WIND BLADE MANUFACTURING FOR THE CAL POLY WIND POWER CLUB

Final Design Review

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Abstract

The Cal Poly Wind Power Club is entering the 2021 Collegiate Wind Competition (CWC) in June. Last year, three senior project teams were assigned to collaborate and assist the club with the pitching mechanism, the rotor balancing, and the manufacturing process. As the manufacturing team, the goal of our project was to design a manufacturing process for the blade geometry given. The manufacturing process was required to meet the team's expectations and CWC's performance requirements to place highly in the competition taking place in June 2021. These expectations included creating a manufacturing process that is repeatable and reliable for future competitions. The manufactured blades had to be dimensionally accurate up to less than one percent error between each of the three blades. The blades also needed to be as light as possible to be efficient, thus the blades needed to be less than half a pound each. The manufactured blades also needed to be as smooth as 0.25 microns to ensure aerodynamic performance is not compromised. Our finalized process met the requirements for almost all these requirements. The dimensional accuracy of the blades is less than one percent error between the blades, however, some additional changes will be needed for future blades which be explained later in the report. The finalized blades far surpass the goals given by the WPC, only weighing 1/8 of a pound each compared to the half pound goal. Lastly the surface roughness of the blades did not meet the 0.25-micron requirement, however, we believe that the final design reaches a smoothness that will be acceptable for the competition. Solutions to make the blades smoother are also given in the report if the WPC believes the finalized blades do not meet their requirements.

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Chapter 1 – Introduction

According to the U.S. Department of Energy, wind power will supply 20% of the nation's electricity in 2020. They hope to increase the use of wind energy for the electrical grid to 35% by 2035. To accomplish this goal, more qualified workers will be needed to improve and facilitate the growth of wind power plants across the country. The U.S. Department of Energy created the Collegiate Wind Competition in 2014 to help reach their goal. The competition features teams of students from colleges across the U.S. who are tasked to create a scaled down wind turbine that must pass a series of tests and requirements. The purpose of the competition is to spark the interest of college undergraduates who will be the face of new wind power technology in the years to come.

In 2021, Cal Poly's Wind Power Club will be entering the competition for their first time. Three senior project teams were assigned to help the club with certain mechanisms and processes for their turbine: the pitching mechanism team, the rotor balancing team, and the manufacturing team. As the manufacturing team, the goal of this project was to develop a blade manufacturing process for the turbine blades. This project included prototyping and creating a finalized product of the blades.

This paper serves to document the complete process we took in designing the process. It is split into eight main sections.

The Background section presents information obtained from our sponsor and different types of manufacturing processes researched for wind turbine blades. These processes include molding techniques, the use of composites, as well as 3D printing. These different manufacturing techniques will be compared, assessing the advantages and disadvantages of each process for the blade design given. Manufacturing processes used by teams in past competitions were also assessed and considered for the blade process finally chosen. Specifically, researching what manufacturing process were used by teams that placed in the top three of the competition in 2019 and attempting to apply their methods to the process chosen.

The Objectives section outlines the goals of our project, including the scope/boundary of our project, the requirements, and the specifications. A boundary diagram and QFD house of quality are presented to show the relation between specifications and the importance of each.

Our research accumulates into a Concept Design section, including our ideation process, controlled convergence, and justifications for our selected design as of Spring 2020.

Final Process Selection outlines new research and updates to the design created during Fall 2020. It also ends with the selection of multiple manufacturing processes for the blades and possible post-processing options, which are tested against each other in the design verification plan section.

Design verification plan outlines the tests that were taken to ensure our blades meet the requirements and specifications given to us by the WPC. It also includes a final recommendation for the WPC when printing their final blades.

Our completed project timeline, deviations from our plan, and difficulties we faced are outlined in the project management section of the report.

Chapter 2 - Background

2.1 Wind Turbine Design Considerations

The wind turbine for this project is designed to be specialized for the competition guidelines. Blades are to be as light as possible while still having enough structural integrity so that the blades do not deflect to the point where they hit the turbine stand.

Additionally, the blade must withstand a wind speed of up to 22 m/s without breaking or bending to the point of losing structural integrity.

Creating the blade in one piece is desirable due to there being less risk of variance in mass properties, but some of the methods listed below are not able to be done in one piece.

After research on small wind turbine blades, the consensus is that wind blades of this size are commonly hollow.

2.2 Manufacturing Process Options

2.2.1 Fused Deposition Modeling (FDM)

Fused Deposition Modeling or Material Extrusion works by heating a spool of plastic (often PLA, ABS or PET) to nearly its melting point then gradually squeezing it out of an extrusion nozzle. The nozzle maneuvers in a 2D plane to place plastic at specific coordinates. The plastic is placed this way one layer at a time until it forms a solid 3D part.

FDM is the most popular 3D printing style used, as it is cheap and easy to use. Cal Poly has many available printers on campus. The layer lines on FDM printing are the most prominent out of any 3D printing process. This means that the surface finish will be rougher than the other processes. There is an array of post-processing options available to improve the surface finish of FDM parts, outlined in Section 2.3. With the smaller printers on campus, the blades would have to be printed in two parts, possibly creating a critical point at the mending point.

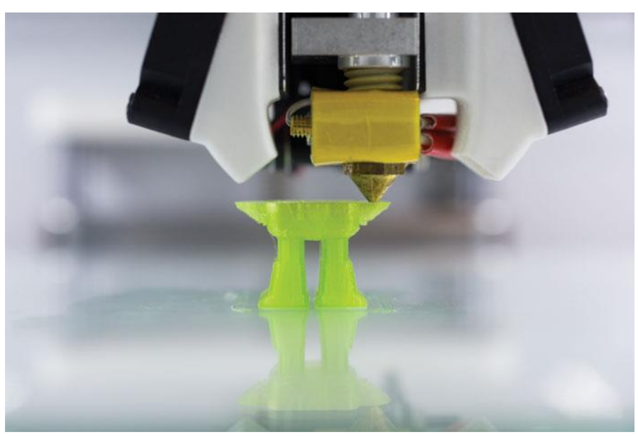

Figure 2-1. Object being created through the Material Extrusion process [5]

2.2.2 Selective Laser Sintering (SLS)

This 3D printing process utilizes thermoplastic powder such as Nylon 12. A mass of powder is heated up to approximately 178 °C, just below the powder's melting point. Then, a laser selectively solidifies each point within the powder layer-by-layer until the object is completed. This technique can produce a part with a surface finish similar to that of SLA, but given the very tight surface roughness tolerance for the airfoil this would still need to undergo post-processing.

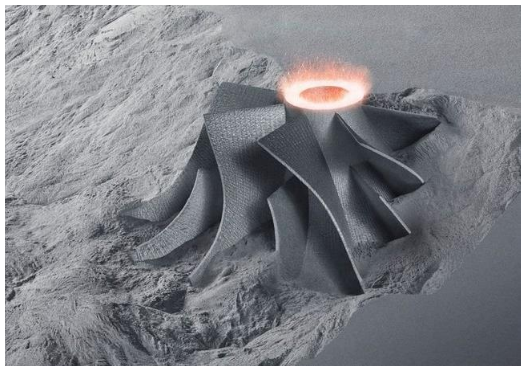

Figure 2-2. A 3D part being created out of thermoplastic powder using SLS [3]

2.2.3 Stereolithography (SLA)

Stereolithography (SLA) is a similar process to Laser sintering. The key difference between the two processes is that SLA utilizes liquid resins made of UV-curable photopolymers, as opposed to thermoplastic powder resins. The rest of the process is virtually identical: a laser exposes the resin to certain wavelengths of light, layer by layer.

There are three primary methods of SLA printing: Laser SLA, DLP SLA and Masked SLA. Laser SLA utilizes a laser which focuses on one point at a time, gradually creating a 2D shape before moving onto the next layer. DLP SLA utilizes a projector to flash light patterns and solidify entire layers of resin at once. Similarly, Masked SLA utilizes an LCD mask which selectively darkens to block light from reaching the resin.

Each SLA process comes with an array of advantages and disadvantages. Laser SLA has the crispest surface finish but has a longer manufacturing time. Both DLP and Masked SLA result in voxel lines (print lines aligned with the XYZ axes) across the surface due to the pixelated light displays used, which could cause possible critical failure points.

SLA printing is a highly modifiable and repeatable process. Layer thickness can be adjusted to obtain a higher surface finish, albeit with a higher manufacturing time. The amount of time between each layer process, also known as over cure, affects the tensile strength of the part. The adaptability and reliability of this process makes it an attractive choice. However, the Cal Poly SLA printer can cost upwards of $150 per print.

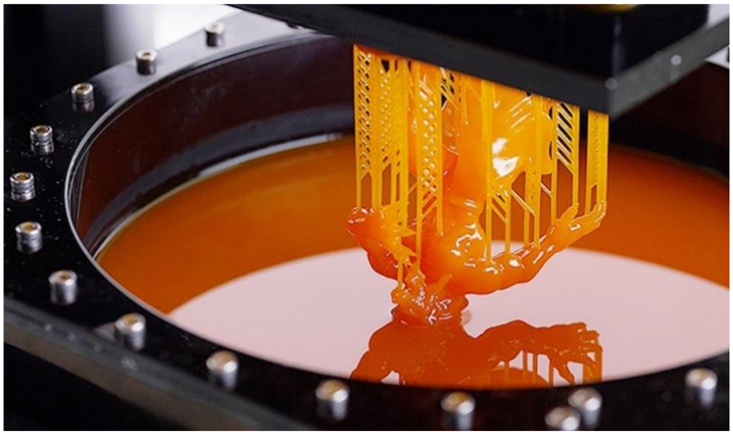

Figure 2-3. Stereolithography printer creating a complex 3D shape [4]

2.2.4 Wet Layup

Wet layups produce a product made from stronger composite material. In this process the fiber of choice, such as carbon fiber, is placed into an open mold. The fibers are impregnated with resins by hand, utilizing paint brushes and rollers. Wet layups are the cheapest composite method. They are highly adaptable since each step is done by hand, but this makes the final product difficult to reproduce within a tight tolerance. It also requires a deal of skilled labor, to ensure evenly distributed resin and a wrinkle-free surface finish.

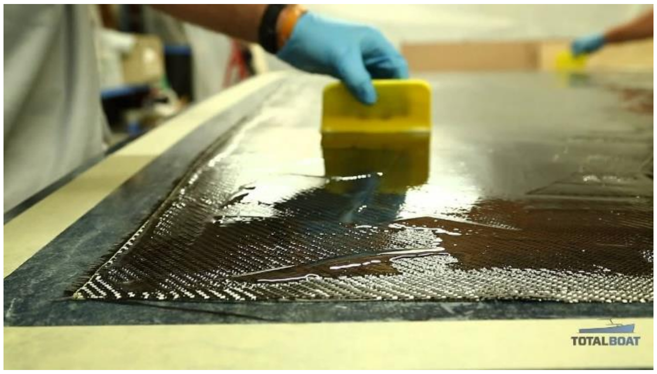

Figure 2-4. Wet layup being performed by hand [6]

2.2.5 Pre-preg

The pre-preg process utilizes composite fibers that are industrially impregnated with resin before they enter the hands of the consumer. Pre-preg is sold in rolls that are kept refrigerated to increase their longevity. To start the pre-preg process, each side of the mold is covered in masking tape, then cut to use as a template. The most popular reliable pre-preg molds are made out of either epoxy with glass fiber or epoxy model boards. 3D pre-preg shapes are made using split molds, meaning it is a 2-part mold with slight overlap to fuse the two halves together. Depending on the durability requirements of the part, one might utilize multiple plies of pre-preg to increase durability. Finally, after smoothing the pre-preg onto the mold, the mold and pre-preg are put into an autoclave for heat curing.

Due to pre-preg's limited shelf life, it needs to be applied within a certain time or else it is wasted. This means that industry connections who have almost expired pre-preg might be inclined to donate their pre-preg, circumventing the high price point of normal pre-preg parts. Pre-preg has other issues that prevent it from being a frontrunner, even with cost out of the picture. An important aspect of this project is for the wind blade designs to be tweakable and repeatable. While the pre-preg process is repeatable for the same blade design, small design adjustments would require a new mold to be created. This slows the design pipeline significantly, as there are two required steps to change anything in the blade shape.

Figure 2-5. Pre-preg being used to create a carbon fiber part [2]

2.2.6 Vacuum Infusion

Vacuum Infusion or VARTM (Vacuum Assisted Resin Transfer Molding) is the most widely used process for modern full-sized wind blades. In this process, the fibers are arranged in a sealed mold, and the resin is injected into the mold. After the resin has filled the cavity, the composite is cured in an autoclave. This method is called, "vacuum infusion" because the resin is injected at a pressure below atmospheric. There is little variation from part-to-part, and the process is cheaper than making pre-preg parts. Unsuitably, only one side of the VARTM mold can have a smooth finish.

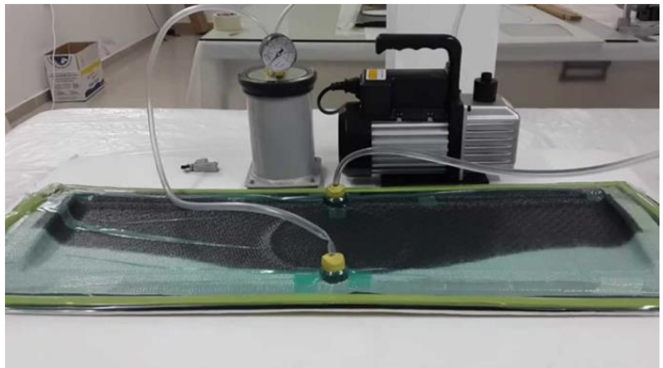

Figure 2-6. A composite part being created by VARTM [1]

2.3 Post-Processing Options

2.3.1 Manual Sanding

Sanding a part by hand is an economical but labor-intensive process. The sanding is typically performed with sandpaper, steel wool, or files. To get a part down to a smooth surface finish, multiple sanding steps are required, going from coarse to fine grit. To get a polished surface, the final stage of sanding can be performed after the part has been dipped in water. This does not remove much material but can get the surface finish to be very smooth.

2.3.2 Abrasive Milling

Abrasive milling is a process in which rotating abrasive tool heads of varying grit sizes are used to remove material and improve surface finish. This process can produce highly dimensionally accurate parts, with up to a 90% improved surface finish. It is important to note that when employed on thermally reactive parts, there is a risk of this process generating enough heat to warp the part.

2.3.3 Sand Blasting

Sand blasting involves using pressurized air to spray abrasive sand onto the surface of the part. This process is often done after the vapor smoothing process and is considered an ultra-fine finishing process, improving surface roughness by up to 96%.

2.3.4 Vibratory Bowl Abrasion

Vibratory bowl abrasion is a process used to improve surface finish and break edges of SLA parts. The model part is placed in a bowl containing abrasive media and water. The bowl is then vibrated at a constant speed, based on the surface roughness specifications and the size of the part. The abrasive media tends to get stuck in parts with complex surface geometry. Due to the convex shape of the wind blade, this is likely not an issue for wind blade manufacturing. This process results in higher dimensional accuracy for smaller parts and longer manufacturing times.

Due to the small size of the turbine blade, as well as this step being towards the end of the manufacturing process, vibratory bowl abrasion may be well suited to the needs of the turbine. Vibratory bowl abrasion has been observed to offer up to a 73% improvement in surface finish. It is important to note that while the other surface finish measurements were performed on FDM parts, the data for the VBA process was gathered on SLA parts.

2.3.5 Tumble Finishing

The tumbling process is like the vibratory bowl abrasion process. The key difference is that instead of vibrating in a vat, the part is placed in a washing machine-like structure then rotated on the horizontal axis.

Tumbling is well suited to small parts and is cheaper and faster than vibratory bowl abrasion. However, the abrasive media tends to hit the model surface too hard and create surface imperfections.

2.3.6 Acetone Smoothing

Acetone smoothing, a method of vapor smoothing, is a process in which an ABS part is exposed to a vapor bath of acetone for a controlled amount of time. When exposed to the acetone, the ABS plastic experiences a chemical reaction which melts the surface layer of the part. The acetone is introduced to the part in vapor form so that the concentration is low enough to cause too severe of a chemical reaction and destroy the structural integrity of the part. When the part is taken out of the vapor bath, the surface layer rehardens with a significantly smoother surface finish.

The effects of this process on the roughness, strength, elasticity, and ultimate strength of the part are largely dependent on the amount of time the part is in the acetone bath. In general, prolonged exposure to the acetone decreases surface roughness and the elastic modulus, while increasing the ultimate strain to failure.

2.4 Considerations for 3D Printing

There are a few important considerations when 3D printing.

Layer thickness refers to the thickness of each 2D slice. A lower layer thickness means the surface finish will be smoother, and the dimensional accuracy will be higher. However, there is a direct correlation between layer thickness and time to print. The thinner the layers are, the more times the print head will have to pass over the part to complete it, and therefore the longer the printing process will take.

Percent infill refers to the ratio of hollow to filled-in sections on the interior of a part. Since it would take a very long amount of time to fill in each layer of a 3D printed part all the way, the interior is often composed of a lattice structure to maintain structural integrity while keeping print times reasonable. Every 25% increase in infill density comes with a 10% increase in strength, so choosing an infill density is a balancing act between print time and strength.

The infill shape has a similar effect as infill density. The honeycomb is one of the most popular patterns because of its compromise between strength and print time. However, the diamond pattern has a lower print time because the print head has to make less passes to draw the shape, but it has comparable strength.

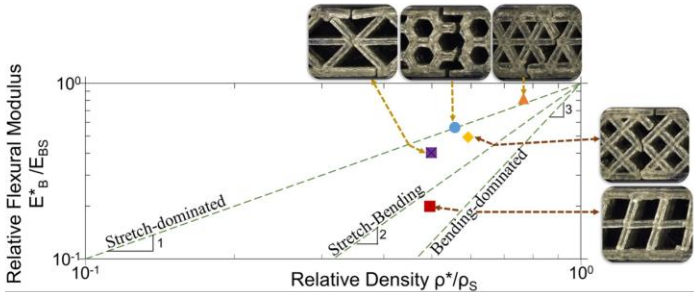

Figure 2-7. Comparison of Infill Shape Properties

It is important to note that choosing multiple printing options with high print time have a compounding effect. Choosing high-print time settings for each of these aspects has a multiplicative effect rather than an additive one.

2.4 Competition Designs

The most directly relevant existing designs for small wind turbines is the previous top-placers from the CWC 2019 competition.

Table 2-1. Manufacturing Processes used for CWC 2019 Top Teams' Manufacturing Processes

Team Name	Team Award	Manufacturing Process Used
Penn State	1st place overall	Selective laser sintering 3D printing method using Nylon 12
Virginia Tech	2nd place overall	3D printed, followed by a coating of Smooth-On XTC-3D to improve surface roughness.
California Maritime Academy	3rd place overall	3D printed in PLA plastic with a Makerbot Replicator+.
Iowa State	Project Development	Unspecified 3D printing method.

Most of the top placing teams did not delve into their reasonings for choosing their manufacturing process, only mentioning it in a single sentence. Penn State and Virginia state were the only ones to rigorously describe their reasoning and process.

Penn State chose Nylon 12 because of its strong yet flexible properties. They needed a material that would be sufficiently stiff to resist bending in high wind speeds but not so brittle that it snapped. They utilized finite element analysis to determine the material properties they needed to resist the bending moment imparted by the wind. They determined that Nylon 12 was the material that was most well suited for withstanding the stress concentrations at the root of the blade.

Virginia Tech previously used form-fitting foam in negative molds to manufacture their blades. They came to a similar conclusion as our team: processes requiring mold manufacturing are unfriendly to rapid iterative design processes. To solve this issue last year, they switched to FDM printing. They noted that while FDM printing provides high dimensional accuracy, it had a rough surface finish. They coated the part with Smooth-On XTC-3D to remedy this.

2.5 Summary of Patent Search Results

As stated before, the only resources available online for wind turbine manufacturing are those that are full-scale. As this information might not be useful for the scale required by the competition. As shown in Table 2-1, every top placer in CWC 2019 utilized 3D printing methods. As such, the relevant patents to this project are a mix of wind-blade related patents and 3D printing related patents.

Table 2-2. Patent Search Results

Patent Name	Date Filed	Useful Information from this Patent
Method for repairing and/or modifying component parts of a gas turbine	4/1/2004	Outlines how to use additive manufacturing to create parts of a similar turbine, a gas turbine.
Wind turbine and method of manufacture	7/17/2006	Contains valuable information about how full-size wind turbines are constructed.
Method for manufacturing of a fiber reinforced laminate, use of a wrinkle-preventing material, wind turbine blade and wind turbine	11/19/2007	Mitigates wrinkles in fiber-reinforced laminate by carrying out curing at controlled temperature gradients.
Method of manufacturing a wind turbine blade comprising steel wire reinforced matrix material	3/23/2011	Offers a method of using metal fibers instead of glass fibers in the VARTM method.
Laser sintering apparatus and methods	3/14/2014	Offers information on how the laser sintering process is performed.

2.6 List of Regulations

As this project is intended to be used in a competition it must adhere to the CWC 201 Guidelines' codes and regulations. The rules listed below are only the rules that are relevant to the manufacturing process.

1. The entire turbine must be contained within a 45 cm by 45 cm by 45 cm cube.
2. The turbine must be designed to withstand continuous winds of up to 22 m/s during operation and up to 25 m/s when parked.
3. The turbine must be able to handle a cut-in speed of as low as 2.5 m/s.

2.7 Customer Interactions

The Wind Blade Manufacturing (WBM) team was in contact with the sponsor for this project, former Wind Power Club President Jessica Dent. A weekly meeting time had been set up every Monday at 3 pm in which progress was reported and questions were asked to clarify the project.

Below is a summarized list of Spring 2020 interactions with the sponsor.

> The WBM team confirmed expectations of the project scope with the sponsor. This included determining the overlap with other teams and obtaining the design documents of the previous turbines. The sponsor described the process that the Wind Power team used in 2019. The sponsor referred the WBM team to many helpful contacts at Cal Poly. The WBM team worked closely with the sponsor when creating the QFD.
>
> In the beginning our sponsor was heavily in support of composites as it was a unique to the project. The new 2020 leads, however, were heavily in support of 3D printing. Thus, we researched each method equally to help them with their decision.

Chapter 3 – Objectives

3.1 Problem statement

As of the beginning of the project, the Cal Poly Wind Power club did not have a manufacturing process to produce designs for their turbine blades. The scope of this project was to design a manufacturing process that produces reliable wind turbine blades with consistent mass properties. The process had to be repeatable and modifiable for different blade profiles and twist distributions. The resulting turbine blade must also conform to the rules stated in the U.S Department of Energy Collegiate Wind Competition, including withstanding wind speeds up to 25 m/s, fitting within a 45 cm x 45 cm x 45 cm cube, and having a cut-in speed as low as 2.5 m/s. The final product should be as light as possible.

3.2 Boundary diagram

Through a closer analysis of our problem statement, the bounds of our project were further defined, as seen below in Figure 3-1. Our team worked macroscopically under the rules provided by the Department of Energy Collegiate Wind Competition Requirements. The rotor balance, pitching mechanism, and Cal Poly Wind Power Club (WPC) teams also worked within this boundary. The rotor balance and pitching mechanism teams reported directly to the WPC, who used their work to design the blade geometry. The blade geometry will be the result of a bi-directional informational flow. The blade geometry was the input of our project and dependent on the work of the other teams, with a final say by the WPC who will bring it to competition. As the manufacturers, it was our job to be informed on proper and feasible techniques. Therefore, our team worked with the WPC to ensure a blade geometry that was optimized for their needs and feasible for our process.

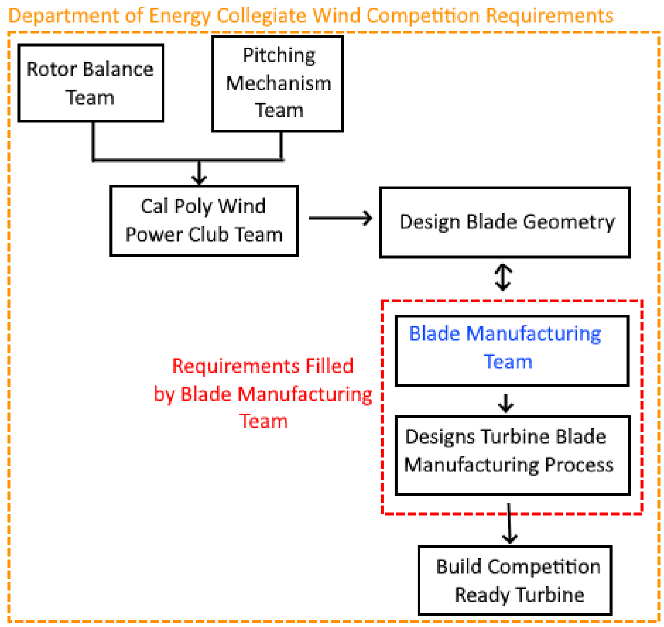

Figure 3-1. Boundary Diagram

3.3 Customer Requirements

The project must:

1. Be repeatable.
2. Accommodate minor design changes.
3. Produce standardized characteristics (minimal variation between output).
4. Have a sturdy base.
5. Operate with up to 22 m/s wind speed.
6. Have a cut-in speed as low as 2.5 m/s.
7. Withstand 25 m/s wind when parked.

The rotor and non-rotor turbine parts must be contained in a 45 cm x 45 cm x 45 cm cube. The non-rotor turbine parts are defined as anything that does not capture energy from the moving air, including the mounting flange.

The rotor will need to pass a runaway test to ensure that the turbine will not fail. The runaway test will be performed by the WPC. Strength and stiffness of the blade will directly affect the results of the test. Attachment of the blade will also be integral to a successful runaway test.

The three-blade turbine must have three blades that are as similar as possible, to maintain aerodynamic properties that are as similar as possible.

3.4 Quality Function Deployment

The Quality Function Deployment (QFD) method was utilized through the House of Quality (Appendix 8-1) to determine the most important customer of a product. The house of quality produces these results by considering the relationship between specifications and customer requirements. Similar products are also ranked against each other by how well they meet the requirements and specifications. This information was then condensed into a measure of weighted importance.

Our team compared five different casting processes: 3D printing, wet lay-ups, pre-preg, resin vacuum infusing, and blue foam molding. Of our requirements, standardizing the characteristics of each product was found to be the most important, with repeatability and ability to accommodate minor design changes following. Of our specifications, variability of results and cost efficiency were the most important.

3.5 Engineering Specifications Table

Through consideration of the completed QFD, the specifications seen below in Table 3-1 have been selected as the bounds of our project. The measurements of each specification will be determined as followed:

- Weight: A general analysis will be done through computer analysis, but the final product will be mostly dependent on material. The final weight was tested with a scale and compared by similarity to the design with other materials.
- Cost Efficient: Measured through research and analysis. The cost will vary greatly, thus similarity will be the most accurate measurement of efficiency.
- Complexity of the Process: The process is defined as the entirety of the blade creation from start to finish. Compared by similarity. The process should be reproducible for varying skill levels with low variability of results. A less complex process will produce a better product.
- Variability of Results: Variability was measured in post-production by comparing the specifications of two printed blades for consistency. This will be performed through weight and length testing by scale testing and through inertia testing by momentum swing calculations. Inspection of the outer surface with a flatness meter was considered to minimize the differences in air foil effects.
- Number of Manufacturers Required: Compared by similarity. The process should not require more than 3 manufacturers per part. More than this would be excessive for such a small part. Less manufacturers also ensures a less complex process. The excess manufacturers were to be delegated elsewhere.
- Labor Intensity: Labor intensity is defined as the amount of time and energy required of the manufacturer. Through testing and similarity, labor intensity can be determined. The process should minimize the amount of labor intensity. Automated processes are assumed to have the least amount of labor intensity.

The high-risk specifications of our project include variability of results and cost efficiency. The most popular process to manufacture small scale turbine blades is 3D printing. Printing with common filaments like PLA or ABS would be cost efficient, but the results would vary highly. The current printers on campus do not support the size of our blade, meaning we would have had to print in parts, further increasing variability. Outsourcing printing would remedy the problem of variability, while also allowing us the option to print with stronger material such as carbon fiber or Nylon 12, at the expense of higher cost. An investment for specialty tooling by the WPC was also an option that would minimize variability but increase cost efficiency. The specialty tooling could be used by the WPC indefinitely and for other projects, therefore saving money in the long run. More research is outlined further in the report to decide how to best minimize variability without incurring too high of a cost.

Table 3-1. Engineering Specifications Table

Spec. #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Weight	Under .40 lbs per blade	+/- .05 lbs	L	A, T, S
2	Cost Efficient	Costs under $250	+/- $100	H	A, S
3	Complexity of the process	Least Complex	Compared by Similarity	M	T, S
4	Variability of results	2% variability of blade design between molded blade	Max.	H	T, A, I
5	# Manufacturers needed	3 Manufacturers per process	Max.	L	T, S
6	Labor Intensity	Least Labor Intensive	Compared by Similarity	M	T, I, S

After further consideration, we decided to get rid of specifications three and six, complexity of the process and labor intensity. This is because these specifications are extremely hard to quantify and verify. After talking with the WPC, we also decided these means of assuring a speedy and easy process were not of utmost importance to them, since they have months leading up to competition to make the blade.

Chapter 4 – Concept Design

4.1 ~~Concept Generation/Sketches~~Possible Manufacturing Processes

To begin our concept generation, the general shape of the blade, along with possible physical manufacturing options were considered and sketched, seen in Figure 4-1. The blade could be printed in one or two pieces. It could be hollow inside or completely solid. The finish will be smoothed either naturally or in post-processing. A top-coat may be added for some processes.

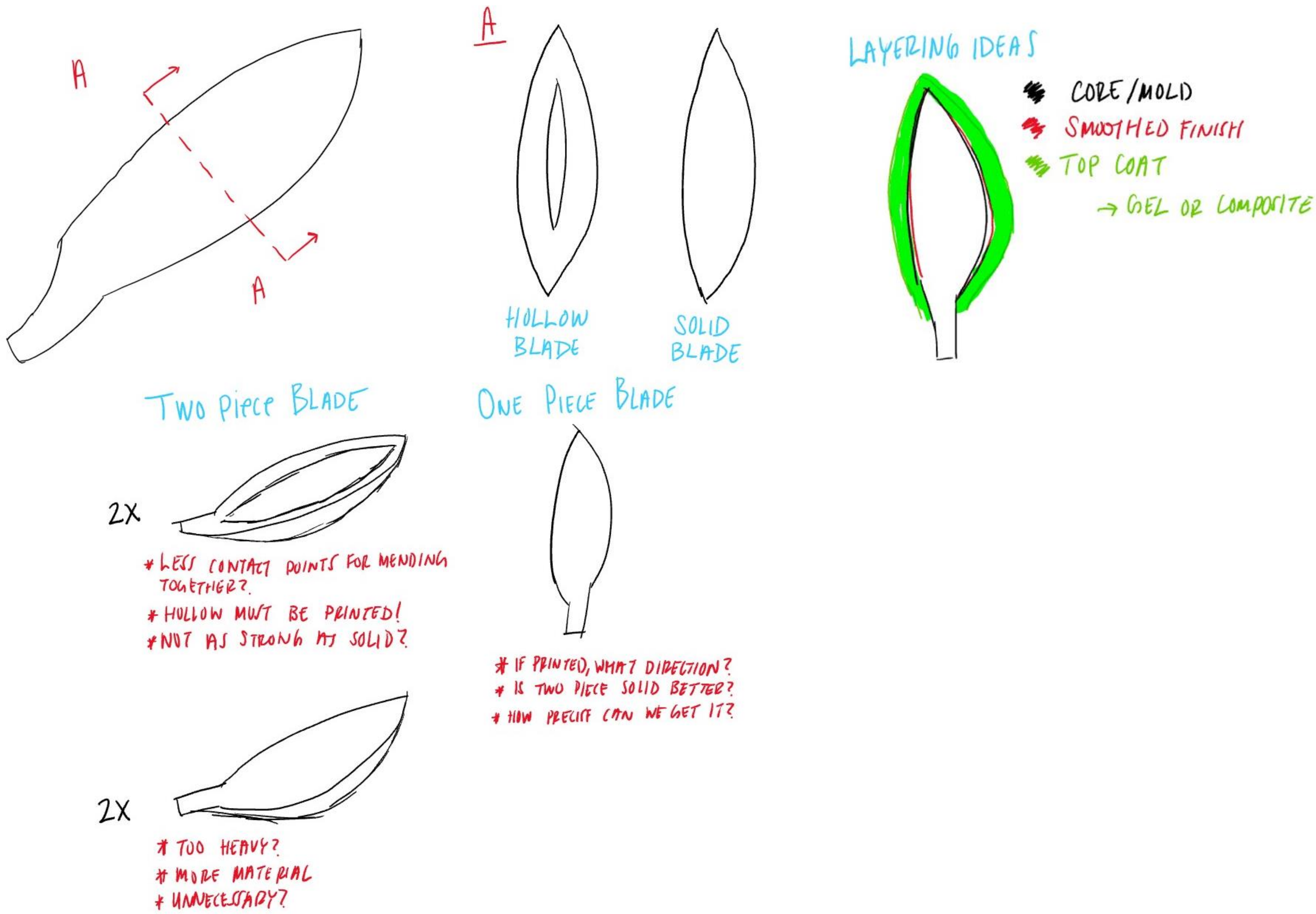

Figure 4-1. Physical blade manufacturing options

Next, the steps for each process were abstracted from our background research and applied to blade creation. Each process was sketched below in a flow chart.

For 3D printing, the blade can be made in one or two pieces. The one-piece option requires five steps and the two-piece option requires six. The two-piece option requires an extra step of epoxying before surface finishing. 3D printing requires the ability to model with a computer-aided design program and possibly a specialty tooling path program. Considering the repeatability requirement, print properties can be constant inputs, but cheaper printers or materials could product inconsistent results. Considering a smooth finish, a filler may be required and further surface smoothing.

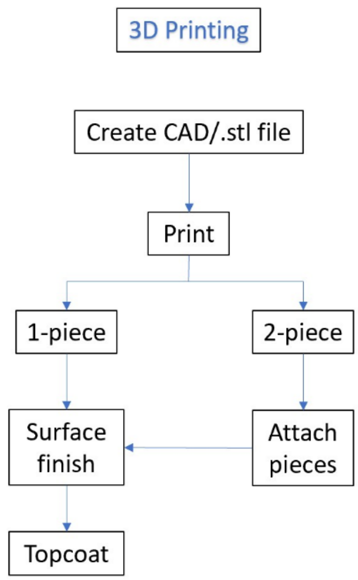

Figure 4-2. 3D printing steps

For wet-layups, five steps are required. Composites do not require post-processing due to the material already being relatively smooth. Fundamentally, lay-ups create hollow parts. Because of this, it is more difficult to make solid parts through these lay-ups. The wet-layup can only make half the blade, therefore the process must be done twice per blade. Curing may be done at room temperature. Considering repeatability, the multiplicity of steps done by hand creates many opportunities for error and inconsistencies. For example, temperature would have to be constant, epoxy would have to be metered, and the material outline must be exact. For its finish, wrinkles must be smoothed by hand and prevented during additions of lay-ups.

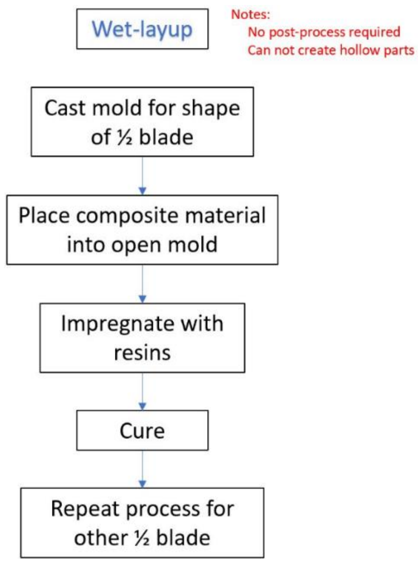

Figure 4-3. Wet-layup steps

Pre-preg requires six steps. As a composite process, pre-preg also requires no post-process surface smoothing. Like wet-layups, it also cannot create hollow parts and must make half the blade at a time. Pre-preg processes require an autoclave for curing. Considering repeatability, the outline must each be cut the same and cure time must be regulated. Its surface finish will come out as smooth as the mold it is created in.

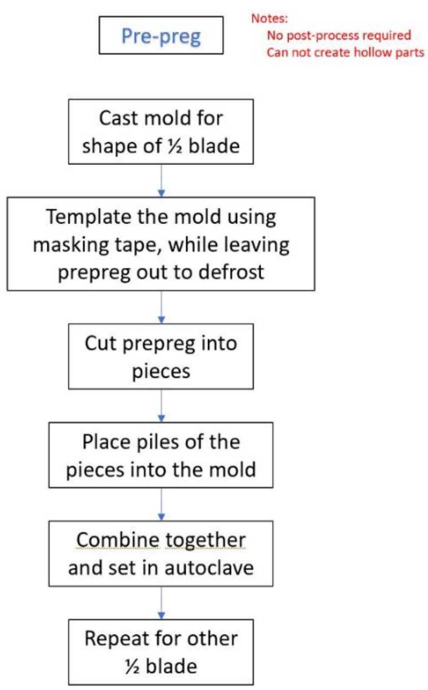

Figure 4-4. Pre-preg steps

A mixture of the above processes was previously used by the WPC. A 3D printed core can be used as a mold, with the wet-layup being placed on top of it. This process requires fives steps.

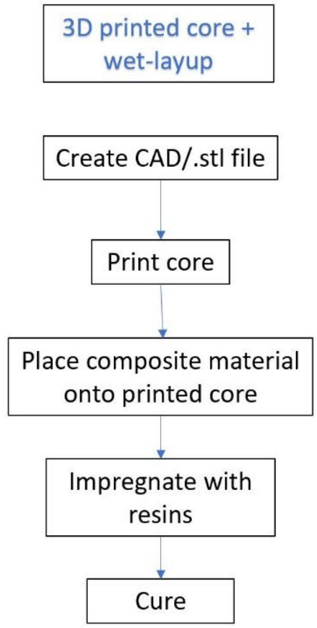

Figure 4-5. Wet-layup with a 3D printed core steps

Vacuum-infusion requires five steps. It can only make half a blade at a time, therefore it must be performed twice per blade. It requires special machining for injection below atmospheric pressure and an autoclave. Given our requirement of repeatability, vacuum-infusion would not be a first-choice option, since each new blade design would require special machining, incurring high costs and time.

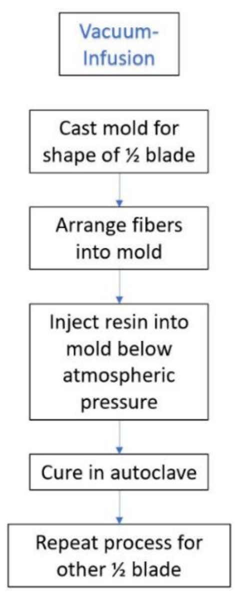

Figure 4-6. Vacuum-infusion steps

4.2 Manufacturing Process Decision Making

After deciding our specifications from our QFD, the next step in the design process was functional decomposition. For the functions of smooth finishing, cost, repeatability, and material properties, we listed how 3D printing, wet-layup, and pre-preg met the requirements. The decomposition can be seen in Appendix 8.2. Using our newfound relationships, we furthered the decision process into a Pugh Matrix.

Refer to the Processing Options Pugh Matrix, Table 8-3 in the Appendix.

The weights were determined from the priorities outlined from the club sponsor. Repeatability and precisions of dimensions were outlined as important aspects of the project. Cost was added as a high-weighted factor due to the relatively low budget of the project, increasing the importance of being cautious of budgeting concerns. Fused deposition modeling was used as a datum due to its wide accessibility and simplicity.

While composites offer incredible strength for their weight, additive manufacturing methods are the frontrunners. Due to the design of the wind blade being unfinished, it is important for the chosen process to be adaptable to small design changes. Composites require the manufacturing of a mold as well as the part itself, which makes them very rigid in their design process. On the other hand, 3D printing can produce many varied prototypes in a fraction of the time.

FDM is widely available on campus and free in many cases. SLA is also available on campus, but it was estimated to cost over $100, a large portion of the budget. At this stage in the project, quick, efficient, and cheap prototyping was valued more than premium manufacturing options. Thus, we decided to move forward with FDM for the prototyping phase of the project, which on the Cal Poly campus allows us to use PLA and ABS, but can expand to Nylon 12 or SLA if outsourced.

4.3 Post Processing Decisions

To decide which post-processing method to move forward with, another Pugh matrix was utilized. The weights of the matrix are explained in Section 4.2. Refer to the Post-Processing Options Pugh Matrix in Table 8.2 in the Appendix.

A large part of this project is to create a repeatable, reliable process that future generations of the club can easily reproduce. Manual sanding, abrasive milling and sand blasting are all processes which rely on a skilled and detailed-oriented laborer to provide consistent mass properties. This attention to detail can not necessarily be conveyed in an instruction manual, so we decided to choose post processing options that had less margin for human error.

Of the hands-off post processing techniques, vapor smoothing and vibratory bowl abrasion provide the most improvement in surface finish. We decided that it was worthwhile to attempt to pursue and test both processes. Vapor smoothing is a process that can be done in-house, whereas

VBA requires outside help. We have contacted the closest company that offers VBA, C&M Manufacturing in Santa Barbara, and inquired about receiving a student discount or sponsorship.

4.4 Blade Design Considerations

For the blade design we evaluated deflection between a hollow and solid blade design. Hand calculations are attached in Appendix 8.4. A study was done by Pourrajabian, et al. (2016) proving that small turbine blades can be modeled with simple beam theory. Accordingly, simple beam theory for a circular cantilever beam was used. It was determined that a solid blade will have less deflection than a .005 m thick hollow blade. Testing deflection ranging from a hollow blade thickness of .001 m up to when it becomes solid, we came up with Figure 4-7 below.

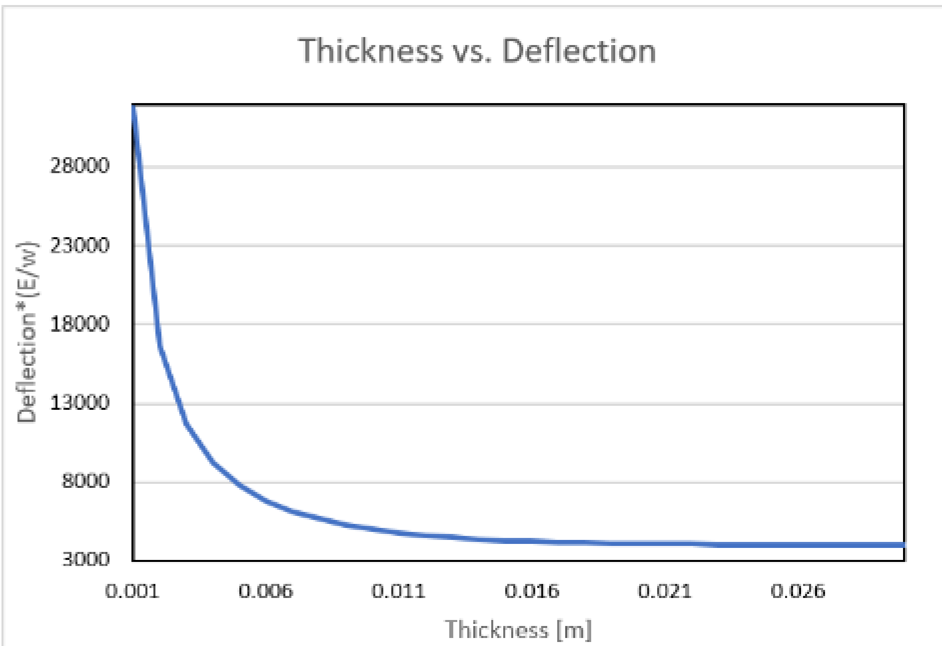

Figure 4-7. Thickness vs. deflection for a .225 m long hollow cantilever beam.

As shown, there is a large slope for a thickness between 0.001 and 0.004 m. Around 0.013 m of thickness, the deflection is equivalent to the deflection of the solid beam. Therefore, the decision is between a solid beam or an equivalent hollow beam.

The hollow beam would require less material, meaning less cost. The solid beam would be more material, meaning a higher mass. Due to the small size of the turbine, the effect of such a minute mass difference is negligible.

4.5 Material Property Considerations

After considering possible processes, we began investigating material property considerations for SLA, ABS, PLA, carbon fiber pre-preg, and a carbon fiber wet-layup, as referenced in Appendix 8.2. First, we compared their tensile strengths.

We found that SLA had the greatest tensile strength, at 65.0 MPa. Carbon fiber in a wet-layup was the second strongest at 2.1 GPa, but still not nearly as strong as the SLA. Carbon fiber in pre-preg was the third strongest at 600 MPa, but once again with a significant difference from the stronger material before it. Next, Nylon 12 had a tensile strength of 50 MPa. Lastly, the two most common printer filaments, ABS and PLA, had tensile strengths of 27 MPa and 37 MPa respectively. From a strength standpoint, all of these are viable options since our blades will at max only be subjected to forces around 2.33 N-m.

To test for tensile strength, we analyzed deflection with the same technique used previously to evaluate deflection of hollow and solid blade design, as shown in Appendix 8.4. This time, we picked an updated blade length of 19.6 cm and a diameter of 0.004 m, which is the smallest point on the blade. We also used a force of 2.64 N, which was calculated by the WPC to be the greatest normal flap-wise force. The material tensile modulus and resulting deflections are listed below in Table 4-1.

Table 4-1. Deflections of materials subjected to a 2.64 N force, modeled as a solid cantilever beam.

Materials	E (Pa)	Deflection (m)
SLA	2900000000	0.006685295
ABS	2300000000	0.008429285
Nylon12	1400000000	0.013848112
PLA	2700000000	0.007180502
Carbon Fiber	10300000000	0.001882268

Nylon 12 experiences the greatest deflection at 1.3 cm, but along with the other materials, stays within the 2 cm deflection limit given by the WPC. Therefore, all materials are usable by virtue of its tensile and strength properties.

To further narrow down our options, we moved on to the requirement of cost. Considering cost, we were given a budget of $800.00. This cost will be analyzed later, depending on available printers in the region. We found that for pre-preg, the cheapest roll is around $48.95 for a yard. Likewise, 1 L of SLA resin is around $40. At the cheapest price, a 1 kg spool of PLA is around $20. Lastly, the price of a wet layup varies by the type of resin, but at the very least $40-50 will be spent on epoxy. If any of the other materials are chosen, but printing in parts is preferred, epoxy may still need to be purchased. The cost of labor and production by a third-party is not considered in this early-stage cost analysis.

4.6 Selected Design Direction

For PDR, we decided to move forward with prototyping using FDM printers located on campus, in either PLA or ABS. Our final product was determined to be printed on campus with an SLA printed final product using ABS resin material. This final product should meet all requirements, but we were continuing to investigate SLA printing off-campus with stronger materials. We also planned on contacting vapor smoothing companies. We had been emailing C&M Manufacturing in Santa Barbara in hopes of using their machines.

We thought we would pursue a hollow blade design, since it requires less material for creation, while maintaining the same aerodynamic properties of a solid blade.

Since PDR, many changes have occurred to our design from new research and calculations. These are outlined below in Chapter 5.

Chapter 5 – Final Process Selection

5.1 Overall Process Selection

5.1.1 Composites

In the PDR stages of this project, composites were heavily discussed as an option for manufacturing the wind blades.

Composites are commonly used in full-sized wind turbines because of their excellent properties for their weight. Industrial wind turbines have steadily become larger to obtain a greater efficiency of energy capture. An increase in size is also accompanied by an increase in the loads the blades and the rest of the structure experiences. As such, it is important to optimize weight for large-scale applications.

However, the purpose and constraints of this project are significantly different than industrial applications. Firstly, the size of this project is constrained, which means that the loads on this part are significantly smaller. Also, this project is much more akin to a prototype model than a finished product ready for mass production. These two reasons mean that the focus shifts to the ease of manufacturing and the repeatability of the process.

The downside of every composite process is the time and effort it takes to make minor changes to the design. Creating a composite part requires meticulous planning, cutting of fiber sheets, and supervision of the process. This workload does not lessen after the first composite part is made. If the design undergoes a minor change, the process essentially needs to be restarted with the same level of care and detail. For professional blade designs that are already locked in, this downside does not come into play. However, since the blade design for this project is still in the testing phase, it is important to be able to pivot designs quickly and effortlessly. This issue of needing a very hands-on process is compounded in the COVID era. A process which requires multiple hours and multiple people at the Cal Poly Shops is unfortunately not feasible in these times.

For the reasons listed above, the decision was made to pursue other methods of manufacturing the blade.

5.1.2 3D Printing

As stated previously, 3D printing is widely known to be well suited to rapidly manufacturing prototypes, but it has also been used for manufacturing applications to produce small-scale wind blades. 3D printing comes with the benefit of creating a part directly from a computer design.

While there are considerations that need to be made when choosing the printing settings, the process needs considerably less meticulous labor than composite processes. Additionally, the work that needs to be done in choosing the printer settings and material can carry over to other prototypes even if the design changes slightly. This process can also be completed with a relatively small amount of in-person contact, because it is possible to send the part files to printing companies in SLO and have a single group member pick them up or receive them in the mail.

There are a few general disadvantages to consider when looking into 3D printing processes. First, to achieve an optimal surface finish on the parts, some post processing is required. Due to the nature of how 3D printing splits the part into thin slices, the dimensional accuracy of the sections along the layer lines will be higher than the sections that cross the layer lines. A figure is shown below to demonstrate this concept.

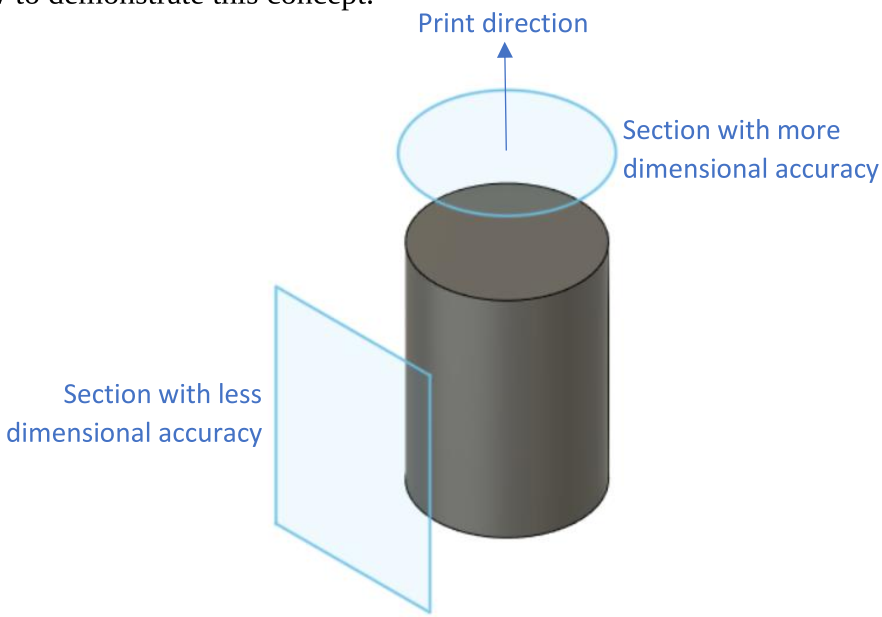

Figure 5-1. Representation of dimensional accuracy parallel and perpendicular to layer lines

This means that there needs to be special consideration when deciding the direction to print in. This will be explained more in later sections, but overall this limitation is one that is outweighed by the benefits of 3D printing.

For the reasons we listed above, we decided to pursue 3D printing as our manufacturing process of choice.

5.2 Final Process Selection

With our ideas for the blade manufacturing process organized, the first blade design was finally given by the Wind Power Club. The initial design given had a few design flaws that needed attention. Although it was known that the blade design would be long and thin to maximize the aerodynamic performance of the blade, the initial blade given had a thickness at the tip of the blade that was too small that could be feasibly print in Fusion Deposition Modeling. This was determined using the program, Cura, which allows users to see what a theoretical 3D printer can print using an STL file.

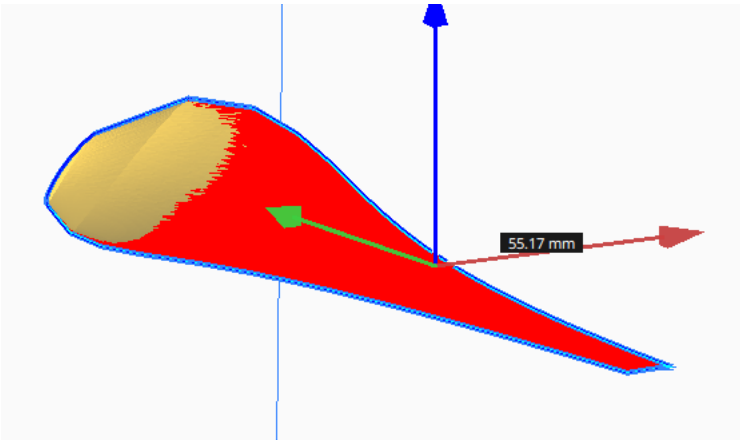

Figure 5-2. STL file of the blade in Cura showing unprintable area in red

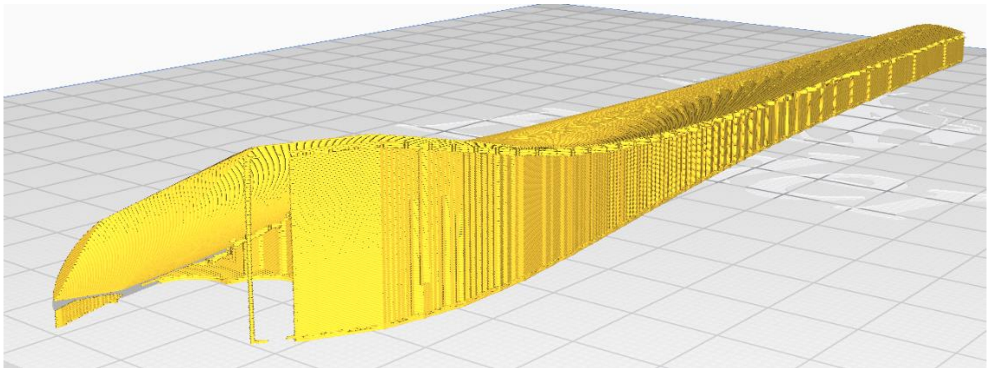

Figure 5-3. STL file of the Blade in Cura showing structural supports

Looking at Figure 5-2, the red color indicates where the printer cannot print due to the very thin nature of the blade. This clearly shows that based on the blade and current print orientation, the blade cannot be printed. Another downside to printing horizontally, is the high probability of the part breaking to the large number of supports necessary to print the part as shown in Figure 5-3.

Realizing this issue would be the same for almost all the blade designs since they all are too thin in nature, we looked at a different approach to printing the blades. The flaw was the length and thinness of the blade would be impossible to print horizontally. From research and advice from our industry contact, Andrew Cunningham, who is an engineer that specializes in 3D printing at GM, a possible solution to this problem would be printing the blade vertically. Printing the blade vertically eliminates the need for structural supports since the blade would be printed from top to bottom versus left to right.

Based on these findings, we decided to print vertically for our prototypes and final blades. As shown in Figure 5-4 below, printing vertically will create layer lines parallel to the incoming air velocity, which also is advantageous in terms of aerodynamic performance.

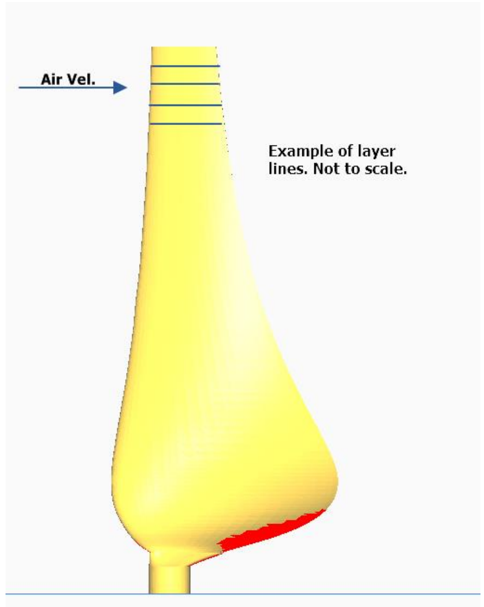

Figure 5-4. STL file of blade printed Vertically

5.3 Post-process Selection

5.3.1 Sanding

During the PDR stages of the project, sanding was considered but not one of the frontrunners. One of the concerns was that machine sanding would generate too much heat, thus causing the part to warp. This concern was confirmed, as the thin sections of the blade would succumb to the effects of heat even sooner, meaning it would be more of an issue. The other concern was that sanding the part by hand might cause the part to lose its dimensional accuracy due to the margin for human error.

However, after researching the sanding process more and discussing it with our sponsor and Andrew Cunningham, we changed our mind on the subject. Initially we were worried that sanding would not be able to hit the surface roughness requirement. Once we received the specific surface roughness requirement this quarter, .25 microns, we realized that this could easily be achieved with fine grit sandpaper.

Table 5-1. *Common Grit Size and Corresponding Surface Roughness* [Engineering Toolbox]

Grit Size	Surface Roughness (Microns)
80	1.8
120	1.32
150	1.06
180	0.76
240	0.38
320	0.3
500	0.18
600	0.13

Additionally, every website that informed how to finish 3D printing parts suggested sanding. Even with acetone smoothing it is recommended to sand the part first. For these reasons we decided to research the best sanding methods.

When sanding the part, it is important to start with a coarse grit then progress to a finer grit. Additionally, wet sanding steps can be used to polish the surface of the part. The planned sanding process is shown below. For each of these steps, it will be performed evenly along the surface, changing sanding spots enough so that the part does not become too hot. For each step in this process, if any imperfections are noticed they will be removed with the course grit sandpaper and the process will be repeated for that section.

Table 5-2. Sanding Progression

Grit Size	Wet / Dry
80	Dry
150	Dry
240	Dry
320	Dry
500	Wet

With these considerations made, sanding can be selected as the initial post-processing process we move forward with. If the first round of airfoils does not pass our DVPR, we would have progressed to using vapor smoothing processes.

5.3.2 Vapor Smoothing

Vapor smoothing is a reliable process that can greatly improve the surface finish of a part, however it is only available for ABS parts, so it is essentially linked to that.

An essential consideration when deciding whether to use vapor smoothing was the level of dimensional accuracy that the process retained. When researching the effects of vapor smoothing on dimensional accuracy, several sources were found that tested the material properties of small ABS dog bone specimens undergoing the effects of vapor smoothing.

Table 5-3. Average absolute dimensional changes for vapor polished specimens [Neff]

Geometry	1 mm sample	2 mm sample	4 mm sample
Δ Thickness (mm)	-0.01 ± 0.00	0.02 ± 0.00	0.03 ± 0.02
Δ Length (mm)	-0.82 ± 0.07	-0.22 ± 0.08	0.02 ± 0.04
Δ Width (mm)	-0.20 ± 0.07	-0.06 ± 0.60	0.06 ± 0.02

Another trait that was discovered about acetone smoothing was that it affected the material properties of the surface layer of the specimens. When the specimens were taken out at 45 minutes, the time in which the surface roughness reached a surface roughness of .25 microns, changes to certain material properties were observed, as shown below.

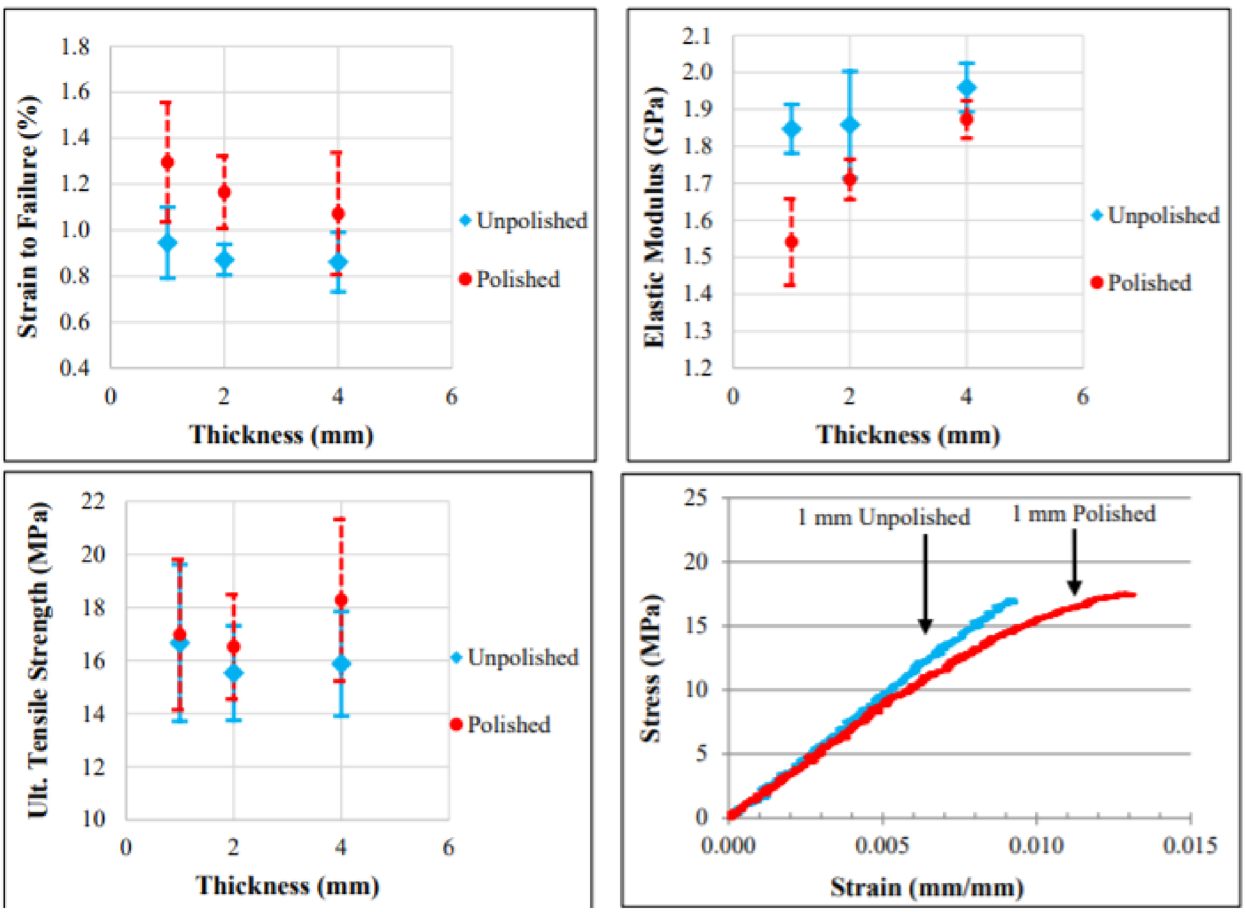

Figure 5-5. Change in material properties from unpolished to polished (vapor smoothed) specimens [Neff]

Certain characteristics, like the elastic modulus, seemed to converge as the size increased, likely because less of the part percentage was affected by the vapor smoothing process. Others, like the change in ultimate tensile strength and strain to failure are traits that can be assumed to be experienced by the full-sized blade as well. As there is no significant trend in the dimensional changes for the different sample sizes, it can be assumed that the data from this experiment can be scaled up to the size of the wind blade. A variance of length of even 0.9 mm, the maximum dimensional change in the chart, is acceptable for this application.

It is important to consider that the experiment was conducted on test specimens that were significantly smaller than the wind blade. To apply these results to a larger blade, a few assumptions must be made. First, that the vapor bath is applied evenly along the entire blade surface. Second, the trends observed in the smaller specimens must be carefully considered whether they can be applied to larger specimens.

Overall, the vapor smoothing process could be utilized to significantly improve the surface finish of a part, with the risk of changing the material properties of the final product. As the loads seen by this part are relatively small, the changes to material properties caused by this process are a price we are willing to pay to improve the surface roughness. However, this process might be overkill for the first round of testing, so this process will be utilized if the first round of sanded FDM parts do not pass DVPR.

5.3.3 Abrasion Processes

Abrasion processes such as vibratory bowl abrasion and tumbling abrasion were heavily considered in the PDR stage of the project.

Abrasion processes typically are well suited for parts which do not have any small concave surfaces or details. As the wind blade is entirely convex, we initially thought this would mean that these processes are well suited for our design.

However, after we had received the finalized blade design, we had reconsidered our stance on these processes. Abrasion processes come with the risk of chipping or breaking a part if the part is too thin or small. The blade sent to us by the WPC has a thin trailing edge, which would be vulnerable to being damaged in the abrasion processes.

Figure 5-6. Representation of areas too thin for abrasion processes (shown in red)

It is not as simple as thickening the trailing edge, because the trailing edge cannot be thickened without changing the blade length if the aerodynamic properties are to stay the same. As the entire turbine is constrained in size, the length does not have much leeway to grow, which also means the trailing edge cannot grow by a meaningful amount either.

For the reasoning stated above, we decided to pursue a finishing process that is more well suited to delicate parts.

5.4 Failure Mode and Effects Analysis (FMEA)

Through FMEA, we could understand our design better by investigating failures that can occur in every function and system involved in our product. Then, proper actions could be decided to control or design around them. This will improve safety of the design, while also ensuring a product that matches the project specifications. The full FMEA table can be found below in Appendix 11.6.

5.4.1 3D Printing

Our first system to analyze for potential failures is 3D printing.

Its first function was to create a physical product representative of the given WPC design. Given this function, a failure can occur if the computer-aided design (CAD) does not meet the requirements of the printer. This can be caused by parts being too thin to print or the design being too complex. The design would also be considered unprintable if the price to print the design incurs a cost higher than the allocated budget. These failures were preventable by design verification in the print preview window of the printer application.

Its second function includes the production of three identical blades. These blades must each meet the design requirements and have an equal center of mass and inertia. If they are to fail these requirements, the performance of the turbine may not meet performance specifications and/or the blade may become unbalanced. This can result from imperfections or warping during printing or a miscalibration of the printer. This can be prevented with inspection through dimensional analysis of each print being compared to the desired CAD dimensions. If a blade that does not pass inspection is found, it can be printed before it moves on to the design verification plan.

Third, the print must maintain desired blade properties including airfoils and twist angles. If these differ from the WPC design, the angle of attack, lift and drag may be compromised, or different than the intended design. This can likewise be caused through imperfections during printing or miscalibration of the printer. Therefore, it can also be prevented through inspection and review of printer calibration settings.

Lastly, the blade must maintain the desired tensile and bending strength. If it fails to do so, the blade may flex or break, therefore leaving the WPC with no blades to compete with. This can be prevented by making sure the print is comparable to the CAD design and does not have any imperfections along the layer lines that could cause failure.

*5.4.*2 Manual Sanding

The main function of manual sanding is to remove any burrs or surface imperfections on the print. As all the individual processes work together to make one single part, they all share potential failure modes and effects.

Like printing, a failure in manual sanding’s core function will result in airfoils and twist angles varying from the WPC design, and the blades not meeting similarity requirements. If these failures are to occur, the angle of attack, lift, and drag may not match the requirements or specifications. Through this, the windspeed requirement may not be met. This can be caused by the removal of too much material, too little material, or creating an uneven finish. To prevent this, an optimal constant sanding pressure and time per grit paper must be found and documented to be used on every blade.

5.4.3 Vapor Smoothing

Like manual sanding, the main function of vapor smoothing is to remove any burrs or surface imperfections on the print. Since they share a function, they also share the same failure modes and effects, with the addition of one. Vapor smoothing incurs an addition failure mode through the possibility of over-warping the material. If this happens, the surface area, lift, and drag may be compromised. To prevent vapor smoothing failures, the proper smoothing time, or time for the print to be in the acetone, should be calculated and remain constant from blade to blade.

5.4.4 Epoxy

For the two-piece SLA print, epoxy could be used to connect the parts. Potential failure modes include the surfaces of the pieces not being flush, the pieces not sticking, the material being ruined by the properties of the epoxy, or the blades not meeting similarity requirements. The effects would be compromised airfoils, lift, drag, and angle of attack values. If the blade does not stick, the blade could break and would not be able to compete. Possible causes include choosing an epoxy incompatible to the material, too little epoxy, too little cure time, or the parts not being lined up properly. The failures can be mitigated by ensuring a minimum cure time be met and creating a male-female connecting surface where the epoxy will stick.

5.4.5 Highest Risk

Due to the simple nature of our processes, most risks were of low priority. 3D printing problems could be fixed with a low-cost reprint, with each print becoming better through testing and documentation. Likewise, manual sanding risks were able to be mitigated through thorough documentation and testing of different techniques. Nonetheless, through our FMEA calculations, the highest risks include the blade losing structural integrity during 3D printing, and over-warping during vapor smoothing. These were remedied with supports during printing and periodic check-ins while vapor smoothing.

All failure modes will be detected in the design verification plan, as described later in the report in Chapter 7.

5.5 Cost Analysis

Since our design consisted of strictly one component, we broke down the cost of the 3D printing method chosen as well as the possible materials that we chose in our final design selection. For the 3D printing method, we broke it down into two possible choices; FDM and SLA. From there we reached out to companies to find a quote with either ABS or SLA to print our part as shown below.

Table 5-4. Cost Analysis of Possible Companies to outsource

Company	Process	Material	Quote (cost)
3Dhubz	FDM	ABS	$66.31
	SLA	Formlabs Resin	$152.35
Shapeways	FDM	Versatile Plastic	$26.00
	SLA	SLA Plastic	$173.69
Makexyz	FDM	ABS	$17.90
	SLA	Accura Xtreme	$122.90
EE Helpdesk (free, just need material)	FDM	ABS	$15
	SLA	PLA	$40
Xometry	FDM	ABS	$27.95
	SLA	PLA	$79.66

Looking at Table 5-2, it's clear that FDM processes with ABS material is the cheaper method while SLA is much more expensive. Based on the cheaper costs of FDM, this had been selected as the process for the initial prototyping while SLA has been chosen for the final blade manufacturing. The EE Helpdesk located at Cal Poly is currently the manufacturer of choice since the actual printing process is free and the only requirement is the purchasing of the material.

Chapter 6 – Manufacturing Plan

Once the blade design and 3D printing has been selected, the blade could be sent to a manufacturer to be printed. As stated earlier, our first prototypes will be using FDM with ABS as the material. The following process describes how to manufacture any blade design given. The first step was to choose the manufacturer. For our initial prototypes, we chose the cheapest option, which is the EE Helpdesk located at Cal Poly, but there are many different companies one can choose from. The next step would be choosing the printer settings for your blade, which includes making sure the blade will be printed vertically as well as setting your desired infill settings. Since the blade needs to be lightweight and the loads are minimal from the calculations given to us by the WPC, an infill of 40-50% is all that is needed to satisfy the loading requirements. Depending on the manufacturer chosen, either the material will be provided for you or you will have to buy it separately. Once the part is printed, structural supports will be carefully removed and then the steps to post processing are followed. This will be done using sandpaper for the prototypes, and a combination of both sanding and vapor smoothing for the final blades. The following table outlines the possible materials that were expected to be purchased for this process.

Table 6-1. Materials Procurement Table

	Material	Quantity	Seller	Price
1	80-500 grit Sandpaper	1	Home Depot	$5.00-$15.00
2	Roll of ABS	1	Amazon	$19.99
3	SLA Resin	1	Amazon	$28.00
4	Acetone	1	Home Depot	$8.00

Depending on the manufacturer chosen, the print would have either been picked up at their location or delivered to a desired address. Once the printed blade is received, make sure the blade meets the WPC requirements by following the design verification plan outlined in the next chapter. Once these are satisfied, sanding can begin starting from 80 grit sandpaper up to 500 grit sandpaper until the desired 25-micron surface finish is achieved, and then your part is ready to be attached to the turbine.

6.1 Overall Top-half Turbine Component Layout

As our project is a single piece in the Wind Power Club's turbine, it is important to understand how our project connected with the rest of the turbine at the end of production.

The produced blades were to be attached to a blade hub with a hole in the middle. The blade hub will slide onto a shaft to connect it to the face of the nacelle, which houses all the drive components.

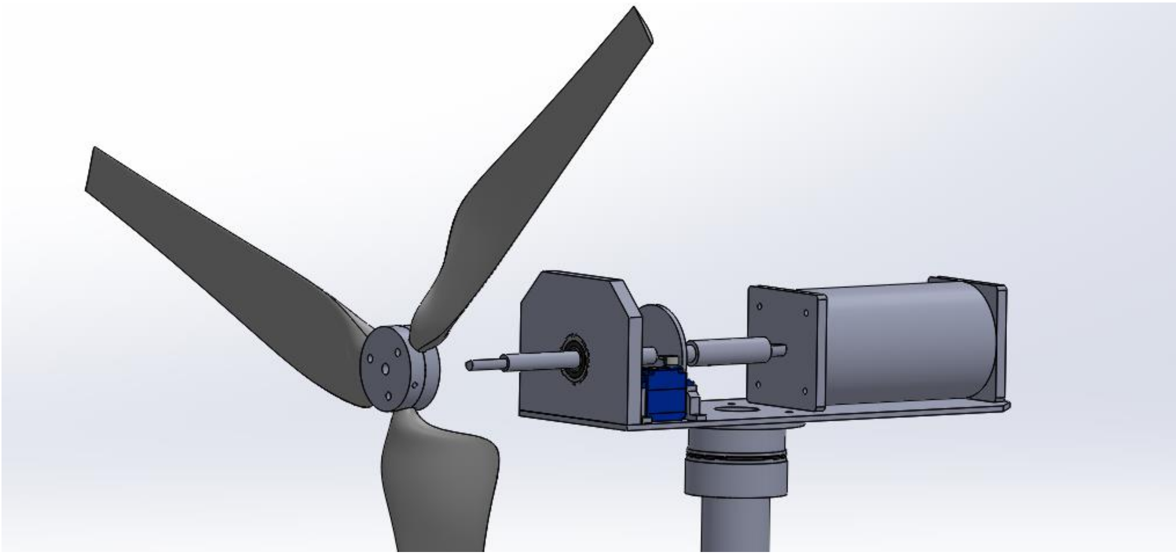

Figure 6-1. Component layout of the top half of the turbine, illustrating how the blades fit into the overall turbine project.

The blade design, as of Oct 22, 2020, is pictured below. The blade was planned to be attached through a dovetail on the end of the blade, which is not shown.

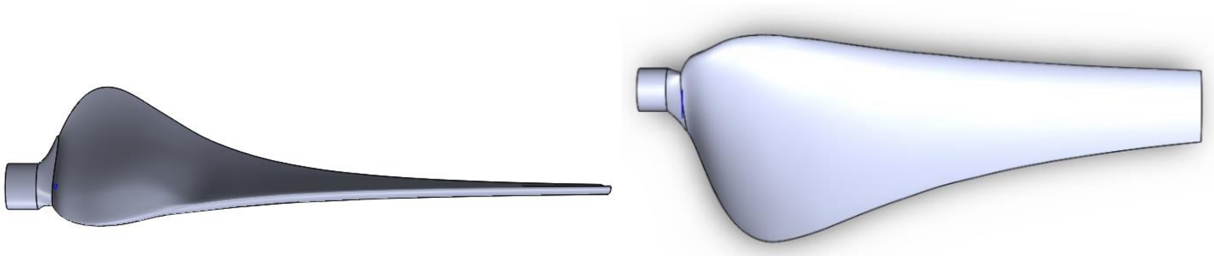

Figure 6-2. Most recent blade design (10.22.20).

6.2 Manufactured Blades

Throughout the project, our team ended up printing three sets of blades from three different providers. Ideally, we would have printed multiple times with each provider, then compare the blades in groups of providers, then against each provider. But, due to the COVID-19 pandemic, long wait times and shut-downs forced us to print one set of blades per each provider. The results of the blades are therefore affected by the printer and the skill level of the operators. The three sets of blades are shown in the Figure 6-3.

Figure 6-3. Printed with Creality Pro v2 by EE Help Desk

The blade in Figure 6-3 was printed on campus by the electrical engineering help desk, by an operator with a year and a half of 3D printing experience. The print may have been affected by its open-casing and temperature changes due to a more than 20 degree drop in temperature over its 12 hour print time. The blades were printed with ABS filament. From initial inspection, the blades contained an extensive number of burrs and the supports at the base of the blade were very difficult to separate from the print. The general shape of the blade seemed accurate to design, including the trailing edge. These blades will be referenced as “FDM blades”.

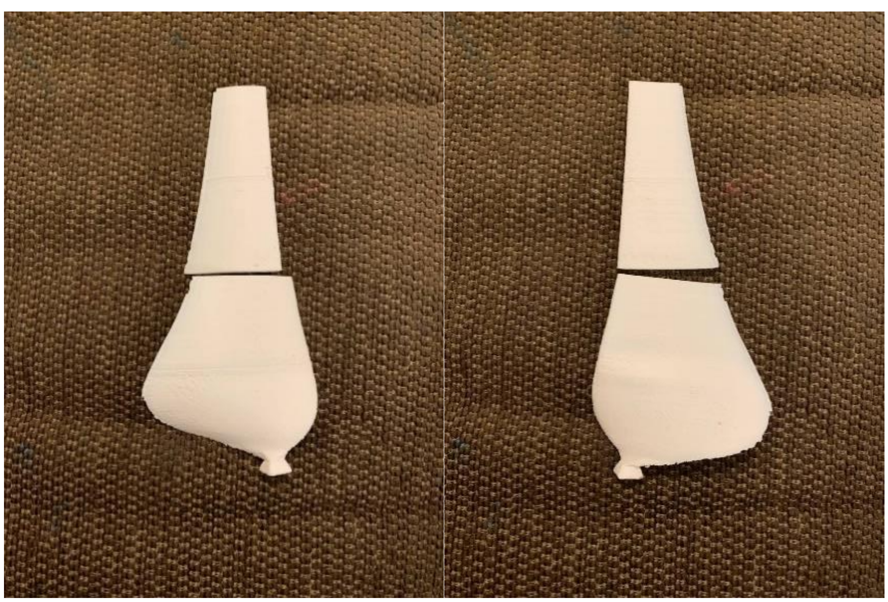

Figure 6-4. Printed with Flashforge Creator Pro by private commission

The blade in Figure 6-4 was our second print, printed by a private commission with a Flashforge Creator Pro printer, which is an FDM printer as well as the first, but advertised as specifically being good with ABS. The blades were printed with ABS filament. The print bed on this printer was not long enough on the Z-axis, so the print blade had to be printed in two parts. From initial inspection, the blades had much less burrs than the first FDM blades. The operator had cleaned off the supports before mailing and the trailing edge was also smooth. The general shape of the blade seemed accurate to design. These blades will be referenced as “ABS-specific” blades.

Figure 6-5. Printed with SLA printer by MakeXYZ

Lastly, we took to an online printer provider called, MakeXYZ to print our SLA blades, as shown in Figure 6-5. The blades were printed with Accura Xtreme, which is advertised as an ABS-like material. From initial inspection, the blades did not have any burrs. The print had smooth edges, and the general shape was accurate to the design. Printing three blades came out to be $399.49 and were delivered within a week. These blades will be referenced as “SLA” blades.

After receiving all the blades, each blade went through design verification, as outlined in Chapter 7, to determine the print that best met the design requirements.

Chapter 7 – Design Verification Plan

To test to see if our processes created blades that met our specifications, a design verification plan had been devised. The design verification plan can be found in Appendix 11.7.

7.1a Blade Length Verification

The first and easiest verification to perform was verifying whether the blade length was to the WPC’s specifications. The blade’s tip and root surfaces are ideally flush with each other, so it would be relatively easy to align a caliper along the blade length. To visualize this easier, Figure

7-1 of the blade and measurement area is included below.

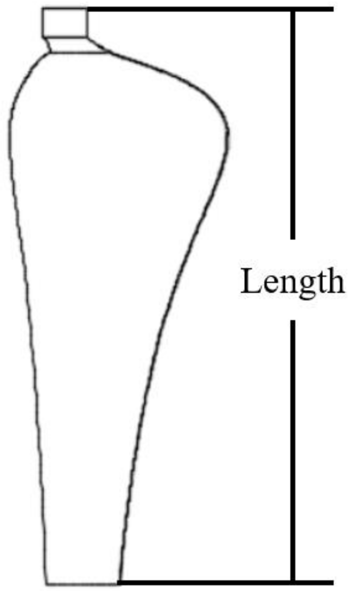

Figure 7-1. Blade length measurement diagram

The length of the blade is 19.5 centimeters, which is larger than a 6 inch caliper, so a 12 inch caliper should be utilized. Vernier calipers typically measure with a 1 mm precision, which is more than enough to verify whether the blades successfully pass the length requirement of 19 ± 1 cm.

7.1b Blade Length Verification Results

A Pittsburgh 12" Digital Caliper with a precision of ±0.001 cm was used to perform this test. The blades were measured from tip to base as shown below.

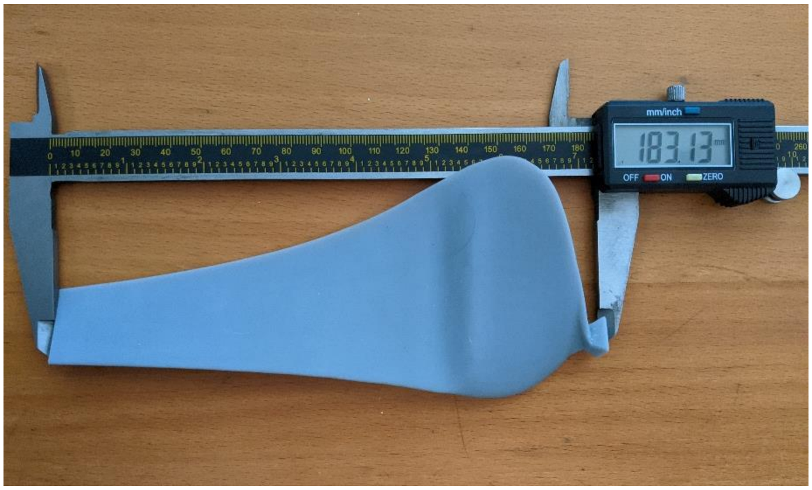

Figure 7-2. Blade Length Test

Each blade was measured and tabulated, shown below. The reason for the FDM blades having a different length is that they were a print of a previous design with a longer extension at the base of the blade.

Table 7-1. Blade Length Verification Test Results

Printing Method	Lengths (cm)	Spread (cm)	Pass or Fail
FDM	19.592	0.022	Pass
	19.614		Pass
SLA	18.312	0.007	Pass
	18.319		Pass
	18.319		Pass
ABS-specific	18.396	0.038	Pass
	18.397		Pass
	18.358		Pass

Every blade passed the 19±1 cm constraint laid out by the WPC team. Predictably, the SLA was the most precise method, while the ABS-specific was the least. A possible reason for the lack of precision in the ABS-specific blade was that the blade was built in two pieces and the ends were not entirely flat.

However, we believe that the constraint was too loose, and recommend that the constraints for the blade length be more precise.

7.2a Mass Test

To measure the mass of the blades, a simple triple beam balance was to be utilized. The weight of each blade was recorded for calculations in later tests. The precision of a triple beam balance is usually 0.5 grams. Although a weight requirement was not given by the WPC, for balancing purposes a set of blades was only considered successful if they had weights within 5% of each other.

7.2b Mass Test Results

This test was focused on comparing the masses within each set of blades rather than comparing the sets of blades with each other. This test was focused on comparing the similarity of the measured weights and was not as concerned with the weight values themselves.

The allowable range that the weights could fall under was calculated by taking 5% of the average weight of each set of blades. Since the allowable spread of weights was greater than a gram, it was not necessary to use a device with a greater precision that 1 gram. Due to this, a simple kitchen scale was used to measure the blade weights due to its accessibility.

Table 7-2. Mass Test Results

Printing Method	Allowable Spread (g)	Weights (g)	Pass or Fail
FDM	2.65	53	Pass
		53	Pass
SLA	2.8	56	Pass
		56	Pass
		56	Pass
ABS-specific	2.3	46	Pass
		45	Pass
		45	Pass

Each blade passed the mass test, although the ABS-specific blades had the highest variance in mass.

7.3a Hanging Center of Gravity Test

For balancing purposes, it is important to have knowledge of where the center of gravity is located. This test was based on a scaled-down version of the hanging center of gravity test performed for the Static Balancing of the Cal Poly Wind Turbine Rotor thesis. [Simon] Overall, the process was similar, but with considerations made to accommodate for a smaller part.

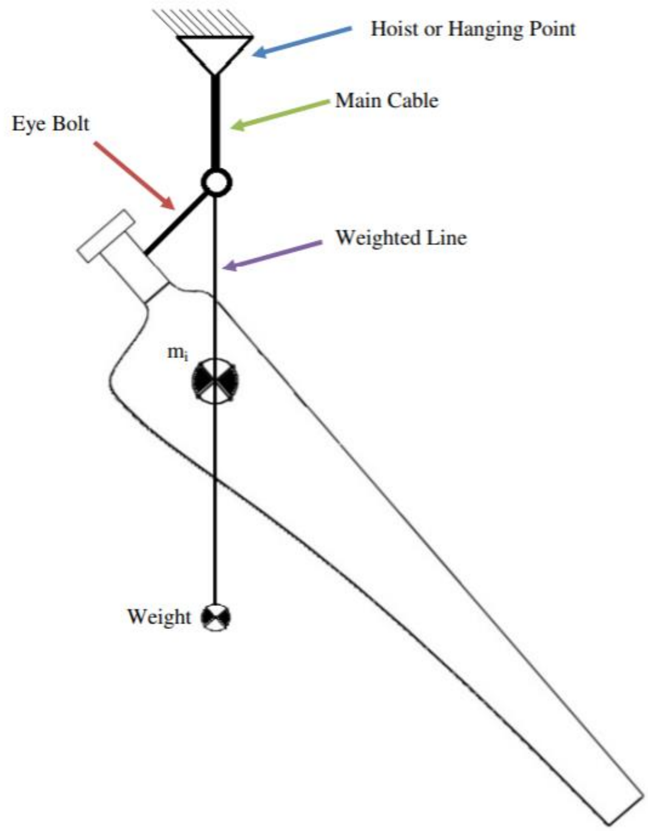

Figure 7-3. Hanging Method Formulation [Simon]

The first step was to hang the blade in an off-axis manner. In front of the blade, hang a weighted fishing line. Once the system comes to rest, we carefully taped the fishing line to the blade, then cut the blade's fishing line from the weight and the main cable. We repeated this process, except with the blade rotated 180 degrees. The intersection point of the two fishing lines was marked as the center of mass for later tests. We visually inspected the location of each center of mass. Blades that were not find them to be visibly different, were considered to have passed this test.

7.3b Hanging Center of Gravity Test Results

Using this method, both ABS and SLA manufactured blades were tested for their center of mass. Each type of blade resulted in almost the exact same center of mass, with the SLA being slightly more accurate than the ABS. This makes sense since the SLA was much more dimensionally accurate compared to the ABS blade which still had supports on the end of the blade since the printer couldn't precisive print as well compared to the SLA printer. From this test, SLA is the recommended blade since it's center of mass is basically identical between each blade.

7.4a Moment of Inertia Swing Test

To estimate the moment of inertia of the wind blades, it will be sufficient to utilize a swinging moment test. The way this test works is by observing the natural frequencies of the blade when swinging and back-calculating to find the moment of inertia.

The blade's moment of inertia was measured by using the bifilar pendulum method, where two fixed points with two strings will attach to each end of the blade and the amount of time will be recorded for a set number of oscillations.

First, the blade was set up using two strings attached to each end of the string which are attached to fixed point on a hook. In order for this method to be accurate, the distance D, had to be the same on both the top fixed points as well as the points on the blade. A picture of the setup is shown below.

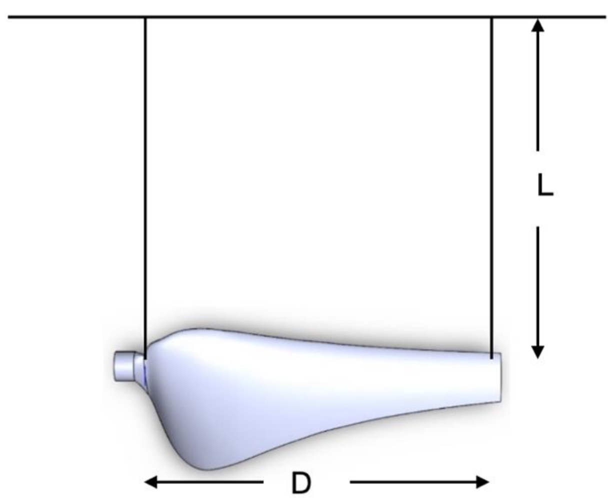

Figure 7-4. Moment of inertia test setup

Once setup, the blade was twisted at a fixed point so that the same distance is used each time. Using a stopwatch, we timed the amount of time it took for the blade to complete 10 oscillations. The values were then be averaged to obtain a higher degree of accuracy.

The blade is assumed to be able to be treated as a compound pendulum, meaning the following equation could be used to calculate its moment of inertia.

$$I = \frac{D^2 W f}{16\pi^2 L}$$

The weight, W, was obtained in the mass test and using gravity. The lengths, D and L, are measured using a ruler once the setup is complete. The value, f, is the period calculated using the average time of oscillations for each test. This experimental value was compared for each blade to see if the moment of inertia's was similar.

There was not an exact constraint given for the similarity of moment of inertia between the blades. However, since this is an important constraint, we did not consider a set of blades to be successful unless they are within a 3% margin of each other.

7.4b Moment of Inertia Swing Test Results

Using this method, the following is one set of data for calculating the mass moment of inertia of the blade.

Table 7-3. Data collected to find the mass moment of inertia of a single blade

Run	Time (s)	Period (s)	Mass Moment (kg-$m^2 \times 10^{-4}$)
1	6.12	0.612	1.3787
2	6.15	0.615	1.39225
3	5.98	0.598	1.31634
4	6.16	0.616	1.39678
5	6.21	0.621	1.41954
6	6.14	0.614	1.38772
7	6.17	0.617	1.40132
8	6.23	0.623	1.4287
9	6.14	0.614	1.38772
10	6.12	0.612	1.3787

Using this data, the average mass moment of inertia was found for the blade using all the data points found. This was done for each blade that we printed except for the FDM blades, as they were in two separate pieces and we did not find an appropriate method to epoxy the blades accurately. The final results of the mass moment of inertia of the blades are shown in Table 7-4.

Table 7-4. Mass moment of inertias for each blade

	Mass Moment ($kg\text{-}m^2 \times 10^{-4}$)	Pass/fail
SLA	1.3887	Pass
	1.4011	
	1.3982	
FDM	1.3685	Pass
	1.3578	

Looking at the results, each blade had a mass moment of inertia within less than one percent of each other. The SLA blades were slightly closer together than the FDM blades, but both types of blades pass the WPC requirements of less than three percent difference between each blade.

7.5a Airfoil Dimensional Accuracy Test

To test the accuracy of the airfoils, we utilized laser cut profiles of airfoils at certain lengths along the blade tip. These laser-cut profiles can be done at Mustang 360.

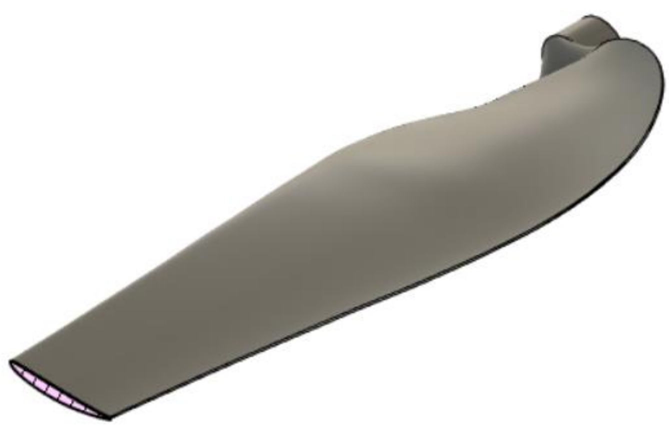

Figure 7-5. Profile at 3 cm from the blade tip

Figure 7-6. Profile at 7 cm from the blade tip

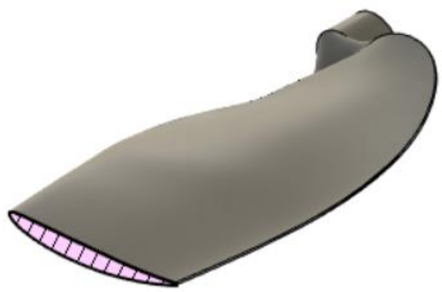

Figure 7-7. Profile at 10 cm from the blade tip

After laser cutting the profiles above, we were to slide the cutouts along from the tip towards the base. We could only do the test in this direction because the dovetail at the blade root prevented us from sliding cutouts from the root to the tip.

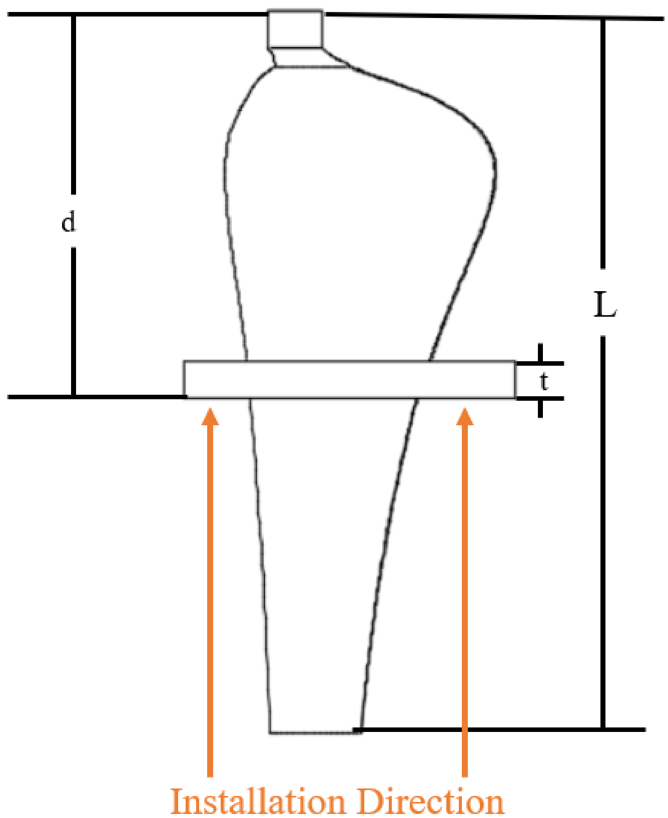

Figure 7-8. Testing variables and installation method

We were then to slide the cutout profiles along the blade until they reached the point where they could not go any further. At this point, we were to visually inspect if the airfoil and the cutout match. If they did, we would continue with the next step. The distance to the blade tip could be calculated using the equation below. The variables are shown on the figure above.

$$Distance\ to\ Tip = L + t - d$$

If the experimental distance to the tip was within 1 cm of where the cutout was obtained from, we were to consider the blade to have passed this test. This criterion was chosen based on the ±1 cm length constraint given to us by the WPC.

7.5b Airfoil Dimensional Accuracy Test Results

There were two attempts to make the cutouts for the airfoil dimensional accuracy test. The first attempt was done with water jetting on low-carbon steel, and the second was done with laser cutting on wood hardboard. The procedure for preparing the file needed to cut the material was the same between both tests, which will be covered first.

To build the airfoil cutouts for the airfoil dimensional accuracy test, the following procedure was employed. For each of the cutouts, a plane was offset from the tip of the blade at the desired distance.

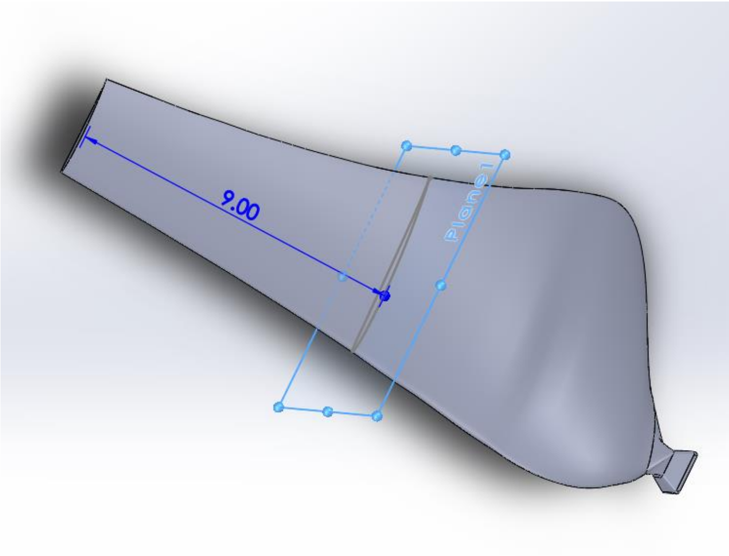

Figure 7-9. Plane Offset from Tip of Blade

Then, a sketch was created on the plane and the Intersection Curve function was used to project the airfoil cutout onto the sketch plane.

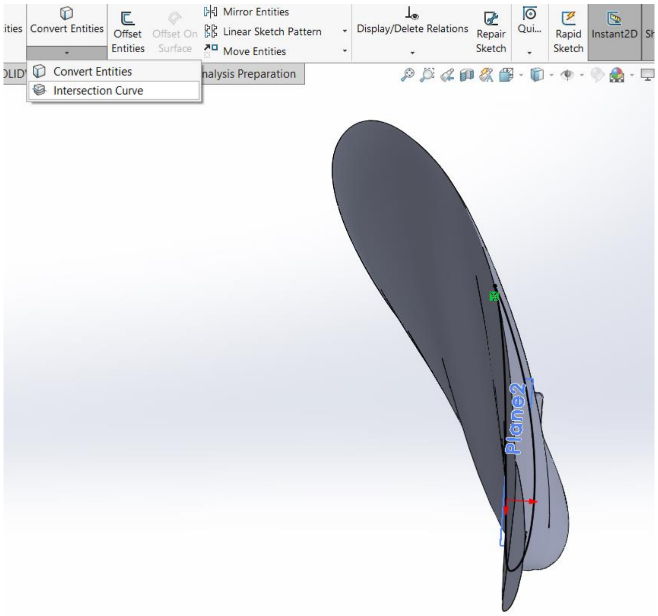

Figure 7-10. Using Intersection Curves to Generate an Airfoil Cutout

Then, outside of the sketch view, the model was hidden, leaving only the sketch visible.

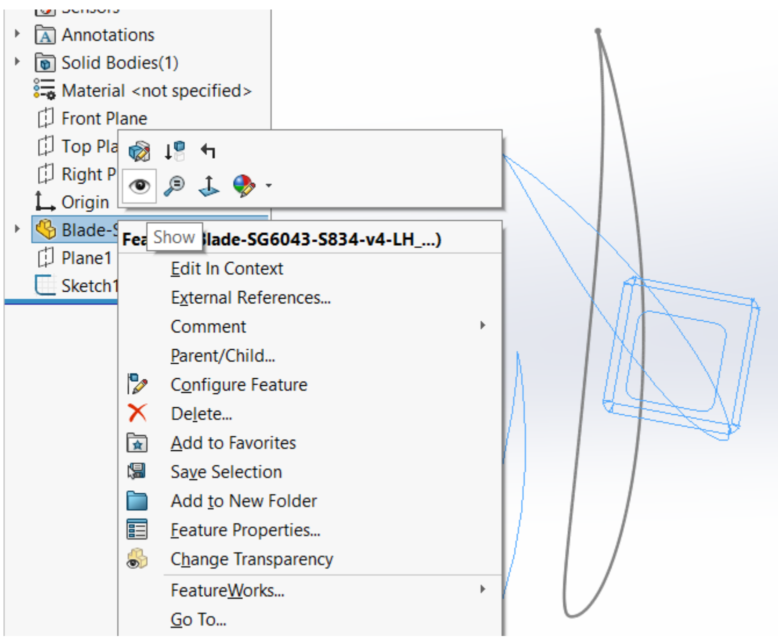

Figure 7-11. Hiding the Model

This was repeated for 3cm, 6cm, 9cm, and 12 cm from the blade tip, each in a different file. The reason why four cutouts was chosen rather than the original three was because the only material available was in a large stock, leaving a lot of extra room for cutouts. Then, each of the cutouts was placed into a drawing.

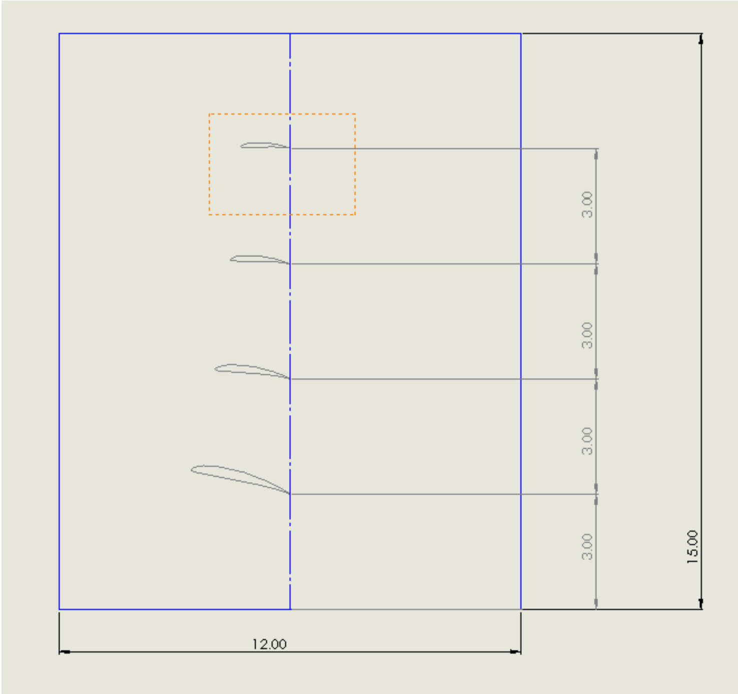

Figure 7-12. Drawing of Airfoil Cutouts

The drawing was then saved as an STL file.

The first attempt at cutting out the airfoils was done with the waterjet. A 12"x15"x0.0220" Low-Carbon Steel Sheet from McMasterCarr was used as the stock for this cut. The metal was cut in Mustang60's waterjet machine, with the following results.

Figure 7-13. Waterjet Airfoil Cutouts

The waterjet was not able to cut the sharp turns that the airfoil cutouts required, resulting in the blotching effect near the thin edges of the blades. The shop techs recommended using a laser cutter as it has a thinner kerf and thus would be able to cut the sharp turns that the cutouts would require. For the laser cutting, a 1/4" thick hardboard sheet was used. The width and height were a lot larger than needed, and had to be cut down, so it would be ideal to buy a different size if there are plans to repeat this test in the future. The Universal Laser System laser cutters employed by Mustang 60 require an Adobe Illustrator file as input, but thankfully there are computers at the shop that can be used to convert STL files to Illustrator files. The laser cut airfoil cutouts are shown below, and it is evident that the laser cutter handled the sharp turns much better than the waterjet.

Figure 7-14. Laser-cut Airfoil Cutouts

Unfortunately, the laser cutter was in imperial while the STL file was in metric, so it was necessary to manually resize the prints and as such the airfoils did not fit into the cutouts. As it took a long time to do the waterjet and the laser cutting was a last-minute backup plan, there were not enough laser cutting time slots available before the shops closed to be able to get the part cut again.

There is more than enough space on the hardboard to attempt more airfoil cutouts. Fixing the dimensioning problem is as simple as going into Settings > Document Properties > Units and changing the Unit System to IPS, but it is not possible to cut another cutout until the shops open up again in spring quarter. There are plans to cut correctly dimensioned airfoil cutouts in spring quarter and perform the test then.

7.6a Surface Roughness Test

A surface roughness tester can be found in Cal Poly's IME department. This device works by holding sections of the blade up to the surface profile measurement device, then reading the output on the dial.

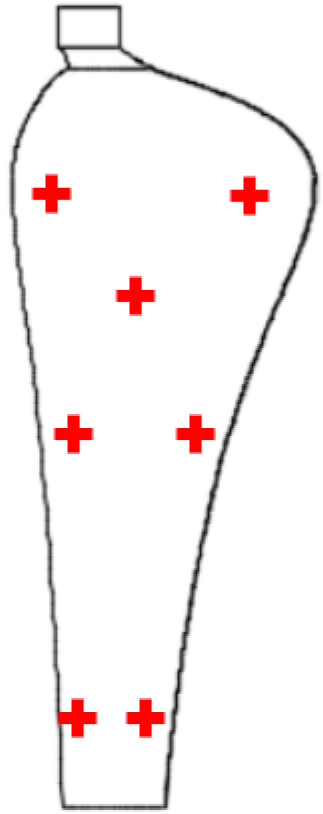

Figure 7-15. Surface profile measurement locations

To gain an accurate understanding of the entire surface profile of the part, we measured seven points on each side then average the measurements to obtain our general surface roughness measurement. A blade that has an average surface roughness measurement of .25 microns or below will pass this test.

7.6b Surface Roughness Test Results

Due to IME lab restrictions, we were not allowed to do the measurements ourselves, and the technicians were only able to get a quick reading, with two points on each blade being measured, as shown below in Figure 7-16.

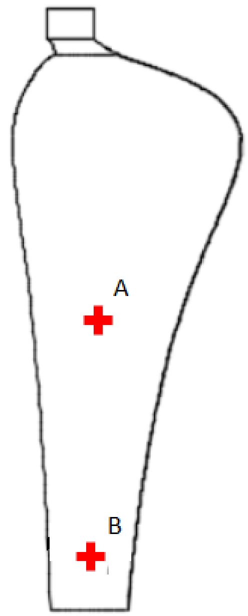

Figure 7-16. Surface roughness test points

The measured values for each point are shown below in Table 7-5.

Table 7-5. Surface roughness test results per blade (in microns)

	A	B	Average
FDM	8.44	18.61	13.53
ABS-specific	13.03	28.55	20.79
SLA	9.53	9.21	9.37

Accordingly, after print, the parts do not meet the 0.25 micron criteria without post-processing. After discussing with the Wind Power Club, it was decided that this criterion may have been too tight of a constraint. A coat of epoxy or sanding could be performed to improve results, but our sponsor preferred keeping the high roughness over risking ruining the geometry of the print.

7.7 Recommendations for Future Manufacturing Based on DVP&R

After completion of our design verification, it was clear that the SLA printed blades were the best option for competition ready blades. Our recommendation for the WPC would be to continue printing through MakeXYZ, for the best quality prints at a reasonable price. We believe that the .25 micron criteria should be investigated, to see if it is possible to raise the minimum roughness. If the new roughness criteria are still not matched by the SLA blade, the team should epoxy the blade, at the risk of ruining the blade geometry. The epoxy should fill in the tiny gaps in the print, adding extra smoothness. A roughness test should be performed post-epoxy to see if the extra smoothness is worth the possible loss in design accuracy. Likewise, we believe that the blade length constraint should be reevaluated. We were given the constraint of +/- 1 cm, which is quite large, since one centimeter would be a 5% change in the blade length. We believe this should be a much tighter constraint, allowing for more consistency with the blade properties.

Chapter 8 – Project Management

To accomplish this project before the competition in June 2021, a schedule was set forth including a list of deliverables that must be finished by certain dates with intent to have a finalized manufacturing process by the scheduled completion date in mid-March of 2021. This included key milestones set by the leads of Cal Poly Wind Power team as well as our senior project team. The milestones, along with any other communication and plans to stay on track are outlines in the sections below.

8.1 Communication Plan

Throughout the project there were three informal weekly status updates and two semi-quarterly formal updates. A project manager status update meeting with the project manager occurred every Thursday for 30 minutes. Weekly progress reports were shared along with feedback and mentoring. A client status update occurred weekly between the Blade Team and the WPC. Feedback and exchange of new findings were shared to make sure the project stays in alignment with the other sectors of the full turbine. Weekly planning meetings occurred between the members of the Blade team to ensure deliverables are being made in a timely manner. Work was divided evenly between team members with inter-work communication through GroupMe and Microsoft Teams.

Table 8-1. Communication Matrix

#	Format	Format	Frequency	Escalation	Description
1	PM Status Update	Zoom	Weekly	Project Manager (PM, Fabijanic)	Update and receive guidance and feedback
2	Client Status Update	Zoom	Weekly	Client (WPC)	Report and receive new findings and feedback.
3	Weekly Planning	Zoom	Weekly	Team members	Assign work for the following week. Check deadlines.
4	Design Updates	Document, Presentation	Semi-Quarterly	PM, class	CDR, FDR
5	Cost Estimation	Document, Presentation	Semi-Quarterly	PM, class	Included in updates in CDR, FDR

8.2 Timeline and Deliverables

Since submitting our Conceptual Design Report, we progressed greatly with much more with printing and testing. Our team completed a design review of three different blade printing styles. At the end of our testing, we decided that printing through MakeXYZ, who uses an SLA printer with Accura Xtreme material, is the best printing method for competition ready blades.

Our process will be utilized by the WPC to create competition ready blades, which will be used in the June 2021 Collegiate Wind Competition. Below is a completed timeline for our project.

Table 8-2. Project Timeline

Major Deliverable	Description	Deadline
Prototype Printing*	Single blades will be printed to create test subjects for sanding. After best sanding practices are chosen, two of a kind blades will be sanded and will move on to DVP. Deliverables include two of a kind smooth blades to be tested for specifications including similarity.	Nov 14, 2020
Manual Sanding Testing*	Single blades will endure different sanding techniques, with each result being tested against each other for surface roughness and dimensional accuracy to the given design. Deliverables include a detailed documented process for sanding that can be reproduced.	Nov 14, 2020
First Design Verification	Blades will be verified against project specifications. Full DVP plan is detailed in Chapter 7. Deliverables include a blade that meets all specifications and is accepted by the WPC for competition.	Nov 24, 2020
Competition Prototype Printing	The optimal print and sanding techniques chosen through the first round of DVP will be used to create three competition-ready prototype blades. Deliverables include three competition-ready blades, ready to be tested in second-round DVP.	Jan 16, 2020**
Second Design Verification	Blades will be verified against project specifications. Full DVP plan is detailed in Chapter 7. Deliverables include a blade that meets all specifications and is accepted by the WPC for competition.	Jan 24, 2020
Operator's Manual	Full user's manual to perform the blade manufacturing process. Deliverables include detailed instructions for each part of the process, pictures, and a list of safety hazards.	By March 15, 2021
Final Design Review (FDR)	Final project review. Includes changes and updates made during testing and prototyping. Deliverables include a complete review of the design and testing performed, and an operator's manual for future use of the product.	By March 15, 2021

Prototype printing and manual sanding testing will occur at the same time. **Printing may have to be redone after the deadline if the WPC updates their blade design.

8.3 Risk Assessment

Although our design dictates mainly outsourcing for processes, such as 3D printing and surface smoothing, it is not safe to assume future WPC members will not perform the entire blade manufacturing process themselves. Therefore, there are many safety concerns to speak of. The following risks are reiterated in the Design Hazards Checklist in Appendix Appendix 11.8.

3D Printing

- *Automatic, high acceleration:* The printer uses a printer head that moves with high acceleration to its input in the X, Y, and Z axes. Keep hand away from the printer bed and head when in use.
- *Pinch points:* Printers that use pulley systems may have pinch points. Keep fingers away from these areas.
- *High temperatures, flammable:* Printer must be watched when in use with temperature of the machine and components being monitored. Electrical fires can be caused by wire, connector, or individual component overheating and failure. Printer head and material also heat up to dangerous levels. Most printer material is flammable as well.
- *Falling*: Ensure that the printer is placed on a stable surface that can handle its weight. Falling may occur.

Surface Smoothing (Not to be done at home, approval required for on-campus)

- *Toxic chemicals*: Chemicals such as acetone may be used, which is highly toxic to inhale and harmful to skin. When using toxic chemicals, make sure to wear gloves and a gas mask when needed. Check for spills and ensure the chemical is cleaned up when use is finished.
- *Flammable:* Avoid high heat near chemicals, as they may be flammable.
- *High temperatures:* During smoothing process, be sure to keep hands away from the vessel to avoid burning.
- *Spilling:* Do not spill the chemical as it can damage the user and the surface. Any spills must be cleaned up immediately.

Wind Turbine

- *Rotating Parts:* Use eye protection when running the rotor with the blade attached.
- *Overspeed:* If the motor is running at too high a speed, failure may occur resulting in flying pieces and damaged equipment. Eye protection is required.
- *High Accelerations:* Turbine is subject to initial high accelerations. Keep hands away from the blades when starting the turbine.

8.4 Completed Process and Deviations

As intended after CDR, our project primarily focused on comparing FDM and SLA prints, since composites were ruled out due to their difficult skill level and high margin of error. For our FDM prints, we used 100% infill with a 45° zigzag pattern, with ABS filament. For our SLA print, we printed through an online printer, MakeXYZ, who printed with Accura Xtreme. The specifics of this process were described in detail in Section 6.2.

There were many deviations from the original manufacturing plan due to complications from COVID. This limitation primarily came into effect for the DVP&R portion of the project. There was a lot of distance between team members, so it was not always easy to pass the blades between each team member to perform their test. This lengthened the testing timeline considerably.

As mentioned in Section 7.5b, there were multiple deviations in the manufacturing of the airfoil cutouts for the dimensional accuracy test. There was an initial pivot to waterjet cutting because it was thought that a thinner material such as the steel sheet would allow for a more accurate measurement of whether the airfoil was accurate or not. However, as this process did not work, there was the fallback plan of using laser cutting, but there was not enough time to perform it again and fix the mistakes due to the time that water jetting took.

Chapter 9 – Conclusion

The detailing of the final design review of this project, as described in this document, serves as the agreement between us and our sponsor of the final design process for the manufacturing of the blades. With the finalized manufacturing process, the Wind Power Club has all the tools necessary to print their final design of the blades for the competition in June. Based on our results which are outlined in this document, we recommend using SLA for printing the final blades as it was the best process that fit the criteria required of the WPC. If the team wants to continue to test blades for a cheaper option, ABS and FDM are still viable for prototyping for future design changes.

Chapter 11 – References

10.1 Resources

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Staff. (2007, November 1). Resin infusion processes. Retrieved from https://www.compositesworld.com/columns/resin-infusion-processes

easycompositestv. (n.d.). Easy Composites Ltd. Retrieved from https://www.youtube.com/channel/UC7F-suscQATns3qRYHpyijw

10.2 Patents

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Burris, Matthew. *LASER SINTERING APPARATUS AND METHODS.*

Calley, Gregory. *WIND TURBINE AND METHOD OF MANUFACTURE.*

Grabau, Peter. *METHOD OF MANUFACTURING A WIND TURBINE BLADE COMPRISING STEEL WIRE REINFORCED MATRIX MATERIAL*.

Lange, Anja. *METHOD FOR REPAIRING AND/OR MODIFYING COMPONENT PARTS OF A GAS TURBINE*

10.3 Images

[1] Composite Dimensions. (2015, September 30). Vacuum Assisted Resin Infusion Process. Retrieved from https://www.youtube.com/watch?v=mbrq2fDN8bA

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Chapter 11 – Appendices

11.1 QFD (House of Quality)

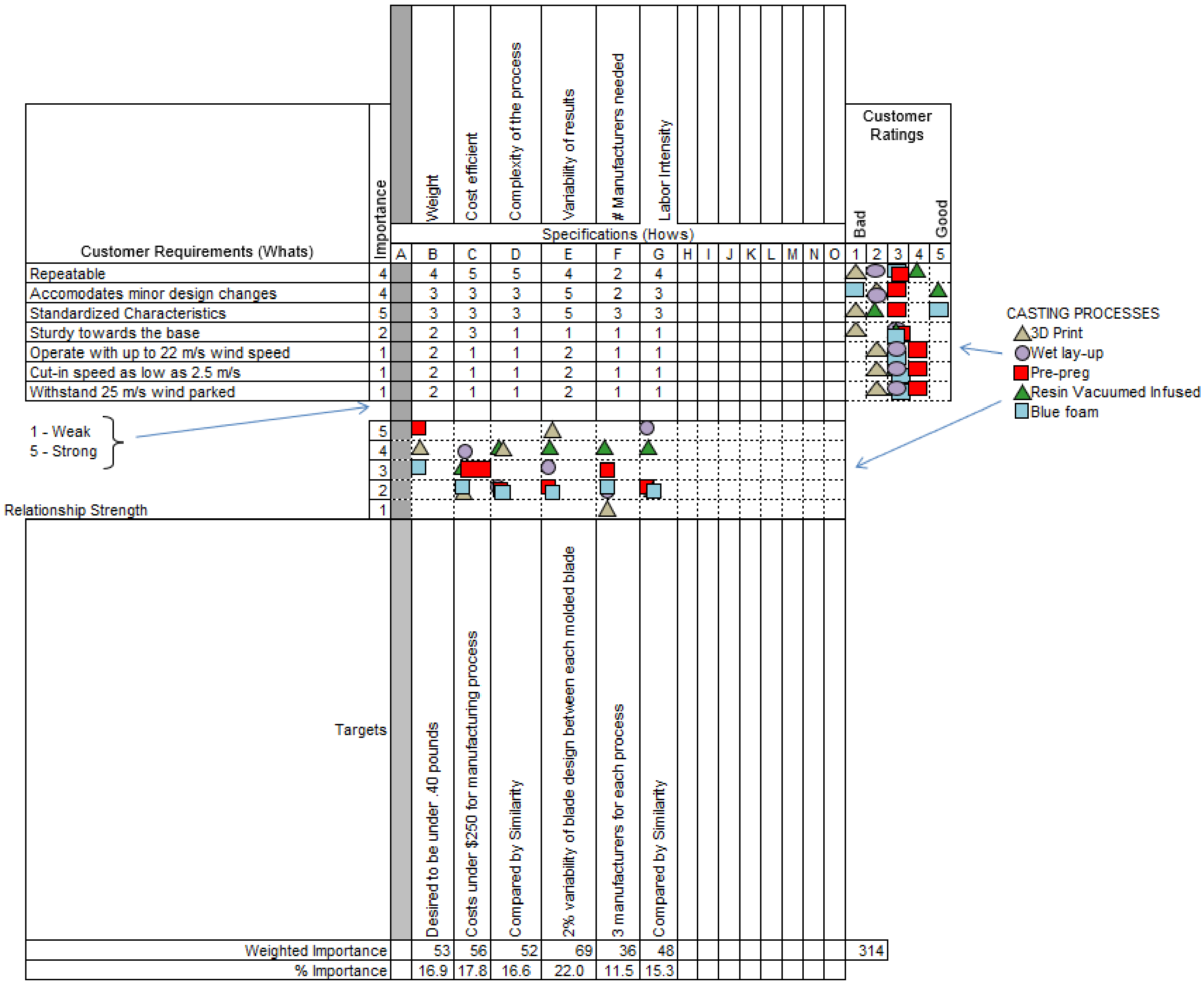

Figure 11-1. House of Quality for the blade manufacturing process.

11.2 Functional Decomposition

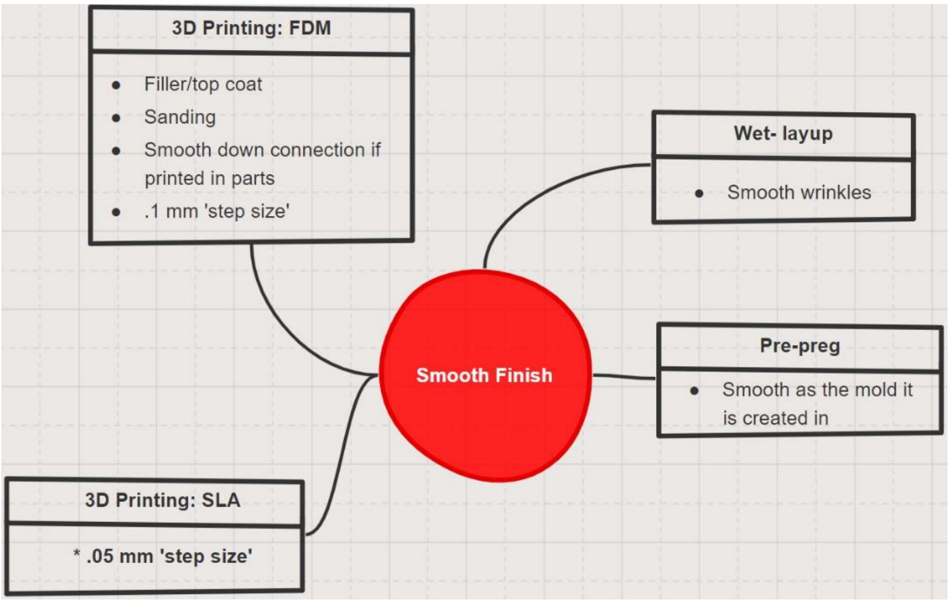

Figure 11-2. Functional Decomposition for Surface Finish

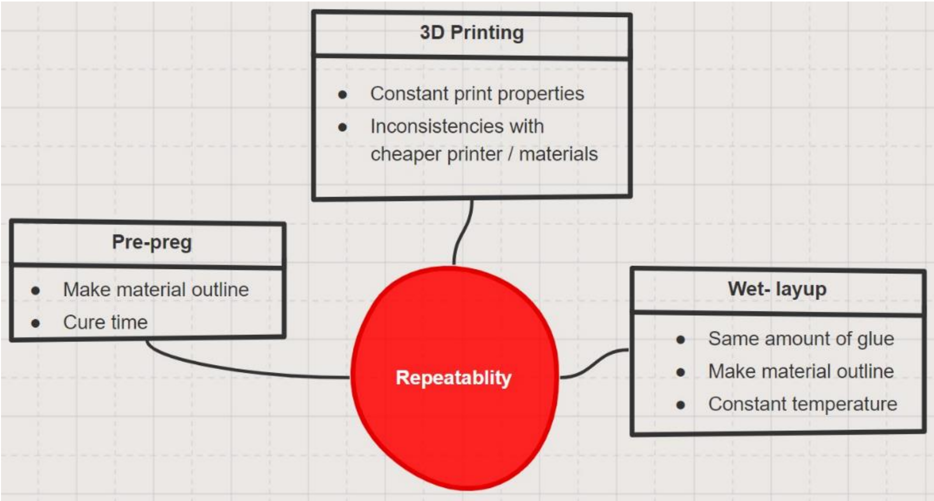

Figure 11-3. Functional Decomposition for Repeatability

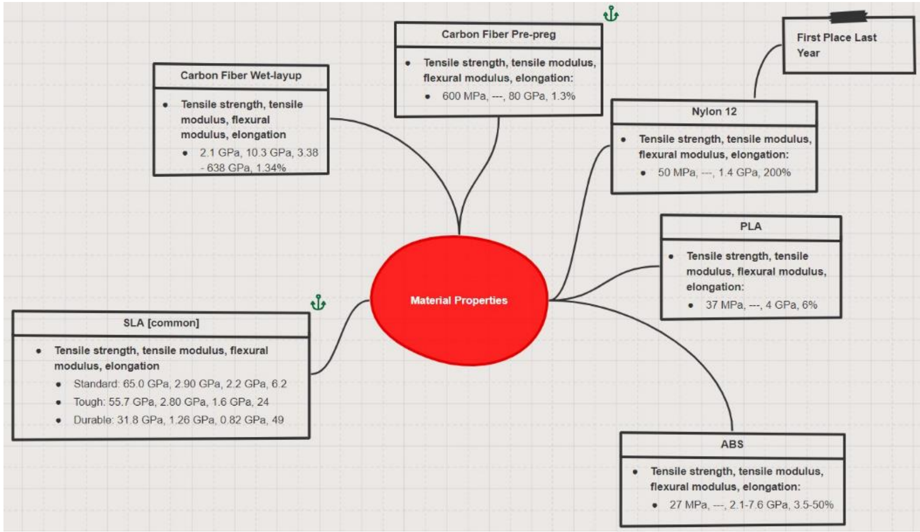

Figure 11-4. Functional Decomposition for Material Properties

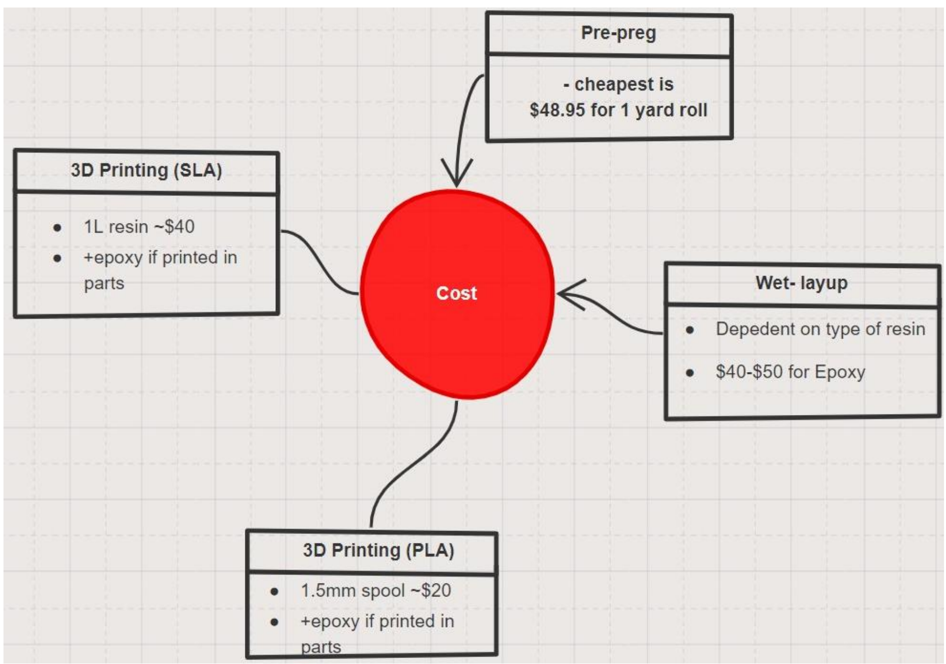

Figure 11-5. Functional Decomposition for Cost

11.3 Pugh Matrices

Table 11-1. Processing Options Pugh Matrix

Criteria	Weight	FDM	SLS	SLA	WL	PP	VARTM
Availability of Resources	3	0	-1	-1	0	-1	-1
Cost to Implement	4	0	-1	-1	-1	-1	-1
Time to Implement	1	0	0	0	0	-1	-1
Accepts Design Changes	4	0	0	0	-1	-1	-1
Precision of Dimensions	5	0	2	2	0	2	2
Labor Involvement	2	0	0	0	-2	-1	-1
	Totals	0	3	3	-12	-4	-4

FDM: Fused Deposition Modeling • SLS: Selective Laser Sintering • SLA: Stereolithography
WL: Wet Layup • PP: Pre-Preg • VARTM: Vacuum Infusion

Table 11-2. Post Processing Pugh Matrix

Criteria	Weight	MS	AM	SB	TF	VBA	VS
Availability of Resources	3	0	-1	-1	-1	-1	-1
Cost to Implement	4	0	-1	-1	-1	-2	-2
Time to Implement	1	0	1	1	-1	-1	-2
Repeatability	4	0	0	0	1	1	1
Precision of Dimensions	5	0	1	1	0	1	2
Labor Involvement	2	0	0	0	2	2	1
	Totals	0	-1	-1	0	1	3

MS: Manual Sanding • AM: Abrasive Milling • SB: Sand Blasting • TF: Tumble Finishing
VBA: Vibratory Bowl Abrasion • VS: Vapor Smoothing

11.4 Sample Deflection Calculations

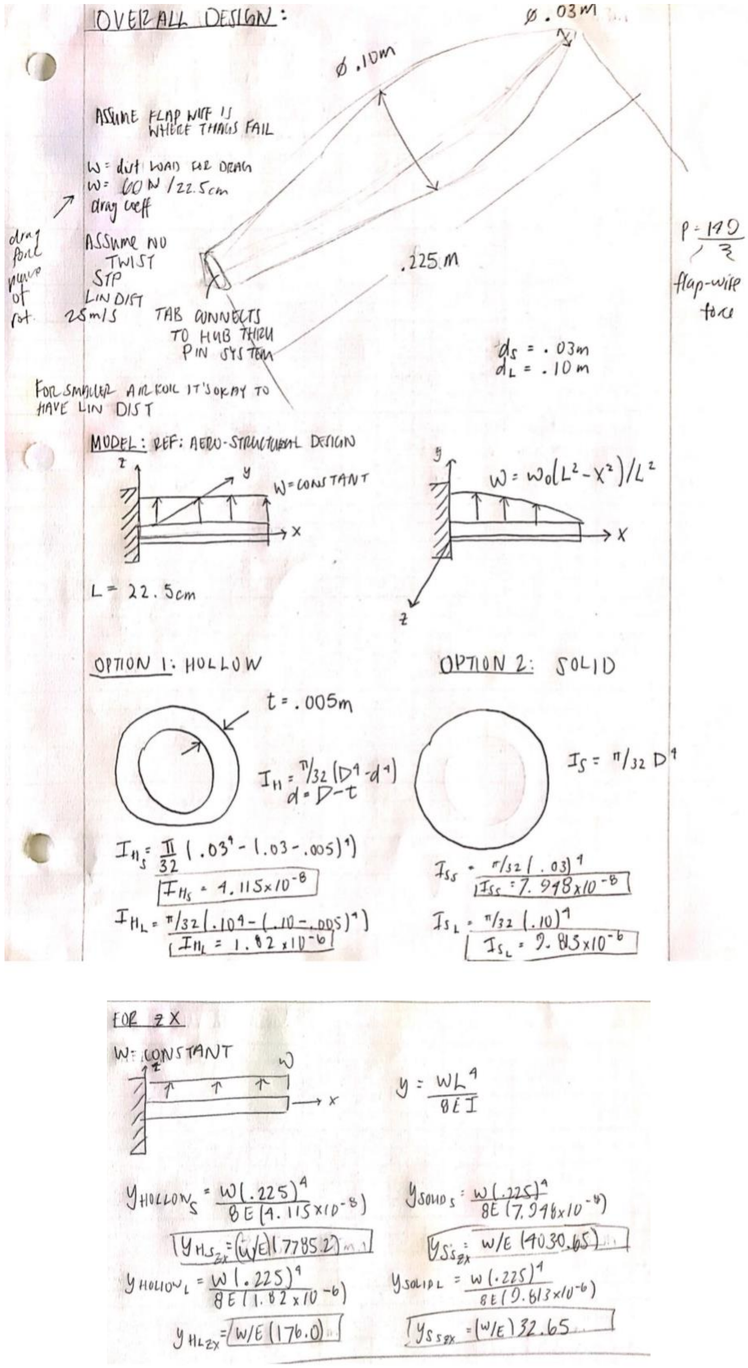

Figure 11-6. Deflection Calculations

11.5 Material Properties

Table 11-3. Material Properties Specifications Table

Material	Tensile Strength	Tensile Modulus	Flexural Modulus	Elongation	Cost
SLA	65 MPa	2.9 GPa	2.2 GPa	6.20%	$50/L
ABS	27 MPa	2.3 GPa	2.1-7.6 GPa	3.5-50%	$15-20/kg
Nylon-12	50 MPa	-	1.4 GPa	200%	$80/kg
PLA	37 MPa	2.7 GPa	4 Gpa	6%	$15-20/kg
Carbon Fiber	2.1 GPa	10.3 GPa	3.38-638 GPa	1.34%	$20/ 300mm^2

11.6.1 FMEA: 3D Printing

System	Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)
3D Printing	Creates physical product	CAD does not meet printer requirements	No blades produced	10	Too thin to print; design too complex; extreme cost	Verify design with print preview	1	Was it able to print?	1	10	
	Produces 2-3 identical blades	Blades do not meet similarity requirements	Performance does not meet specifications	8	Imperfections during printing or curing; printer not calibrated correctly	Review printer calibrations and print preview; ensure constant print environment	2	Final testing (Inertia swing test; surface roughness test; wind tunnel test)	2	32	
			Turbine unbalanced	8	Imperfections during printing or curing; printer not calibrated correctly		3		1	24	
	Maintains desired airfoils	Airfoils vary from design	Lift/drag compromised	7	Imperfections during printing or curing; printer not calibrated correctly; design too complex		4		5	140	
	Maintains desired length	Blade exceeds size limits or is too short	MOI compromised	7	Imperfections during printing or curing; printer not calibrated correctly		3		1	21	

System	Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)
3D Printing	Maintains Desired Length	Blade exceeds size limits or is too short	Loses structural integrity	9	Imperfections during printing or curing; printer not calibrated correctly; design too complex	Review printer calibrations and print preview; ensure constant print environment	5	Final testing (Inertia swing test; surface roughness test; wind tunnel test)	5	225	Add supports
			Turbine unbalanced	7	Imperfections during printing or curing; printer not calibrated correctly		2		1	14	
	Maintains desired twist angles	Angles differ from design	Angle of attack compromised	7	Imperfections during printing or curing; printer not calibrated correctly; design too complex		5		5	175	
	Maintains desired tensile/bending strength	Blade flexes or breaks	Turbine can't compete	10	Imperfections during printing or curing; material poorly chosen		1		1	10	
	Maintains desired moment of inertia (MOI)	MOI varies between blades and from the design	Turbine unbalanced	7	Imperfections during printing or curing;		5		2	70	

11.6.2 FMEA: Manual Sanding Printing

System	Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)
Manual sanding	Removes any burrs or surface imperfections	Burrs maintained	Airfoils change	6	Removing too much material; removing too little material; Uneven finish;	Constant sanding pressure; constant sanding time per grit paper;	3	Final testing (Inertia swing test; surface roughness test; wind tunnel test)	4	72	
			Lift/drag compromised	6			3		4	72	
		Airfoils vary from design	Wind speed req. not met	8			3		4	96	
			Lift/drag compromised	7			3		4	84	
			Angle of attack compromised	7			3		3	63	
		Twist varies from design	Angle of attack compromised	7			3		3	63	
		Blades do not meet similarity requirements	Wind speed req. not met	8			6		3	144	
			Lift/drag compromised	7			6		3	126	
			Angle of attack compromised	7			6		3	126	

11.6.3 FMEA: Vapor Smoothing

System	Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)
Vapor Smoothing (ABS only?)	Removes any burrs or surface imperfections	Burrs maintained	Airfoils change	6	Part not left in vapor long enough; vapor not diligent enough - burrs not removed; vapor causes warping	Calculate proper smoothing time; keep constant time in vapor	5	Final testing (Inertia swing test; surface roughness test; wind tunnel test)	5	150	
			Lift/drag compromised	6			5		5	150	
		Airfoils vary from design	Wind speed req. not met	8			1		5	40	
			Lift/drag compromised	7			5		5	175	
			Angle of attack compromised	7			5		5	175	
		Twist varies from design	Angle of attack compromised	7			5		5	175	
		Material overwarped	Surface area compromised	8			5		5	200	Periodic check-ins every 5 minutes.
			Lift/drag compromised	8			5		5	200	Periodic check-ins every 5 minutes.
		Blade does not meet similarity requirements	Wind speed req. not met	8			6		4	192	
			Lift/drag compromised	7			6		4	168	
			Angle of attack compromised	7			6		3	126	

11.6.4 FMEA: Epoxy

System	Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)
Epoxy	Attach blade pieces together into one smooth blade	Airfoils vary from design	Wind speed req. not met	8	Epoxy not compatible, parts not flush	Constant amount of epoxy used; constant epoxy spread technique used	2	Final testing (Inertia swing test; surface roughness test; wind tunnel test)	3	48	
			Lift/drag compromised	7			2		3	42	
			Angle of attack compromised	7			2		3	42	
		Surfaces not flush	Airfoils change	6	Epoxy not compatible, parts not lined up, too much epoxy	Male-female connecting surface where they connect	2	Dimensional accuracy and visual inspection	2	24	
			Lift/drag compromised	7			2		2	28	
			Blade breaks	10			3		1	30	
			Angle of attack compromised	7			2		2	28	
		Not stick	Blade breaks	10	Too little epoxy, epoxy not compatible, too little dry time	Constant amount of epoxy used; constant epoxy spread technique used	2	Dimensional accuracy and visual inspection	1	20	
		Deteriorates the part	Lift/drag compromised	7	Epoxy not compatible to print material	Research and material testing on proper epoxy	1	Dimensional accuracy and surface inspection	3	21	
			Angle of attack compromised	7			1		3	21	

System	Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)
Epoxy	Attach blade pieces together into one smooth blade	Deteriorates the part	Airfoils change	6	Epoxy not compatible to print material	Research and material testing on proper epoxy	1	Dimensional accuracy and surface inspection	3	18	
		Blades do not meet similarity requirements	Wind speed req. not met	8	Epoxy not compatible, too much epoxy, too little epoxy, too little dry time, parts not lined up	Constant amount of epoxy used; constant epoxy spread technique used	2	Final testing (Inertia swing test; surface roughness test; wind tunnel test)	2	32	
			Lift/drag compromised	7			2		2	28	
			Angle of attack compromised	7			2		2	28	

11.7 DVPR

Report Date		Sponsor	Cal Poly Wind Power Club				Component/Assembly		REPORTING ENGINEER:				
TEST PLAN								**TEST REPORT**					
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES Quantity	SAMPLES Type	TIMING Start date	TIMING Finish date	TEST RESULTS Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	Blade Length Verification	Measure the length of the blade using a 12" veneer caliper.	19 ±1 cm	BMT	PV	3	C	3.15.21	3.15.21	Pass	3	0	
								3.15.21	3.15.21	Pass	3	0	
								3.15.21	3.15.21	Pass	2	0	
2	Mass Test	Compare the masses of each blade by weighing each on a triple beam balance.	<5% difference	BMT	PV	3	C	3.15.21	3.15.21	Pass	3	0	
								3.15.21	3.15.21	Pass	3	0	
								3.15.21	3.15.21	Pass	2	0	
3	Hanging Center of Gravity Test	Hang the blade off-axis with a fishing line in front of it, cut and tape the fishing line to the blade once it reaches steady state, repeat with a different angle, The intersection point is the center of gravity.	Same under visual inspection	BMT	PV	3	C	3.11.21	3.11.21	Pass	3	0	
								3.11.21	3.11.21	Pass	3	0	
								Did not perfom test					
4	Moment of Inertia Swing Test	Swing each blade by their root and measure the oscillations to calculate the natural frequency. From there, calculate the moment of inertia. Compare.	<3% difference	BMT	PV	3	C	3.11.21	3.11.21	<3%	3	0	
								3.11.21	3.11.21	<1%	3	0	
								Did not perfom test					
5	Airfoil Dimensional Accuracy Test	Create airfoil cutouts at certain lengths along the blade. Slide them from tip to root and measure the length that they stop at. Compare to the length the cutout was taken from.	<1 cm difference	BMT	PV	3	C	***was not able to perform test**					
6	Surface Roughness Test	Use the surface roughness tester in the Cal Poly IME department to measure the roughness of the part.	.25 microns	BMT	PV	3	C	3.4.21	3.4.21	13.53	0	1	
7								3.4.21	3.4.21	20.79	0	1	
8								3.4.21	3.4.21	9.37	0	1	

FDM	
ABS-specific	
SLA	

11.8 Design Hazard Checklist

Table 11-4: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: Wind Blade Manufacturing Faculty Coach: John Fabijanic

Y	N	
■	□	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
■	□	2. Can any part of the design undergo high accelerations/decelerations?
■	□	3. Will the system have any large moving masses or large forces
□	■	4. Will the system produce a projectile?
■	□	5. Would it be possible for the system to fall under gravity creating injury?
□	■	6. Will a user be exposed to overhanging weights as part of the design?
□	■	7. Will the system have any sharp edges?
□	■	8. Will any part of the electrical systems not be grounded?
□	■	9. Will there be any large batteries or electrical voltage in the system above 40 V?
□	■	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
■	□	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
□	■	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
■	□	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
■	□	14. Can the system generate high levels of noise?
■	□	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
■	□	16. Is it possible for the system to be used in an unsafe manner?
□	■	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

11.9 Gantt Chart

Table 11-5: Gantt Chart Schedule for the Entire Timeline of the Project

Name	**Duration**	**Start**	**Finish**
Blade Manufacturing Senior Project	**3 Quarters**	**Apr 6, 2020**	**Mar 2021**
ME 428	**Spring 2020**	**Apr 13, 2020**	**June 12, 2020**
Introduction	**~3 Weeks**	**April 13, 2020**	**May 6, 2020**
Letter to Sponsor/Intro Meeting	1 Week	April 3, 2020	April 10, 2020
Team Contract	2 Days	April 15, 2020	April 17, 2020
Research	4 Weeks	**April 13, 2020**	**CONTINUOUS**
Scope of Work	**~2 Weeks**	**April 23, 2020**	**May 7, 2020**
QFD	1 Week	April 24, 2020	May 1, 2020
Finish report	1 Week	May 1, 2020	May 7, 2020
Concept Development	**3 Weeks**	**May 8, 2020**	**May 29, 2020**
Model	1.5 Weeks	May 8, 2020	May 20, 2020
Prototype	2 Weeks	May 15, 2020	May 29, 2020
Preliminary Design Report	**2 Weeks**	**May 29, 2020**	**June 7, 2020**
Report	2 Weeks	May 29, 2020	June 4, 2020
Presentation	2 Weeks	May 29, 2020	June 7, 2020
ME 429	**Fall 2020**	**Sept 14, 2020**	**Dec 12, 2020**
Critical Design Report	**6 Weeks**	**Sept 14, 2020**	**Oct 22, 2020**
Report	2 Weeks	Sept 15, 2020	Oct 22, 2020
Presentation	2 Weeks	Sept 16, 2020	Oct 15, 2020
Structural Prototype	4 Weeks	Oct 22, 2020	Nov 14, 2020
Status Report	**4 Weeks**	**Nov 14, 2020**	**Dec 12, 2020**
Manufacturing and Test Review	3 Weeks	Nov 14, 2020	Dec 5, 2020
Project Update Memo to Sponsor	1 Week	Dec 5, 2020	Dec 12, 2020
ME 430	**Winter 2021**	**Jan 4, 2021**	**Mar 19, 2021**
Verification Prototype Sign off	**2 Weeks**	Jan 4, 2021	Jan 18, 2021
Testing Sign off	**2 Weeks**	Jan 18, 2021	Feb 1, 2021
Operator Manual	**4 Weeks**	Feb 12, 2021	March 12, 2021
Final Design Review	**4 Weeks**	Feb 19, 2021	March 19, 2021
Verify Prototype	4 Weeks	Feb 14, 2021	Mar 14, 2021
Report	3 Weeks	Feb 26, 2021	Mar 19, 2021