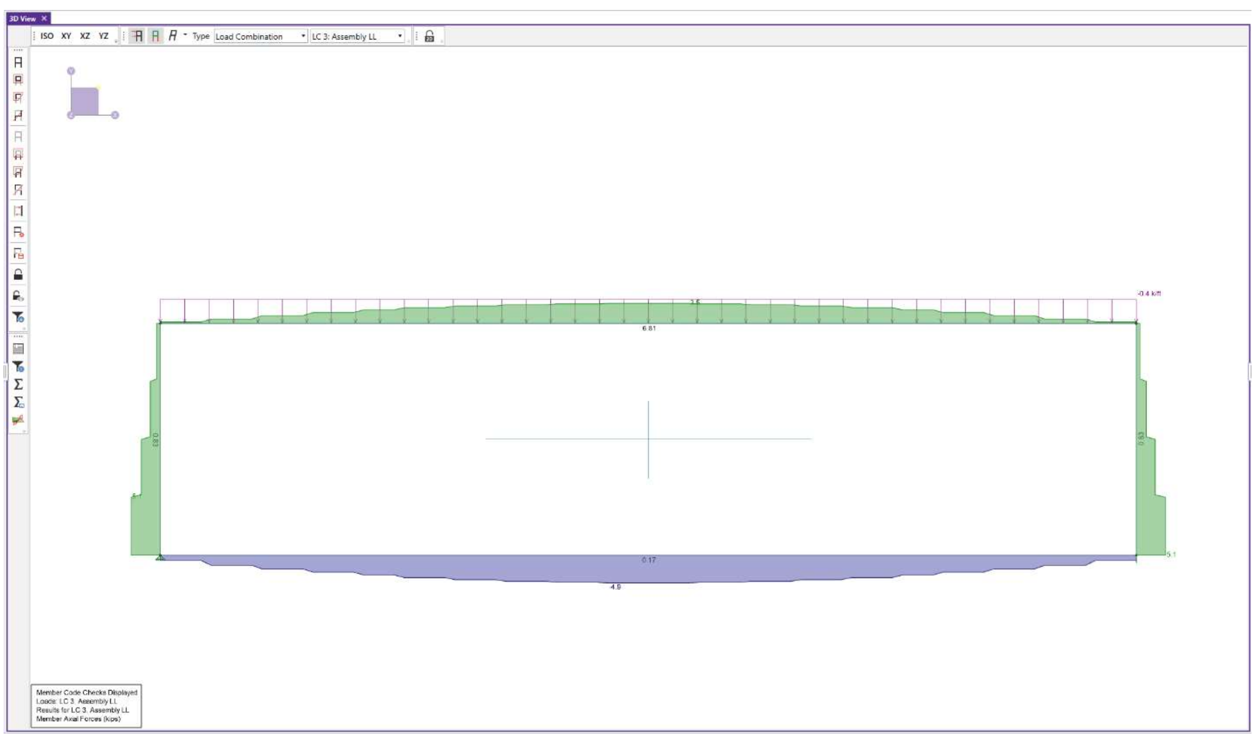
Model 3: Structural Truss with Verticals and Horizontals of a 40-foot High-cube Shipping Container Axial Force Distribution

Model 4: Structural Frame with Wall Panels



Model 4: Structural Truss with Wall Panels of a 40-foot High-cube Shipping Container with Member Types

Model 4: Structural Truss with Wall Panels of a 40-foot High-cube Shipping Container with Member Renders



Model 4: Structural Truss with Wall Panels of a 40-foot High-cube Shipping Container with Axial Force Distribution

Appendix B: Structural Load Calculations

Self-Weight Dead Load

8.4 kips/container / 4 corner posts = **2.1 kips / corner post**

Assembly Live Load

Tributary Area of one Top Side Rail = 4'-0" x 40'-0" = 160 sf

100 psf x (160 sf) = 16,000 lbs / (1000 lbs/kip) = 16 kips

16 kips / 40'-0" = **0.4 kips/ft Uniform Distributed Load on Each Top Side Rail**

Applied Dead Load

27 psf x (8'-0" x 40'-0') = 8,640 lbs / 1,000 lbs/kip = 8.64 kips

8.64 kips / (40'-0" + 40-0" + 8'-0" + 8'-0") = **0.09 kips/foot Uniform Distributed Load on All Top Rails**

Equation 1: Wind Load

$F_w = \frac{1}{2} pv^2 A$

Where:

F_w = Wind Force [N]

p= density of air [kg/m^3]

v= wind speed [m/s]

A= surface area [m^2]

40'-0" x 9'-6" side:

$F_w = \frac{1}{2} (1.2\ kg/m^3)(13.4\ m/s)^2 (12.192\ m * 2.896\ m) = 3803.95\ N * 0.224809\ lbf/N = 854.95\ lbf$

854.95 lbf / (40'-0" x 9'-6") = 2.249 psf / (1000 lbs/kip) = **0.0022 ksf**

8'-0" x 9'-6" side:

$F_w = \frac{1}{2} (1.2\ kg/m^3)(13.4\ m/s)^2 (2.438\ m * 2.896\ m) = 760.66\ N * 0.224809\ lbf/N = 171.00\ lbf$

171.00 lbf / (8'-0" x 9'-6") = 2.250 psf / (1000 lbs/kip) = **0.0022 ksf**

20'-0" x 9'-6" side:

$F_w = \frac{1}{2} (1.2\ kg/m^3)(13.4\ m/s)^2 (6.096\ m * 2.896\ m) = 1{,}901.97\ N * 0.224809\ lbf/N = 427.58\ lbf$

427.58 lbf / (20'-0" x 9'-6") = 2.25 psf / (1000 lbs/kip) = **0.0022 ksf**

Seismic Equations

Equation 2: Design Short Period Spectral Acceleration Parameter (2018 IBC 1613.2.4)

$S_{DS} = \frac{2}{3} F_a S_s$

Where:

S_{DS} = Design Short Period Spectral Acceleration Parameter

F_a = Short Period Site Coefficient

S_S= Mapped Short Period Acceleration Parameter for the MCE @ 5% damping

S_{DS} = ⅔ (1.2)(0.62) = 0.496 → Seismic Design Category C

Equation 3: Design Long Period Spectral Acceleration Parameter (2018 IBC 1613.2.4)

$S_{Dl} = ⅔ F_v S_l$

Where:

S_{D1} = Design Long Period Spectral Acceleration Parameter

F_v = Long Period Site Coefficient

S_l = Mapped Long Period Acceleration Parameter for the MCE @ 5% damping

S_{D1} = ⅔ (2.4)(0.28) = 0.448 → Seismic Design Category D

Equation 4: Seismic Base Shear Coefficient (ASCE 7-10 Section 12.8.8.1)

$C_S = S_{DS} / (R/I)$

Where:

C_S = Seismic Base Shear Coefficient

S_{DS} = Design Short Period Spectral Acceleration Parameter (from Equation 2)

R = Response Modification Coefficient → Steel Moment Frame → R = 8

I = Occupancy Importance Factor → Occupancy Category III → I = 1.25

C_S = (0.496) / (8/1.25) = 0.0775

Equation 5: Base Shear (ASCE 7-10 Section 12.8.1)

$V = C_S * W$

Where:

V = Base Shear [kips]

C_S = Seismic Base Shear Coefficient (from Equation 4)

W = Seismic Weight = all structural and non-structural elements

V = (0.0775)(8.4 kips) = 0.651 kips

Equation 6: Lateral Force at Each Story (ASCE 7-10 Section 12.8.3)

$F_x = [(V-F_t)\, w_x h_x]/(\Sigma w_i h_i)$

Where:

F_x= force at story x [kips]

V = base shear force [kips] (from Equation 5)

F_t = 0 for most low rise buildings

w_x = weight of story x

h_x = height of story x

w_i= weight of the building up to story x

h_i = height of the building up to story x

Three Story Seismic Forces

Level	w_x [k]	h_x [ft]	$w_x h_x$ [kft]	$w_x h_x / \Sigma w_i h_i$	F_x [k]	F_x [ksf] 8'-0" x 9'-6" wall
3	8.4	28.5	239.4	0.500	**0.3225**	0.0042
2	8.4	19.0	159.6	0.333	**0.2168**	0.0029
1	8.4	9.5	79.8	0.167	**0.1087**	0.0014
Totals	25.2		478.8	1	0.651	

Four Story Seismic Forces

Level	w_x [k]	h_x [ft]	$w_x h_x$ [kft]	$w_x h_x / \Sigma w_i h_i$	F_x [k]	F_x [ksf] 8'-0" x 9'-6" wall
4	8.4	38.0	319.2	0.400	**0.2604**	0.0034
3	8.4	28.5	239.4	0.300	**0.1953**	0.0026
2	8.4	19.0	159.6	0.200	**0.1302**	0.0017
1	8.4	9.5	79.8	0.100	**0.0651**	0.0009
Totals	33.6		798.0		0.651	

Appendix C: Foundation Design Calculations

<u>Foundation Design Equations:</u>

Required Footing = Column Load / Soil Bearing Capacity

Column Load = Total gravity loads transferred through container corner posts

Soil Allowable Vertical Foundation Pressure = 1,500 psf

**Assuming Load Bearing Values for soil to be the minimum conditions described in IBC 2018 Table 1806.2 (Class of Materials: Clay, sandy clay, silty clay, clayey silt, silt and sandy silt)*

Column Loads for Administration Building Tower:

Dead Loads:

Self-weight DL of 40-foot container	8775	lbs / container
Self-weight of DL 20-foot container	4850	lbs / container
DL of Stairs	15345	lbs
DL of roof deck	27	psf

Calculation of Stair DL:

EXIT STAIRWAY DESIGN TABLES

TWO-FLIGHT STAIR: ENGLISH UNITS

Floor-to-Floor Height (ft-in.)	Number of Risers	Riser Height (in.)	Tread Depth (in.)	Overall Inside Length of Stair Enclosure (ft-in.) 36" Width	44" Width	56" Width	66" Width	88" Width
7-8[a]	14	6.57	11	11-6	12-10	14-10	16-6	20-2
8-0[a]	14	6.86	11	11-6	12-10	14-10	16-6	20-2
8-4	15	6.67	11	12-5	13-9	15-9	17-5	21-1
8-8	15	6.93	11	12-5	13-9	15-9	17-5	21-1
9-0	16	6.75	11	12-5	13-9	15-9	17-5	21-1
9-4	16	7.00	11	12-5	13-9	15-9	17-5	21-1
9-8	17	6.82	11	13-4	14-8	16-8	18-4	22-0
10-0	18	6.67	11	13-4	14-8	16-8	18-4	22-0
10-4	18	6.89	11	13-4	14-8	16-8	18-4	22-0
10-8	19	6.74	11	14-3	15-7	17-7	19-3	22-11
11-0	19	6.95	11	14-3	15-7	17-7	19-3	22-11
11-4	20	6.80	11	14-3	15-7	17-7	19-3	22-11
11-8	20	7.00	11	14-3	15-7	17-7	19-3	22-11
12-0	21	6.86	11	15-2	16-6	18-6	20-2	23-10
12-4	22	6.73	11	15-2	16-6	18-6	20-2	23-10
12-8	22	6.91	11	15-2	16-6	18-6	20-2	23-10
13-0	23	6.78	11	16-1	17-5	19-5	21-1	24-9
13-4	23	6.96	11	16-1	17-5	19-5	21-1	24-9
13-8	24	6.83	11	16-1	17-5	19-5	21-1	24-9
14-0	24	7.00	11	16-1	17-5	19-5	21-1	24-9
14-4	25	6.88	11	17-0	18-4	20-4	22-0	25-8
14-8	26	6.77	11	17-0	18-4	20-4	22-0	25-8
15-0	26	6.92	11	17-0	18-4	20-4	22-0	25-8
16-0	28	6.86	11	17-11	19-3	21-3	22-11	26-7
17-0	30	6.80	11	18-10	20-2	22-2	23-10	27-6
18-0	31	6.97	11	19-9	21-1	23-1	24-9	28-5
19-0	33	6.91	11	20-8	22-0	24-0	25-8	29-4
20-0	35	6.86	11	21-7	22-11	24-11	26-7	30-3
21-0	36	7.00	11	21-7	22-11	24-11	26-7	30-3
22-0	38	6.95	11	22-6	23-10	25-10	27-6	31-2
23-0	40	6.90	11	23-5	24-9	26-9	28-5	32-1
24-0	42	6.86	11	24-4	25-8	27-8	29-4	33-0

[a]The headroom in these stairs may be deficient, depending on the detailing of the stair structure.
Stairway widths may be determined rapidly by using the tables and graphs on pages 302–303 and 308–309.

From The Architect's Studio Companion[1]

A ~9'-8" height difference between stories → 17 Risers, h = 6.82," d= 11.00" → 56" Width → 16'-8" stair enclosure length

Weight of Concrete with Reinforcement = 150 lbs/ft^3

Volume of one stair = (6.82"/12"/') x (11.00"/12"/') x [(56"/2)/12"/'] = 1.216 ft^3
Total Volume for 3 Flights = 1.216 ft^3 x 17 stairs/flight x 3 flights = 61.016 ft^3
Weight of Stairs = 62.016 ft^3 x 150 lbs/ft^3 = 9302.4 lbs

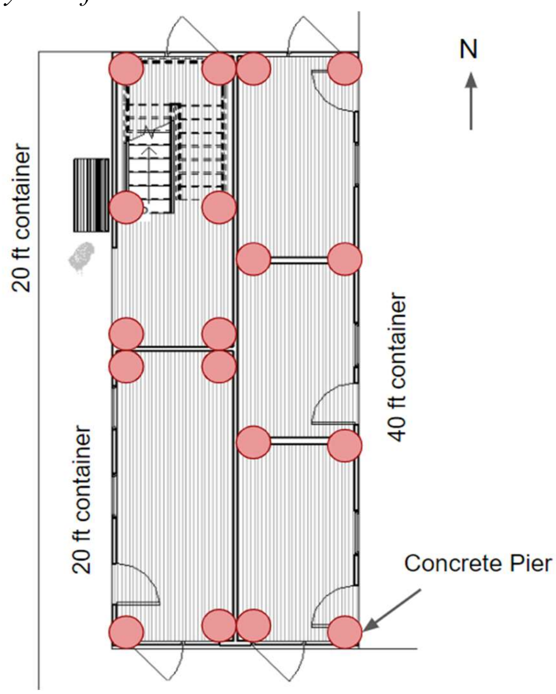
Volume of landings = (6.5"/12"/') x (48"/12"/') x (56"/12"/') = 10.11 ft^3
Total Volume of 4 landings = 10.07 ft^3 x 4 = 40.28 ft^3
Weight of Landings = 40.28 ft^3 x 150 lbs/ft^3 = 6042.6 lbs

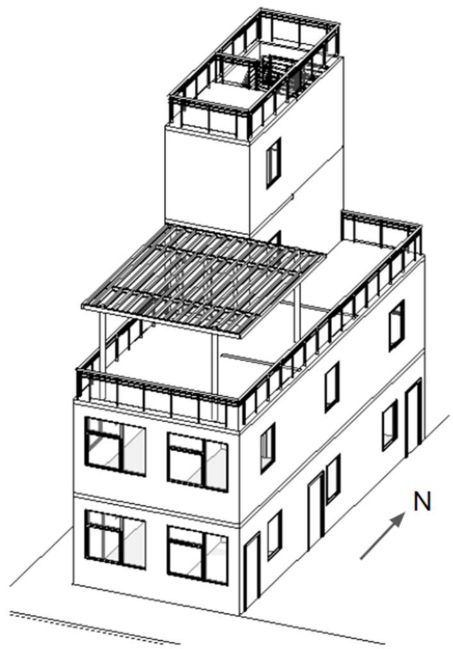
Total Dead Load Of Staircases = 9302.4 lbs + 6042.6 lbs = **15345 lbs**

Live Loads for Administration Building Tower:

	Uniform LL		Concentrated LL		
LL of office space	50	psf	2000	lbs	IBC Table 1607.1
LL of roof deck	100	psf	-	-	IBC Table 1607.1
LL of stairway	100	psf	-	-	IBC Table 1607.1
LL of Tower Terrace	100	psf	-	-	IBC Table 1607.1

Layout of Concrete Piers:





NW 20-foot container stack (4 containers) - Stairway

Total DL = (4850 lbs)(4) + 15345 lbs + (27 psf)(8')(10') = 36905 lbs

Total LL = (100 psf)(8')(20')(4) + (100 psf)(8')(10') = 72000 lbs

Combined Gravity Load = DL + LL = 36905 lbs + 72000 lbs = 108905 lbs

Total Load per corner column = 108905 lbs / 6 = 18150.83 lbs / pier

Required Footing = 18150.83 lbs / 1,500 psf = **12.10 sf ~ 12.5 sf**

Six 12.5 sf footings required

SW 20-foot container stack (2 containers) - Offices

Total DL = (4850 lbs)(2) + (27 psf)(8')(20') = 14020 lbs

Total LL = (50 psf)(8')(20')(2) + 2000 lbs + (100 psf)(8')(20') = 34000 lbs

Combined Gravity Load = DL + LL = 14020 lbs + 34000 lbs = 48020 lbs
Total Load per corner column = 48020 lbs / 4 = 12005 lbs / pier
Required Footing = 12005 lbs / 1,500 psf = **8.00 sf ~ 8 sf**

Four 8 sf footings required

E 40-foot container stack (2 containers) – Offices
Total DL = (8775 lbs)(2) + (27 psf)(8')(40') = 26190 lbs
Total LL = (50 psf)(8')(40')(2) + 2000 lbs + (100 psf)(8')(40') = 66000 lbs
Combined Gravity Load = DL + LL = 26190 lbs + 66000 lbs = 92190 lbs
Total Load per corner column = 92190 lbs / 8 = 11523.75 lbs / pier
Required Footing = 11523.75 lbs / 1,500 psf = **7.68 sf ~ 8 sf**

Eight 8 sf footings required

Appendix D: Thermal Load Calculations

Equations:

Walls/Roof Heating: $Q = UA(T_{in}-T_{out})$

Floor Heating: $Q = UA(T_{in}-T_{earth})$

All Cooling: $Q = UA*CLTD$

$U = 1/R$

$R = R_{out} + \frac{x}{k} + R_{in}$

Infiltration: $Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Where:

Q = heat loss (W)

A = area of exposed surface (m^2)

T_{in} = inside air temperature (ºC)

T_{out} = outside air temperature (ºC)

T_{earth} = earth temperature (ºC)

CLTD = cooling load temperature difference (ºC)

U = overall heat transmission coefficient (W/m^2K)

R = thermal resistivity (m^2K/W)

R_{out} = outside air thermal resistivity (m^2K/W)

R_{in} = inside air thermal resistivity (m^2K/W)

x = thickness of material (m)

k = thermal conductivity of material (W/mK)

ACH = air changes per hour (no unit)

V = volume of the space (m^3)

Shipping Container Building Material Properties

	Material	Thickness (m)	Thermal Conductivity (W/mK)	Area of Exposed Surface (m^2)
Walls	Steel	0.0016	56.1	84.9

	Insulation	0.1524	0.04	
	Drywall	0.0127	0.17	
Floor	Plywood	0.028	0.13	29.8
Roof	Steel	0.002	56.1	29.8
	Insulation	0.1524	0.04	
	Drywall	0.0127	0.17	

Maputo Climate Values

	Winter		Summer	
	Inside	Outside	Inside	Outside
Air R-Values (m^2K/W)	0.12	0.03	0.12	0.044
Worst Case Outdoor Temperature (ºC)	-	12.4	-	30.8
Average Case Outdoor Temperature (ºC)	-	19.1		25.6
Earth Temperature (ºC)	-	20.3	-	24
Indoor Temperature (ºC)	22	-	22	-

Calculations

Single Container

Heating

With Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $\quad R = 0.03 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $\quad R = 4\ m^2K/W$

$U = 1/R \qquad U = 1/4 \qquad U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 84.91 * (22-12.4)$ **$Q = 202.03$ W**

Average Case: $Q = 0.25 * 84.91 * (22-19.1)$ **$Q = 61.03$ W**

<u>Floor:</u>

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.37\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ $Q = 2.74 * 29.77 * (22-20.3)$ **$Q = 138.50$ W**

<u>Roof:</u>

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 29.77 * (22-12.4)$ **$Q = 70.83$ W**

Average Case: $Q = 0.25 * 29.77 * (22-19.1)$ **$Q = 21.40$ W**

<u>Infiltration:</u>

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.85 * 86.33 * (22-12.4)$ **$Q = 3.52$ W**

Average Case: $Q = 0.005 * 0.85 * 86.33 * (22-19.1)$ **$Q = 1.06$ W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 202.03 + 138.50 + 70.83 + 3.52$ **$Q_T = 414.88$ W**

Average Case: $Q_T = 61.03 + 138.50 + 21.40 + 1.06$ **$Q_T = 221.99$ W**

Without Insulation

<u>Walls:</u>

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 84.91 * (22-12.4)$ **$Q = 3627.19$ W**

Average Case: $Q = 4.45 * 84.91 * (22-19.1)$ **$Q = 1095.71$ W**

Floor:

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ $Q = 2.74 * 29.77 * (22-20.3)$ **$Q = 138.50$ W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 29.77 * (22-12.4)$ **$Q = 1271.56$ W**

Average Case: $Q = 4.45 * 29.77 * (22-19.1)$ **$Q = 384.12$ W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.85 * 86.33 * (22-12.4)$ **$Q = 3.52$ W**

Average Case: $Q = 0.005 * 0.85 * 86.33 * (22-19.1)$ **$Q = 1.06$ W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 3627.19 + 138.50 + 1271.56 + 3.52$ **$Q_T = 5040.78$ W**

Average Case: $Q_T = 1095.71 + 138.50 + 384.12 + 1.06$ **$Q_T = 1619.40$ W**

Cooling

With Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4$ m^2K/W

$U = 1/R$ $U = 1/4$ $U = 0.25$ W/m^2K

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 84.91 * 10.30$ **Q = 216.02 W**

Average Case: $Q = 0.25 * 84.91 * 7.00$ **Q = 146.81 W**

Floor:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38$ m^2K/W

$U = 1/R$ $U = 1/0.38$ $U = 2.64$ W/m^2K

$Q = UA*CLTD$ $Q = 2.64 * 29.77 * 0$ **Q = 0 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4$ m^2K/W

$U = 1/R$ $U = 1/4$ $U = 0.25$ W/m^2K

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 29.77 * 17.20$ **Q = 126.46 W**

Average Case: $Q = 0.25 * 29.77 * 13.90$ **Q = 102.20 W**

Internal Loads:

Lighting: Q = W/area *area Q = 9.67 * 29.77 Q = 287.86 W

Equipment: Q = 300 W/desktop * 2 desktops Q = 600.00 W

People: Q = 65 W/person * 4 people Q = 260.00 W

$Q_{internal} = 287.86 + 600.00 + 260.00$ **$Q_{internal}$ = 1147.86 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **Q = 2.26 W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **Q = 0.92 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 216.02 + 0 + 126.46 + 1147.86 + 2.26$ **Q_T = 1492.59 W**

Average Case: $Q_T = 146.81 + 0 + 102.20 + 1147.86 + 0.92$ **Q_T = 1397.79 W**

Without Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R U = 1/0.24 $U = 4.19\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 4.19 * 84.91 * 10.30 **Q = 3663.46 W**

Average Case: Q = 4.19 * 84.91 * 7.00 **Q = 2489.73 W**

Floor:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

U = 1/R U = 1/0.38 $U = 2.64\ W/m^2K$

Q = UA*CLTD Q = 2.64 * 29.77 * 0 **Q = 0 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R U = 1/0.24 $U = 4.19\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 4.19 * 29.77 * 17.20 **Q = 2144.62 W**

Average Case: Q = 4.19 * 29.77 * 13.90 **Q = 1733.15 W**

Internal Loads:

Lighting: Q = W/area *area Q = 9.67 * 29.77 Q = 287.86 W

Equipment: Q = 300 W/desktop * 2 desktops Q = 600.00 W

People: Q = 65 W/person * 4 people Q = 260.00 W

$Q_{internal} = 287.86 + 600.00 + 260.00$ **$Q_{internal}$ = 1147.86 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **$Q = 2.26$ W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **$Q = 0.92$ W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 3663.46 + 0 + 2144.62 + 1147.86 + 2.26$ **$Q_T = 6958.19$ W**

Average Case: $Q_T = 2489.73 + 0 + 1733.15 + 1147.86 + 0.92$ **$Q_T = 5371.66$ W**

Two Containers Side by Side

Heating

With Insulation

Walls (each container):

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 49.53 * (22-12.4)$ **$Q = 117.85$ W**

Average Case: $Q = 0.25 * 49.53 * (22-19.1)$ **$Q = 35.60$ W**

Floor (each container):

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.37\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ $Q = 2.74 * 29.77 * (22-20.3)$ **$Q = 138.50$ W**

Roof (each container):

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 29.77 * (22-12.4)$ **$Q = 70.83$ W**

Average Case: $Q = 0.25 * 29.77 * (22-19.1)$ **$Q = 21.40$ W**

Infiltration (each container):

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.85 * 86.33 * (22-12.4)$ **$Q = 3.52$ W**

Average Case: $Q = 0.005 * 0.85 * 86.33 * (22-19.1)$ **$Q = 1.06$ W**

Total:

$Q_T = \Sigma Q_{components}$

Each Container:

Worst Case: $Q_T = 117.85 + 138.50 + 70.83 + 3.52$ **$Q_T = 330.70$ W**

Average Case: $Q_T = 35.60 + 138.50 + 21.40 + 1.06$ **$Q_T = 196.56$ W**

Total Configuration:

Worst Case: $Q_T = 330.70 + 330.70$ **$Q_T = 661.41$ W**

Average Case: $Q_T = 196.56 + 196.56$ **$Q_T = 393.12$ W**

Without Insulation

Walls (each container):

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 49.53 * (22-12.4)$ **$Q = 2115.86$ W**

Average Case: $Q = 4.45 * 49.53 * (22-19.1)$ **$Q = 639.17$ W**

Floor (each container):

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ $Q = 2.74 * 29.77 * (22-20.3)$ **$Q = 138.50$ W**

Roof (each container):

R = R_{out} + $\frac{x_{steel}}{k_{steel}}$ + $\frac{x_{drywall}}{k_{drywall}}$ + R_{in} R = 0.03 + $\frac{0.002}{56.1}$ + $\frac{0.0127}{0.17}$ + 0.12 R = 0.22 m^2K/W

U = 1/R   U = 1/0.22   U = 4.45 W/m^2K

Q = UA(T_{in}-T_{out})

Worst Case: Q = 4.45 * 29.77 * (22-12.4)   **Q = 1271.56 W**

Average Case: Q = 4.45 * 29.77 * (22-19.1) **Q = 384.12 W**

Infiltration (each container):

Q = 0.005 * ACH * V * (T_{in}-T_{out})

Worst Case: Q = 0.005 * 0.85 * 86.33 * (22-12.4)   **Q = 3.52 W**

Average Case: Q = 0.005 * 0.85 * 86.33 * (22-19.1) **Q = 1.06 W**

Total:

Q_T = Σ$Q_{components}$

Each Container:

Worst Case: Q_T = 2115.86 + 138.50 + 1271.56 + 3.52   **Q_T = 3529.45 W**

Average Case: Q_T = 639.17 + 138.50 + 384.12 + 1.06   **Q_T = 1162.85 W**

Total Configuration:

Worst Case: Q_T = 3529.45 + 3529.45   **Q_T = 7058.89 W**

Average Case: Q_T = 1162.85 + 1162.85   **Q_T = 2325.70 W**

Cooling

With Insulation

Walls (each container):

R = R_{out} + $\frac{x_{steel}}{k_{steel}}$ + $\frac{x_{ins}}{k_{ins}}$ + $\frac{x_{drywall}}{k_{drywall}}$ + R_{in} R = 0.044 + $\frac{0.0016}{56.1}$ + $\frac{0.1524}{0.04}$ + $\frac{0.0127}{0.17}$ + 0.12   R = 4 m^2K/W

U = 1/R   U = 1/4   U = 0.25 W/m^2K

Q = UA*CLTD

Worst Case: Q = 0.25 * 49.53 * 10.30   **Q = 126.01 W**

Average Case: $Q = 0.25 * 49.53 * 7.00$ **Q = 85.64 W**

Floor (each container):

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

$U = 1/R$ $U = 1/0.38$ $U = 2.64\ W/m^2K$

$Q = UA*CLTD$ $Q = 2.64 * 29.77 * 0$ **Q = 0 W**

Roof (each container):

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 29.77 * 17.20$ **Q = 126.46 W**

Average Case: $Q = 0.25 * 29.77 * 13.90$ **Q = 102.20 W**

Internal Loads (each container):

Lighting: Q = W/area *area $Q = 9.67 * 29.77$ Q = 287.86 W

Equipment: Q = 300 W/desktop * 2 desktops Q = 600.00 W

People: Q = 65 W/person * 4 people Q = 260.00 W

$Q_{internal} = 287.86 + 600.00 + 260.00$ **$Q_{internal}$ = 1147.86 W**

Infiltration (each container):

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **Q = 2.26 W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **Q = 0.92 W**

Total:

$Q_T = \Sigma Q_{components}$

Each Container:

Worst Case: $Q_T = 126.01 + 0 + 126.46 + 1147.86 + 2.26$ **Q_T = 1402.59 W**

Average Case: Q_T = 85.64 + 0 + 102.20 + 1147.86 + 0.92 **Q_T = 1336.62 W**

Total Configuration:

Worst Case: Q_T = 1402.59 + 1402.59 **Q_T = 2805.18 W**

Average Case: Q_T = 1336.62 + 1336.62 **Q_T = 2673.23 W**

Without Insulation

Walls (each container):

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R U = 1/0.24 $U = 4.19\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 4.19 * 49.53 * 10.30 **Q = 2137.02 W**

Average Case: Q = 4.19 * 49.53 * 7.00 **Q = 1452.34 W**

Floor (each container):

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

U = 1/R U = 1/0.38 $U = 2.64\ W/m^2K$

Q = UA*CLTD Q = 2.64 * 29.77 * 0 **Q = 0 W**

Roof (each container):

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R U = 1/0.24 $U = 4.19\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 4.19 * 29.77 * 17.20 **Q = 2144.62 W**

Average Case: Q = 4.19 * 29.77 * 13.90 **Q = 1733.15 W**

Internal Loads (each container):

Lighting: Q = W/area *area Q = 9.67 * 29.77 Q = 287.86 W

Equipment: Q = 300 W/desktop * 2 desktops Q = 600.00 W

People: Q = 65 W/person * 4 people Q = 260.00 W

$Q_{internal}$ = 287.86 + 600.00 + 260.00 **$Q_{internal}$ = 1147.86 W**

Infiltration (each container):

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **$Q = 2.26$ W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **$Q = 0.92$ W**

Total:

$Q_T = \Sigma Q_{components}$

Each Container:

Worst Case: $Q_T = 2137.02 + 0 + 2144.62 + 1147.86 + 2.26$ **$Q_T = 5431.75$ W**

Average Case: $Q_T = 1452.34 + 0 + 1733.15 + 1147.86 + 0.92$ **$Q_T = 4334.27$ W**

Total Configuration:

Worst Case: $Q_T = 5431.75 + 5431.75$ **$Q_T = 10863.51$ W**

Average Case: $Q_T = 4334.27 + 4334.27$ **$Q_T = 8668.55$ W**

Four Containers Block Configuration

Heating

With Insulation

Walls (each container):

Bottom Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 49.53 * (22-12.4)$ **$Q = 117.85$ W**

Average Case: $Q = 0.25 * 49.53 * (22-19.1)$ **$Q = 35.60$ W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 49.53 * (22-12.4)$ **$Q = 117.85$ W**

Average Case: $Q = 0.25 * 49.53 * (22-19.1)$ **$Q = 35.60$ W**

Floor (each container):

Bottom Containers:

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.37\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ $Q = 2.74 * 29.77 * (22-20.3)$ **$Q = 138.50$ W**

Top Containers:

$R = R_{in} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.12 + \frac{0.028}{0.13} + 0.12$ $R = 0.45\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.20\ W/m^2K$

$Q = UA(T_{in}-T_{in})$ $Q = 2.20 * 29.77 * (22-22)$ **$Q = 0$ W**

Roof (each container):

Bottom Containers:

$R = R_{in} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.12 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4.17\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.24\ W/m^2K$

$Q = UA(T_{in}-T_{in})$

Worst Case: $Q = 0.24 * 29.77 * (22-22)$ **$Q = 0$ W**

Average Case: $Q = 0.24 * 29.77 * (22-22)$ **$Q = 0$ W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 29.77 * (22-12.4)$ **$Q = 70.83$ W**

Average Case: $Q = 0.25 * 29.77 * (22-19.1)$ **$Q = 21.40$ W**

Infiltration (each container):

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.85 * 86.33 * (22-12.4)$ **Q = 3.52 W**

Average Case: $Q = 0.005 * 0.85 * 86.33 * (22-19.1)$ **Q = 1.06 W**

<u>Total:</u>

$Q_T = \Sigma Q_{components}$

Bottom Containers:

Worst Case: $Q_T = 117.85 + 138.50 + 0 + 3.52$ **Q_T = 259.88 W**

Average Case: $Q_T = 35.60 + 138.50 + 0 + 1.06$ **Q_T = 175.17 W**

Top Containers:

Worst Case: $Q_T = 117.85 + 0 + 70.83 + 3.52$ **Q_T = 192.20 W**

Average Case: $Q_T = 35.60 + 0 + 21.40 + 1.06$ **Q_T = 58.06 W**

Total Configuration:

Worst Case: $Q_T = 259.88 + 259.88 + 192.20 + 192.20$ **Q_T = 904.16 W**

Average Case: $Q_T = 175.17 + 175.17 + 58.06 + 58.06$ **Q_T = 466.45 W**

Without Insulation

<u>Walls (each container):</u>

Bottom Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 49.53 * (22-12.4)$ **Q = 2115.86 W**

Average Case: $Q = 4.45 * 49.53 * (22-19.1)$ **Q = 639.17 W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 49.53 * (22-12.4)$ **Q = 2115.86 W**

Average Case: Q = 4.45 * 49.53 * (22-19.1) **Q = 639.17 W**

<u>Floor (each container):</u>

Bottom Containers:

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.22\ m^2K/W$

U = 1/R U = 1/0.37 $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ Q = 2.74 * 29.77 * (22-20.3) **Q = 138.50 W**

Top Containers:

$R = R_{in} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.12 + \frac{0.028}{0.13} + 0.12$ $R = 0.45\ m^2K/W$

U = 1/R U = 1/0.37 $U = 2.20\ W/m^2K$

$Q = UA(T_{in}-T_{in})$ Q = 2.20 * 29.77 * (22-22) **Q = 0 W**

<u>Roof (each container):</u>

Bottom Containers:

$R = R_{in} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.12 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.31\ m^2K/W$

U = 1/R U = 1/0.31 $U = 3.18\ W/m^2K$

$Q = UA(T_{in}-T_{in})$

Worst Case: Q = 3.18 * 29.77 * (22-22) **Q = 0 W**

Average Case: Q = 3.18 * 29.77 * (22-22) **Q = 0 W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

U = 1/R U = 1/0.22 $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: Q = 4.45 * 29.77 * (22-12.4) **Q = 1271.56 W**

Average Case: Q = 4.45 * 29.77 * (22-19.1) **Q = 384.12 W**

<u>Infiltration (each container):</u>

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: Q = 0.005 * 0.85 * 86.33 * (22-12.4) **Q = 3.52 W**

Average Case: $Q = 0.005 * 0.85 * 86.33 * (22-19.1)$ **$Q = 1.06$ W**

Total:

$Q_T = \Sigma Q_{components}$

Bottom Containers:

Worst Case: $Q_T = 2115.86 + 138.50 + 0 + 3.52$ **$Q_T = 2257.88$ W**

Average Case: $Q_T = 639.17 + 138.50 + 0 + 1.06$ **$Q_T = 778.73$ W**

Top Containers:

Worst Case: $Q_T = 2115.86 + 0 + 1271.56 + 3.52$ **$Q_T = 3390.95$ W**

Average Case: $Q_T = 639.17 + 0 + 384.12 + 1.06$ **$Q_T = 1024.35$ W**

Total Configuration:

Worst Case: $Q_T = 2257.88 + 2257.88 + 3390.95 + 3390.95$ **$Q_T = 11297.66$ W**

Average Case: $Q_T = 778.73 + 778.73 + 1024.35 + 1024.35$ **$Q_T = 3606.16$ W**

Cooling

With Insulation

Walls (each container):

Bottom Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4$ m^2K/W

$U = 1/R$ $U = 1/4$ $U = 0.25 \text{ W/m}^2\text{K}$

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 49.53 * 10.30$ **$Q = 126.01$ W**

Average Case: $Q = 0.25 * 49.53 * 7.00$ **$Q = 85.64$ W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4$ m^2K/W

$U = 1/R$ $U = 1/4$ $U = 0.25 \text{ W/m}^2\text{K}$

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 49.53 * 10.30$ **$Q = 126.01$ W**

Average Case: Q = 0.25 * 49.53 * 7.00 **Q = 85.64 W**

Floor (each container):

Bottom Containers:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

U = 1/R U = 1/0.38 $U = 2.64\ W/m^2K$

Q = UA*CLTD Q = 2.64 * 29.77 * 0 **Q = 0 W**

Top Containers:

$R = R_{in} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.12 + \frac{0.028}{0.13} + 0.12$ $R = 0.45\ m^2K/W$

U = 1/R U = 1/0.37 $U = 2.20\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 2.20 * 29.77 * 5.60 **Q = 366.07 W**

Average Case: Q = 2.20 * 29.77 * 2.20 **Q = 143.81 W**

Roof (each container):

Bottom Containers:

$R = R_{in} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.12 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4.17\ m^2K/W$

U = 1/R U = 1/4 $U = 0.24\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 0.24 * 29.77 * 5.60 **Q = 40.41 W**

Average Case: Q = 0.24 * 29.77 * 2.20 **Q = 15.88 W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

U = 1/R U = 1/4 $U = 0.25\ W/m^2K$

Q = UA*CLTD

Worst Case: Q = 0.25 * 29.77 * 17.20 **Q = 126.46 W**

Average Case: Q = 0.25 * 29.77 * 13.90 **Q = 102.20 W**

Internal Loads (each container):

Lighting: $Q = W/area * area$ $Q = 9.67 * 29.77$ $Q = 287.86$ W

Equipment: $Q = 300$ W/desktop * 2 desktops $Q = 600.00$ W

People: $Q = 65$ W/person * 4 people $Q = 260.00$ W

$Q_{internal} = 287.86 + 600.00 + 260.00$ **$Q_{internal} = 1147.86$ W**

Infiltration (each container):

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **$Q = 2.26$ W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **$Q = 0.92$ W**

Total:

$Q_T = \Sigma Q_{components}$

Bottom Containers:

Worst Case: $Q_T = 126.01 + 0 + 40.41 + 1147.86 + 2.26$ **$Q_T = 1316.54$ W**

Average Case: $Q_T = 85.64 + 0 + 15.88 + 1147.86 + 0.92$ **$Q_T = 1250.30$ W**

Top Containers:

Worst Case: $Q_T = 126.01 + 366.07 + 126.46 + 1147.86 + 2.26$ **$Q_T = 1768.65$ W**

Average Case: $Q_T = 85.64 + 143.81 + 102.20 + 1147.86 + 0.92$ **$Q_T = 1480.43$ W**

Total Configuration:

Worst Case: $Q_T = 1316.54 + 1316.54 + 1768.65 + 1768.65$ **$Q_T = 6170.39$ W**

Average Case: $Q_T = 1250.30 + 1250.30 + 1480.43 + 1480.43$ **$Q_T = 5461.45$ W**

Without Insulation

Walls (each container):

Bottom Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

$U = 1/R$ $U = 1/0.24$ $U = 4.19\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 4.19 * 49.53 * 10.30$ **$Q = 2137.02$ W**

Average Case: $Q = 4.19 * 49.53 * 7.00$ **$Q = 1452.34$ W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R U = 1/0.24 U = 4.19 W/m^2K

Q = UA*CLTD

Worst Case: Q = 4.19 * 49.53 * 10.30 **Q = 2137.02 W**

Average Case: Q = 4.19 * 49.53 * 7.00 **Q = 1452.34 W**

<u>Floor (each container):</u>

Bottom Containers:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

U = 1/R U = 1/0.38 U = 2.64 W/m^2K

Q = UA*CLTD Q = 2.64 * 29.77 * 0 **Q = 0 W**

Top Containers:

$R = R_{in} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.12 + \frac{0.028}{0.13} + 0.12$ $R = 0.45\ m^2K/W$

U = 1/R U = 1/0.37 U = 2.20 W/m^2K

Q = UA*CLTD

Worst Case: Q = 2.20 * 29.77 * 5.60 **Q = 366.07 W**

Average Case: Q = 2.20 * 29.77 * 2.20 **Q = 143.81 W**

<u>Roof (each container):</u>

Bottom Containers:

$R = R_{in} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.12 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.31\ m^2K/W$

U = 1/R U = 1/0.31 U = 3.18 W/m^2K

Q = UA*CLTD

Worst Case: Q = 3.18 * 29.77 * 5.60 **Q = 529.64 W**

Average Case: Q = 3.18 * 29.77 * 2.20 **Q = 208.07 W**

Top Containers:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R U = 1/0.24 U = 4.19 W/m^2K

$Q = UA*CLTD$

Worst Case: $Q = 4.19 * 29.77 * 17.20$ **$Q = 2144.62$ W**

Average Case: $Q = 4.19 * 29.77 * 13.90$ **$Q = 1733.15$ W**

Internal Loads (each container):

Lighting: $Q = W/area *area$ $Q = 9.67 * 29.77$ $Q = 287.86$ W

Equipment: $Q = 300$ W/desktop * 2 desktops $Q = 600.00$ W

People: $Q = 65$ W/person * 4 people $Q = 260.00$ W

$Q_{internal} = 287.86 + 600.00 + 260.00$ **$Q_{internal} = 1147.86$ W**

Infiltration (each container):

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **$Q = 2.26$ W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **$Q = 0.92$ W**

Total:

$Q_T = \Sigma Q_{components}$

Bottom Containers:

Worst Case: $Q_T = 2137.02 + 0 + 529.64 + 1147.86 + 2.26$ **$Q_T = 3816.78$ W**

Average Case: $Q_T = 1452.34 + 0 + 208.07 + 1147.86 + 0.92$ **$Q_T = 2809.20$ W**

Top Containers:

Worst Case: $Q_T = 2137.02 + 366.07 + 2144.62 + 1147.86 + 2.26$ **$Q_T = 5797.82$ W**

Average Case: $Q_T = 1452.34 + 143.81 + 1733.15 + 1147.86 + 0.92$ **$Q_T = 4478.09$ W**

Total Configuration:

Worst Case: $Q_T = 3816.78 + 3816.78 + 5797.82 + 5797.82$ **$Q_T = 19229.19$ W**

Average Case: $Q_T = 2809.20 + 2809.20 + 4478.09 + 4478.09$ **$Q_T = 14574.57$ W**

Single Container with Glass (Single Glazing)

Heating

With Insulation

Walls:

R = $R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ R = $0.03 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ R = 4 m^2K/W

U = 1/R U = 1/4 U = 0.25 W/m^2K

Q = $UA(T_{in}-T_{out})$

Worst Case: Q = 0.25 * 68.19 * (22-12.4) **Q = 162.25 W**

Average Case: Q = 0.25 * 68.19 * (22-19.1) **Q = 49.01 W**

Windows:

Q = $UA(T_{in}-T_{out})$

Worst Case: Q = 5.00 * 16.72 * (22-12.4) **Q = 802.56 W**

Average Case: Q = 5.00 * 16.72 * (22-19.1) **Q = 242.44 W**

Floor:

R = $R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ R = $0.03 + \frac{0.028}{0.13} + 0.12$ R = 0.37 m^2K/W

U = 1/R U = 1/0.37 U = 2.74 W/m^2K

Q = $UA(T_{in}-T_{earth})$ Q = 2.74 * 29.77 * (22-20.3) **Q = 138.50 W**

Roof:

R = $R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ R = $0.03 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ R = 4 m^2K/W

U = 1/R U = 1/4 U = 0.25 W/m^2K

Q = $UA(T_{in}-T_{out})$

Worst Case: Q = 0.25 * 29.77 * (22-12.4) **Q = 70.83 W**

Average Case: Q = 0.25 * 29.77 * (22-19.1) **Q = 21.40 W**

Infiltration:

Q = 0.005 * ACH * V * $(T_{in}-T_{out})$

Worst Case: Q = 0.005 * 0.85 * 86.33 * (22-12.4) **Q = 3.52 W**

Average Case: Q = 0.005 * 0.85 * 86.33 * (22-19.1) **Q = 1.06 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 162.25 + 802.56 + 138.50 + 70.83 + 3.52$ **Q_T = 1177.66 W**

Average Case: $Q_T = 49.01 + 242.44 + 138.50 + 21.40 + 1.06$ **Q_T = 452.41 W**

Without Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 68.19 * (22-12.4)$ **Q = 2912.96 W**

Average Case: $Q = 4.45 * 68.19 * (22-19.1)$ **Q = 879.96 W**

Windows:

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 5.00 * 16.72 * (22-12.4)$ **Q = 802.56 W**

Average Case: $Q = 5.00 * 16.72 * (22-19.1)$ **Q = 242.44 W**

Floor:

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ $Q = 2.74 * 29.77 * (22-20.3)$ **Q = 138.50 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 4.45 * 29.77 * (22-12.4)$ **Q = 1271.56 W**

Average Case: $Q = 4.45 * 29.77 * (22-19.1)$ **Q = 384.12 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.85 * 86.33 * (22-12.4)$ **Q = 3.52 W**

Average Case: $Q = 0.005 * 0.85 * 86.33 * (22-19.1)$ **Q = 1.06 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 2912.96 + 802.56 + 138.50 + 1271.56 + 3.52$ **Q_T = 5129.11 W**

Average Case: $Q_T = 879.96 + 242.44 + 138.50 + 384.12 + 1.06$ **Q_T = 1646.08 W**

Cooling

With Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4$ m^2K/W

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 68.19 * 10.30$ **Q = 173.48 W**

Average Case: $Q = 0.25 * 68.19 * 7.00$ **Q = 117.90 W**

Windows:

North:

$Q = UA*CLTD$

Worst Case: $Q = 5.00 * 8.36 * 13.30$ **Q = 555.94 W**

Average Case: $Q = 5.00 * 8.36 * 8.90$ **Q = 372.02 W**

South:

$Q = UA*CLTD$

Worst Case: $Q = 5.00 * 8.36 * 13.30$ **Q = 555.94 W**

Average Case: $Q = 5.00 * 8.36 * 9.40$ **Q = 392.92 W**

Floor:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

$U = 1/R$ $U = 1/0.38$ $U = 2.64\ W/m^2K$

$Q = UA*CLTD$ $Q = 2.64 * 29.77 * 0$ **Q = 0 W**

<u>Roof:</u>

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA*CLTD$

Worst Case: Q = 0.25 * 29.77 * 17.20 **Q = 126.46 W**

Average Case: Q = 0.25 * 29.77 * 13.90 **Q = 102.20 W**

<u>Internal Loads:</u>

Lighting: Q = W/area *area Q = 9.67 * 29.77 Q = 287.86 W

Equipment: Q = 300 W/desktop * 2 desktops Q = 600.00 W

People: Q = 65 W/person * 4 people Q = 260.00 W

$Q_{internal}$ = 287.86 + 600.00 + 260.00 **$Q_{internal}$ = 1147.86 W**

<u>Infiltration:</u>

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: Q = 0.005 * 0.595 * 86.33 * (30.8-22) **Q = 2.26 W**

Average Case: Q = 0.005 * 0.595 * 86.33 * (25.6-22) **Q = 0.92 W**

<u>Total:</u>

$Q_T = \Sigma Q_{components}$

Worst Case: Q_T = 173.48 + 555.94 + 555.94 + 0 + 126.46 + 1147.86 + 2.26

Q_T = 2561.94 W

Average Case: Q_T = 117.90 + 372.02 + 392.92 + 0 + 102.20 + 1147.86 + 0.92

Q_T = 2133.82 W

<u>Without Insulation</u>

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R   U = 1/0.24   U = 4.19 W/m^2K

Q = UA*CLTD

Worst Case: Q = 4.19 * 68.19 * 10.30   **Q = 2942.09 W**

Average Case: Q = 4.19 * 68.19 * 7.00   **Q = 1999.48 W**

Windows:

North:

Q = UA*CLTD

Worst Case: Q = 5.00 * 8.36 * 13.30   **Q = 555.94 W**

Average Case: Q = 5.00 * 8.36 * 8.90   **Q = 372.02 W**

South:

Q = UA*CLTD

Worst Case: Q = 5.00 * 8.36 * 13.30   **Q = 555.94 W**

Average Case: Q = 5.00 * 8.36 * 9.40   **Q = 392.92 W**

Floor:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

U = 1/R   U = 1/0.38   U = 2.64 W/m^2K

Q = UA*CLTD   Q = 2.64 * 29.77 * 0   **Q = 0 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

U = 1/R   U = 1/0.24   U = 4.19 W/m^2K

Q = UA*CLTD

Worst Case: Q = 4.19 * 29.77 * 17.20   **Q = 2144.62 W**

Average Case: Q = 4.19 * 29.77 * 13.90   **Q = 1733.15 W**

Internal Loads:

Lighting: $Q = W/area * area$ $Q = 9.67 * 29.77$ $Q = 287.86$ W

Equipment: $Q = 300$ W/desktop * 2 desktops $Q = 600.00$ W

People: $Q = 65$ W/person * 4 people $Q = 260.00$ W

$Q_{internal} = 287.86 + 600.00 + 260.00$ $\mathbf{Q_{internal} = 1147.86\ W}$

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **Q = 2.26 W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **Q = 0.92 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 2942.09 + 555.94 + 555.94 + 0 + 2144.62 + 1147.86 + 2.26$

$\mathbf{Q_T = 7348.70\ W}$

Average Case: $Q_T=1999.48 + 372.02 + 392.92 + 0 + 1733.15 + 1147.86 + 0.92$

$\mathbf{Q_T = 5646.35\ W}$

Single Container with Glass (Double Glazing)

Heating

With Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 0.25 * 68.19 * (22-12.4)$ **Q = 162.25 W**

Average Case: $Q = 0.25 * 68.19 * (22-19.1)$ **Q = 49.01 W**

Windows:

$Q = UA(T_{in}-T_{out})$

Worst Case: $Q = 3.00 * 16.72 * (22-12.4)$ **Q = 481.54 W**

Average Case: Q = 3.00 * 16.72 * (22-19.1) **Q = 145.46 W**

Floor:

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.37\ m^2K/W$

$U = 1/R$ $U = 1/0.37$ $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ Q = 2.74 * 29.77 * (22-20.3) **Q = 138.50 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{stee}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: Q = 0.25 * 29.77 * (22-12.4) **Q = 70.83 W**

Average Case: Q = 0.25 * 29.77 * (22-19.1) **Q = 21.40 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: Q = 0.005 * 0.85 * 86.33 * (22-12.4) **Q = 3.52 W**

Average Case: Q = 0.005 * 0.85 * 86.33 * (22-19.1) **Q = 1.06 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: Q_T = 162.25 + 481.54 + 138.50 + 70.83 + 3.52 **Q_T = 856.64 W**

Average Case: Q_T = 49.01 + 145.46 + 138.50 + 21.40 + 1.06 **Q_T = 355.44 W**

Without Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

$U = 1/R$ $U = 1/0.22$ $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: Q = 4.45 * 68.19 * (22-12.4) **Q = 2912.96 W**

Average Case: Q = 4.45 * 68.19 * (22-19.1) **Q = 879.96 W**

Windows:

$Q = UA(T_{in}-T_{out})$

Worst Case: Q = 3.00 * 16.72 * (22-12.4) **Q = 481.54 W**

Average Case: Q = 3.00 * 16.72 * (22-19.1) **Q = 145.46 W**

Floor:

$R = R_{out} + \frac{x_{plywood}}{k_{plywood}} + R_{in}$ $R = 0.03 + \frac{0.028}{0.13} + 0.12$ $R = 0.22\ m^2K/W$

U = 1/R U = 1/0.37 $U = 2.74\ W/m^2K$

$Q = UA(T_{in}-T_{earth})$ Q = 2.74 * 29.77 * (22-20.3) **Q = 138.50 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.03 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.22\ m^2K/W$

U = 1/R U = 1/0.22 $U = 4.45\ W/m^2K$

$Q = UA(T_{in}-T_{out})$

Worst Case: Q = 4.45 * 29.77 * (22-12.4) **Q = 1271.56 W**

Average Case: Q = 4.45 * 29.77 * (22-19.1) **Q = 384.12 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: Q = 0.005 * 0.85 * 86.33 * (22-12.4) **Q = 3.52 W**

Average Case: Q = 0.005 * 0.85 * 86.33 * (22-19.1) **Q = 1.06 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: Q_T = 2912.96 + 481.54 + 138.50 + 1271.56 + 3.52 **Q_T = 4808.08 W**

Average Case: Q_T = 879.96 + 145.46 + 138.50 + 384.12 + 1.06 **Q_T = 1549.10 W**

Cooling

With Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.0016}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4$ m^2K/W

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 68.19 * 10.30$ **Q = 173.48 W**

Average Case: $Q = 0.25 * 68.19 * 7.00$ **Q = 117.90 W**

Windows:

North:

$Q = UA*CLTD$

Worst Case: $Q = 3.00 * 8.36 * 8.30$ **Q = 208.16 W**

Average Case: $Q = 3.00 * 8.36 * 6.10$ **Q = 152.99 W**

South:

$Q = UA*CLTD$

Worst Case: $Q = 3.00 * 8.36 * 8.30$ **Q = 208.16 W**

Average Case: $Q = 3.00 * 8.36 * 6.10$ **Q = 152.99 W**

Floor:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

$U = 1/R$ $U = 1/0.38$ $U = 2.64\ W/m^2K$

$Q = UA*CLTD$ $Q = 2.64 * 29.77 * 0$ **Q = 0 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.1524}{0.04} + \frac{0.0127}{0.17} + 0.12$ $R = 4\ m^2K/W$

$U = 1/R$ $U = 1/4$ $U = 0.25\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 0.25 * 29.77 * 17.20$ **Q = 126.46 W**

Average Case: $Q = 0.25 * 29.77 * 13.90$ **Q = 102.20 W**

Internal Loads:

Lighting: $Q = W/area * area \quad Q = 9.67 * 29.77 \qquad Q = 287.86$ W

Equipment: $Q = 300$ W/desktop * 2 desktops $\qquad Q = 600.00$ W

People: $Q = 65$ W/person * 4 people $\qquad Q = 260.00$ W

$Q_{internal} = 287.86 + 600.00 + 260.00$ $\qquad$ **$Q_{internal}$ = 1147.86 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ $\qquad$ **Q = 2.26 W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ $\qquad$ **Q = 0.92 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 173.48 + 208.16 + 208.16 + 0 + 126.46 + 1147.86 + 2.26$

Q_T = 1866.39 W

Average Case: $Q_T = 117.90 + 152.99 + 152.99 + 0 + 102.20 + 1147.86 + 0.92$

Q_T = 1674.86 W

Without Insulation

Walls:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in} \quad R = 0.044 + \frac{0.0016}{56.1} + \frac{0.0127}{0.17} + 0.12 \qquad R = 0.24\ m^2K/W$

$U = 1/R \qquad U = 1/0.24 \qquad U = 4.19\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 4.19 * 68.19 * 10.30$ $\qquad$ **Q = 2942.09 W**

Average Case: $Q = 4.19 * 68.19 * 7.00$ $\qquad$ **Q = 1999.48 W**

Windows:

North:

$Q = UA*CLTD$

Worst Case: $Q = 3.00 * 8.36 * 8.30$ $\qquad$ **Q = 208.16 W**

Average Case: $Q = 3.00 * 8.36 * 6.10$ **Q = 152.99 W**

South:

$Q = UA*CLTD$

Worst Case: $Q = 3.00 * 8.36 * 8.30$ **Q = 208.16 W**

Average Case: $Q = 3.00 * 8.36 * 6.10$ **Q = 152.99 W**

Floor:

$R = R_{out} + \frac{x}{k} + R_{in}$ $R = 0.044 + \frac{0.028}{0.13} + 0.12$ $R = 0.38\ m^2K/W$

$U = 1/R$ $U = 1/0.38$ $U = 2.64\ W/m^2K$

$Q = UA*CLTD$ $Q = 2.64 * 29.77 * 0$ **Q = 0 W**

Roof:

$R = R_{out} + \frac{x_{steel}}{k_{steel}} + \frac{x_{drywall}}{k_{drywall}} + R_{in}$ $R = 0.044 + \frac{0.002}{56.1} + \frac{0.0127}{0.17} + 0.12$ $R = 0.24\ m^2K/W$

$U = 1/R$ $U = 1/0.24$ $U = 4.19\ W/m^2K$

$Q = UA*CLTD$

Worst Case: $Q = 4.19 * 29.77 * 17.20$ **Q = 2144.62 W**

Average Case: $Q = 4.19 * 29.77 * 13.90$ **Q = 1733.15 W**

Internal Loads:

Lighting: Q = W/area *area $Q = 9.67 * 29.77$ Q = 287.86 W

Equipment: Q = 300 W/desktop * 2 desktops Q = 600.00 W

People: Q = 65 W/person * 4 people Q = 260.00 W

$Q_{internal} = 287.86 + 600.00 + 260.00$ **$Q_{internal}$ = 1147.86 W**

Infiltration:

$Q = 0.005 * ACH * V * (T_{in}-T_{out})$

Worst Case: $Q = 0.005 * 0.595 * 86.33 * (30.8-22)$ **Q = 2.26 W**

Average Case: $Q = 0.005 * 0.595 * 86.33 * (25.6-22)$ **Q = 0.92 W**

Total:

$Q_T = \Sigma Q_{components}$

Worst Case: $Q_T = 2942.09 + 208.16 + 208.16 + 0 + 2144.62 + 1147.86 + 2.26$

$Q_T = 6653.15$ W

Average Case: $Q_T=2799.27 + 152.99 + 152.99 + 0 + 1733.15 + 1147.86 + 0.92$

$Q_T = 5187.39$ W

Appendix E: Sustainability Calculations

Rainwater Calculations

Area of Dorm Roof = 80'-6" x 35'-0" + 35'-0" x 35'-0" + 80'-6" x 55'-0"
= 6860 SF

Area of CC Roof = 16'-0" x 40'-0" + 2 x 40'-0" x 80'-0" + 60'-0" x 40'-0" + 20'-0" x 20'-0"
= 9840 SF

Average Annual Precipitation at Macaneta Beach = 800 mm/year = 31.5"/year

Average Rainwater Collection Per Inch of Rain = 550 gallons/1000 SF

Dorm Roof Rainwater Total = 6860 SF / 1000 SF x 550 gallons/" x 31.5" = **118850 gallons**

CC Roof Rainwater Total = 9840 SF / 1000 SF x 550 gallons/" x 31.5" = **170478 gallons**

Solar Energy Calculations

Daily Energy Usage 10 Containers = 727 W x 10 x 176 hours/month / 30 days/month / 1000
= 42.65 kWh/day

Energy Produced by 1 310 W Solar Panel = 310 W x 7.78 hours sunlight / 1000
= 2.41 kWh/day

Number of 310 W Solar Panels = 42.65 kWh/day / 2.41 kWh/day
= **18 solar panels**

Cost = 2.81 USD/watt * 18 panels * 310 watts/panel
= **15,680 USD**
= **1,157,811 MZN**