Design of a Vertical Axis Wind Turbine

A Major Qualifying Project Report
submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
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degree of Bachelor of Science

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Abstract

Working in conjunction with a Worcester Polytechnic Institute (WPI) mechanical engineering major qualifying project (MQP) team, our civil engineering team worked to design the structural components of a vertical axis wind turbine based on a preliminary design created by architect Emil Jacob, founder of WindRays Energy and our project sponsor.

Our team was tasked with the structural design of the blades, turbine shaft, exterior supporting shell, and foundation based on said initial architectural design. The mechanical and structural teams' findings and recommendations prompted various alterations of the initial structural design. For this project, our team analyzed the loading conditions the structure would experience, researched structural material properties, and performed structural analysis under the expected loading conditions to determine the ideal structural members. We analyzed deflections, buckling, and member failure based on these expected loading conditions. Based on these results and calculations, our team recommended alterations to the initial design informing the sponsor of the respective strengths and weaknesses.

Acknowledgements

This project would not have been possible without the help and support of the WPI Civil and Environmental Engineering department, faculty, and administration. With special thanks to:

Our project sponsor, Emil Jacob, for the opportunity to collaborate on the design of the novel structure. His positive attitude and willingness to help provided supportive backing conducive to developing the product.

Our project advisors, Professor Nima Rahbar and Professor Ahmet Sabuncu, for their advice and direction throughout the project. Their collective support and assistance were an invaluable asset to us and guided the project's success.

Capstone Design

One of the main goals of the MQP is to give students the opportunity to solve an open-ended, multifaceted project. This gives students the opportunity to experience real world research and design in their primary field of study. To fulfill this goal, our team gave extra consideration to numerous factors, outside of the driving factors of the project (the structural and mechanical), those factors are as follows.

Economic: The shaping principle of our design process, designated by the sponsor, was cost. Our goal was to produce instruments of service displaying the structural integrity of the sub/superstructure with emphasis on cost of the design. To achieve this, we investigated load distribution paths of the blade and shaft loads to the supporting truss and column structure. Additionally, we looked at transfer of load from the superstructure to the substructure to the surrounding soil. This investigatory process involved multiple designs and redesigns, influenced by research and consultation, prioritizing cost.

Social: The final design recommendation was the culmination of seven months of weekly meetings of four parties with varying expertise; the civil team, mechanical team, the advisors, and the sponsor. Teamwork and cooperation were instrumental to the progress of this project. The main points of discussion between the other parties and our civil team were structural mechanics, project scope, and cost. Overall, this project was a testament to the achievements of teamwork and cooperation.

Environmental: The design investigated sustainable materials including their lifespans and structural benefits, which were considered in the design process. Similarly, the very purpose of the structure is to produce “green energy” with the benefit of the environment in mind. The turbine produces energy through wind power resulting in less emissions than traditional sources. Additionally, the excavation of the foundation and piles would follow current field practices and would consider the proximity of Boston Harbor. Finally, the structure would be encased in a fine netting to prevent disturbances to wildlife.

Sustainability: The recommended structural coatings would resist corrosion and deterioration, however, overtime the components must be maintained. The modular design is intended to provide ease of access for repairs and maintenance. The structure provides renewable or “green energy” by harnessing wind and converting it to electricity, which is one of the most sustainable methods currently available.

Health and Safety: The height of the structure coupled with the mechanical nature of the rotating blades posed safety concerns. Additionally, the intent to construct within an urban environment on filled soil prompted discussion on safety. The design processes intended to minimize these concerns of structural failure and movement. Numerous factors of safety were incorporated into the calculations to account for the many variable conditions the structure would encounter in its service life. An analytical model was also created to simulate the expected movement of the structure and verify the calculations.

Ethical: The first canon in the American Society of Civil Engineers (ASCE) code of ethics contains two points that were emphasized in this project. They read as follows (ASCE, 2020):

a. First and foremost, protect the health, safety, and welfare of the public
b. Enhance the quality of life for humanity

The design of this project fulfils both principles. As mentioned above, the health and safety of the people who would interact with the structure was of paramount importance to us. The structure was designed using safety factors and maximum loading conditions to ensure the structure would exceed even the most rigorous conditions. This wind turbine design also has the capability of enhancing the quality of life of humanity by decreasing the dependence on carbon emitting energy sources, to help preserve the planet. This is beneficial for the generations to come. While these principles from the ASCE code of ethics were emphasized, the entirety of the code was followed in the design process to ensure we made the correct ethical decisions throughout the project.

Political: In the design of this structure, there were building codes and zoning ordinances that had to be adhered to. These regulations are set by the local governments and are changed and updated over time. Our design is limited in application due to these regulations varying from city to city and state to state. The design was created with the end location in mind and, as such, our design may not be applicable in other locations. Similarly, there are different green initiatives throughout the different cities in the country, which impacts the implementation rate of renewable energy sources in the respective cities.

Constructability and Manufacturability: The structure was designed with modularity and uniformity for efficiency in the organization, transportation, and erection of the components. Similarly, the connections were designed to be the same for the similar connections throughout the structure to ease the assembly process. These considerations will make the design components easier to manufacture and make the structure more straightforward to erect on site.

Executive Summary

Our team was one of two Major Qualifying Project (MQP) teams working to optimize the design of a vertical axis wind turbine, based on the initial architectural design created by architect Emil Jacob, founder of WindRays Energy, our project sponsor. Our project team consisted of four civil engineering students from Worcester Polytechnic Institute (WPI), focused on designing the sub and super structure of the wind turbine. The collaborating team was a group of five WPI mechanical engineering students tasked with the optimization of the blades and mechanical connections of the turbine. Both teams shared the scope of the project and collaborated in the design, while solving respective problems.

To aid the design of the structure, our team investigated similar existing structures to examine the materials, member and connection types, and foundations. The research included vertical and horizontal axis wind turbines, lattice towers (cell towers and transmission towers), and water towers. We discussed with Emil the design specifications to ensure a shared understanding of the structural outcome. Based on the design specifications, we researched the mechanical and chemical properties, environmental implications, and sustainability of the materials. Efficiency, cost-effectivity, availability, and sustainability controlled/bounded the material design of the structure.

In addition to material properties and member properties, we researched the loading conditions the wind turbine would experience during its service lifetime, including wind, snow and ice, seismic, dead, and live loads. These loading conditions would be the primary factors of our design process. Our calculations and research informed our structural design recommendations to our sponsor. The complexity of the structure prompted multiple design recommendations with unique advantages and disadvantages, giving our sponsor a well-rounded decision background.

Table of Contents

List of Figures

List of Tables

Authorship

This project is the result of a team effort to solve a real-world style problem over the course of several months. Each member of the team had different experiences and different levels of knowledge regarding the various aspects of this project. This was considered in our approach to the project, to ensure the strengths of the team members were being properly utilized. This led to the following work breakdown.

The model was completed by Bryan and Joe, due to their previous experiences with similar software. This prior experience allowed them to successfully replicate the design in the analysis software to ensure the design was sufficient for the expected loading. This process included updating the model as the design was altered throughout the project based on the new information and criteria established throughout the process.

The structural calculations were primarily completed by Andrew and Ian. The design of the substructure was led by Ian due to his knowledge base regarding soils and foundation design. The design of the super structure was completed by Andrew, due to his design experience from previous classes. These respective designs were updated and refined throughout the course of the project to accommodate each other and to meet the criteria set by the sponsor in the most effective way possible.

The team met frequently throughout the project duration to collaborate on their respective work, so the team could brainstorm, and solve problems together. This input of diverse ideas and perspectives allowed the final design to better meet the criteria of the sponsor, while being cost effective with a high structural integrity.

This report was a team-wide undertaking, with all members contributing to all sections to the maximum extent possible. The introduction and conclusions were written and edited by the entire team to ensure they were succinct, yet informative of the project and its findings. The background was similarly researched, written, and edited by the entire team to ensure the information provided increased the understanding of the project. The methodology, results, and discussion sections were written by the different team members based on who performed which aspects of the design, as outlined above. The editing of these sections was again a teamwide effort to ensure they were clear and succinct in their message.

Introduction

As the demand for the increased use of renewable energy grows, so does the need for new innovations in wind energy, to help meet the world's ever increasing energy needs. Wind energy has been increasing in popularity the past few decades due to its abundant availability around the world. It has immense capabilities for energy production, in the United States alone, "a group of 12 states in the mid-section of the country have enough wind energy potential to produce nearly four times the amount of electricity consumed by the nation in 1990". (Elliott et al., 1993) This incredibly high potential for wind energy makes it a worthwhile investment for the future.

Wind energy is an incredibly sustainable source of energy, as the kinetic energy of the wind is converted to electricity through mechanical processes in wind turbines. Every innovation in wind turbine technology makes this process more efficient, allowing us to generate more energy from the wind. Many of these innovations are feats of engineering that push the boundary of what was thought to be possible and help to increase the use of sustainable energy. The increased use of wind energy will help increase the sustainability of energy production, which in turn will help in the effort against climate change.

The purpose of this MQP is to analyze, design, and make recommendations on the structural aspects of a novel vertical wind turbine design. This idea utilizes layers of turbines to capture wind energy, in addition to solar panels to capture solar energy. Our team will optimize the structure to be able to handle all the expected loading conditions, without hindering energy production, and minimize the cost to make this design as feasible and efficient as possible.

Background

The structure and structural elements that were designed during this project was based on and heavily influenced by the initial concept design created by the project sponsor. The basic idea consists of two parts: the mechanical aspects that need the ability to rotate and the purely structural aspects that support the mechanical. The mechanical portion of the design includes the blades, which are made from the flaps that comprise the blades and the blade frames that support the flaps, and the central shaft that the blades attach to. As the wind blows through the structure, the blades and central shaft rotate, which turns a generator, creating electricity. The structural portions of the design are meant to support these mechanical pieces. The central shaft is supported under each set of blades by sixteen trusses that support the shaft using ball bearings, to not impede the rotation, their layout is shown in figure 1. The trusses carry the load to a set of exterior columns which carry the load to the ground. The exterior columns also support a series of solar panels, which supplement the electricity produced by the wind. The pictures below are screenshots from the initial model of the structure.

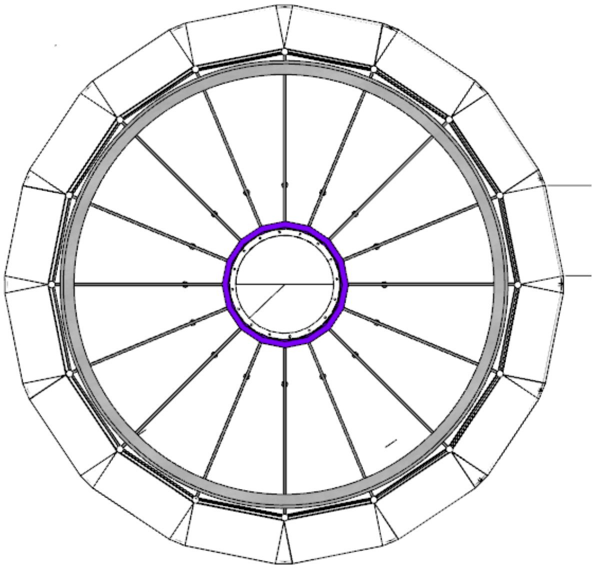


Figure 1: Truss Layout and Solar Support

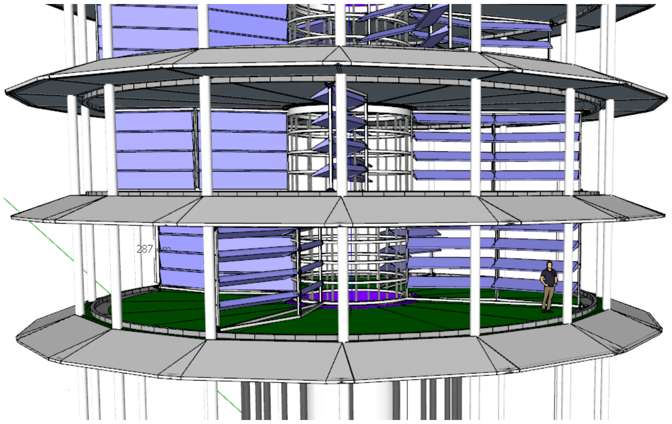


Figure 3: Detailed Layer Layout

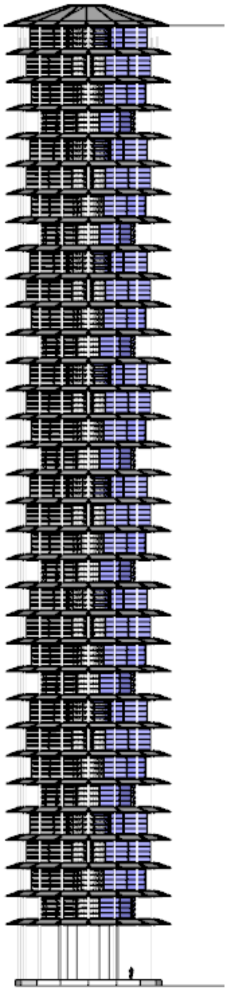


Figure 2: Overall Design

Before beginning the design calculations for the structure of the wind turbine, our team researched different aspects of the design to get a baseline of information to use in our calculations. This baseline information allowed our calculations to be as accurate and realistic as possible. Similarly, we researched the requirements set forth by the city where the wind turbine will be located to determine any design requirements that would need to be incorporated to ensure the zoning requirements are met. In addition to these requirements, we researched previous implementations of sustainable energy production methods in the city to determine the suitability of the location for the wind turbine.

Cambridge Zoning Ordinance

The proposed location for this wind turbine is the city of Cambridge, Massachusetts. The zoning ordinances for Cambridge contain an entire section dedicated to the regulation of wind turbines and their implementation in the city. Specifically, it is Section 22.70 – Wind Turbine Systems, located in Article 22.000 Sustainable Design and Development (*Zoning Ordinance,* 2021). Within this section the application requirements and location requirements are detailed thoroughly, while there are minimal requirements for the structure and its design. In reading through the section, the only one relevant in our design process is Section 22.72.1 Dimensional Limits (*Zoning Ordinance,* 2021). That section reads as follows:

1. Height. There shall be no maximum height limit for a Wind Turbine, but the permitted height of a Wind Turbine shall be specifically approved by the Planning Board.
2. Setbacks. There shall be no required minimum yard setbacks for a Wind Turbine, but the permitted placement of a Wind Turbine with respect to public street lines and adjacent lot lines shall be specifically approved by the Planning Board. All equipment and structures accessory to the Wind Turbine shall be subject to the yard requirements of the applicable zoning district unless waived by the Planning Board.

The height of the structure and the setbacks it has from other structures are the only two regulated aspects of the structural design. Both requirements are determined on a case-by-case basis, there are no defined minimums or maximums for these values. There are other criteria outlined in the subsequent sections that could dictate the design of the structure, such as noise production, which cannot be determined until a design is completed and a prototype is built and analyzed. Therefore, the requirements used in this design process were limited to those from Section 22.72.1.

Green Energy in Cambridge

Massachusetts has a history of incorporating and promoting the use of green energy sources and technologies, especially since the turn of the century (*Renewable Energy Snapshot*). There are a multitude of programs and incentives designed to increase the use of renewable energy throughout the state. In addition to some of the more well-known green energy options, like solar and wind, the state is also investigating the use of “biomass, clean heating and cooling, and advanced bio-fuels” (*Renewable Energy Snapshot*). Cambridge in particular takes the use of green energy one step further. They have a goal “to eliminate greenhouse gas emissions by 2050 and ensure that our city, its residents, and its businesses are prepared to cope with expected impacts of climate change” (*Energy Efficiency & Clean Energy,* 2020). To accomplish this, they have a number of resources available to their citizens and businesses that give them access to a variety of sources, so they can make informed decisions regarding their energy sources. There is also a program in place that automatically opts the electricity users into helping to support the development of their new solar project, which will supply the city with renewable energy when the project is complete. The city also has 100% renewable energy supply options available for citizens and businesses that elect to use them (*Cambridge Community Electricity Program* 2022). Overall, the outlook of clean, renewable, energy is very high and should continue to gain support and use in the future.

Existing Structures

Our research included exploring similar, existing, structures to determine the types of materials used in these applications, the different types of structural members used, the types of connections used between the members, and when possible, why that was the case. The structures we researched included existing wind turbines, both horizontal axis and vertical axis designs, lattice towers, and water towers.

Wind Turbines

Wind turbines are generally grouped into two types, horizontal axis and vertical axis. Figure 4, on the right, shows the distribution of types of wind turbines. Horizontal axis wind turbines (HAWT) are turbines that rotate on a horizontal axis, that parallels the direction of the wind. Vertical axis wind turbines (VAWT) are turbines that rotate around a vertical axis, that is perpendicular to the direction of the airflow (Zhao et al., 2019). Typically, horizontal axis designs have a higher efficiency compared to the vertical axis designs. (Cengel and Cimbala, 2017).

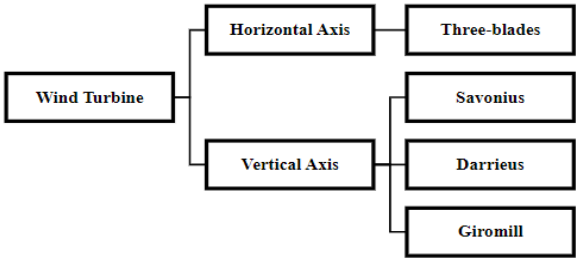


Figure 4: Classification of Wind Turbine (Zhao et al., 2019)

Horizontal axis wind turbine designs have several advantageous features over their vertical axis counterparts (Zhao et al., 2019). These advantages are as follows:

- Most stable wind turbine design to be applied.
- Can operate at lower cut-in wind velocity and result in higher energy conversion efficiency.
- Excellent performance at fluctuating wind velocity, due to better angle control.

However, horizontal axis designs also have relative disadvantages compared to the vertical axis designs, such as (Zhao et al., 2019):

- Require yaw drives to turn the turbine toward the oncoming wind.
- More substantial structural support is needed for the massive generators and gearboxes.
- Installation and maintenance costs are higher because of the taller tower heights.

Figure 5: GE's Hiliade-X Wind Turbine (Haliade-X Offshore Wind Turbine)

Horizontal axis wind turbines are currently the most common type of wind turbine in use due to these relative advantages (National Geographic Society, 2019). Many HAWTs have similar designs, the three-blade design mention in figure 4, that share a similar look that most people are familiar with, such as General Electric's Hiliade-X wind turbine, shown in figure 5. These types of turbines were typically constructed out of aluminum due to its favorable properties, but they were subject to fatigue damage in the blades, caused by cyclic aerodynamic stresses. To mitigate these stresses, modern turbine blades are made out of composite materials, which have the additional benefit of being fairly sustainable. (ERIKSSON et al., 2008).

Due to the sustainable nature of the energy production from a wind turbine, there have been moves in recent years to build them using sustainable materials (Pradeep et al., 2019). Research has designated four groupings of composite materials with advantageous properties for use in turbines. These grouping are natural composites, hybrid composites, thermoplastic composites, and nanocomposites (Pradeep et al., 2019; Thomasa and Ma, 2018). Each of these groups has advantageous and disadvantageous properties that need to be considered when selecting the material to use in a specific application. Examples of materials for use in wind turbines from these groups are polyester, glass fiber, copper-aluminum-nickel, copper-zinc-aluminum, and nickel-titanium (Prabowoputra et al., 2020).

While the application of these existing wind turbines is the same as our design, the novelty of the design we are analyzing prevents us from getting more usable information from researching existing wind turbines. The structures vary too much from our own to be of use to us, we can only use the material data gathered to improve our design. While we noted advantageous aspects of these existing designs, to make recommendations for alternative designs for our novel concept, keeping our design as similar to the conceptual design prevents us from using these advantageous features.

Lattice Towers

As shown above, there are different types of cell phone towers, each with different structural designs. Each type of tower is designed to be used in a different application, where the benefits of the tower are emphasized. The type of tower most similar to our wind turbine design is a lattice tower, so we will be focusing on the structural considerations and materials for that type of tower.

Figure 6: Types of Cell Towers (RF Wireless World- Cell phone tower basics, n.d.)

Lattice towers are free standing framework towers that are self-supporting. These designs utilize the strength of triangles in their design to maximize their strength while minimizing their weight. The most common lattice towers are used in broadcasting (cell towers) to support the antennas that send and receive signals and in energy distribution (transmission towers) carrying high voltage wires.

Lattice towers are typically made from L-shaped steel profiles which are connected by bolts. The larger base dimensions and use of trusses help the towers resist applied loads more effectively and the open design of the tower allows for the reduction of the wind loads (Gencturk et al., 2014). By using standard member profiles (L-shaped) and standard connections (bolting), the manufacturing cost is significantly reduced compared to other structural designs (Gencturk et al., 2014). Similarly, because lattice towers can be transported to the site in multiple small pieces, they also offer savings in terms of construction costs (Gencturk et al., 2014). However, there are also disadvantages to this type of structural design, which includes vulnerability against fatigue, being less aesthetically pleasing, and maintenance issues in cold regions (Gencturk et al., 2014).

Water Towers

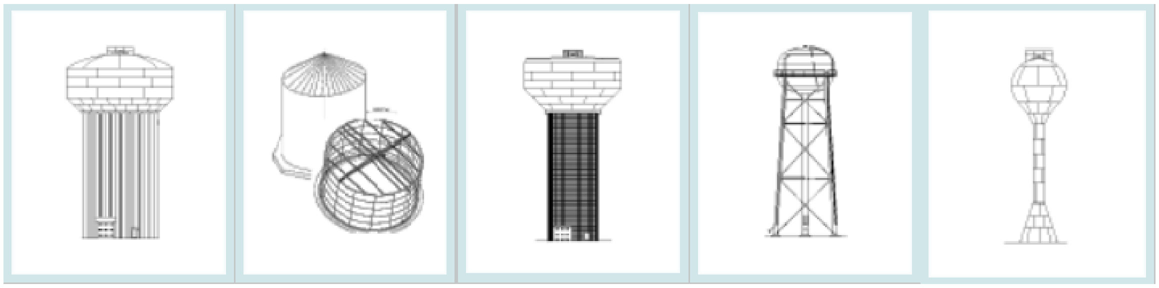


Figure 7: Different Types of Water Towers (Water Tank Guide, n.d.)

Water towers come in a variety of shapes and sizes, some of which are shown in the image above. They hold large stores of water, which can weigh upwards of hundreds of thousands of pounds, requiring the towers to be strong and well designed. These towers are typically made from steel frames encased in steel plates that sit on large, reinforced concrete foundations. Steel has advantageous properties that allow it to be successful in these scenarios due to its immense strength and durability. Typically, these members are welded together to ensure they hold the water without leaking. (Water Tank Guide, n.d.)

Materials and Material Properties

Based on our research of the different materials used in existing structures that are similar to our preliminary wind turbine design, we further researched these materials to determine their feasibility for our design.

Upon further research regarding the four grouping of sustainable materials being used in the construction of wind turbines the following information regarding the groupings was found. Natural composites have excellent mechanical properties, relatively low costs, and are environmentally friendly, but a major disadvantage is their moisture absorption. Composite hybrids are capable of producing static tensile loads and resisting fatigue. The difficulty of hybrid composite materials is that they cause the mechanical properties of high carbon fibers to become simple composite properties. The advantage of thermoplastic composites are their stiffness and high strength. Nanomaterial has the same advantages as thermoplastic composites, which are stiffness and high strength (Pradeep et al. 2019). These materials are environmentally friendly, so materials like natural bio-composite materials and thermoplastics are useful for making wind turbine blades (Thomasa and Ma, 2018).

A study was performed by Okokpujie et al. (2020) to determine beneficial materials to use in wind turbines. The criteria that were used in the material evaluation included weight, durability, price, and corrosion resistance. The evaluation was carried out using a rating scale of 1-5, for the following materials: variations in mild steel, glass fiber, stainless steel, and aluminum alloy (Okokpujie et al. 2020). The results of the study are shown in figure 4, shown below. The figure shows a comparison of durability, corrosion resistance, and density for the different materials. The results of the study determined mild steel has the highest density value, stainless steel has the highest durability, and aluminum alloy has the highest corrosion resistance. Additionally, figure 6 shows that stainless steel has the highest price, while mild steel has the lowest price.

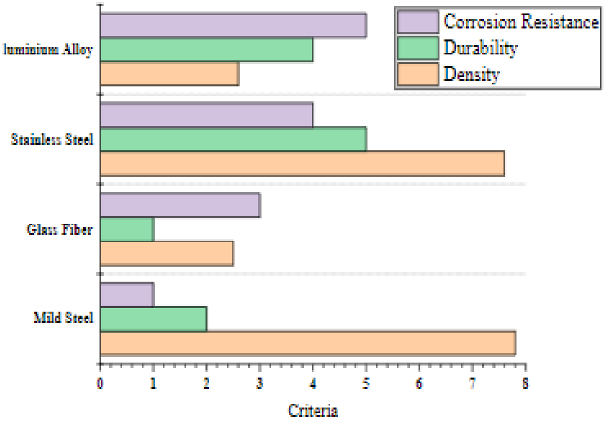


Figure 8: The comparison of materials with criteria (Okokpujie et al., 2020).

Finally, the factors were combination to determine the overall best suited material to use in wind turbines, which resulted in aluminum alloy having the highest score. These results are shown below, in figure 9. The result of the study suggests aluminum alloy is the best material to use in the construction of wind turbines due to its well-balanced material properties, when compared to the other materials. (Okokpujie et al. 2020).

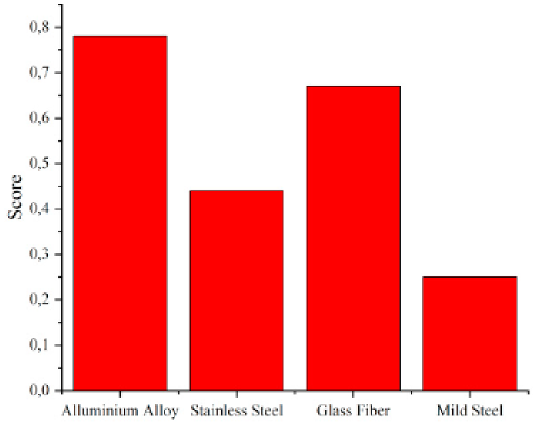


Figure 9: The performance value analysis of alternatives materials (Okokpujie et al., 2020).

Additional studies have been conducted comparing the properties of materials used in wind turbines. (Dathu and Hariharan, 2020). This research has been done to compare the effect of wind speed on the material. The materials studied were glass fiber, polyester, copper-aluminum-nickel (Cu-Zn-Ai), copper-zinc-aluminum (Cu-Ai-Ni), and nickel-titanium (Ni-Ti). Figure 10, shown below, displays the correlation between shear stress & wind speed. A smaller increase in shear stress means a more durable material (Dathu and Hariharan, 2020).

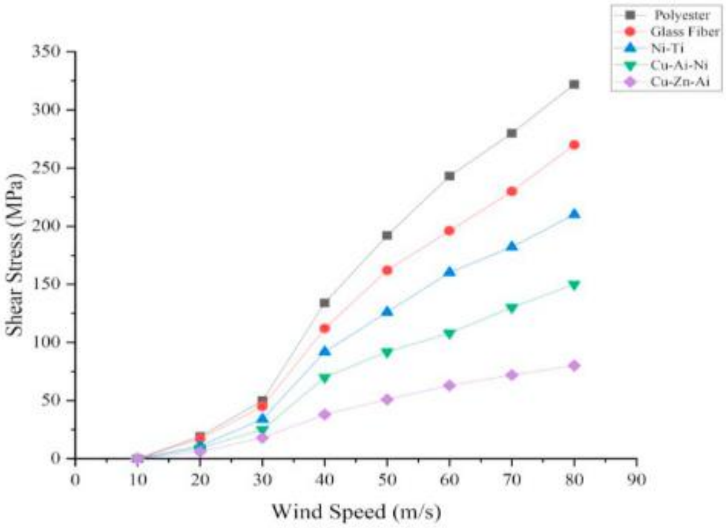


Figure 10: Correlation between shear stress and wind speed (Dathu and Hariharan, 2020).

While this study did not include aluminum alloy, the results show that composite metals are more durable than glass fibers and polyester. The first study mentioned determined that aluminum alloy was roughly twice as durable as glass fibers, which is in the range of the copper-aluminum-nickel and the nickel titanium. However, when the densities of the composite metals and aluminum are compared, as shown in table 1, below, aluminum weighs significantly less than the composite metals.

Material	Density (g/cc)
nickel titanium	6.45
copper-aluminum-nickel	7.64
copper-zinc-aluminum	7.12
aluminum	2.70
steel	7.85

Table 1: Properties of Materials (Dathu and Hariharan, 2020).

The results of these studies and analysis of material properties suggest that aluminum is the best material to use in the construction of our wind turbine design due to its favorable properties. But, the cost of the structure was the greatest concern to our sponsor, so we placed emphasis on the cost of the material and as such further investigated steel. The density of steel is relatively consistent with those of the composite materials; however, it has a lower cost and a higher strength. These are beneficial for the application of our design. But the corrosion resistance of steel, or the lack thereof, is a concern as our structure will have high exposure throughout its service lifetime. To mitigate this problem, we researched coating systems that could be used to protect the structure from the elements. The various options and their associated costs are shown in table 2, below.

Coating System	Initial Cost ($/sq. ft.)	Life-Cycle Cost ($/sq. ft.)	Average Equivalent Annual Cost ($/sq. ft.)
Hot-Dip Galvanizing	$1.76	$4.17	$0.11
Epoxy/Epoxy	$2.61	$38.31	$0.99
Epoxy/Polyurethane	$2.82	$51.90	$1.34
IOZ/Epoxy	$2.85	$35.91	$0.93
IOZ/Epoxy/Polyurethane	$4.17	$38.26	$0.99
Galvanizing/Epoxy/Polyurethane (Duplex)	$5.22	$22.45	$0.58
Zinc Metallizing/Sealer	$8.13	$60.99	$1.58

Table 2: Coating Systems Cost (AGA, 2015)

As shown from the table, hot-dipped galvanizing is the most cost-effective option both in terms of initial cost and life cycle cost. This will help to reduce the cost, as galvanized structural steel is less expensive than other corrosion resistant materials, as shown in table 3.

Material	Cost ($/lb.)
Galvanized Structural Steel	$0.80
Stainless Steel	$2.02
Aluminum	$2.79
Titanium	$4.10

Table 3: Material Prices (Metal prices archive, n.d.; Wallace, 2019)

This table shows the most cost-effective option would be to use galvanized structural steel for the structure. However, there could be aesthetic concerns with the final appearance of these members. Using one of the other coating options, such as the epoxy and polyurethane options, could have a better visual appearance that better aligns with the desired design.

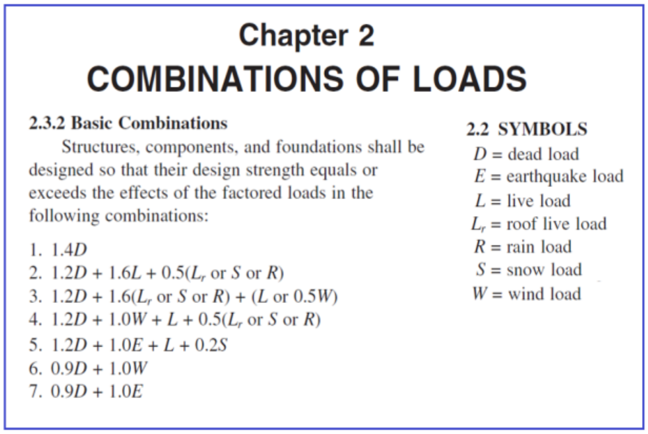
Loading Conditions

We also needed an understanding of the loading the structure would face during its service lifetime. The loads are also subject to a factor that adjusts the loading based on criteria of the structure, as a matter of safety. The loading conditions and adjustment factors we researched included the wind load, snow and ice load, seismic load, and the dead and live loads. Our research determined that the seismic load was negligible due to the proposed location of the wind turbine, which has minimal seismic activity. The other loading conditions will be the focus of our structural design, as they are the most relevant to the structure.

Methodology

Structural Design Process

When performing the necessary calculations for structure, it was of paramount importance to ensure the structure would be designed to handle the most extreme of the loading conditions outlined in the previous section. To this end, we utilized ASCE-7 to determine the optimal load factoring combination to use, to ensure our structure could withstand any remotely possible condition it may experience. The different load combinations are shown in figure 11, below. The load combination that produced the most dramatic result was caused by combination 4, as such this was the combination used for our design.



Chapter 2

COMBINATIONS OF LOADS

2.3.2 Basic Combinations

Structures, components, and foundations shall be designed so that their design strength equals or exceeds the effects of the factored loads in the following combinations:

1. $1.4D$
2. $1.2D + 1.6L + 0.5(L_r$ or S or $R)$
3. $1.2D + 1.6(L_r$ or S or $R) + (L$ or $0.5W)$
4. $1.2D + 1.0W + L + 0.5(L_r$ or S or $R)$
5. $1.2D + 1.0E + L + 0.2S$
6. $0.9D + 1.0W$
7. $0.9D + 1.0E$

2.2 SYMBOLS

D = dead load
E = earthquake load
L = live load
L_r = roof live load
R = rain load
S = snow load
W = wind load

Figure 11: ASCE-7 Combination of Loads (Van Laan, 2018)

To begin the calculations, the wind force needed to be determined. Based on the proposed location of the wind turbine, the corresponding maximum design wind speed was determined using ASCE-7. The location of the wind turbine will be Cambridge, Massachusetts, where the maximum design wind speed is 140 mph. This wind speed was then converted to a wind force using Bernoulli's Equation. The resulting force was then factored using the modifier identified from load combination 4, which was 1.0, meaning the factored wind load was the same as the original calculated wind load.

To begin the structural design, the flaps were the first element we tackled. We used the wind force previously calculated to determine the required thickness of the flap that would limit their deflection to an allowable amount. We used this thickness, along with the length and height values from the original design. Using these values, a volume calculation was performed to determine the total volume of one flap. The volume of the flap was then multiplied by the density of the material to determine the total weight of one flap. We analyzed and performed calculations for different materials to determine the best material to make the blades out of. The two materials with the best results were aluminum and steel, but between the two aluminum was the more ideal material, and as such was the one carried throughout our calculations.

The next step in the design was the frames for each blade. Using the total weight of the flaps on a single blade as well as the self-weight of the blades, the downward deflection due to gravity was calculated. This calculation required optimization, as after every calculation the frame member sizes would change and thus change the problem. The calculation was repeated until the variation from one calculation to the next approached zero. This deflection was limited by the allowable deflection given in ASCE-7 and used to determine the thickness of the frame. A similar deflection calculation was performed to limit the horizontal deflection caused by the wind force. As with the self-load, due to gravity, the wind load was an optimization problem that had to be repeated until the difference approached zero. We used the larger of the two sizes required by the calculation, which was typically driven by the horizontal deflection limit.

The combined weight of the blade frame and flaps was used to calculate the load applied to the central shaft, which was used to design the shaft against crushing. Using the stress limit for the material and the load to be applied, due to the shaft being a "short column", the required moment of area for the shaft was calculated. This required area was paired with the desired outer diameter of the shaft to calculate the required thickness. The next step was to ensure the shaft met the torsional limits due to the loading caused by the wind force. Using the equation for torsion in a hollow cylinder we again calculated the required thickness of the shaft. As with the blade frame design, the larger of the values from the two calculations was used.

With the thickness of the column the weight of the central shaft could be calculated. The combined weight of the shaft, blade frame, and flaps was used as the self-weight for one layer. This self-weight was used as a load distributed among the sixteen trusses on each layer. The trusses were designed in MATLAB using the dimensions from the design and the load created by the weight of one layer. The design was again driven by deflection limits to determine the required size of the members. These trusses would also carry axial loads in specific scenarios and had to be designed accordingly. The results from MATLAB were checked to ensure the members could carry the axial loads without failing.

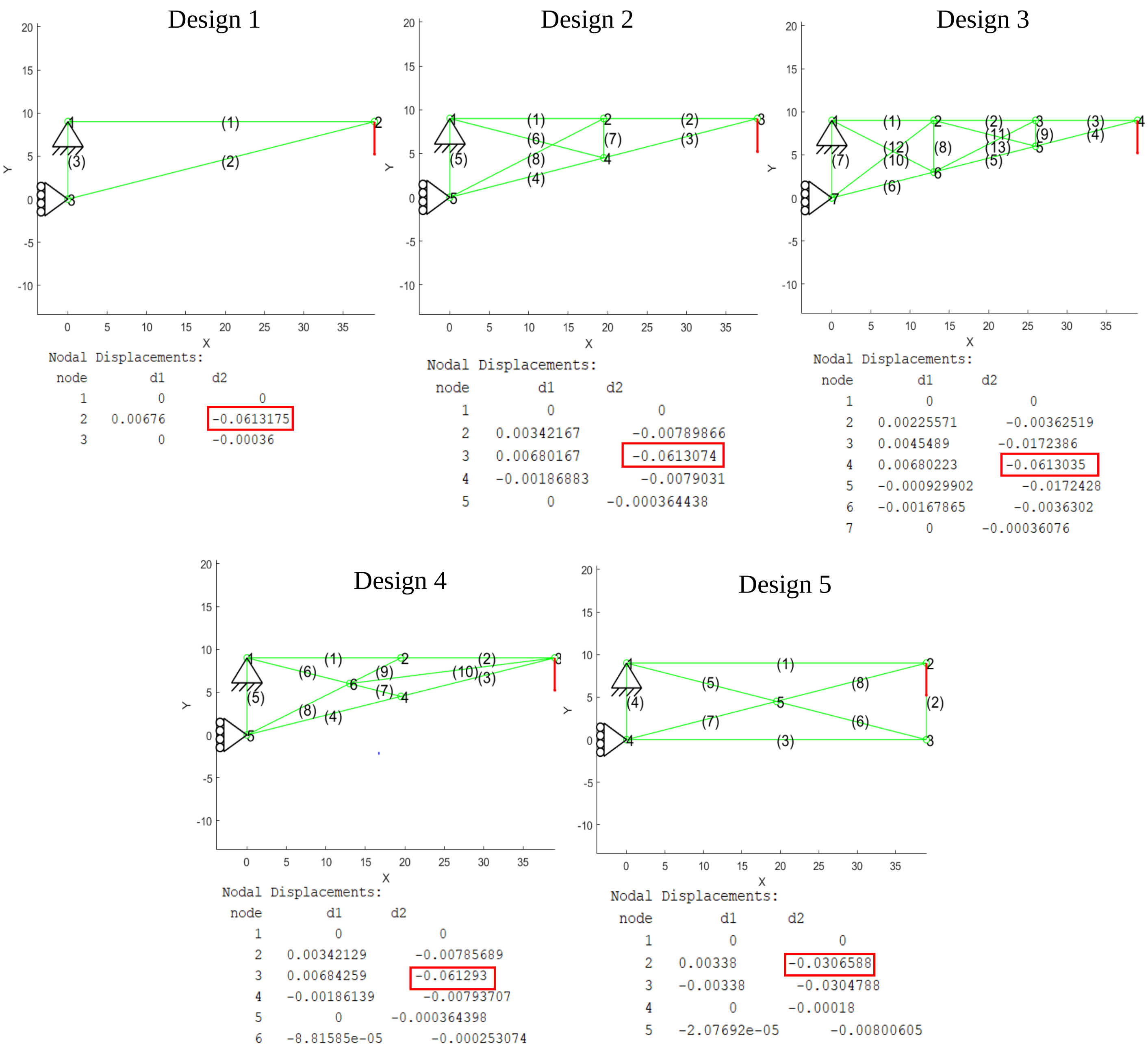
The weight of the trusses from one layer were added to the weight of the central shaft and the blades to determine the load that would be carried by the columns caused by one level. This weight was then factored using the load combination factor that was determined in the previous steps. To prevent excessive over design the columns were broken into four layer "modules". The columns for each of these modules were designed to carry the load from their module, in addition to the modules on top of it. These calculations were fundamentally based on the Euler Buckling equation, as the columns are all slender columns. Using the information from the previous steps, from the design, and from our material research, the calculations were performed to determine the required moment of inertia of the columns. Using this calculated value, we selected an adequate member size from various HSS square sizes. The calculation was repeated to include the self-weight of the column until the variations in the solutions approached zero. This was repeated for each module, including the load from on modules on top of said module in the calculations.

The final design calculation to be designed was the structural connections between members. The axial load and shear load that would be applied to the fasteners at the various connections were determined and used to determine the required area of the fasteners. In the calculation process we tested different sizes of fasteners and different numbers of fasteners to determine the most effective combination for the particular instance.

These calculations and estimates were repeated for varying load carrying conditions within the structure. It was experimented to see how the cost and weight estimates would change when the central shaft and outer columns carried varying percentages of their shared load. By changing the stiffness of the trusses that support the center shaft, we could control the portion of the load carried by the trusses to the columns and the portion that was transferred down the column. Some elements of the design, such as the solar panels and trusses, are only carried by the columns and as such their loads were not divided between the columns and shaft in these calculations. The only loads included were the deadloads caused by the blades (blade frame and flaps) and the central shaft. These calculations used twenty-one differed distributions of said load between the outer column and the central shaft. The calculations began with 100% of the load being carried through the outer columns and none through the central shaft. While this condition is theoretically impossible because it would require the trusses to have infinite stiffness, we included it so all load conditions from one extreme to the other could be compared. The calculation was repeated, decreasing the load carried by the columns by 5% and increasing the load carried by the shaft by 5%, until 100% of the load was carried by the central shaft and none was carried by the columns.

One of the few elements that could be modified without having dramatic effects on the rest of the structure was the trusses located in between each layer, that supported the central shaft. Due to this design flexibility, a variety of designs were analyzed to determine the most efficient design, balancing the cost and the strength considerations, to use in the structure. The trusses were designed using the same member sizes, member materials, boundary conditions, and same loading conditions to effectively compare the resulting displacements between the different designs. The deflection at the furthest point from the columns, where the truss contacts the central shaft and is transferred to the load, was compared between the different designs. The material cost for each design was then calculated to determine the cost efficiency of each one. The deflections and costs for each design were compared to determine their relative benefits and detriments. The different truss designs and the displacement at the point of interest, displayed in a red box, are shown below in figure 12.

This analysis of the truss designs was performed in MATLAB, which allowed for the load conditions, member sizes and properties, and the overall size of the truss to be easily updated as the design of the structure was updated. The cost for each design was calculated following the equation and process outlined in the previous section. These costs and deflections were compared between the various designs to determine which would be best suited to the application of this project.



Design 1

```
Nodal Displacements:
 node        d1         d2
   1          0          0
   2    0.00676   -0.0613175
   3          0   -0.00036
```

Design 2

```
Nodal Displacements:
 node         d1             d2
   1           0              0
   2   0.00342167     -0.00789866
   3   0.00680167     -0.0613074
   4  -0.00186883      -0.0079031
   5           0   -0.000364438
```

Design 3

```
Nodal Displacements:
 node          d1           d2
   1            0            0
   2   0.00225571    -0.00362519
   3    0.0045489   -0.0172386
   4   0.00680223    -0.0613035
   5  -0.000929902     -0.0172428
   6  -0.00167865     -0.0036302
   7            0  -0.00036076
```

Design 4

```
Nodal Displacements:
 node          d1          d2
   1            0           0
   2   0.00342129    -0.00785689
   3   0.00684259   -0.061293
   4  -0.00186139     -0.00793707
   5            0  -0.000364398
   6  -8.81585e-05     -0.000253074
```

Design 5

```
Nodal Displacements:
 node          d1          d2
   1            0            0
   2      0.00338   -0.0306588
   3     -0.00338     -0.0304788
   4            0   -0.00018
   5  -2.07692e-05       -0.00800605
```

Figure 12: Truss Designs

Cost Analysis

A series of cost estimates were prepared using the results from the various calculations. In some instances, pricing data was unavailable and had to be extrapolated from data available. For seventy-nine different height/width and thickness member combinations we had data on the weight per foot, the length, and the cost. The table in Appendix A contains all the data for each respective member. The cost for each member was divided by its respective length to get the cost per foot for each member. This calculated term is included in the table in Appendix A for each member. The cost per foot and the weight per foot were graphed to determine if there was a relation between cost and weight for the respective members, shown below in figure 13.

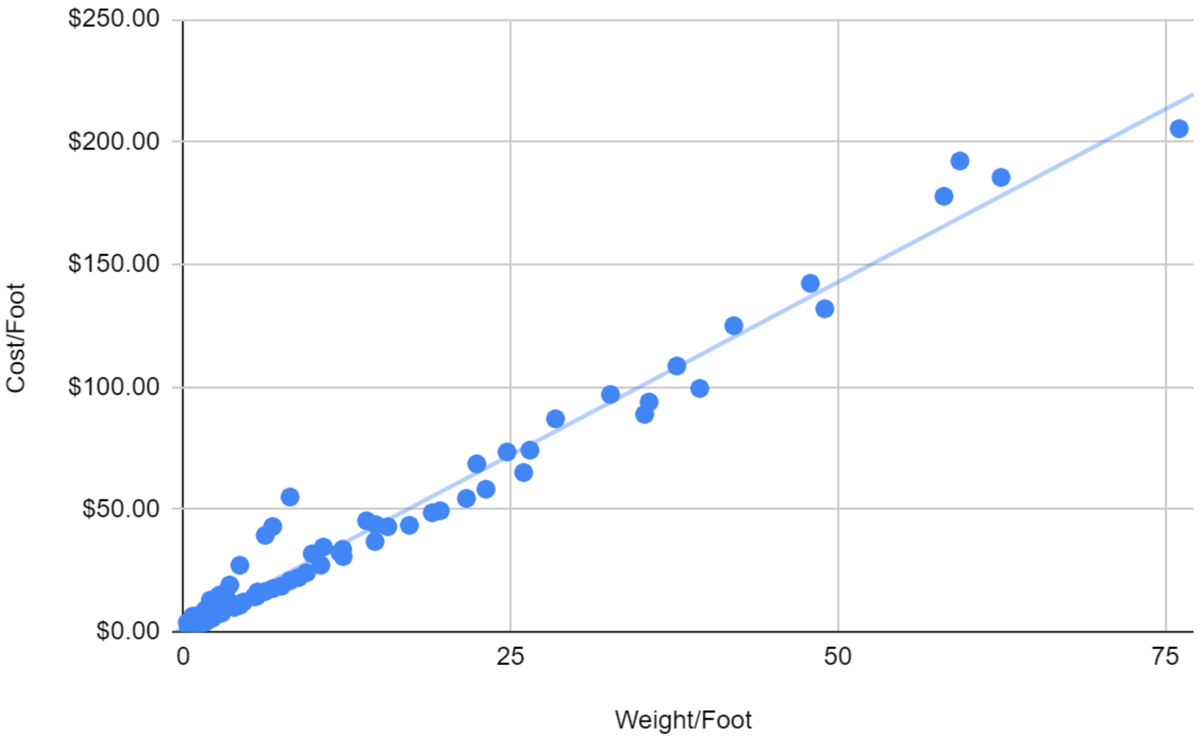


Figure 13: Cost vs Weight Analysis

As seen in the graph, there is a relatively linear relationship between the weight of the member and the cost of the member. The data has an R^2 value of 0.976, which means the linear model is an accurate representation of the relationship between the weight and cost. The trend line for this graph is as follows:

$$\text{Cost} = 2.82 * \text{Weight} + 1.65$$

This equation was used in our cost estimating procedures to determine a rough cost of a specific member based on its weight.

For elements that would have to be custom made, the material cost and a labor cost was used to estimate the cost of said element. Additionally, a labor cost for assembling the structure on site was also included in the estimate. Finally, a weight estimate of the structure was also prepared to be used in the foundation design calculations.

Sub Structure Design Process

The sub-structure or foundation design began with the projected location of the structure. The sponsor intends to erect the building in Cambridge, Massachusetts. Having no geotechnical soil report of the specific location, a sample soil report with a geological profile was obtained from a Massachusetts Institute of Technology (MIT) master's thesis in 1972 evaluating the floating foundations of MIT academic buildings. (FIGURE 96) The first twenty feet consisted of topsoil fill. The following hundred feet consisted largely of blue clay with the addition of silty sand transitioning to stones and hard packed gravel.

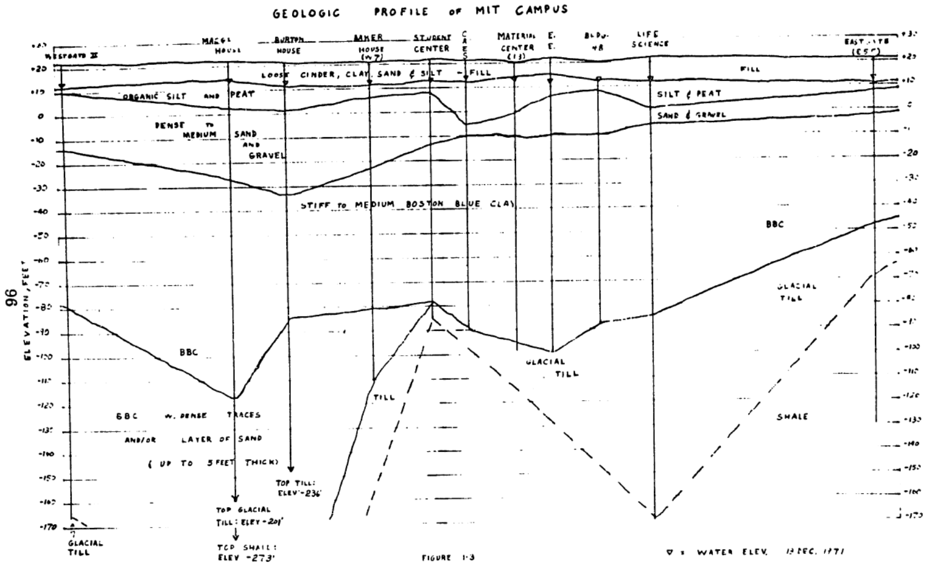


Figure 14: MIT Soil Profile

The bearing pressure of the superstructure was calculated by taking the sum of the vertical column weights and the self-weight of the proposed shallow foundation and divided by the area of the base. The pore water pressure was subtracted from the total. The proposed shallow foundation base was designed as a circular base 60 feet in diameter by 4 feet deep. The weight of the foundation was calculated using normal weight concrete at 150 pounds per cubic foot. This did not account for the recommended reinforcing steel to prevent cracking. The rebar design was number four half inch rebar laid every six inches spiraling from the center to the outside ring. Additionally, the rebar was placed every six inches from the top to the base of the foundation considering cover. Finally, rebar ties were spaced every six inches vertically to secure the layers and into the steel pipe piles.

The ultimate bearing capacity was calculated using Terzaghi's method for a circular foundation. The factors were based on blue clay's cohesion angle. The unit weight of blue clay obtained from a MIT geological report was used and the corresponding cohesion angle. Based on the ultimate bearing capacity the soil could hold the bearing pressure of the structure and shallow foundation. However, intuitively the moment created by the height of the structure resisting the wind would cause rotation of the structure. Therefore, a deep foundation was required to be designed.

The deep foundation consisted of steel pipe piles filled with concrete. Nine piles were used designed at a depth of 120 feet. This provided additional uplift to the structure resisting sinking into the soil. Additionally, the piles prevented sliding of the structure and resisted tensile loads. Toe bearing and side friction were considered.

The cost was determined from the total concrete, rebar, pipe pile, and drilling. The total cubic feet of the concrete was multiplied by 15 dollars per cubic foot. The total feet of number four steel rebar was multiplied by two dollars per foot. The concrete filled steel pipe pile was 2.5 feet by 120 feet at a rate of 102 dollars per foot. This factor was derived from a 2006 Federal Highway Administration report on cost data of driven piles at 82 dollars per foot of pipe pile and 20 dollars per foot to drive the pile. In conclusion the cost of the shallow foundation was about $236,000 and the deep foundation was $110,000 see Appendix C.

Results

Based on the calculations and analysis discussed in the previous section, a variety of possible designs were developed, ranging in cost and weight. These differences are due to the various design alternatives and design choices that were made during the calculation process.

Truss Design

The analysis of the truss design was the first step to be completed, due to the influence of these members on the rest of the structure. The cost and deflection values for each design were compared to determine which of the designs was the most efficient. These cost and deflection values for each truss design are displayed in the table below. The cost is represented by the total cumulative length of the members. Due to all five designs using the same sized members, the cost for each will be proportional to the total member length for each.

Truss Design	Cost ($)	Deflection (in.)
Truss 1	88.02	0.0613175
Truss 2	134.02	0.0613074
Truss 3	155.21	0.0613035
Truss 4	154.68	0.061293
Truss 5	176.02	0.0306588

Table 4: Truss Design Costs and Deflections

The cost is the detriment of each design, and the deflection is the benefit for each. All the designs were compared to the first design to determine their cost and deflection as a percentage of the first design, which was the simplest of the designs. Those values are shown in the table below.

Truss Design	Cost (%)	Deflection (%)
Truss 1	100%	100%
Truss 2	152%	99.984%
Truss 3	176%	99.977%
Truss 4	176%	97.02%
Truss 5	200%	50%

Table 5: Cost and Deflection Comparison

As shown by the table, the first four designs have very similar deflections, but are increasingly more expensive. The fifth design is the only design with a significant decrease in deflection from the first design with a 50% reduction, however the cost is double that of the first design. Based on these comparisons, we narrowed the recommendation to between the first and fifth options due to their balance between cost and deflection. Ultimately, we recommend the first design due to its simplicity and additional benefits, that were not initially included in the analysis, such as transportation and assembly costs, which would be lower for this design than the fifth design.

We used the weight and deflection values for this design in the other design calculations as needed. The design of many aspects of the structure are dependent on the design selected for the truss and new calculations would be needed if a different design is selected.

Main Structure

Due to the required thickness of the central shaft due to torsion being greater than the required thickness for crushing in the maximum loading condition, the central shaft does not increase in size as more load is applied. This causes the structure to weigh less and cost less, as more load is carried by the central shaft, due to it becoming less overdesigned. These results are shown by the graph, in the figure below.

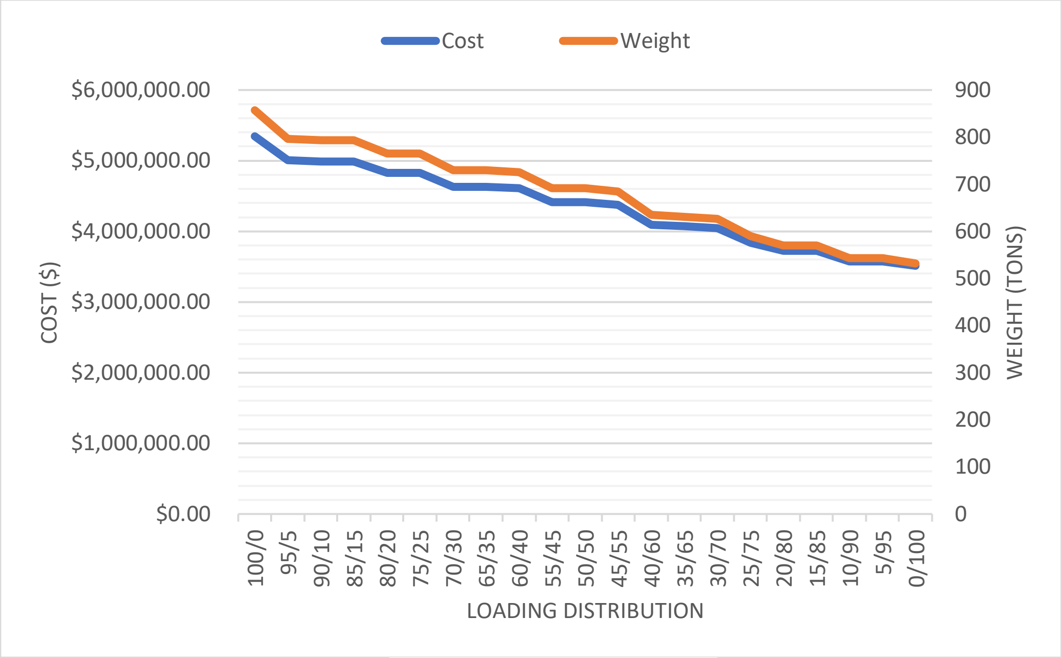


Figure 15: Loading Distributions

The recommendation for which loading distribution was a difficult recommendation to make due to the effects of friction caused by the load on the center shaft. As more load is carried by the center shaft the effects of gravity and friction will be increased as the base of the shaft, which will lead to energy loss. The purpose of the structure is to generate electricity, so our goal is to minimize this energy loss. However, as previously mentioned, as more load is carried by the shaft the cost and weight of the structure decrease. So, the benefits of carrying the load down the central shaft need to be analyzed in comparison to the detriments to determine the ideal ratio between the two, which would inform which load distribution to use in the design. But the effects of gravity and friction on the energy output were not explicitly studied during this project, so a definitive result is not available.

Between the various loading distributions, the blade frame and flap designs are the same. For the blades, they will need to be custom made to the size and shape of the initial design as that shape was determined to be sufficient if made from both steel and aluminum. However, we recommend they be made of aluminum due to its beneficial properties, such as low density and high strength. For the blade frame, we recommend using ten-inch square hollow structural sections (HSS) with a thickness of one quarter of an inch. Additionally, we recommend using steel due to its high strength and low cost. As for the member type, we recommend using square HSS due to the uniform strength it has in both the X and Y directions. The central cylinder also has the same design, size and thickness, in all load distributions due to the torque caused by the wind requiring more area than the area needed to prevent crushing, as previously mentioned. While the truss and column member sizes change between the loading distributions, we recommend they also be made from square HSS members due to the benefits previously mentioned. Especially in the case of the columns this is beneficial as the unsupported length of the columns is the same in both the X and Y directions, so the column needs to be equally stiff in both directions to prevent buckling.

For member lengths, the desired location of the final product had to be considered, which was an urban setting. This would limit the allowable length of the members in the design. We decided to limit the member sizes to what would fit on an eighteen-wheeler, flatbed, trailer which is typically around 48 – 50 feet long. This is the largest delivery method that can safely navigate the urban landscape, but even then, deliveries may need to be made during non-peak traffic hours. Most of the members would not have an issue as their length was less than the maximum allowable. The only components that would need to abide by this maximum were the central shaft and columns, as they run the entire height of the structure and need to be designed in segments. We recommend having columns run continuously for four levels, while being supported horizontally at each level. This will allow for the modular design desired by the sponsor, while minimizing the required assembly for the structure. The length of a column that runs for four levels would be 48.06 feet, which is roughly the maximum that can be accommodated. We similarly recommend the central shaft be divided into sections that span four levels, for the same reasons. In an instance where accessibility is even more restrictive than our current case, we would recommend the use of two-level modular sections. These sections could fit onto a flatbed truck, or a trailer pulled by a smaller truck and would be roughly 28 feet long. They would provide similar benefits to the four-level modular section, reduced assembly and still be a modular design, while making transportation easier.

This modular design also allowed the column size to vary depending on the location within the structure. Columns near the bottom of the structure would need to carry more load and therefore be bigger and stronger. Conversely, columns near the top of the structure would carry less load and could be designed smaller. This variation in column design reduces the over design of the structure, as the columns are closer to the proper sizing the smaller the modules are. This reduces the deadload of the structure, saving both money and material.

Similarly, to reduce cost, we recommend removing the “floor” and “ceiling” plates from the design. From a structural standpoint they provide minimal benefits while adding to the load carried by the cantilever trusses, causing them to be larger and heavier themselves. Additionally, in discussion with the mechanical engineering team, it was determined the plates provide no mechanical benefit to the structure. Therefore, the detriments of the plates outweigh the benefits, which is the justification for removing them.

The specific cost and weight of each design iteration can be seen below in table 6. As the structure becomes less over designed, due to the central shaft carry loads increasing closer to its capacity, the cost and weight decreases, as the member sizes of the other structural elements decrease. The respective cost of each iteration is an estimate of the sum of the member costs, which were derived from the equation outlined in the cost analysis section.

Load Case (Exterior Load/Interior Load)	Cost	Weight (tons)
100/0	$5,344,959.23	857.07
95/5	$5,004,562.27	796.71
90/10	$4,989,816.69	794.10
85/15	$4,989,816.69	794.10
80/20	$4,826,633.09	765.17
75/25	$4,826,633.09	765.17
70/30	$4,630,376.22	730.37
65/35	$4,630,376.22	730.37
60/40	$4,606,392.98	726.12
55/45	$4,410,171.14	691.32
50/50	$4,410,171.14	691.32
45/55	$4,371,290.53	684.43
40/60	$4,095,187.96	635.48
35/65	$4,071,161.35	631.22
30/70	$4,045,074.68	626.59
25/75	$3,840,967.91	590.40
20/80	$3,729,184.84	570.58
15/85	$3,729,184.84	570.58
10/90	$3,575,871.25	543.40
5/95	$3,575,871.25	543.40
0/100	$3,512,104.97	531.87

Table 6: Load Distribution Cost and Weight

While more expensive, we would recommend using one of the designs where most of the weight is transferred to the outer column structure, rather than be carried by the central shaft. This will reduce the inertia of the mechanical aspects of the design and reduce the effects of gravity, and by extent friction, between the central shaft and its supports. This should allow the structure to generate the most possible energy. While the increased cost will take the investment more time to pay off, the increased energy produced will be a benefit for the service life of the structure. An example of a cost estimate for one of the designs is included in Appendix B, while the totality of these estimates are provided in the supplementary materials that complement this report.

For a traditional, horizontal axis wind turbine, the cost and weight are significantly lower than the values for this design. A 2-megawatt HAWT, depending on several factors, can cost anywhere from $2.4 million to $4 million (Anemoi Energy Services, 2020). As for the weight comparison, a traditional 2-megawatt HAWT, again depending on the type and size, weighs roughly 325 tons (Bauer, n.d.). While these values are lower than that of the recommended design, our design could be implemented in more scenarios than traditional HAWTs, such as in urban environments, due to the smaller required size area.

Connections

For the structural connections between the members, two designs were completed: one for the column-to-column connections and one for the truss connections. The column connections involve adding a base plate and a crown plate to each column during the manufacturing process. These two plates will be bolted together using eight, one inch diameter, bolts. This design is shown in the figure below.

These designs for the structure include columns that change thickness and size as the load carried by the columns change. This connection design will allow for a solid connection between these columns of differing sizes as the plates on either end will help to bridge the difference in size.

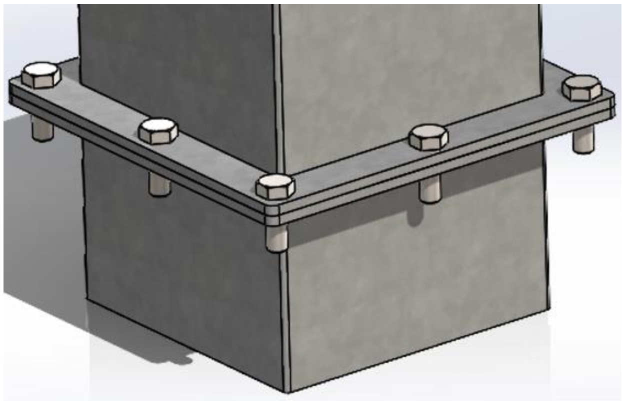


Figure 16: Column Connection

For the truss connections gusset plates will be used to join the truss members to each other and to join the truss members to the columns. Due to the angles of the truss members, using a design like the one above would be difficult and complicated, so gusset plates will be used instead. These gusset plates will similarly be attached to each member with eight, one inch diameter, bolts. An example of gusset plates used in a truss design is shown below.

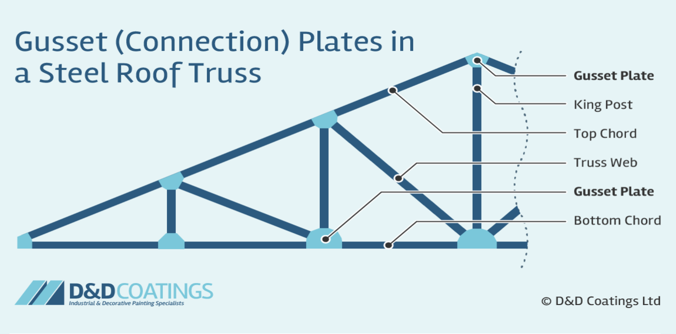


Figure 17: Gusset Plate Connection (D&D Coatings, 2019)

Discussion

Limitations of Final Design

These designs were completed with the specific end location of Cambridge Massachusetts in mind. Due to the different wind speeds, seismic conditions, and environmental conditions (climate) in different locations, not only around the country, but also around the world, this design will likely need to be modified if the design is to be implemented elsewhere. Similarly, differences in building codes and zoning ordinances will require alterations to the design and could limit the size, appearance, and allowable noise production of the structure. The foundation design will also vary depending on the design of the super structure and the soil profile of the proposed location, so it will similarly need to be modified on a case-by-case basis.

A design or small series of designs could be made that would satisfy all conditions that could be found throughout the country. While this would lead to the structure being over designed in some instances, it would eliminate the need to reengineer the design for every implementation, which would save time and money. This could be accomplished by breaking the country into regions based on the wind and seismic conditions and the regional climate and creating a design for each region or even a grouping of similar regions. The designs would have to reflect the harshest conditions that will be found in the region/group of regions the design will be implemented in, to ensure the safety of the design.

Effectivity of Final Design

From a structural standpoint, the final design recommendation is as effective as possible, balancing the safety and integrity of the structure with its overall cost. From a mechanical standpoint, the efficacy of the design will be unknown until a prototype can be built and tested. The mechanical engineering MQP team worked to optimize the design of the blades, the mechanical supports (that supported the central shaft), and the design and orientation of the blade flaps, but they were unable to test them on a prototype that followed the structural design outlined above. That is why the overall mechanical efficiency of the design is unknown at this point. These two components working in tandem are the essence of the design and control the overall efficacy of the design.

The main detriment of vertical axis windmills, such as this one, is the effects of gravity on the structure and the energy output. This design attempted to minimize those effects using an extensive structural system that transferred the loading away from the mechanical portions of the design. This was done through a series of trusses and exterior columns that carried the loading to the ground, rather than carrying the loading through the mechanical components of the structure, like many existing designs. The intention of the design was to for this transfer of load to increase the energy output of the system.

Similarly, the design also incorporates solar panels to augment wind energy with solar energy. The cost associated with adding the solar panels to the design is minimal compared to the overall cost of the structure, while the energy produced is relatively significant. This simple addition increases the efficiency of the design at a minimal cost, which is not something that has been capitalized on by existing wind turbine designs.

Future Work

While extensive work was done throughout the course of this project, there are still many steps that could be undertaken in the future to further improve the design. Additional research and experimentation could yield results that make the design more effective and more practical for everyday implementation.

Structural Connections

The structural connections recommended above were created with the simplicity of construction in mind. Uniform bolt sizes and basic connections were used throughout to make the construction of the structure simpler, to reduce the required labor cost. However, the use of different connection methods could be explored, additional research could be done on connection types, and unique connections could be designed for each connection point. It could be found that one or more of these could reduce the cost of the structure and increase the efficiency of the design.

Truss Design

As shown above, five variations of truss designs were developed and compared with one another. The best design of the five was recommended due to its reduced cost and weight and its relative strength. Alternative truss designs could be explored and alternative load carrying designs could be investigated, such as utilizing steel cables. Due to the truss's interaction with the central shaft, it is possible a more effective design could be found that could help to control vibrations better or could reduce the noise produced by the structure in addition to increasing the efficacy of the design.

Soil Dynamics

Due to the vibration caused by the mechanical functions of the structure soil dynamics would need to be considered. This is especially important because of the proposed geographical location of the structure in Cambridge, Massachusetts and its proximity to the ocean. Testing the foundation design in a computer aided modeling system is required.

Pile and Foundation Design

Alternate pile designs could be considered. Analysis could be conducted on steel H piles, hollow pipe piles, pipe piles filled with rebar or housing a steel H column, and bell piles. The location of the pile on the shallow foundation, number of piles, and depth could also be considered. Using a computer aided modeling system and a geotechnical study of the proposed location is required. The cost considerations are limited due to the lack of current cost information on excavation, drilling, driving, piles, and specialty rebar work.

Column design

Based on the research conducted, the use of square HSS columns was included in the recommended design due to their beneficial properties. Additional research could be done to determine a more effective shape, a design alteration could be made to make better use of a different shape, or a different material could be used (for example, no research was done on the effects of filling the HSS columns with concrete). The columns are the main structural component of the design and have one of the largest impacts on the cost and weight of the structure. If a method is found to improve their design, the structure could be made more effective.

Finer Elements Model

A basic model was created, as previously mentioned, to aid in the design process. However, due to the complex nature of the structure the software was unable to run a successful analysis. Such analysis should be run to ensure the structure operates as intended. Additionally, this model only included one layer of the design and the elements were simplified to ease the use of the modeling software, as we had no prior experience with it. A more comprehensive and detailed model could be created to better understand the relationships between the different members and their significance in the structure. Using a better model could reveal instances where the structure is over designed, or possibly under designed, and the design could be improved using that information.

Conclusions

As the human population grows and concerns over climate increase, so will dependence on renewable energy sources. When the use of renewable energy sources grows, the need and demand for development and innovation of the technologies used will similarly increase. These innovations will allow previously unfeasible or unrealistic technologies to be used or will take existing ideas and concepts to the next level.

This project did exactly that for vertical wind turbine designs. The challenge presented by gravity previously prevented designs from being large scale, like this one. Through the use of the extensive outer structure, the issue of gravity and its effects on energy production were reduced, making the design feasible for large scale energy generation. This design allows for large scale wind turbines to be implemented in urban environments, due to the minimal required area when compared to horizontal wind turbines. This will allow for renewable energy production close to where it will be consumed, so less will be lost in transport, making the overall process more efficient.

Research could be continued in the future to further the design and the technology, not only to make the design more efficient, but to investigate its implementation in different scenarios. Small, rooftop versions would allow homeowners to purchase the design to supply their house with green energy. Similarly, a smaller design could be designed for educational purposes and sold to schools and other institutions for use in their classes. This design has the potential to be applicable in any scenario that considers the use of wind energy. The design is very adaptable and scalable, which makes the design intriguing for use in a multitude of applications.

Bibliography:

American Galvanizers Association. (2015). *Hot-dip galvanizing costs less lasts longer*. Retrieved February 11, 2022, from https://www.daamgalvanizing.com/wp-content/uploads/2015/12/Galvanizing_Costs_Less_Lasts_Longer2015.pdf

Anemoi Energy Services. (2020, November 10). *How much money does a wind turbine produce from electricity it generates?* Anemoi Services. Retrieved March 4, 2022, from http://anemoiservices.com/industry-news/how-much-money-does-a-wind-turbine-produce-from-electricity-it-generates/#:~:text=A%20commercial%20average%2Dsized%20wind,the%20size%20of%20the%20turbine.

ASCE. (2020, October 26). *ASCE Code of Ethics*. American Society of Civil Engineers. Retrieved March 1, 2022, from https://www.asce.org/-/media/asce-images-and-files/career-and-growth/ethics/documents/asce-code-ethics.pdf

Bauer, L. (n.d.). *Vestas V90*. Vestas V90 - 2,00 MW - Wind turbine. Retrieved March 4, 2022, from https://en.wind-turbine-models.com/turbines/16-vestas-v90

Brown, T. L. (1971). *Comparison of Calculated Versus Measured Performance of Floating Foundations at MIT*. S. B. Howard University (1971) at Massachusetts Institute of Technology (1972).

Cambridge Community Electricity Program. MassPowerChoice.com. (2022, February 22). Retrieved February 28, 2022, from https://masspowerchoice.com/cambridge

Cambridge, MA. (2021, October 21). *Zoning Ordinance*. Municode Library. Retrieved February 28, 2022, from https://library.municode.com/ma/cambridge/codes/zoning_ordinance?nodeId=ZONING_ORDINANCE_ART22.000SUDEDE_22.70WITUSY

Cengel, Y.A., Cimbala, J.M., 2017. Fluid Mechanics Fundamentals and Applications. Fourth ed. McGraw Hill Education. New York.

Coduto, D. P. (2001). *Foundation Design: Principles and Practices*. Prentice-Hall, New Jersey.

Dathu, K.P.M.Y.V., Hariharan, R., 2020. Design of wind turbine blade material for higher efficiency. Materials Today: Proceedings, in press, accessed in: https://doi.org/10.1016/j.matpr.2020.05.445.

D&D Coatings. (2019, January 26). *What is Gusset Plate Corrosion?* D&D Coatings. Retrieved February 17, 2022, from https://www.ddcoatings.co.uk/2178/what-is-gusset-plate-corrosion

DOT. (2006). *Design and Construction of Driven Pile Foundations – Lessons Learned on The Central Artery/Tunnel Project: Chapter 5. Cost Data of Driven Piles*. Federal Highway Administration Research and Technology. Retrieved February 28, 2022, from https://www.fhwa.dot.gov/publications/research/infrastructure/geotechnical/05159/chapter5.cfm#:~:text=Steel%20pipe%20piles%20had%20the,for%20the%2041%2Dcm%20piles.

Elliott, D. L., Wendell, L. L., & Gower, G. L. (1993). An assessment of the available windy land area and wind energy potential in the contiguous United States. https://doi.org/10.2172/5252760

Energy Efficiency & Clean Energy. City of Cambridge. (2020, February 4). Retrieved February 28, 2022, from https://www.cambridgema.gov/Services/energyefficiencyresources

ERIKSSON, S., BERNHOFF, H., & LEIJON, M. (2008). Evaluation of different turbine concepts for wind power. *Renewable and Sustainable Energy Reviews*, *12*(5), 1419–1434. https://doi.org/10.1016/j.rser.2006.05.017

Gencturk, B., Attar, A., & Tort, C. (2014). Design optimization of lattice wind turbine towers subjected to earthquake forces. *Structures Congress 2014*. https://doi.org/10.1061/9780784413357.149

Haliade-X Offshore Wind Turbine. World's Most Powerful Offshore Wind Platform: Haliade-X | GE Renewable Energy. (n.d.). Retrieved October 5, 2021, from https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine.

Homeadvisor. *Rebar Cost Per Foot.* Homeadvisor.com. Retrieved February 28, 2022, from https://www.homeadvisor.com/cost/outdoor-living/steel-reinforcement-bars-pricing/

Johnson, E. G. (1989). *Geotechnical Characteristics of the Boston Area*. Boston Geology, Civil Engineering Practice.

Mass.gov. (n.d.). *Renewable Energy Snapshot*. Mass.gov. Retrieved February 28, 2022, from https://www.mass.gov/info-details/renewable-energy-snapshot

Metal prices archive. Metal Miner. (n.d.). Retrieved February 11, 2022, from https://agmetalminer.com/metal-prices/

Michigan. *Foundations Section UIP 1.* State of Michigan. Retrieved February 28, 2022, from https://www.michigan.gov/documents/Vol2-28UIP1Foundations-Frames_121070_7.pdf

National Geographic Society. (2019, May 30). *Wind energy*. National Geographic Society. Retrieved October 5, 2021, from https://www.nationalgeographic.org/encyclopedia/wind-energy/.

Okokpujie, I.P., Okonkwo, U.C., Bolu, C.A., Ohunakin, O.S., Agboola, M.G., Atayero, A.A., 2020. Implementation of multi-criteria decision method for selection of suitable material for development of horizontal wind turbine blade for sustainable energy generation. Heliyon 6, e03142.

Prabowoputra, D. M., Prabowo, A. R., Bahatmaka, A., & Hadi, S. (2020). Analytical Review of material criteria as supporting factors in horizontal axis wind turbines: Effect to structural responses. *Procedia Structural Integrity*, *27*, 155–162. https://doi.org/10.1016/j.prostr.2020.07.021

Pradeep, A.V., Prasad, S.V.S., Suryam, L.V., Kumari, P.P., 2019. A comprehensive review on contemporary materials used for blades of wind turbine. Materials Today: Proceedings 19, 556–559.

RF Wireless World. cell phone tower basics | cell phone tower types, components. (n.d.). Retrieved October 5, 2021, from https://www.rfwireless-world.com/Tutorials/cell-phone-tower-basics-and-cell-phone-tower-types.html.

Thomasa, L., Ma, R., 2018. Advanced materials for wind turbine blade A Review. Materials Today: Proceedings 5, 2635–2640.

Van Laan, T. (2018, May 31). *Version 1.02.18 released – automatic generation of ASCE 7 LRFD load combinations*. Engineering and the Cloud. Retrieved January 14, 2022, from https://blog.cloudcalc.com/2018/05/31/version-1-02-18-released-automatic-generation-of-asce-7-lrfd-load-combinations/

Wallace, D. (2019, March 2). *Price of galvanized steel vs. Stainless Steel*. Sciencing. Retrieved February 11, 2022, from https://sciencing.com/about-6711987-price-steel-vs--stainless-steel.html#:~:text=Steel%20prices%20change%20daily.&text=Galvanized%20steel%20costs%20a%20few,at%20least%20%243%20per%20pound.

Water Tank Guide. Caldwell Tanks. (n.d.). Retrieved October 13, 2021, from http://www.caldwellwatertanks.com/water-tank-guide.html.

Zhao, D., Han, N., Goh, E., Cater, J., Reinecke, A., 2019. Wind Turbines and Aerodynamics Energy Harvesters. Academic Press, ISBN 9780128171356.

Appendix A: HSS Cost Data

Width	Height	Thickness	Weight/ft	Length	Cost	Cost/ft
0.5	0.5	0.049	0.31	20	$78.20	$3.91
0.5	0.5	0.65	0.39	24	$42.00	$1.75
0.625	0.625	0.065	0.5	20	$84.00	$4.20
0.75	0.75	0.065	0.6	24	$42.00	$1.75
0.75	0.75	0.083	0.75	24	$48.48	$2.02
0.75	0.75	0.12	1.03	24	$66.72	$2.78
0.875	0.875	0.065	0.72	20	$129.40	$6.47
1	1	0.065	0.82	24	$57.36	$2.39
1	1	0.83	1.04	24	$66.72	$2.78
1	1	0.105	1.32	20	$142.60	$7.13
1	1	0.12	1.44	24	$86.88	$3.62
1.25	1.25	0.065	1.04	24	$72.24	$3.01
1.25	1.25	0.083	1.32	24	$79.68	$3.32
1.25	1.25	0.109	1.7	24	$219.12	$9.13
1.25	1.25	0.12	1.8	24	$111.12	$4.63
1.25	1.25	0.1875	2.4	24	$186.96	$7.79
1.5	1.5	0.065	1.26	24	$87.60	$3.65
1.5	1.5	0.083	1.67	24	$96.72	$4.03
1.5	1.5	0.109	2.07	24	$311.76	$12.99
1.5	1.5	0.12	2.22	24	$136.08	$5.67
1.5	1.5	0.1875	3.04	24	$239.76	$9.99
1.5	1.5	0.25	4.07	20	$216.00	$10.80
1.75	1.75	0.083	1.88	24	$121.68	$5.07
1.75	1.75	0.12	2.58	24	$172.32	$7.18
1.75	1.75	0.1875	3.68	24	$279.60	$11.65
2	2	0.065	1.71	20	$101.40	$5.07
2	2	0.083	2.14	24	$130.56	$5.44
2	2	0.109	2.81	24	$363.12	$15.13
2	2	0.12	2.94	24	$185.52	$7.73
2	2	0.1875	4.32	24	$261.12	$10.88
2	2	0.25	5.41	24	$345.12	$14.38
2.25	2.25	0.25	6.26	24	$946.32	$39.43
2.5	2.5	0.083	2.73	24	$353.76	$14.74
2.5	2.5	0.105	3.55	24	$460.08	$19.17
2.5	2.5	0.12	3.9	24	$240.48	$10.02
2.5	2.5	0.1875	5.59	24	$347.76	$14.49
2.5	2.5	0.238	6.83	24	$1,032.48	$43.02
2.5	2.5	0.25	7.5	24	$448.08	$18.67
3	3	0.083	3.24	24	$349.92	$14.58
3	3	0.012	4.58	24	$292.08	$12.17

3	3	0.1875	6.87	24	$425.76	$17.74
3	3	0.25	8.81	24	$532.80	$22.20
3	3	0.375	12.17	20	$675.00	$33.75
3.5	3.5	0.12	5.68	20	$327.00	$16.35
3.5	3.5	0.1875	8.15	20	$418.20	$20.91
3.5	3.5	0.25	10.51	24	$653.76	$27.24
3.5	3.5	0.375	14.72	24	$1,049.04	$43.71
4	4	0.083	4.32	24	$653.04	$27.21
4	4	0.12	6.22	24	$394.80	$16.45
4	4	0.1875	9.42	24	$579.84	$24.16
4	4	0.25	12.21	24	$738.24	$30.76
4	4	0.375	17.27	24	$1,044.48	$43.52
4	4	0.5	21.63	20	$1,090.00	$54.50
4.5	4.5	0.1875	10.7	20	$693.20	$34.66
4.5	4.5	0.25	14	20	$907.20	$45.36
5	5	0.12	8.16	24	$1,321.92	$55.08
5	5	0.1875	11.97	20	$646.20	$32.31
5	5	0.25	15.62	20	$859.00	$42.95
5	5	0.375	23.12	20	$1,165.20	$58.26
5	5	0.5	28.43	20	$1,739.80	$86.99
6	6	0.125	9.85	20	$638.20	$31.91
6	6	0.1875	14.65	20	$738.20	$36.91
6	6	0.25	19.02	24	$1,167.84	$48.66
6	6	0.375	26.48	20	$1,483.80	$74.19
6	6	0.5	35.24	20	$1,776.00	$88.80
7	7	0.25	22.42	20	$1,372.00	$68.60
7	7	0.375	35.58	20	$1,876.60	$93.83
7	7	0.5	42.05	20	$2,499.40	$124.97
8	8	0.1875	19.63	20	$989.20	$49.46
8	8	0.25	26	20	$1,301.20	$65.06
8	8	0.375	37.7	20	$2,170.80	$108.54
8	8	0.5	49	20	$2,637.80	$131.89
8	8	0.625	59.32	20	$3,843.80	$192.19
10	10	0.1875	24.73	20	$1,468.80	$73.44
10	10	0.25	32.63	20	$1,938.20	$96.91
10	10	0.375	47.9	20	$2,845.20	$142.26
10	10	0.5	62.46	20	$3,710.00	$185.50
12	12	0.25	39.45	20	$1,987.20	$99.36
12	12	0.375	58.1	20	$3,555.60	$177.78
12	12	0.5	76.07	20	$4,107.60	$205.38

Appendix B: Estimate Example

Cost Analysis - Four Layer Modules

Purpose	Line Item	Member Length (ft)	lb/ft	Estimated $/ft	Estimated $/member	#	Cost
Truss Member 1	HSS 6 x 6 x 5/16	24.28	23.34	$67.47	$1,638.14	512	$838,728.94
Truss Member 2	HSS 6 x 6 x 5/16	24.38	23.34	$67.47	$1,644.89	512	$842,183.34
Module 1 Columns	HSS 9 x 9 x 3/16	48.06	22.18	$64.20	$3,085.34	16	$49,365.39
Blade Frame	HSS 10 x 10 x 1/4	9.42	32.63	$93.67	$882.34	288	$254,113.74
Blade Frame	HSS 10 x 10 x 1/4	11.95	32.63	$93.67	$1,119.32	384	$429,817.29
Horizontal Bracing	HSS 10 x 10 x 1/4	12.5	32.63	$93.67	$1,170.83	512	$599,466.24
Blade Frame	HSS 10 x 10 x 1/4	21.72	32.63	$93.67	$2,034.44	192	$390,612.20
Module 2 Columns	HSS 12 x 12 x 1/4	48.06	39.43	$112.84	$5,423.22	32	$173,542.89
Modules 4 and 5 Columns	HSS 14 x 14 x 5/16	48.06	57.36	$163.41	$7,853.25	32	$251,304.13
Modules 6, 7, and 8 Columns	HSS 16 x 16 x 5/16	48.06	65.87	$187.40	$9,006.61	48	$432,317.16
	Line Item		**Unit Price**		**Units**		**Cost**
	Central Cylinder - Aluminum		$2,250.00	per ton	7.33	tons	$16,486.12
	Flaps - Aluminum		$2,250.00	per ton	108.48	tons	$244,081.10
	Labor		$8.00	per sqft	102,867.59	sqft	$822,940.69
						Total Cost:	**$5,344,959.23**
						Total Weight (tons):	**857.07**

Appendix C: Foundation Estimate

Cost Analysis for Foundation		
Circular Shallow Foundation	**Cubic Feet of Concrete**	**Cost**

60’x4’	11,310	$169,649
#4 ½" rebar	2 $/ft (every 6” spaced)	$67,858
Concrete filled Steel Pipe Pile Deep Foundation	**Cost per Pile**	**Cost for 9 Piles**
2.5’x120’	$12,240 102 $/ft (82 $/ft pile, 20 $/ft drive)	$110,160
Cost Analysis for Hybrid Foundation		
Shallow Foundation	Cost	$237,504
Deep Foundation	Cost	$110,160
	Total Cost	**$347,664**