Design Automation of the Manufacturing Process for VAWT Blade & its Mould by parametrization.

By

Nitesh Poudel

2263995

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ABSTRACT

The report is based on the design automation process for manufacturing of vertical axis wind turbine blade by the means of parametrization technique associated with VAWT-X Energy collaborating with Flinders University. It aims in developing parametric design of aerofoil, blade and mould with a vision of obtaining change in mould as per the change in design of blade considering the manufacturing approach for VAWT Blade section. Different literature articles were studied, including different parametrization technique, ideas of lap-joints assembly, manufacturing approach and the mould design. The parametrization technique implemented in this project is based on Cubic Bezier Curve in case of aerofoil. New design of sectionized VAWT blade with the features of hollow cavity supported by Z- section and step lap-joint for assembly is created in accordance to manufacturing approach of using 3 layer of carbon fibre under the Vacuum Assisted Resin Infusion method. Then, the design of mould is created and parametrically linked with the design of blade section carried out in inventor. The design modified blade facilitates reduction in weight of the blade profile, and enhanced overlapping in joints by the concept of step lap joint. It is resulted that that parametric design of the aerofoil profile is validated with the standard design of the NACA 0018 profile with the concept of overlapping. And the link between the blade and mould can be achieved and it is represented by the pictorial changes in the dimensions of the blade and mould. The manufacturing of blade using 3 carbon fibre layers under Vacuum Assisted Resin Infusion Method is verified through the development of the mould digitally. In future, the digital manufacturing approach that the paper represents can be tested by manufacturing of the blade and implementing it in an experimental setup.

Keywords: VAWT-X Energy, Parametrization, Cubic Bezier Curve, Vacuum Assisted Resin Infusion.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university.
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
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I certify that I have read this thesis. In my opinion it is/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Engineering (Mechanical). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully (please circle).

Signature of Principal Supervisor

Print name of Principal Supervisor.............Dr. Amir Zanj......................................

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ABBREVIATIONS

Abbreviations	Descriptions
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
NACA	National Advisory Committee for Aeronautics
RTM	Resin transfer Moulding
VARTM	Vacuum Assisted Resin Transfer Moulding
VARI	Vacuum Assisted Resin Infusion

CHAPTER ONE: INTRODUCTION

One of the most pressing concerns, the world is facing is the energy problem. And they are articulated by the supply and demand of the energy. Renewable energy, especially wind energy has become one of the inevitable parts of solutions to these problems. Especially, talking about today's market wind energy has gained popularity and has become one of the fastest-growing industries in the world (Kaygusuz, 2004). There is a recent trend called decentralization of power generation in the field of energy development, which creates opportunities for small-scale industries to generate electricity by reducing the price neglecting the transmission price from long distances (Dhunny, Allam, Rughooputh, Lollchund, & Dookhitram, 2019). In the context of wind energy, two types of turbines are used for energy generation, i.e., Vertical Axis Wind Turbines (VAWT) and Horizontal Axis Wind Turbines (HAWT). HAWTs have dominated the market because of their maximum energy generation capability and VAWTs cannot be in competition with HWAT in terms of performance but the ability to perform at a wide range of speeds without considering the speed of wind has become very crucial for the existence of the VAWT system and this system also has the flexibility to simple fabrication, easy maintenance and easy to transport makes them the ideal system for the residential areas.

Project Background

This project is associated with the industry called VAWT-X Energy whose main aim is to manufacture and bring the quiet and aesthetic VAWT wind turbine to deliver the best-in-class cost of energy to empower both corporate and individual consumers (VAWT-X Energy Pvt Ltd., 2022). The problem the company facing is, manufacturing the turbine blade. The company patented the helical shape Darrieus Model VAWT blade, with its advantage of tip speed ratio being smaller than that of HAWT which create less noise and is suitable for residentials area. The blade model has a very complex shape; thus, it created a problem in manufacturing the complex shape of the Darrieus model blade at once, but the company came up with the solution of sectionizing the blade. So, VAWT-X decided to create 9 sections of the blade combined by the mean of lap-joints to form one single blade, which can be seen in Fig 1. similarly, the designed model consists of two blades helical shape Darrieus model VAWT blade as shown in fig 1.

Figure 1 (c) represents the laboratory model of the VX-6 Prototype which is situated in Finders University laboratory. And, since the company is still in the testing phase in collaboration with Flinders University, South Australia. This means that the design of the blade can be still changed and tested. The main problem of the company is that since, the change in design and testing is very costly and time-consuming as VAWT-X had to go through scratch while changing the design. And the VAWT-X Energy company being a startup company it is very hard to go through the different iterations of design and testing.

Figure(s) removed due to copyright restriction.

(a) (b) (c)

Figure 1 (a): VX-6 Blade Section (b): VX-6 Prototype and its annotated diagram; (c): VX-6 Prototype laboratory Model (VAWT-X Energy Pvt Ltd., 2022).

So, this project proposed the automation process of design for the blade and mould by the parametrization technique, which provides a solution to the main problem by being able to change the parameters and create a new design for both the blade and the mould, which helps in reducing the cost and time in some extent. However, this project also covers the part of identifying the best possible manufacturing techniques and provides the digital manufacturing approach for the VAWT Blade section.

Project Objective

The main aim of this project is to automate the manufacturing process for the VAWT Blade section. To meet the aim of this project certain objectives have been set up which are as follows,

- To identify the best parameterization technique for NACA 0018 aerofoil profile.
- To design a parametric VAWT Blade section and its mould.
- To link the parameters of Blade and Mould together.
- To identify the best possible manufacturing approach.
- To develop a digital manufacturing approach for the VAWT blade section.
- To use carbon fibre for a digital manufacturing approach.

- To setup the manufacturing procedure digitally.

Scope of the Project

This project specifically focuses on the automation of the manufacturing technique for Vertical Axis Wind Turbine blades by parameterization and its digital manufacturing approach. So, based on this the main goal of the project was to create a parametric design of a VAWT blade, and its mould identifying the manufacturing techniques and setting up the manufacturing process digitally. Due to the time limitation, this project was only limited to the parametric designing of the VAWT Blade section but not the analysis part of it. Since this project is associated with the industry called VAWT-X Energy, many projects are going parallelly on the Vertical Axis Wind Turbine setup for different parts. So, the FEA analysis for the VAWT blade was another parallel project and the design presented in this paper was sent for analysis to another member who was working on the FEA Analysis of the VAWT Blade as suggested by the supervisor. Since the project is completely focused on the innovative design of VAWT blade, mould and manufacturing approach, it does not collect any data and thus the data interpretation is not done in this project.

This project only creates the design of the Mould, but the materials, cost, and manufacturing of the mould are not considered under the scope of this project. After the design of the mould, the digital manufacturing process was identified. The project highly focuses on step-by-step process for manufacturing of VAWT blade digitally with the chosen manufacturing technique, therefore real manufacturing of the blade was kept beyond the scope of this project.

Thesis Outline

Chapter one talks about the basis introduction to the project. The objective and scope of the project along with the thesis outline are also presented in this chapter. Chapter two talks about the literature review which was required to complete this project. In chapter three the methodology of the project is explained from designing a conceptual blade to its digital manufacturing approach. Chapter four talks about the validation of the results and provides some discussion relating to the literature. Finally, chapter five provides the conclusion and future work of the whole thesis project.

CHAPTER TWO: LITERATURE REVIEW

Introduction

The design automation of the manufacturing process for Vertical Axis Wind Turbine blade section by parametrization technique requires a deep understanding of suitable parametrization technique and manufacturing process. This literature discusses different parametrization techniques of an aerofoil shape which was the essential part of this project for the conceptual design of the VAWT blade section. Next, the different ways of connecting the sectionized blade should be studied to create an innovative lap joint. Different process for the manufacturing VAWT blade was studied which was the foundation for the identification of the design of the mould. However, based on the manufacturing process, different design of the mould was studied, and a suitable design approach was identified using the literature.

Review of Aerofoil shape parametrization techniques

Firstly, the word “aerofoil” in Greek is generated by the combination of two-words aerios and foil. “Aerios” means air and foil means blade. Since, the development of aerofoil it has been refined to the point where an aircraft can fly with a speed of more than 1000 mph (Mishra, Malik, & Singh, 2019). To promote aeronautical research, the National Aeronautics and Space Administration (NACA) was formed in 1915 (Banke, 2010). And since then, they have developed different types of aerofoils like 4-digit, 5-digit NACA series and many other series.

Since the project focuses on the NACA 0018 it comes under the 4-digit series and each of the digits represents the profile of the blade. The first digit of the profile represents the maximum camber which is given in percentage of the chord. The second digit represents the distance of the camber at its maximum from the leading edge, which is at tenth of the chord length. The last two digit represents the maximum thickness of an aerofoil which is in percentage to the chord length. As per the characteristics of the four-digit profile NACA 0018 describes, this profile is symmetric as it has 0 camber.

The goal of automation is parametrization and in the case of an aerofoil, it refers to creating and manipulating the shape and size of an aerofoil using a designed set of parameters. This feature gives a significant advantage since VAWT-x Energy is in the testing phase.

The concept of parameterization technique for an aerofoil can be traced back to the late 1800s when a Russian Mathematician named Georgy Voronoi introduced the conformal mapping technique but then later it was made popular by Theodore von Karman in the 1920s, by using this technique for designing the complex shape of an aerofoil based on principles of fluid mechanics to transform into simpler one with certain properties like angles and shape and it was considered to be one of the breakthrough in aerodynamics field (Selig & Maughmer, 1992). However, there were some limitations in this technique such as limited flexibility, limited controls over the design parameters and complex transformations that were very hard for this technique to cover. But then the technique of Joukowski transformation was introduced by Nikolai Zhukovsky in 1904, in which the concept of mapping a circle in the complex plane in an aerofoil shape by adding the constant to the circle's radius (Cruz, Falcao, & Malonek, 2011). So, the shape of the round edge and the pointing edge of the trailing end could be adjusted by changing the size and position of the added constant. This technique was utilized in the minicomputers for the optimization of the aerofoil, where the author coupled the aerodynamics code to the conjugate gradient, numerical optimization algorithm and penalty function. And the program was written in BASIC which was used in HP 9830 minicomputer. However, there were some limitations for designing the aerofoil with desired pressure distribution and to accurately represent the complex shape of the geometry (Hicks & Szelazek, 1978). The method was much more effective than the method of conformal mapping, however, there are some limitations in getting the exact representation of the aerofoil shape in the Joukowski transformation technique.

Since then, many parameterization techniques have been developed, one of the next parametric techniques was the Bezier parametrization technique, which was introduced by Pierre Bezier in the 1960s. Previously this method was used for designing automobile parts and bodies then they were adapted for designing the aerofoil due to its design flexibility (Talbert & Parkinson, 1990). This technique utilizes the method of Bezier curve with a set of control points for defining the shape of the aerofoil. This method offers flexibility in the design and allows the designer to create the smooth shape of the curve with precision. This method is also easy to implement in the CAD software. With this, the design of the aerofoil can be easily adjusted and modified with changing requirements. However, this method had some limitations, it had limited control over the curvature, this method limited the ability to verify the thickness and this method is limited to non-planar aerofoil. Jaiswal, (2017) in his paper talks about the parametrization of the shape of the airfoil by the use of the Bezier curve. This paper has studied the approximation of aerofoil by the use of the fourth, sixth and eighth order of the bezier curve. The fourth order and sixth order represent they have five control points for the fourth order and seven controlling points for the sixth order. To represent the airfoil a control point has been determined, which is used for controlling the curve. From this paper, the result shows that, in between the comparison of different orders of the bezier curve, the higher the order higher the chance of flexibilty was there for giving an accurate shape of an aerofoil. In this case, NACA 0012 was developed by using this technique and had high-level accuracy in a higher-order curve. Hence concluded that this method can be used to parametrize the aerodynamic shape optimization problems. However, the author talks about the limitations of this method, which are less control over the curvature.

Another method of parametrization called PARSEC was introduced by Michael Selig in the 1990s. This method seems to cover the limitation parts of the Bezier parametrization technique by utilizing the method of dividing the aerofoil segment, where each of the segments has a set of parameters which is used for controlling the shape of an aerofoil (Mukesh , Lingadurai, & Selvakumar, 2014). This method uses 11 parameters to completely define the aerofoil shape. However, this method seems to have limitations in controlling the trailing edge shape where is important flow of air takes place. An article written by Vecchia, Daniele, & Amato, (2014), has mentioned that the PARSEC parametrization technique has the capability of describing the airfoil geometry fully by the use of parameters. This article was presented as a work of the optimization technique and this deals with the PARSEC parametrization method and Nash equilibrium genetic algorithm. This paper explains that it accurately represents the aerofoil shape, and it provides the key control over the design features this method is simple to use however it also has some limitations like limited flexibility because of the limited number of variables that defines the shape of the aerofoil. Also, this method does not have flexible control over the thickness distribution so it may not be the best use for the designing of specific thickness distribution and had limited control over the parameters of the trailing edge.

Also, in the 1990s another method was introduced by H. Sobieczky which was referred to as the Sobieczky method. This method also involves defining the set of parameters for controlling the shape of aerofoil, like the position of maximum thickness, maximum chamber, and thickness distribution (Sobieczky, 1980). As the PARSEC method lacks control on the trailing edge, the Sobieczky method proposes a process of providing the concave shape to the trailing edge by modifying the edge with the method of the divergent trailing edge. This method was able to reduce the limitations of the PARSEC Method (Sobieczky, Parametric Airfoils and Wings, 1999). This method is utilized in combination with the PARSEC method where the sobieczky is used to design the trailing edge and the PARSEC method is used to create other aerofoil bodies.

PARSEC method was also combined with the Bezier curve to test the flexibility of the parametrization technique and this technique was impressive as written in the paper by, Derksen & Rogalsky, (2010), which discusses the combined technique which is developed to improve and extend the typical method of Bezier curve parameterization technique. This method utilizes the combination of four bezier curves to form a single airfoil curve and this technique was found to be fit for the wide range of known existing airfoil profiles. This technique utilizes the four sets of cubic bezier curves and this provides the flexibility in changing the parameters of the profile to match the standard profile of known airfoil.

Therefore, with all this literature review the parametrization technique of cubic bezier curve with the slight touch of the PARSEC method seems to be the ideal option for this project. This method shows the proven concept for matching the profile of a known profile then any other method as mentioned in the paper written by (Melin & Amadori, 2011). Also, this method is easy to understand and this method is easy to implement in the software Inventor by the use of spline and the controlling points.

Different designs of VAWT sectionized Blade

The assembly of two consecutive sectionized blades depends upon the nature of the cross-section assembled between each other. Therefore, the study of the different natures of cross sections that sectionized blades can be assembled is an integral part of a blade design. Different studies were carried out for the study of the segmented blade, however, most of the studies were related to horizontal axis wind turbine blades. This study gives conceptual ideas on assembling blades. There was a study done by Peeters, Santo, Degroote, & Paepegem, (2017), where it talked about the concept for the segment of the wind turbine blades and it has shown the study of 4 different concepts of assembling the blade.

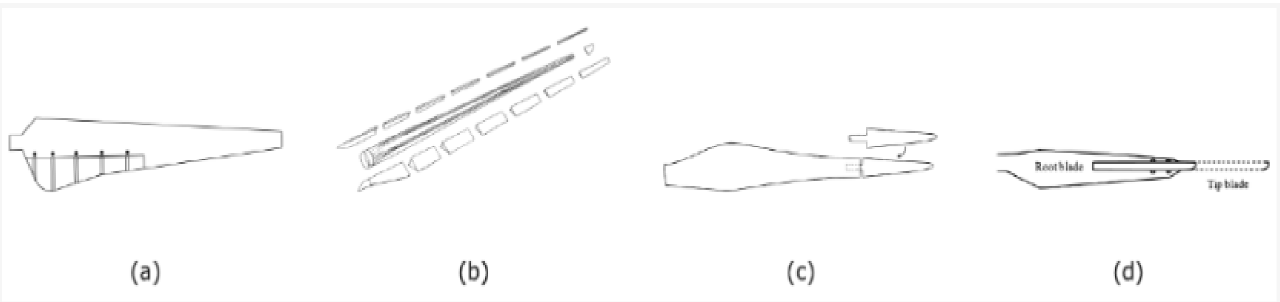


Figure 2 Different strategies for segmentations (a) separate trailing edge segment for reducing with (b) separate leading edge and trailing edge (c) sectionized blade connection (d) telescopic blade design.

From this study, figure (c) gives an idea for connecting the segment of the blades. This concept is the patented design by, Hibbard, Patent No. 8,177,515 (B2), (2012) where they create the blade by comprising the first and second section of the blade and connecting them by spar bridge over the spar joint, which consist of the two extended beam caps connected by ine extending part of the beam webs, which can be clearly shown in the figure below,

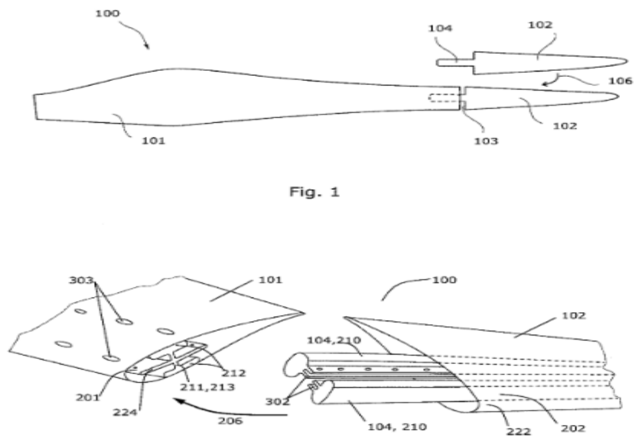


Figure 3 sectional blade concept (U.S Patent No. 8,177,515 (B2), 2012)

This paper talks about its advantages which provide the easy assembly and dissembling of the blade so it can help in repairing the blade or the parts to be replaced. Therefore only the section which comprises the fault component could be repaired by easy dissembling. For this paper, it can be seen that the sectionize of the blade can provide crucial benefits to the repairing of the blades. Another study was carried out by, Mendoza, Yao, Chetan, & Griffith, (2022), with a similar concept of a male and female part as shown in figure 4,

Figure removed due to copyright restriction.

Figure 4 Single lap joint concept (Peeters, Santo, Degroote, & Paepegem, 2017)

In this study, it has mentioned that the segmentation of the blade can be affected by the joints of the blade, the contacting surface of the blade and the location of the blade. while connecting the two parts of the blade it is always essential to get a more contacting surface that gets the support. As the project is going to be implemented by the adhesives in the lapjoint the contacting surface is very important. The more the contacting surface more firm will be the joints, if the contacting surface is more then the load applied can be distributed more effectively by reducing the concentration of stress at any single point (Mendoza, Yao, Chetan , & Griffith, 2022). There was a study done by, (Campilho, Banea, Pinto, da Silva, & de Jesus, 2011) mentioned double lap joint is stronger than a single lap joint by testing in the simulations and testing the lap joint with various overlapping lengths. The paper mentioned the testing of overlap length between 5 to 20 mm and it was found that more overlap length had more load distribution long the surface and was more strong to hold two parts together.

And, by these literature reviews it is also noted that it is essential to create a lap joint with more contacting surface. After analysing the different concepts of assembly of a segmented part, it is noted that the contacting surface for the lap joint should be more in for balanced load distribution, which keeps the sections of the blade connected strongly.

Historical development for manufacturing of VAWT Blade

During the early stage, the development of the wind turbine was done by wet hand layup technology by the used of open mould. The reinforced glass fibre was infused by the paint brush and with the use of rollers. Where the shells were bonded adhesively together to the spars. This sort of technology was used to produce smaller size or medium-sized blades which are up to 35m to 55mm (CAIRNS & SHRAMSTAD, 2000). And, for the blade which is larger than 55 mm, the same technology was used but the webs were inserted and bonded adhesively in between two sides of the blade and the piles which have more fibre content that were used. But this technology has disadvantages which were high labour costs, and the quality of the products were also low along with the environmental problems. After such a problem, many companies and institutes explored the idea of improving the quality of the turbine and reducing the labour cost. This led them to the introduction of vacuum infusion and the prepreg technology which helped them achieve better manufacturing quality (Walker, 2013). This prepreg technology was mostly used in manufacturing components of aircraft, where they utilize the pre-impregnated composite fibre, which already has a certain amount of the material for bonding together. This prepreg technology is widely used by the company called Vestas which produce wind turbine, and it is a Denmark-based company (Jacob , 2001).

A thesis paper published by Skramstad, (1999), submitted to the Department of Mechanical Engineering at Montana State University, talks about the comparison of wet hand layup technology with Resin transfer Moulding (RTM) and at last both the comparison was compared to VARTM Method. However, in this comparison, thickness and volume of fibre content were the parameters which contributed to the strength-to-weight ratio (Skramstad, 1999). In their testing method, they provided the properties and dimensions of the laminates before and after the testing method and they came to the result of the VARTM method providing more identical thickness than that of the other two methods.

Weight has been one of the major areas to be considered in wind turbine industries to get the better results and VAWT-X energy is also concerned about weight, which has also led to this research. There are some more techniques of manufacturing the hollow blade, like centrifugal moulding and filament winding. The research was done by Pereira, Zirak, Shirinbayan, Zywica, & Tcharkhtchi, (2023) where a design and fabrication are done for small HAWT blades done by the use of rotating moulding, where various polymers, thermoplastics and thermosets were used for enhancing the mechanical performance. A result was found that the blade by using the foam was well manufactured but without the use of foam the blade was dispersed as can be seen in the figure 5.

Figure(s) removed due to copyright restriction.

Figure 5 Rotational moulding result with and without the use of foam (Pereira, Zirak, Shirinbayan, Zywica, & Tcharkhtchi, 2023).

Filament winding is also one of the suitable techniques for the manufacturing of hollow section blades. This method is very fast and efficient for laying the resin and reinforcement under tension in the mandrel to create a lightweight structure. A study was done by Stewart, (2009), where the paper talked about the manufacturing of surf and rowing sculls by the use of automated filament winding and it was found that the shaft was stiffer with 10% and 10 % lighter as compared to the traditional methods. However, in the case of manufacturing turbine blades, there are some disadvantages, difficulties in manufacturing complex geometry and it is very difficult to control the thickness of the blade.

Moreover, most companies use it today for manufacturing turbine blades in resin infusion. In this technology, the fibre is kept all closed and the resin is injected under high pressure, and after that, it is provided with the heat to cure it. There are two different types of resin infusion technologies, which are vacuum-assisted resin transfer moulding and resin transfer moulding. In resign transfer moulding the resin is transferred under higher pressure whereas vacuum-assisted resin is inserted by use of vacuum pressure (Verma, et al., 2013).

Vacuum Assisted Resin Infusion method is used as this method is the proven method for manufacturing the turbine blade. This method follows the principal of Darcy's law, which allows the flow of resin on the surface with the assist of the vacuum (Goren & Atas , 2008). This method is very cost-effective, and this method requires a smaller number of labourers to perform the test so this method will also play a significant role is minimizing the cost for the VAWT-x energy company. In the paper written by, Skramstad, (1999), this method will also provide the identical thickness of the blade so this method is suitable for testing in the manufacturing of the turbine blade of VAWT-X energy. Also, VAWT-X Energy is researching and trying to use this technique for manufacturing the blade which made the selection of manufacturing approach much easier. Therefore, this paper will help add more value to the company as it involves the parametric design of the mould.

Review of Designing a Mould for Turbine blade

Wind turbine Blades are very critical as they are subjected to stresses, dynamic loading, and different temperatures, therefore it requires the blade design to be highly precise and durable with smooth finishing. To get a precise and smooth blade, the design of the mould plays a critical role in ensuring high-quality casting with the accuracy of dimensions and good surface finish. Taking about the history of the mould design for manufacturing the turbine blade, one of the early methods was by using single-piece moulds which were used for relatively simple dimensions and basic aerofoils; however, they had some limitations to generate the complex shape of the blade. As the use of technology emerges the mould design emerges. A two-piece mould was developed, and this mould was used in manufacturing complex design components. This type has allowed flexibility to a greater extent than that of single-piece design. This design provides the simple removal of the components after production. As technology advanced multi-piece mould design has been developed to allow a greater extent of flexibility in terms of size and shape of the components. This literature review will talk about the different designs of the mould for manufacturing turbine blades.

Single-piece mould design

Single-piece mould is usually used in manufacturing parts with materials like plastic metals or glass. This is called single-piece mould because it consists of only a mould cavity. This design is very simple, it is also called as closed mould or one-piece mould. Some of the materials that can be manufactured by using single-piece mould are plastics, composites, rubber, ceramics, and metal casting.

An experiment was performed to manufacture the turbine blade by using a single piece mould where they manufactured the two layers of the turbine blade and assembled them. In the paper Post, et al., (2017), they have used this technique for manufacturing the horizontal axis turbine blade section. They have sectionized the blade to manufacture the blade a section so they have manufactured the mould for the blade and they have used vacuum resin infusion technology to manufacture the turbine blade. the design of the mould is manufactured by using additive manufacturing technology. The team was able to eliminate numerous manufacturing steps and also they were able to manufacture mould with out any defects. This article has concluded that building up the mould as one part will decrease the speed by the rate 10 times and also save money.

Two-piece Mould Design or Split mould design

A two-piece mould design is also termed as split mould. These types of mould are used for manufacturing complex shapes of the components. This mould design consists of two halves forming a cavity together to provide the shape of the components. Research was done by Sriram & Reddy, (2022), where they used the design of split mould to design and fabricate the bipolar femoral head. And with the paper they have mentioned that split cavity mould helps for easy design and reduces the time and cost of manufacturing. Their paper suggests that the result obtained from experimentation the product obtained was smoother and more precise with a higher quality finish and, they suggested that this method can be used for complex designed components. However, this design is difficult to maintain as it has various splitting parts. As the design that this project focuses on is a Darrieus type VAWT Blade and this model has a complex curve of the blade, this might also be the possible option for the design that the project is suggesting.

Multi-piece Mould Design

This type of mould design is made from two or more than two pieces of plates. This design is used in manufacturing products that are complex geometries and this design also has easy access undercut which helps in easy release than that of a two-piece mould. The number of pieces of the plate for the mould can vary as per the complexity of the product which is to be manufactured. The design of this type of mould can be complex and time-consuming as each of the parts should be precisely designed to get the output of the turbine blade very accurate and precise.

A study was conducted to design a multi-piece mould based on the linear mixed -integer program (Stoyan & Chen, 2010). This paper especially focuses on the problem of the multi-piece mould design, which is the trouble in designing a greater number of pieces to create the cavity for a complex design. This paper aims to design the mould with the minimum number of pieces, which can be disassembled properly without any damage during the ejection process. To overcome those problems, it proposed the mixed-integer program where lower and upper mould is identified first to identify the given geometry of the parts, then the parts which are required to create the cut shape in design are created secondly. And with this design, they have guaranteed that the method provides a solid foundation for pursuing the multi-piece mould design. And the paper has mentioned that the multi-piece mould can further me improved based on heuristics.

After studying the different types of mould, it should be selected based on suitability for the manufacturing process. So, as per the review of the literature for the manufacturing process VARI method seemed to be the perfect method to carry out. So as per the requirement for this manufacturing approach an open mould concept was suggested by the literature which is to be covered by the vacuum bag to follow the manufacturing process. And lastly multi piece mould could be used for settling the blade and to cure it.

Research Gap

After going through the literature, it was found that there is a lack of research especially on the design of VAWT helical Blade. Most importantly there was a huge absence of research on sectionized VAWT blade design. Also, there has been limited research in the design of hollow helical blades with the feature of a Z-section spar on the blade. In the case of manufacturing, there is limited research on VAWT with helical blades for the Darrieus model. Therefore, this thesis paper will benefit VAWT-X Energy as well as other researchers for understanding automation for the design by using the parametrization technique and digital manufacturing of VAWT Blade. VAWT-X energy is on the verge of the testing and certification phase for which lots of blade design and manufacturing approach is being considered. With the completion of this project, the parametric design of the VAWT Blade section and mould would enhance the design automation process and identifies layer by layer carbon fibre manufacturing under the principle of VARI Method.

CHAPTER THREE: METHODOLOGY

Introduction

This part of the paper talks about the methodologies, which was used to create a parametric design of a VAWT Blade Section and its Mould using the Inventor Software. The parameters of the Blade section are linked with the Mould design parameters, so if there is a certain change in the Blade section then the mould design will also be changed based on the changed parameters of the blade section. The Cubic Bezier Curve technique was used for designing the parametric aerofoil and was verified by using the coordinates of the standard NACA 0018 profile downloaded from the aerofoil tool plotter.

The methodology for the Project follows the following flowchart,

Figure 6 Flowchart of the Methodology

Parametric Design of Aerofoil

For the parametric design of an aerofoil, the paper talks about the parametrization method for a 4-digit NACA profile. Since the project focuses on NACA 0018 profile, this parameterization method is focused on the symmetric profile. After the literature review of different methods and techniques, it suggested going along with Cubic Bezier Curve. Since this method is very easy to understand and can be easily implemented on the inventor software, became one of the perfect reasons to go along with this method.

Bezier Curve is the parametric curve which is used for creating a smooth curve that is controlled by control points. The Bezier curve is defined by the set of control points from $P_o\ to\ P_n$, where n represents the order for the curve, (n=1 mean linear Bezier curve, n=2 means quadratic Bezier curve and n=3 means cubic Bezier curve etc.) (Jaiswal, 2017). The point at first and last always represents the endpoint for the curve. So, the cubic Bezier curve is created by four points which are P_0, P_1, P_2, and P_3 in the plane. In this, the curve starts with the P_0 and finishes with P_3 while going in the direction of P_1 and P_2.

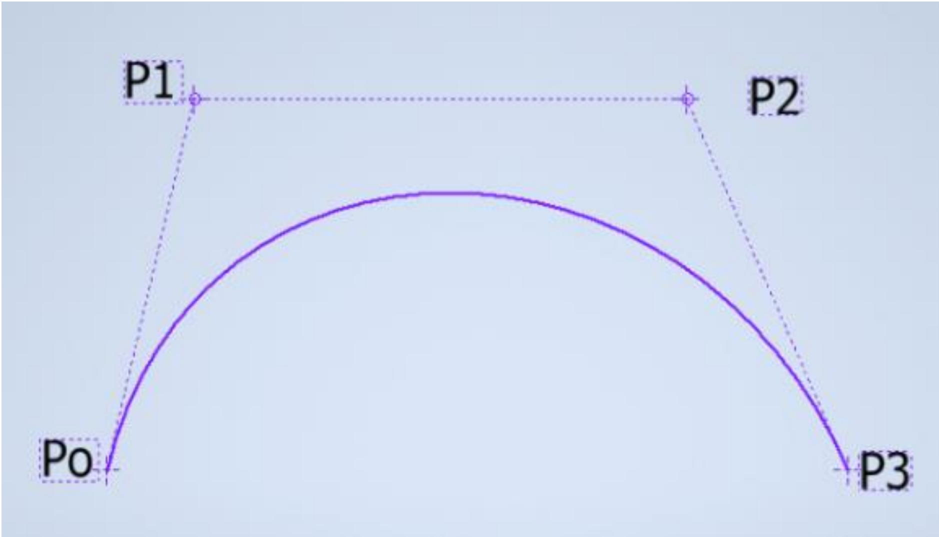


Figure 7 Example of Cubic Bezier Curve with four control points

And the 4 curves are connected by 13 control points to form a single aerofoil section. The development of the aerofoil can be seen in the Appendix A. The use of 4 curve can be seen in the Figure 8.

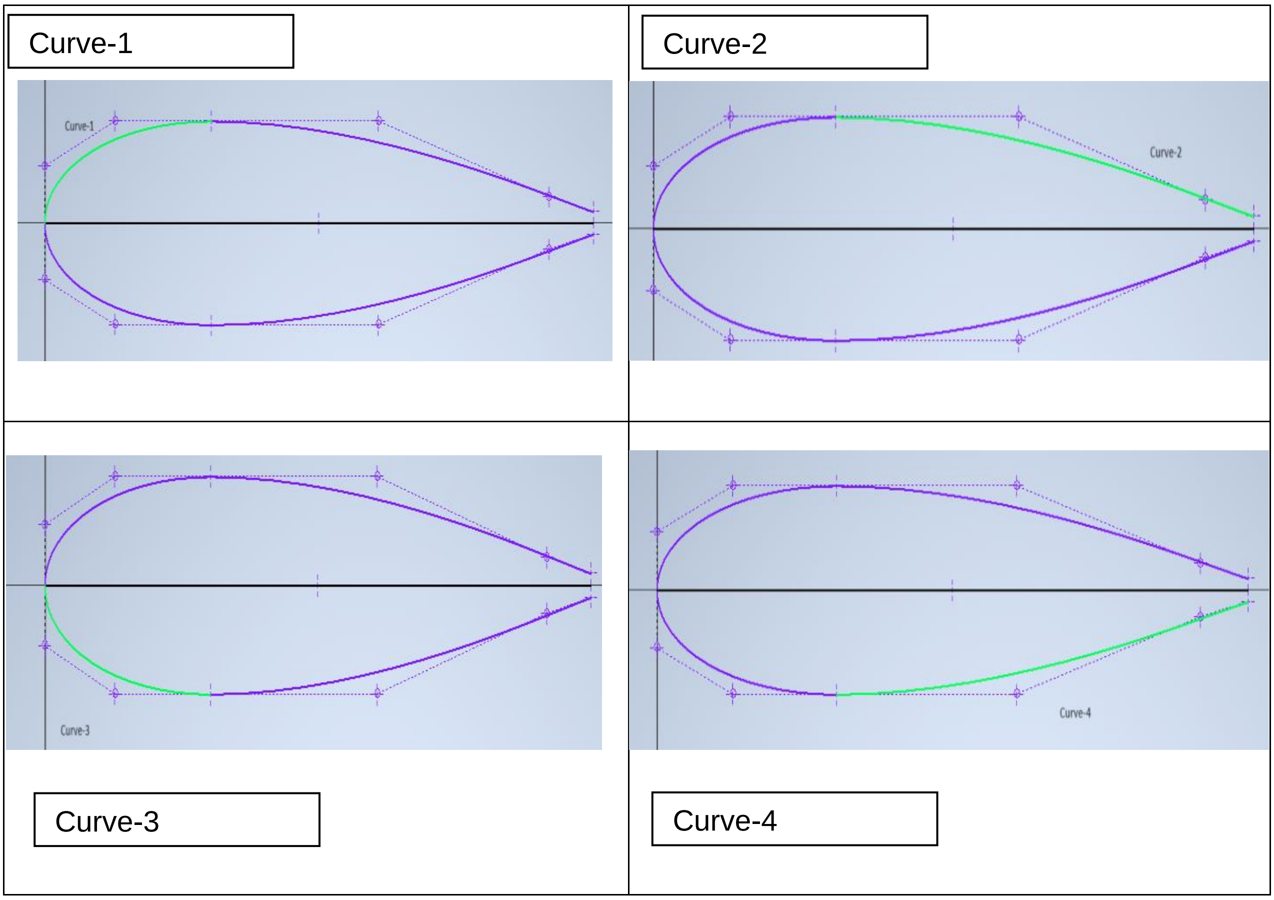


Figure 8: 4 curves representing in an aerofoil.

Therefore, with the four different curves a final parametric aerofoil profile is created for NACA 0018 Profile which can be seen in figure 9,

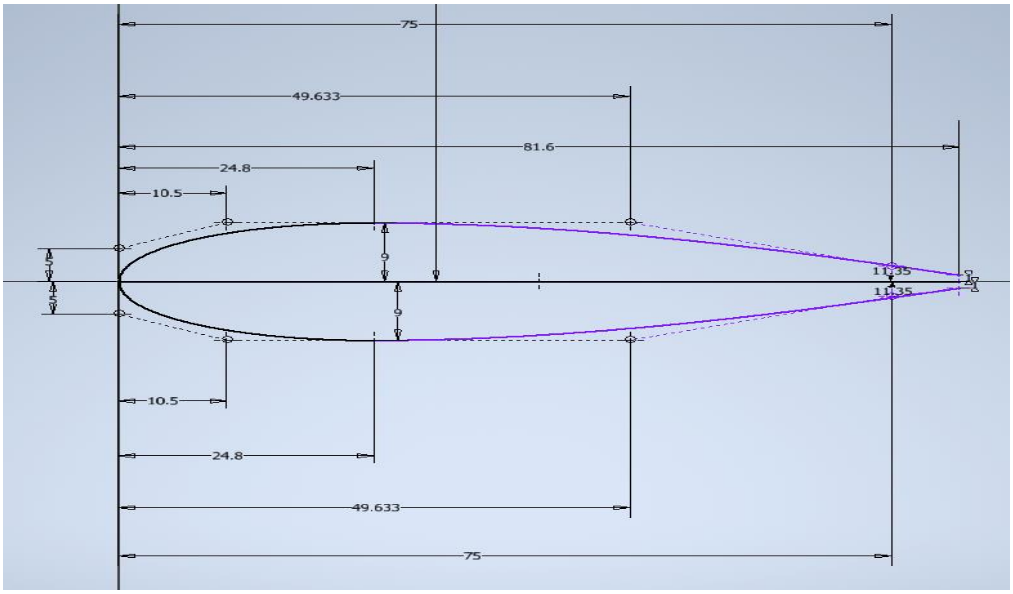


Figure 9: (a) Parametric Profile of aerofoil by Cubic Bezier Curve, (b) Parametric Hollow Profile of aerofoil by Cubic Bezier Curve

From this concept, 13 parameters for the aerofoil were generated. This means 13 parameters can be used in changing the design of an aerofoil. The parameters are separated into 4 different parts which are, leading edge controlling parameters, upper side curve parameters, lower side curve parameters and trailing edge parameters. The list of parameters table can be seen in Appendix A Table 12.

Design Automation of Vertical Axis Wind Turbine Blade process

In this methodology, the first different design of the blade is explained which helped in getting the final design of the blade. After the explanation of different designs, the process of designing the final Blade design section is explained.

Although this thesis is individual, several projects are going on the same VAWT-X model that the project deals with, where one of the team members was assigned with the FEA analysis of every design of the blade section developed throughout the project.

Design iteration of the Blade section

Firstly, it is to be noted that VAWT-X follows its patented design of two two-blade vertical profile which is made up of aerofoil technology. This blade section profile has been provided as the base starting point for the design automation to be carried out in this project. For the design automation of the blade section, various design of the blade section was created and tested as per the study of different literature review as discussed above. To start the design of the blade, there was the original design of the blade from VAWT-X Energy.

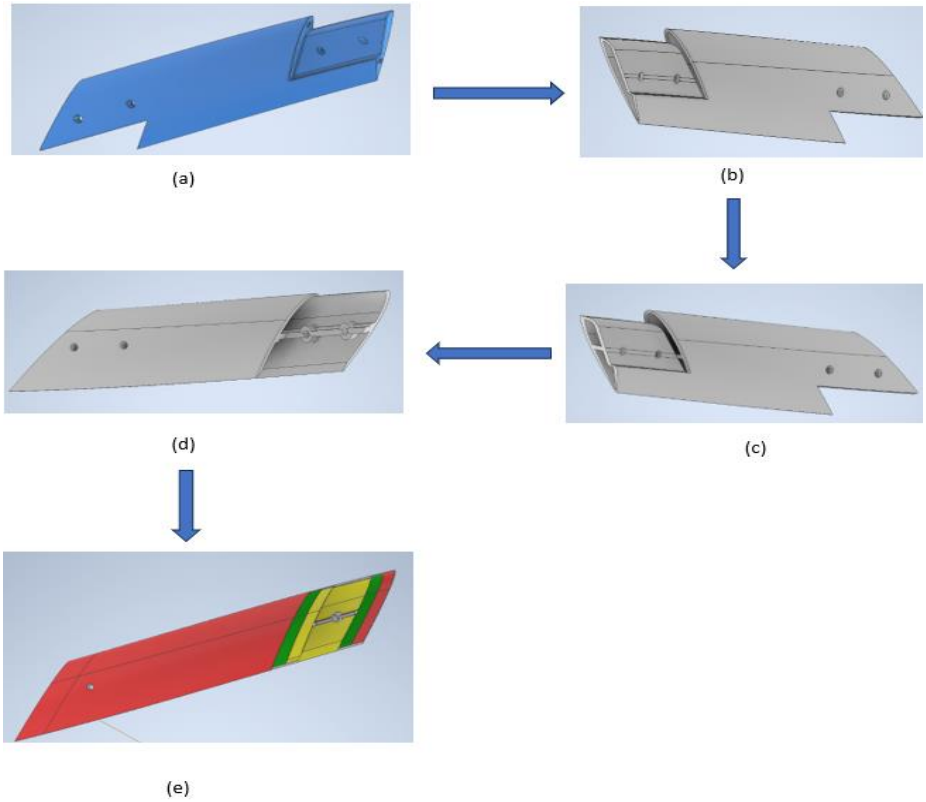


Figure 10 (a) Original Design of Blade VAWT-X Energy company; (b) Hollow Blade Concept; (c)Hollow Blade design with I-Spar; (d) Hollow Blade Design with Z-beam and Hole support (e) Final Blade Design

The project was started with the given design of the VAWT Blade section as shown in figure 10 (a). So, this project aimed to create a hollow section parametric blade with a lap-joint concept. Therefore, figure 10 (b) represents the hollow blade section, which was developed to reduce the weight of the blade and to create a net structure of the whole setup of VAWT by allowing the wires to pass through the blade. However, the analysis, showed that the blade was showing deformation in the hollow section as there was no support. So, it was suggested to design the blade with an I-section spar, therefore the design shown in figure 10 (c), shows the design of the blade with an I-section to support the hollow blade design. However, as the project moved forward, other members of the group decided to go with the wireless method of strain and stress measurement. So, for this system, it was suggested to place some of the components inside of the blade. Therefore, the design had to be changed accordingly and the design with an open lap-joint section with a Z-section was created to support the blade strength, which is shown in figure 10 (d). However, when two blades were connected the analysis showed that there was less contacting surface in the blade, so the lap-joint was breaking off. Then it was suggested to create the blade design which has a more contacting surface in the blade, therefore the final design shown in figure 10 (e) was created. The final design contains a more contacting surface as the step lap joint was created on both sides of the blade to connect the blade strongly. The creation of a step lap joint on the blade surface is shown in step 4 of the blade design.

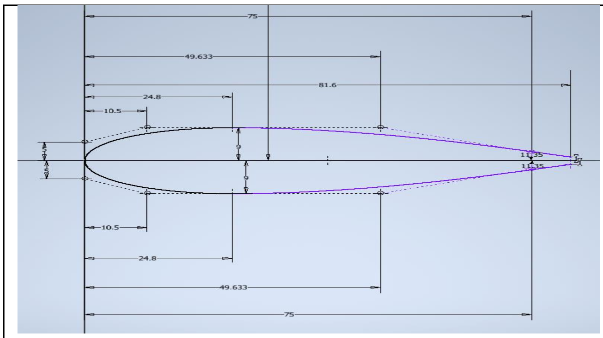
Certain steps were followed to create the parametric design of the blade, which are explained as follows,

Step-1: Selection of the software

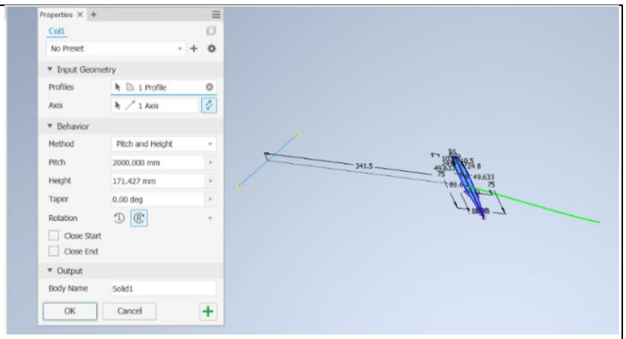
Inventor software from Autodesk was chosen to complete the project, as it is easily accessible to all the students, and it was user-friendly for creating Cubic Bezier Curve using splines and control points. Some of the basic features which are used are 2D Sketch Plane, 3D Sketch Plane and Coil feature along with extrusion feature.

Step 2: Create a simple profile of a blade.

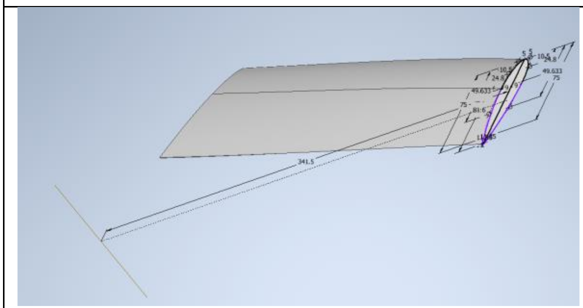
With the use of a Cubic Bezier curve, it can create the aerofoil profile of the blade and the coil feature was to create the simple profile of the blade. As the aerofoil profile was already made parametric, the surface of the blade was also able to change according to those parameters. The feature used can create one parameter (i.e., HB) which could be used for changing the height of the blade section. However, a better picture of the properties used for the coil feature and the close-up view picture can be seen in Appendix A.



(a)



(b)



(c)

Parameters	Variable
Height of Blade	HB

Figure 11 (a) Parametric Aerofoil Profile; (b) Coil feature in Autodesk Inventor; (c) Blade Surface after the coil feature

Step-3: creation of hollow section.

The hollow section for the blade was created with the offset feature in Inventor by offsetting the aerofoil and using the coil feature to the part, which is solid as shown in the figure below. And with the offset feature one more parameter was added to the design which is variable T, and it can be used to control the thickness of the blade section.

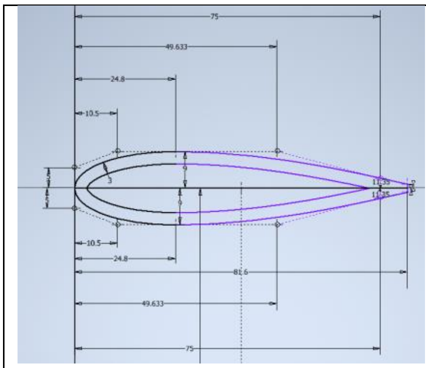
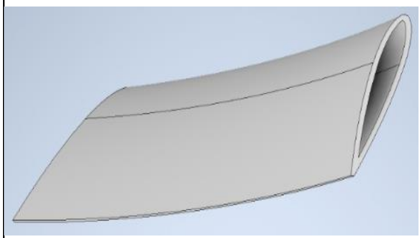
		Parameters	Variables
 (a)	 (b)	Thickness of Blade	T

Figure 12 (a) Offset of Aerofoil; (b) Hollow Blade section.

Step 4: Development of open lap joint and step joint on the side of the blade section.

The open lap-joint concept means extruding each side of the blade to create a lap where another blade can rest to it for the connection. A step lap joint was created on each side of the blade to get a more contact surface for the blade.

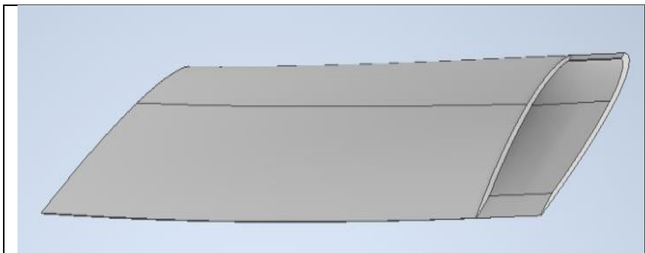
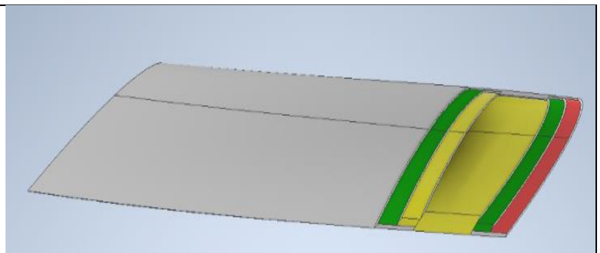
 (a)	 (b)

Figure 13 (a) Open Lap-joint of Blade section; (b) Fig: Step Joint on each side of Blade.

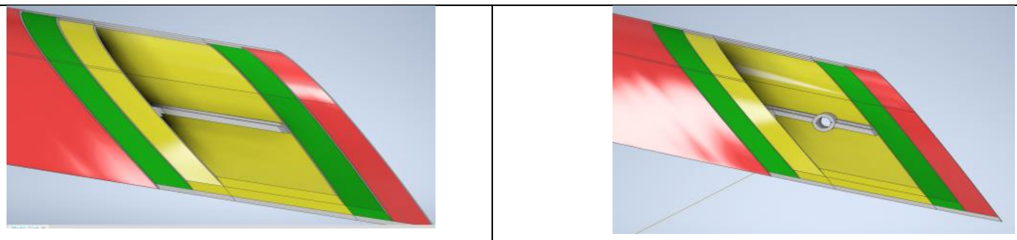
Therefore, in this step few of the parameters were added, such as the parameters of the lap joint and the step joint on every side of the blade. These parameters can be used for changing the dimensions of the lap joint length. For example, if a more contacting surface is required then the parameters of the lap joint can be increased to get a longer lap joint that could give more surface contact.

Table 1 Parameters of open lap joint and step lap joint on each side

Parameters	Variables
Lap-joint on side-1	Lap-1
Lap-joint on side-2	Lap-2
Top Blade step joint inside (side 1)	
Step Joint on side 1	Step-1
2nd step joint on side 1	Step-2
Bottom Blade step joint Outside (side 1)	
Step Joint on side 1	Step-3
2nd step joint on side 1	Step-4
Top Blade step joint outside (Side 2)	
Step joint on side 2	Step-5
2nd step joint on side 2	Step-6
Bottom Blade step joint inside (side2)	
Step joint on side 2	Step-7
2nd step joint on side 2	Step-8

Step-5: Development of spar design (Z- Section), Hole support and Holes.

For the spar design, it was necessary to go with strong support as the blade profile is a hollow section. Z- Section was created for the support of the hollow structure of the blade, after the analysis of the turbine blade it was found that the Z-section was completely able to withstand all the forces acting on the blade section. The concept of creating a hole was presented to test the orientation of the blade by matching the hole together with other blade sections which allows the completed set of turbine blades to get the desired orientation. However, as the hole will act as a concentration point for the blade a whole support was created which also helped in increasing the contacting surface for the blade while connecting with other designs. Creating the Hole section and aligning them together is done by using the 3D sketch feature. Which can be seen in Appendix A Figure 45.



(a) (b)

Figure 14 (a) Closeup view of Z-section with step joints, (b): Blade with Z-section and hole support

After the design of the Z-section and the creation of the hole and its support, some of the parameters were added to the list, from these parameters, the size of the hole and hole support can be modified, and the thickness of the Z-section can be controlled with these parameters. Which can be seen as follows,

Table 2 parameters of Z section, hole, and its support

Parameters for z section and hole support	Variables
Thickness of Z-section	Z-Thickness
Z Half thickness	Z1
Z other half-thickness	Z2
Hole-1	H1
Hole-2	H2
Hole support 1	HS1
Hole Support 2	HS2

Final Design of the Blade

The design of the final conceptual blade and engineering drawing for the blade is shown in Appendix B at the last topic of this paper.

Manufacturing Method

After reviewing lots of literature, it identified that there are many ways of manufacturing a VAWT turbine blade. However, the very usual process of manufacturing is mainly two processes which are assisted resin transfer and with pre-impregnated material. Vacuum-assisted resin transfer process deals with the dry reinforcement material laying down in the mould and allowing the resin to transfer in the sealed mould. However, in the pre-impregnated process, the reinforcement material is already impregnated with the resin which already includes the process of curing agent. The project deals with the vacuum-assisted resin transfer process, but there are many processes of using a vacuum to assist resin. So as per the literature, this project deals with the vacuum-assisted resin infusion method. A decision matrix was created based on different manufacturing techniques studied in the literature review. The decision matrix can be seen in Appendix C. Another major criterion for the selection of this technique is VAWT-X energy is planning to use the VARI method for manufacturing of blades, therefore, this project will add value to the research, and it helps the company since this project designs the parametric model of the mould for VARI method.

Manufacturing Method

For the manufacturing method of the VAWT turbine blade, the top and bottom part of the blade is manufactured separately, and a stiffening spar is manufactured separately for the central support of the blade. All these different parts are connected to form a single blade section.

Vacuum-Assisted resin Infusion Method

This technique is different from the conventional method of wet lay up technique, as in this the reinforcement materials are laid out dry rather than laying pre-wet reinforcement. This technique uses vacuum pressure to direct the resin into the laminates. As mentioned, the reinforcement is laid out dry and is completely sealed with the vacuum bag and all the air inside of vacuum bag is taken out to create a vacuum inside it so with the principle of Darcy's law the resin is allowed to be passed into it and the curing is done to get the finished product. The set up for the process is as shown in the figure below,

Figure removed due to copyright restriction.

Figure 15 Vacuum-assisted resin Infusion method (HindersMann, 2019).

Vacuum Infusion Process

For the manufacturing process of the VAWT blade, a vacuum infusion process is used, and this process uses negative pressure to suck the air which is inside of the mould and at the same time it allows the resin to get sucked into the mould, therefore the resin is impregnated to the reinforcement materials. As mentioned already a dry layer of the reinforcement is laid and the resin is allowed to pass through it to form the matrix, the remaining resin is sucked out of the mould using a vacuum pump. So, as a result, this method is very much efficient in providing the same thickness of the blade with this process. The materials that are manufactured by using the vacuum resin infusion process have a higher fibre-to-resin ratio compared to the hand-layup technique.

The flow of the resin which is transferred to the mould can be determined by the principle of Darcy's law which explains the process of flow of fluid which is passing through the porous medium.

The Darcy's law equation is mentioned as below,

$$Q = \frac{K * A * \Delta P}{\mu * L}$$

Where,

Q= flow of resin in m^3/s

K= permeability of the material in m^2

A= Area of space where the resin flows in m^2

ΔP= Difference in pressure in the lamination kg/ms^2

μ= dynamic viscosity for the resin kg/ms

L= Distance, that the resin needs to travel in m

Benefits of Vacuum-Assisted Resin Infusion

This method would create constant pressure along the bagging area, and it will take the excess rein out. The use of this method will provide high specific strength and stiffness as in this method the access resin is taken out. This will help in increasing the volume fraction of fibre and increase the strength and stiffness.

Material for Mould

As discussed in the previous section, this process involves infusing the resin inside the dry reinforcement under vacuum pressure. Therefore, the mould plays a very important role in ensuring high-quality final parts. The mould could be made from different materials like aluminium, steel, or even composite materials, depending on the budget and the applications. However, the scope of this project only covers the parametric design of the mould. So, the cost and manufacturing of the mould are kept out of the scope for this project.

Parametric Design of a Mould

As in the previous section, the manufacturing process was identified. It gave a clear picture of the design of the mould. As the manufacturing process requires the vacuum sealing bag the design of the open mould was applicable for the project.

Also, the conceptual design of the blade was finalised, and the manufacturing process was also finalized but the process of manufacturing was still a complex part. So, for this process, it was suggested to design the blade as per the manufacturing approach. It was already known that the material for the blade would be carbon fibre. So, the new aerofoil design was created along with the manufacturing approach as shown in figure 16. As the manufacturing process utilizes the layer-by-layer manufacturing approach. So, three layer of carbon fibre each of 1mm thickness are shown in Figure 16 and it also represents the thickness of the blade.

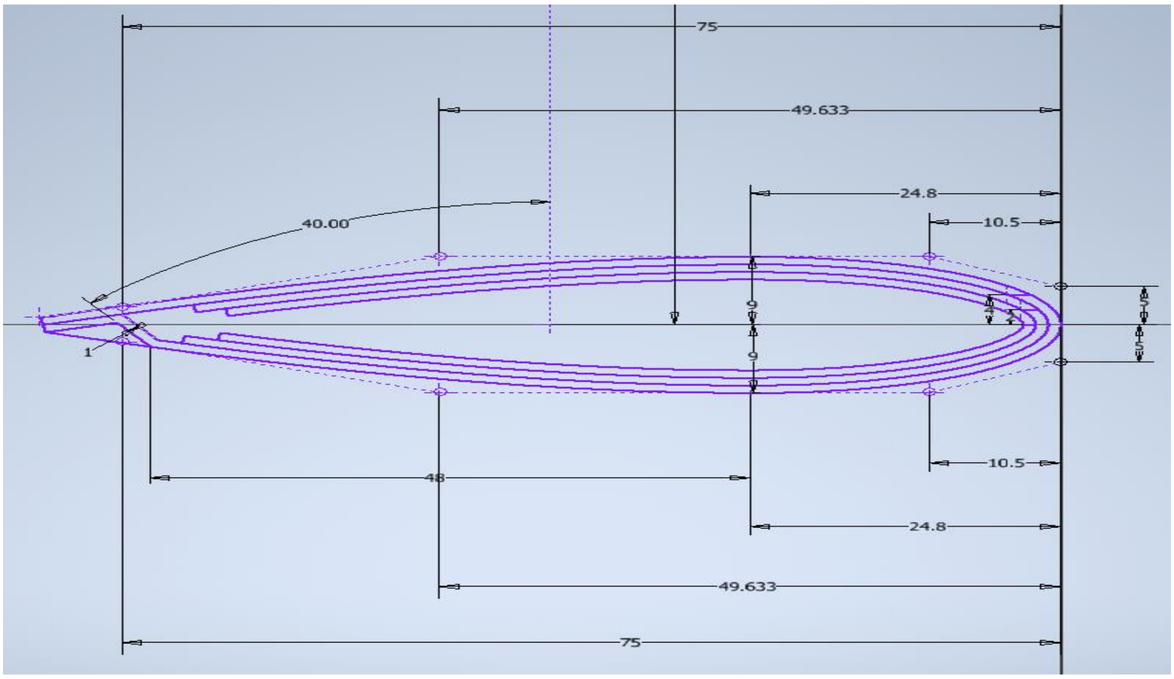


Figure 16 Aerofoil section with manufacturing approach.

The challenge with mould design

The challenge in this design was maintaining the desired thickness of the trailing edge. Because the sandwich of 6 layers of carbon fibre of 1mm would be 6 mm, this is not desired.

Solution

To obtain the desired level of trailing edge, two outer layers of carbon fibre each of 1mm are connected and a triangular-shaped space is created to fill that part with resin in the trailing edge. However, the layer of carbon fibre inside of the surface is shortened so that it can have the desired level of the trailing edge as we can see in the figure above.

Open Mould Design

For the basis outline of mould design, the design of the mould suggested to be female open mould so two different moulds for the top and bottom surface of the blade have been designed. The mould for the z section has been designed separately. Finally, after manufacturing all the parts a new mould is designed which helps in connecting all the parts as a single piece.

Top Mould Design

For the design of the mould same aerofoil profile is used as shown in figure 16 the aerofoil profile acted as the base for the creation of mould for the outer surface of the blade section. So, based on the aerofoil profile, the 2d sketch of the baseline for the blade was generated as can be seen in the figure below,

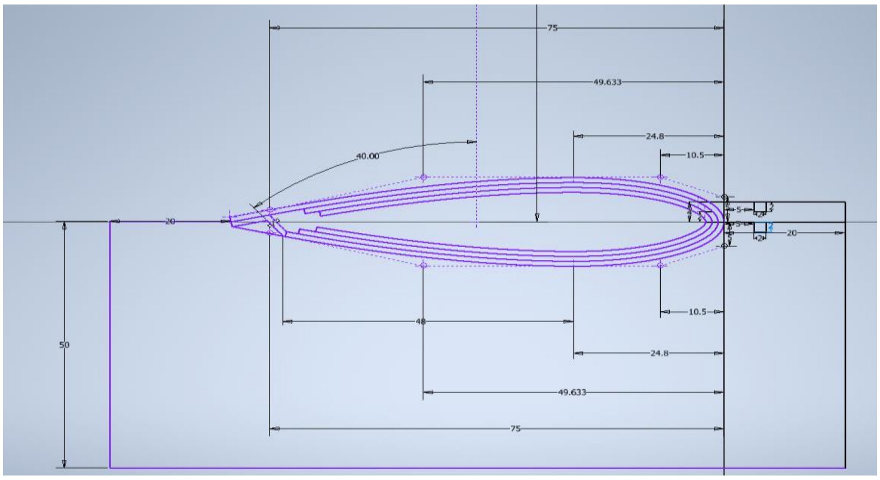


Figure 17 2D sketch for top Mould design

Based on the 2d sketch the CAD model of design for the top blade section was developed. The design consists of 4 different parts of the mould which are combined to create a top blade surface. So, four parts of the mould are combined to form a single mould which can also be called a multi-piece open mould.

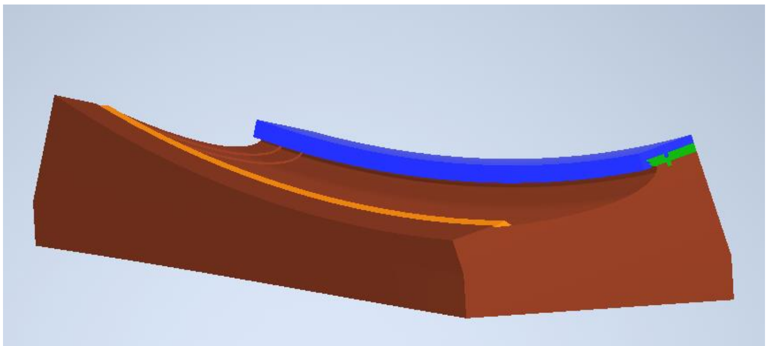


Figure 18 Assembly for Top Mould

The parameters and dimensions for the mould are shown in the table below,

Table 3 parameters of Top Mould Base

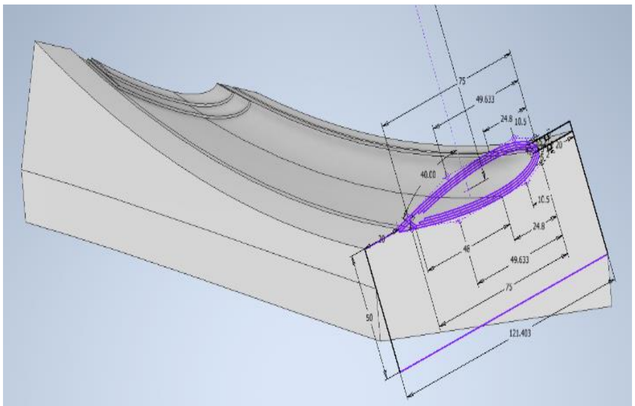
	Parameters	Variables
 **Figure 19 Top Mould Base**	Height of Top Mould	H-Blade= 50mm
	Thickness of the Mould	T-Top Mould= 121.4031985 mm
	Steps 1 and 2	Step-1 =8mm and step 2= 16 mm

Table 4 Parameters for part-1 of Mould

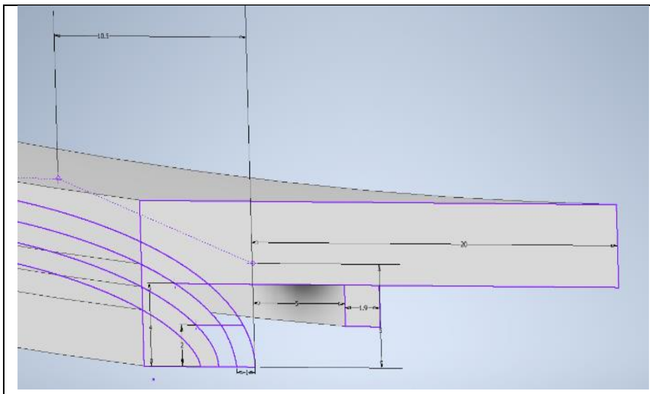
	Parameters	Variables
 Figure 20 part-1 Top Mould	Step 2 at leading edge	Mould step 2= 4 mm
	Width of the part	W-Mould= 26 mm
	Male part	1.8 mm x 1.8 mm
	Height	Height-1 Mould= 4 mm

Table 5 Parameters for part-2 of Top Mould

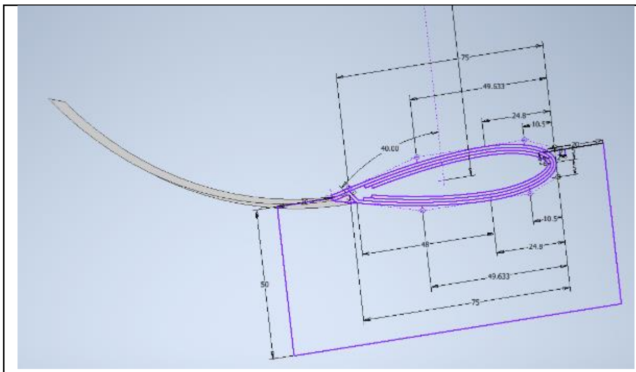


Figure 21 Part-2 Top Mould

Parameters	Variables
Angle of Triangle from a vertical axis	< T = 40 degree
Length	L-triangle= 171.427mm

Table 6 Parameters for part 3 of Top Mould

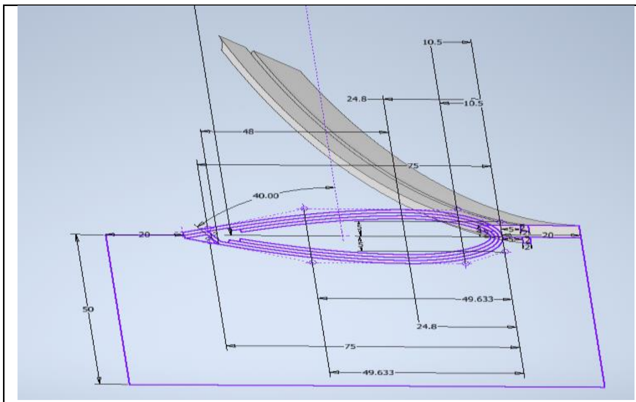


Figure 22 Part-3 Top Mould

Parameters	Variables
Top female part	2mm x 2mm
Bottom male part	1.8 mm x 1.8 mm
Width of the part	W-Mould= 26 mm
Height	Height-3 Mould= 6 mm

Bottom Mould Design

Multi parts mould designed is prepared for manufacturing the bottom part of the VAWT blade. There are altogether of 2 parts, which are as follows,

Table 7 Parameters for Part-1 of Bottom Mould

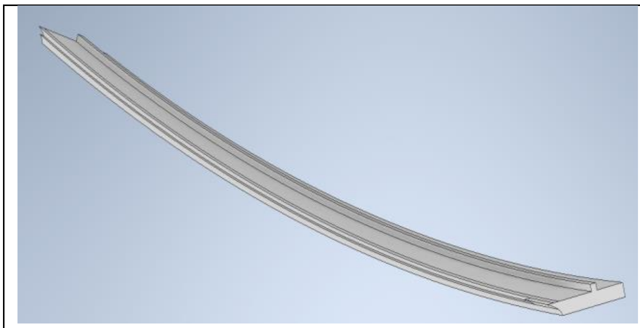
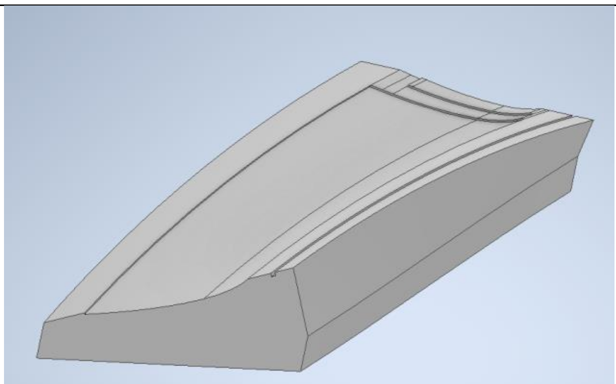


Figure 23 Part-1 for Bottom Mould

Parameters	Variables
Male part	2 mm* 2mm
Height	Bottom part-1H = 4 mm
Width	W-part-1=26 mm

Table 8 Parameters for Base of Bottom Mould

	Parameters	Variables
	Height of Bottom Mould	H-Blade= 50mm
	Thickness of the Mould	T-Bottom Mould= 121.4031985 mm
	Step 3 & 4	Step-3= 8mm and step 4=16 mm
Figure 24 Bottom Mould Base	Female cut	2 mm*2mm

So, two of the parts are connected to form an assembly that can manufacture the VAWT bottom side of the blade. the assembly of the bottom blade mould is as follows,

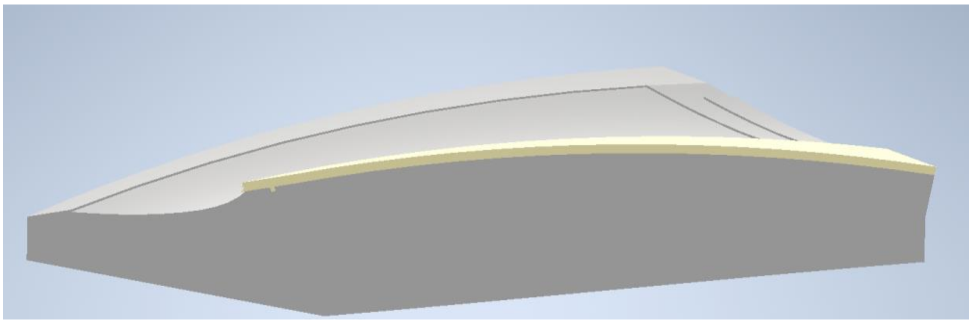


Figure 25 Bottom Mould Assembly

Mould design for Z-section

To design the mould for the z-section first the 2d sketch was created in the aerofoil section for creating the base for the mould.

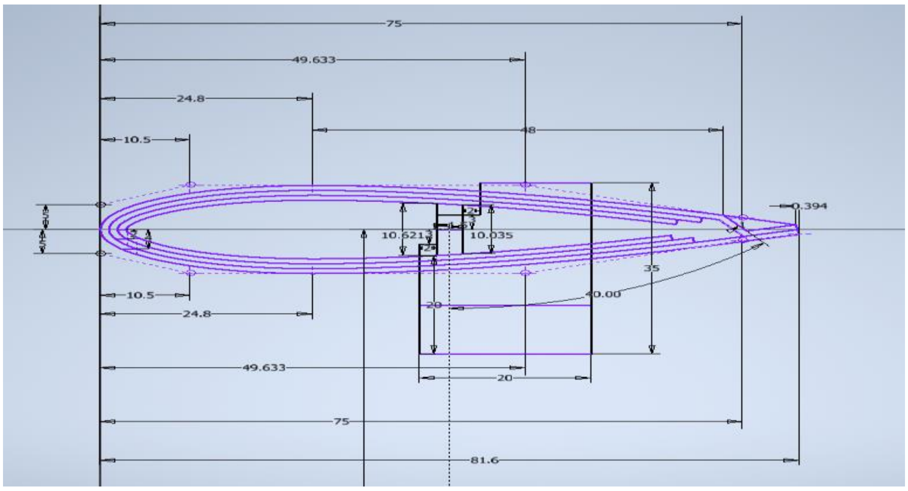


Figure 26 Aerofoil representing z-section.

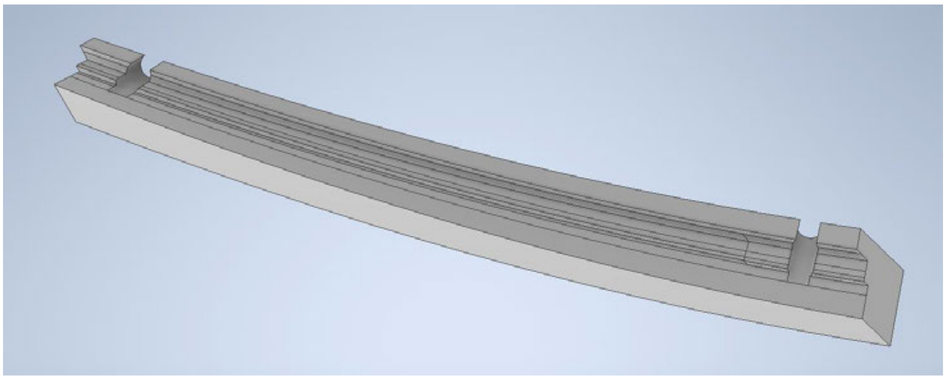


Figure 27 Open Mould for Z-section

The above picture represents the mould for the Z-section and the parameter for this section is as follows,

Table 9 Parameters for Z-section Mould

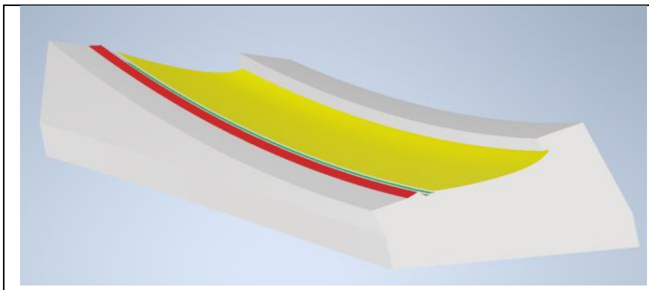
Parameters	Variables
Z-section Mould Parameters	
Thickness of Z-section	Z-Thickness
Z Half thickness	Z1 =1.5 mm
Z other half-thickness	Z2 =1.5 mm
Hole and its support	
Hole-1	H1= 5mm
Parameters	Variables
Hole-2	H2 =5 mm
Hole support 1	HS1= 9mm
Hole Support 2	HS2 =9 mm
Mould thickness	MT= 30 mm
Mould Height	MH= 35 mm

Manufacturing process

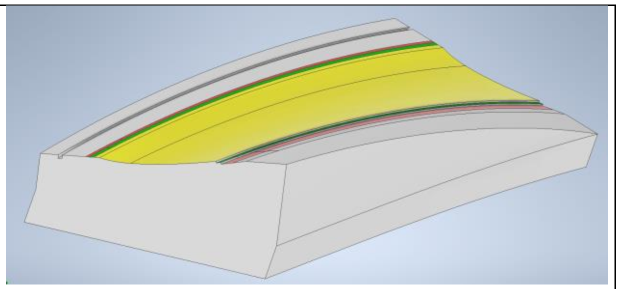
In the previous section all the design of the mould was done and, in this section, how the manufacturing would be carried out for the blade section by use of these moulds would be explained.

Step-1: laying all the dry carbon fibre in the mould.

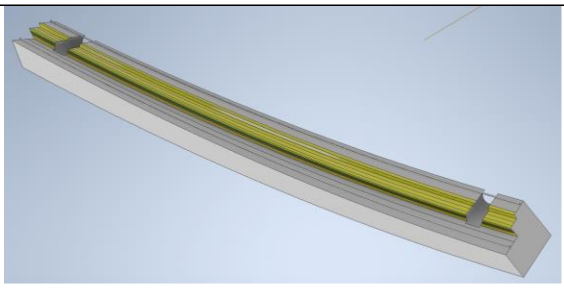
Firstly, the mould is prepared to give a high-quality finish, therefore it is cleaned with a mould release agent. Then, 3 layers of dry carbon fibre are laid out on the mould according to the shape of the mould as shown in the figure below, in the figure different colours represent different layers of the carbon fibre.



(a)



(b)



(b)

Figure 28 (a)Top mould with different layers of carbon fibre; (b) Bottom Mould with reinforcement; (b) Z-section with different layers of fibres.

Step-2: vacuum and resin lines.

In this step, the line for passing resin and the line from where the vacuum comes out is installed before sealing the vacuum bag. For this process spiral tubing is added for the flow of resin to the system and the vacuum lines are added for the vacuum to move out with the help of a compressor.

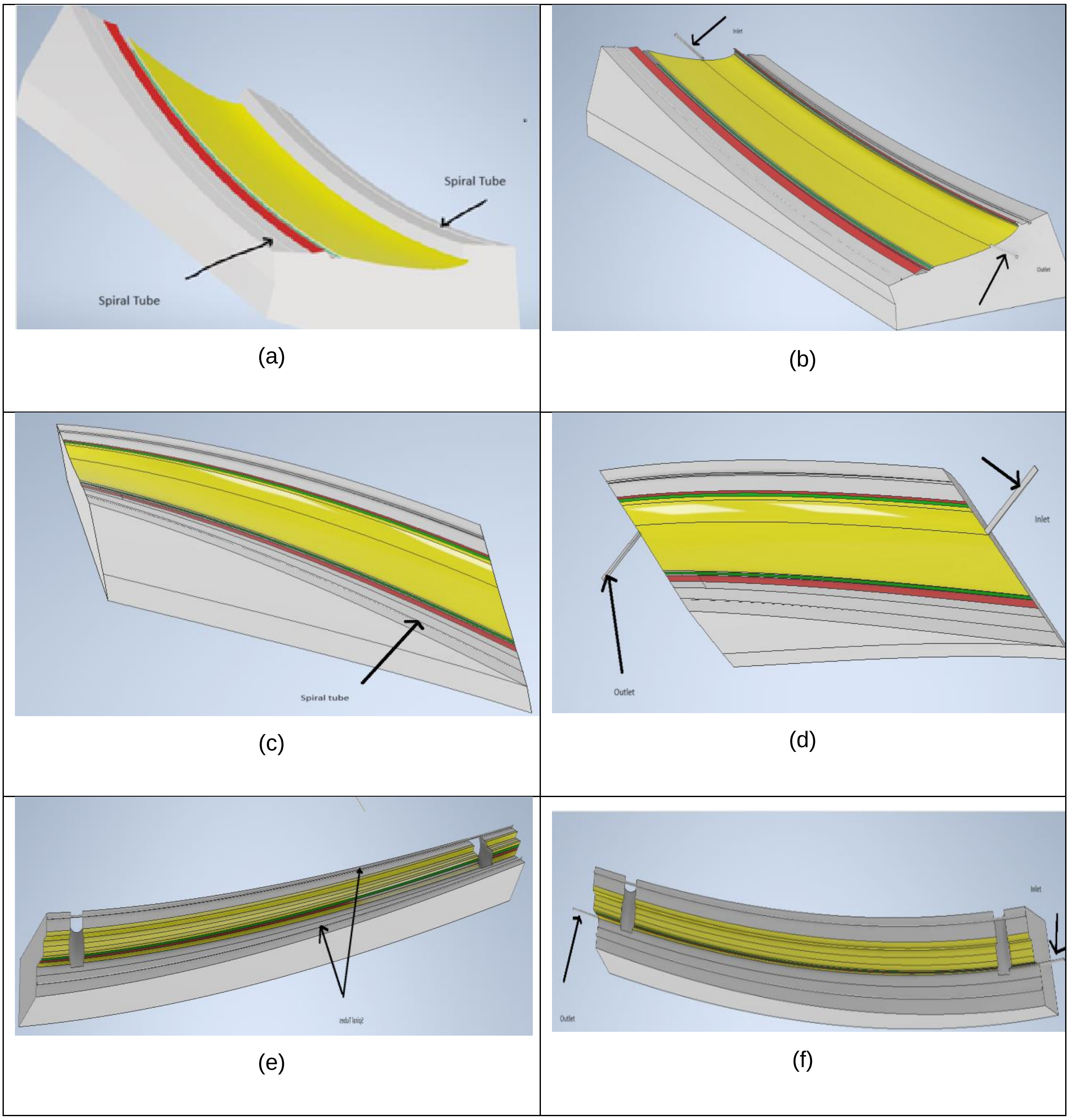
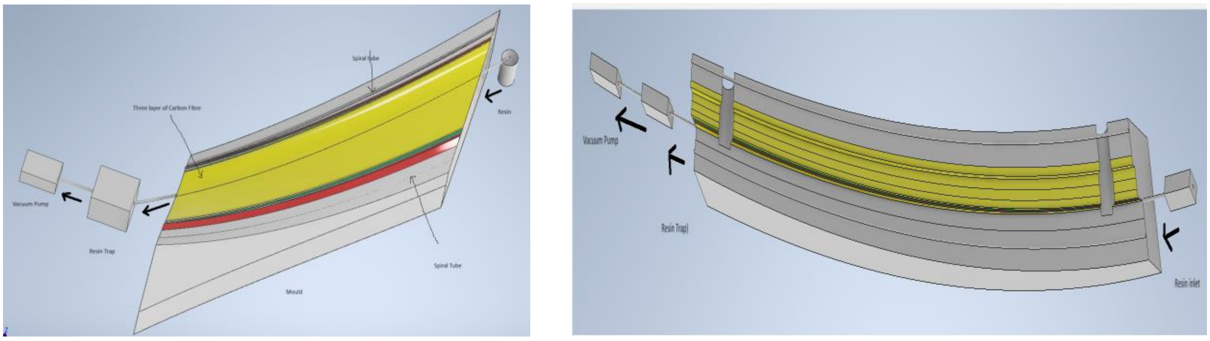


Figure 29 (a) Mould with fibres and Spiral Tubes; (b) Mould with Vacuum inlet and outline line; (c) Bottom Mould with spiral and Fibres; (d) Bottom Mould with vacuum inlet and outlet; (e) Z-section with spiral; (f) Z-section with vacuum inlet and outlet

Step:3 Vacuum Pump and vacuum bagging

In this step, the vacuum pump resin trap and resin are added to the setup. so, after adding all these setups next step is to add the vacuum bag on the top and it is sealed. The vacuum bag is sealed in the flange of the mould on both sides. The vacuum pump is used to suck the air out of the mould inside the sealed area and then with the principle of Darcy's law the resin is allowed to pass inside, and the excessive resin is collected in the resin trap. Which provides the proper reinforcement-to-resin ratio. And finally, the moulded part is allowed to be cured for a certain amount of time and then all the items are dispatched, and the final blade is taken out.



(a) (b)

Figure 30 concept for experimental setup for manufacturing process for (a) Blade sides (b) for Z-section

Note: The vacuum bagging is not shown in the figure for the diagram.

Therefore, with this process, the top blade, bottom blade, and the z-section are manufactured by this vacuum resin infusion technique as shown in Figure 19 & 30.

Step 4: Combining three different parts of the blade.

In previous steps, it was discussed that to manufacture the different parts of the blade, this step talks about combining different parts to form a single blade section. Firstly, to combine it epoxy resin could be used and for setting up the profile a close mould is designed. So, for this setup, the base mould of both the top and bottom blade is taken, and it is connected through connecting parts.

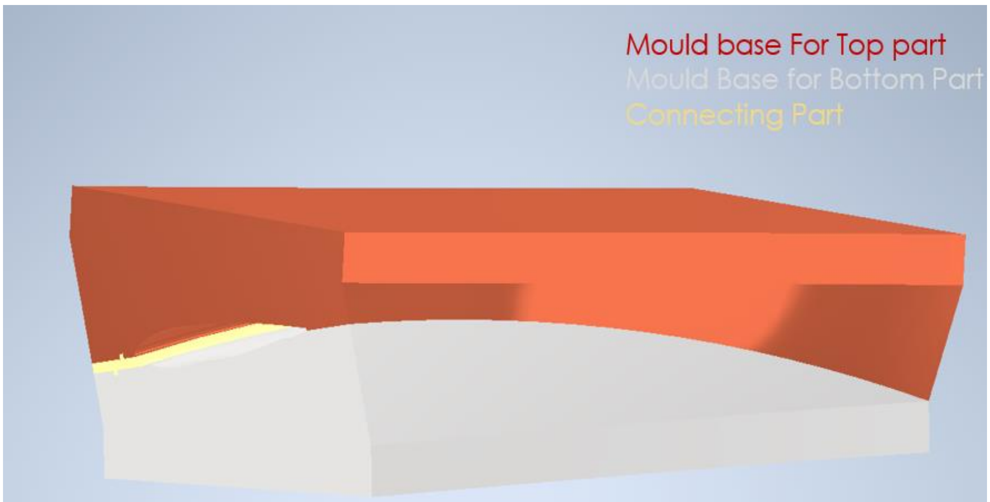


Figure 31 Closed Mould for VAWT Blade section.

CHAPTER FOUR: RESULT AND DISCUSSION

Introduction

This section represents the development of the aerofoil and validation for the aerofoil parametrization technique by the concept of overlapping with the standard NACA 0018 profile. The parameters obtained from the VAWT blade and mould design have been explained and finally, the proof of the link between the parameters of the blade and mould is displayed in pictorial form. It demonstrates the condition that if the parameters of the blade are changed then the parameters of the mould will also be changed accordingly.

Aerofoil Development

Using the Cubic Bezier Curve method, the points for the control points were identified. By means of the trial-and-error method, 4 control points of the curves are determined for a plane with respect to standard NACA 0018 profile, which are the coordinates of P0, P1, P2 and P3, which are as follows,

Table 10 Coordinates of four Control points for curve

Points	Curve-1		Curve-2		Curve-3		Curve-4	
	X	Y	X	Y	X	Y	X	Y
P0	0	0	24.8	9	0	0	24.8	-9
P1	0	5	49.633	9	0	-5	49.633	-9
P2	10.5	9	75	2.325	10.5	-9	75	-2.325
P3	24.8	9	81.6	1	24.8	-9	81.6	-1

After the coordinates of four points were identified, the Cubic Bezier Curve equation was used to identify other points of the aerofoil with the change in the value of "t" for validation with standard NACA 0018 Profile.

$C_0(t) = P_0 * (1-t)^3 + 3 * t * P_1 * (1-t)^2 + 3 * P_2 * t^2 * (1-t) + t^3 * P_3$ For, $0 \leq t \leq 1$ (Zhang, 1999)

By plotting the coordinates as obtained from the formula above, we get,

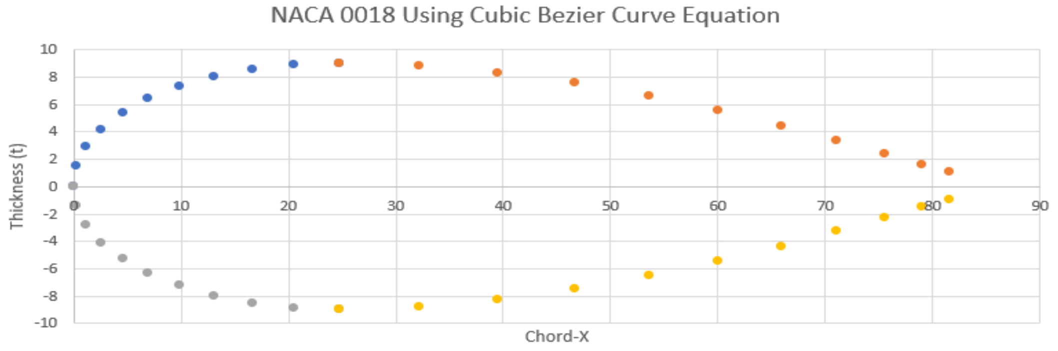


Figure 32 Plot of all the coordinates obtained from the Cubic Bezier Curve Equation

Validation

To validate the Cubic Bezier Curve, standard NACA 0018 profile coordinates were obtained from the website called Aerofoil Tools (Airfoil Tool, 2023). While plotting the coordinates we get the aerofoil as,

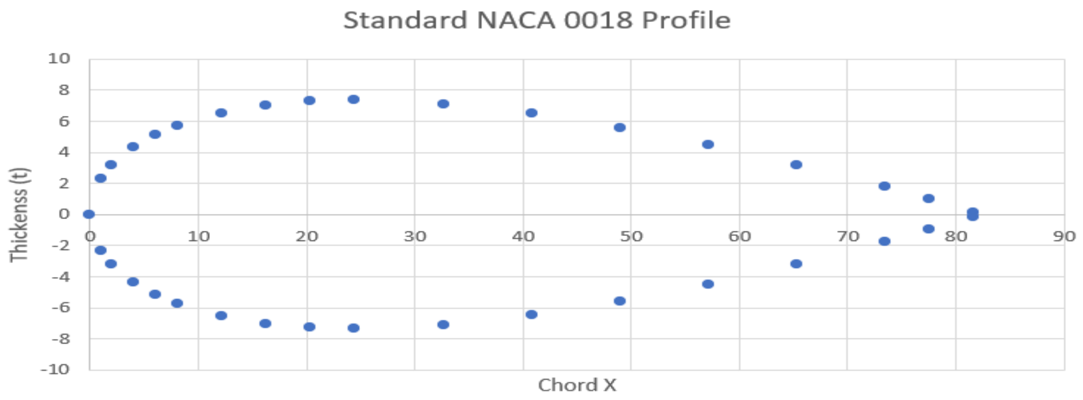


Figure 33 Aerofoil plotted from the standard coordinates.

The coordinates of the aerofoil obtained from the online aerofoil which is developed by using the Cubic Bezier Curve plotted in the inventor software then the result could be found overlapping the curve, so the picture shows that by changing the parameters of the aerofoil created by Cubic Bezier Curve, the standard NACA 0018 profile could be obtained. This validates that the parametrization of the aerofoil is possible for the project.

Figure 34 NACA 0018 coordinates plotted in Inventor software.

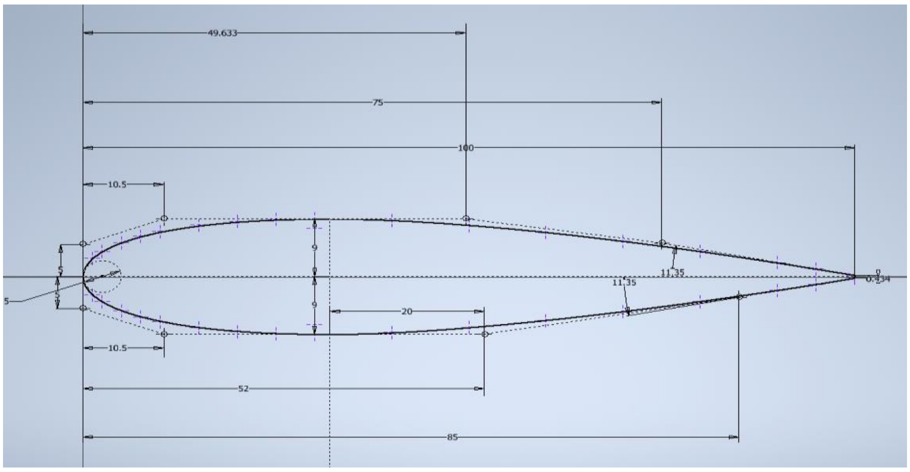


Figure 35 Proof of overlapping of the coordinates of Standard NACA profile and coordinates from Bezier Curve

Blade Section and its Mould Parameters

Using the Bezier curve parametrization method, the conceptual design of the blade was created with an altogether of 32 parameters. The mould section was designed with a similar aerofoil section so the parameter of the aerofoil section for the mould is similar. As per the manufacturing concept, these are the different parts parametric design of the blade and assembly of the blade.

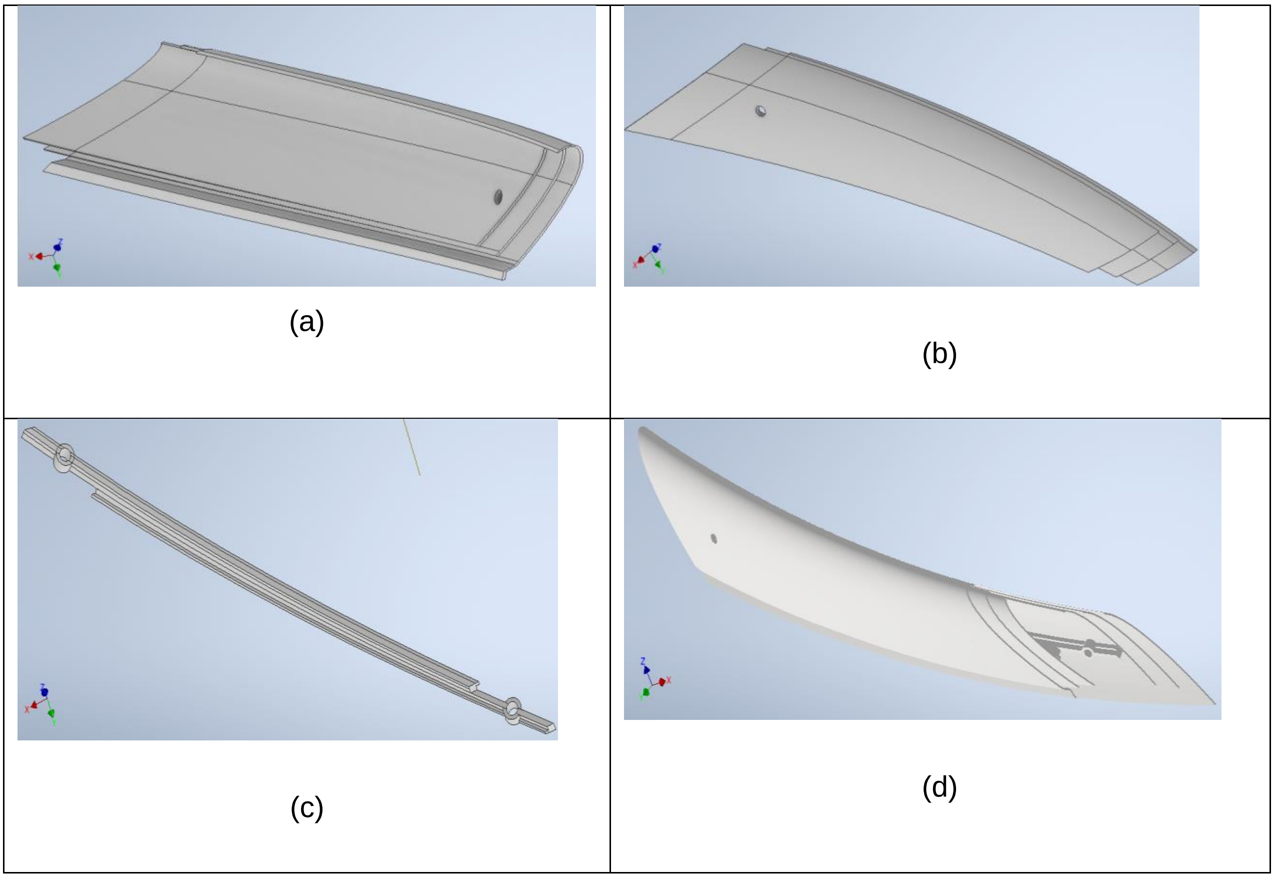


Figure 36 (a) Bottom Part of Blade; (b)Top Part of Blade; (c) Z- section as spar for Blade; (d) Full assembly of part to form single blade section.

The number of parameters for the top mould, bottom mould and Z-section are as follows,

Top Mould = 15 independent parameters and 13 dependent parameters with aerofoil section.

Bottom Mould = 8 independent parameters, 13 dependent parameters with aerofoil section.

Z-section = 9 independent parameters and 13 dependent parameters.

The list of parameters can be seen in the methodology for each section.

The independent parameters represent the parameters which can be changed without the influence of any other parameters and the dependent parameters represent the parameters which are common for each section as this is designed by using the same parametric aerofoil.

Blade Section linked with Mould Design

The parameters of the blade section and mould section are linked by the feature of an inventor. using inventor software, the parameters of the blade were linked with the parameters of the Mould. To link the parameters there is a feature of adding the user parameters to the design and the parameters of the blade were extracted to the parameters of the mould in the user parameter section, which helped in connecting the parameters of the blade with the mould. The parameter section and the parameters added to the user section in inventor can be seen in Appendix D.

As the parameter of the blade was extracted and added to the parameter list of the mould design, it developed an automatic link between the blade design and Mould design by replacing the parameters with the user parameters. So, if the parameter of the blade is changed then the parameters of the mould with be changed.

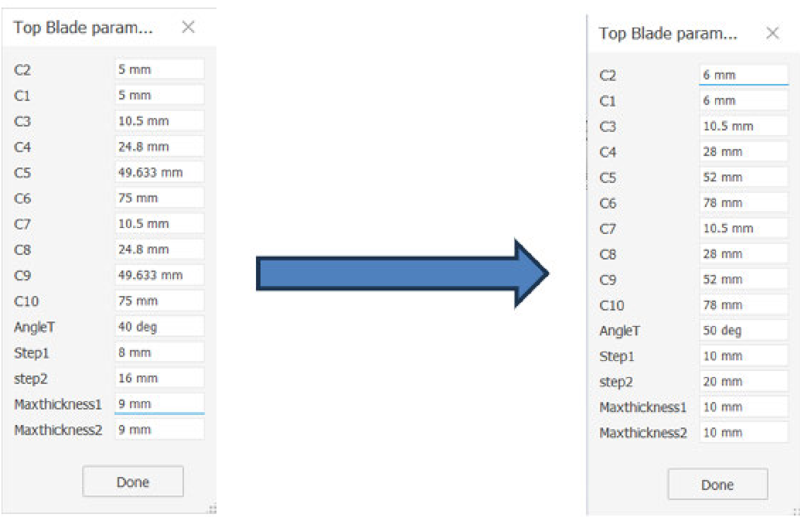


Figure 37 changes in the parameters of Blade.

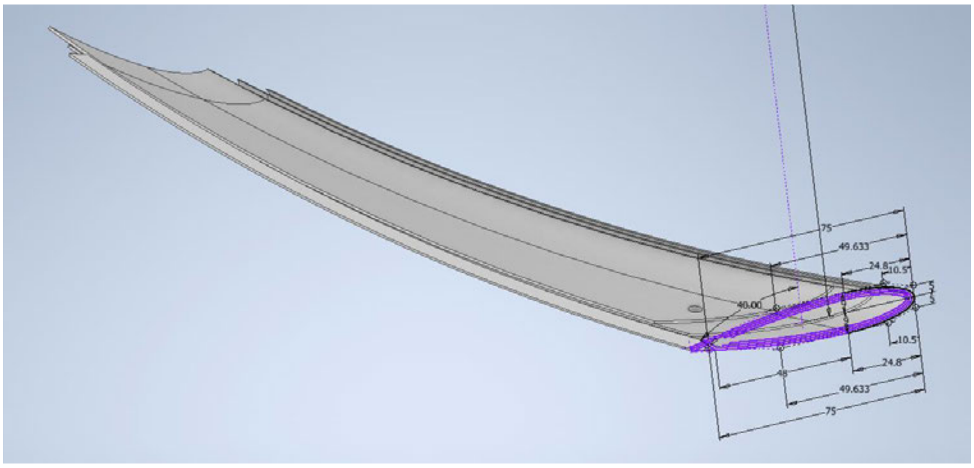


Figure 38 Top part of the Blade with original parameters.

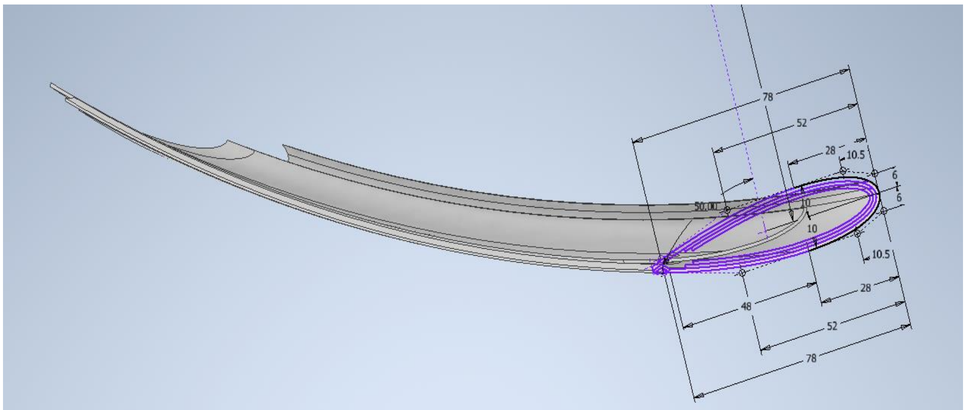


Figure 39 Top part of the blade after changing parameters.

With the change in parameter, the design of the blade was able to change which proves the working of the parametrization technique. Then these parameters were linked to the mould design and the design of the mould was changed accordingly as seen in the figure below,

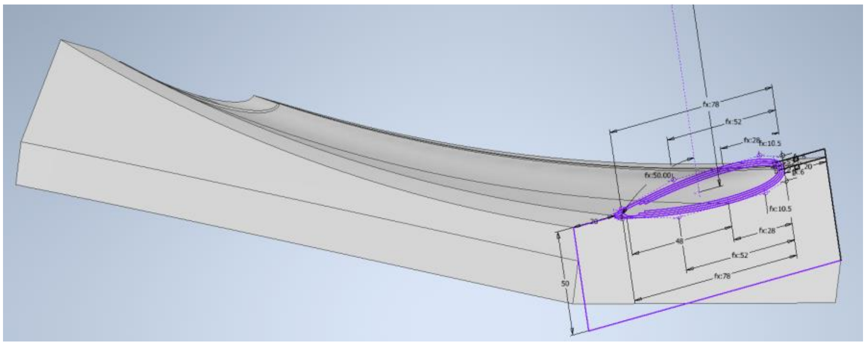


Figure 40 Changed Parameters of Mould with change in Blade parameters.

This proves that, with the change in parameters of the blade section part the parameters of the mould also change, and this provides tremendous benefits to the company by saving time and money for the company.

Discussion

In this section, it is always important to evaluate the results obtained from the project with the outlined objectives. The major aim of this project is to create an automation process for the manufacturing of the VAWT Blade, which is an innovative project. By considering the aim, a major objective had been sorted out, which is to create a parametric design of VAWT Blade and mould. After the design, the parameters of the blade were linked with the mould parameters so that with the change in value of blade parameters the parameter of the mould would also get changed.

Firstly, a parametric aerofoil is created using the cubic Bezier curve method. And it resulted that the aerofoil created can follow the path of the standard NACA 0018 profile which was proved in the result section. Similarly, research done by Melin & Amadori, (2011) for the conceptual parametric design of an aerofoil utilises a similar concept and it tested the method in the creation of different NACA profiles and was able to create a NACA 0012 profile with only RMS error of 0.51 ects and it was considered to a better result. While testing in other profiles which are not symmetrical the error was a bit higher. So the research resulted in this method being suitable for the symmetric profile. Similarly, the profile used in this project is also symmetric and utilises a similar concept, NACA 0018 profile for the VAWT-X testing model was created and it was validated in the result section. Therefore, this method can be accepted for the parametric design of the NACA 0018 profile for VAWT-X energy.

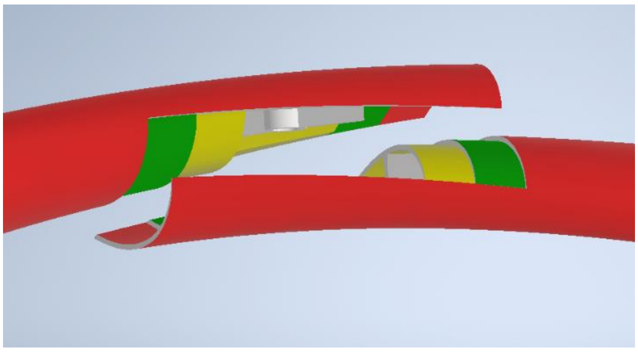
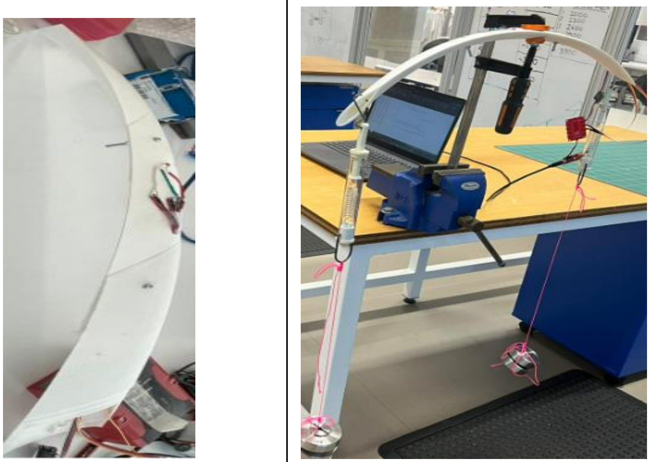


Figure 41 Designed Lap joint Concept.

So now talking about the blade design, VAWT-X has 9 sectionized blade which is connected to form a single profile of the blade. Therefore the study of the lap joint design was crucial. According to the literature review section, it was identified that while creating a lap joint contacting surface plays an important role especially mentioned in the research of Mendoza, Yao, Chetan, & Griffith, (2022). As this is an innovative project, the concept of contacting the surface gave an idea for creating a step lap joint in the blade as shown in Figure 41. So this lap joint connection was done in a 3D printed blade for creating a laboratory model by the use of adhesives. This was verified experimentally by another parallel project associated with VAWT-X. This model was tested by keeping the load on both sides of the blade with 17 N and 8.5 N on different sides as shown in the figure below. From this experiment by another member of a parallel project, it can be concluded that the design of the lap joint had good connections between blades.



(a) (b)

Figure 42 (a) 3D printed blade connection. (b) Experiment model prepared in parallel project of VAWT-X from ongoing thesis project by Deepak Sapkota.

The design of the mould is completely based on the manufacturing approach for the Vacuum Assisted Resin Infusion Method, which led to the design of an open mould for blade manufacturing. The VARI method is one of the proven concepts in manufacturing industries. The blade is designed in such a way that the 3 layers of carbon fibre can be used to manufacture it in an open mould concept as discussed in the methodology. This has been proven as it is governed by the principle of vacuum-assisted resin infusion method. VAWT-X energy has been currently working on the use of the VARI method of manufacturing for the original patented designed blade so this research would add value to their ongoing research and understanding with the parametric concept of mould design.

The limitation of this parametric design is that with changes in all the parameters at once, the change in the design of a blade and mould is found to be distorted for a while. This limitation can be addressed by successive changes in the parameters rather than changes in all the parameters at once. Due to the time constraints the identified manufacturing approach has not been put into practice. The specifications like the cost of materials required for VARI, and mould material should be carried out before real manufacturing is proceeded. This could be one of the future activities to visualise the design concept in practice and it can be also tested experimentally by combining all the blades by the mentioned approach.

CHAPTER FIVE: CONCLUSION AND FUTURE WORK

Conclusion

The major aim of the project is to create a design automation system to manufacture the VAWT Blade and to set up the digital manufacturing approach for it. Firstly, the parametric design of an aerofoil is implemented using the Cubic Bezier Curve technique. To validate the technique an overlapping concept was used, in which the aerofoil created is overlapped with the standard NACA 0018 profile and is allowed to change the parameters and overlap the NACA 0018 profile. The new design of the blade is carried out with the features of a hollow cavity supported by Z- a section and step lap joint for assembly. With this accomplishment, the manufacturing of a blade using 3 carbon fibre layers under Vacuum Assisted Resin Infusion Method was identified, which resulted in the development of mould parametrically linked with blade design. The paper also represents the digital manufacturing process of Vacuum Assisted Resin Infusion method which gives the benefits of ready-to-go manufacturing for the company. The design modified blade provides the advantages of reduction in weight of the blade profile and enhanced overlapping in joints by the concept of step lap joint. The major significance of the report would be the identification of the process of manufacturing VAWT blade section with three layers of carbon fibre under Vacuum Assisted Resin Infusion method. The technique of parametrization can be used to create multiple profiles of NACA aerofoil, and also link the design of the blade and the mould parametrically thereby establishing design automation features. With this design automation, it ensures an easy design iteration process that could go on future work under VAWT-X Energy saving both time and effort in creating the blade and mould design from scratch. However, there are a few limitations to this technique, while changing the parameters few disruptions occurred in the design and it was fixed by modifying related parameters.

Future Works

For future work, the use of the Cubic Bezier Curve technique can be enhanced more efficiently with fewer disruptions. Since the manufacturing process has been identified with a digital manufacturing approach it can be processed for real manufacturing of Blade, but for which cost estimation and material section for mould is yet to be carried out. The full assembly of the blade section manufactured with the moulding concept can be tested for experimental analysis.

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APPENDICES

Appendix A: Aerofoil development, its parameters and blade design details

The cubic Bezier Curve is derived from certain steps of interpolation, which are as follows,

To get the line segment for two points P_0 and P_1, there is the use of a linear Bezier curve function. Which is given as below,

$L_o(t) = P_o * (1 - t) + P_1 * t$ .... (1)

Where t varies from 0 to 1.

Therefore, this function describes that the function is dependent on t. so with every change in the value of t the value of the function changes.

So, to create a curve there must be three points, which are P_0, P_1, and P_2. So, the linear interpolation of P_0, and P_1 is given by,

$L_0(t) = P_0 * (1 - t) + P_1 * t$ .... (1)

The linear interpolation of P_1, and P_2 is given by,

$L_1(t) = P_1 * (1 - t) + P_2 * t$........................ (2)

Then, by interpolating $L_o(t)\ and\ L_1(t)$ we get the Quadratic Bezier Curve

$Q_0(t) = L_0(t) * (1 - t) + L_1(t) * t$........................ (3)

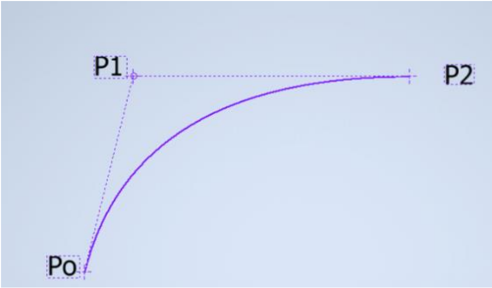


Figure 43 Example of Cubic Bezier Curve with four control points

Or,

$Q_0(t) = P_0 * (1 - t)^2 + 2 * t * P_1 * (1 - t) + P_2 * t^2$.......... (4)

Hence, with the change in value of t, this equation will create a curve as shown in the figure below.

So, the Cubic Bezier curve is created by adding another point P_3. Which makes the number of points 4 (P_0, P_1, P_2, and P_3)

Then after adding a point P_3, a liner interpolation is done between the point P_2 and P_3. Which gives,

$L_2(t) = P_2 * (1-t) + P_3 * t$…………………………………… (5)

Then the interpolation of $L_1(t)$ and $L_2(t)$ is done, then the quadratic curve is generated with the equation of,

$Q_1(t) = L_1(t) * (1-t) + L_2(t) * t$…………………………………… (6)

Finally, to get the cubic Bezier curve equation, the interpolation is done between $Q_0(t)$ and $Q_1(t)$, which is given by,

$C_0(t) = Q_0(t) * (1-t) + Q_1(t) * t$…………………………………… (7)

Or,

$C_0(t) = P_0 * (1-t)^3 + 3 * t * P_1 * (1-t)^2 + 3 * P_2 * t^2 * (1-t) + t^3 * P_3$ For, $0 \leq t \leq 1$ …………………………………… (8)

Therefore, this equation is the basis for creating the aerofoil section. To get the clear aerofoil, four Cubic Bezier Curve are combined to form a single aerofoil.

The coordinates for the aerofoil profile which is calculated by using equation 8 as given below,

$C_0(t) = P_0 * (1-t)^3 + 3 * t * P_1 * (1-t)^2 + 3 * P_2 * t^2 * (1-t) + t^3 * P_3$ For, $0 \leq t \leq 1$

Table 11 Coordinates of the designed aerofoil by using Cubic Bezier Curve

t	Curve-1		Curve-2		Curve-3		Curve-4	
	X(t)	Y(t)	X(t)	Y(t)	X(t)	Y(t)	X(t)	Y(t)
0	0	0	24.8	9	0	0	24.8	-9
0.1	0.3083	1.467	32.24662	8.811775	0.3083	-1.467	32.24662	-8.81178
0.2	1.2064	2.856	39.60947	8.2952	1.2064	-2.856	39.60947	-8.2952

0.3	2.6541	4.149	46.77275	7.522425	2.6541	-4.149	46.77275	-7.52243
0.4	4.6112	5.328	53.62066	6.5656	4.6112	-5.328	53.62066	-6.5656
0.5	7.0375	6.375	60.03738	5.496875	7.0375	-6.375	60.03738	-5.49688
0.6	9.8928	7.272	65.9071	4.3884	9.8928	-7.272	65.9071	-4.3884
0.7	13.1369	8.001	71.11404	3.312325	13.1369	-8.001	71.11404	-3.31233
0.8	16.7296	8.544	75.54237	2.3408	16.7296	-8.544	75.54237	-2.3408
0.9	20.6307	8.883	79.07629	1.545975	20.6307	-8.883	79.07629	-1.54598
1	24.8	9	81.6	1	24.8	-9	81.6	-1

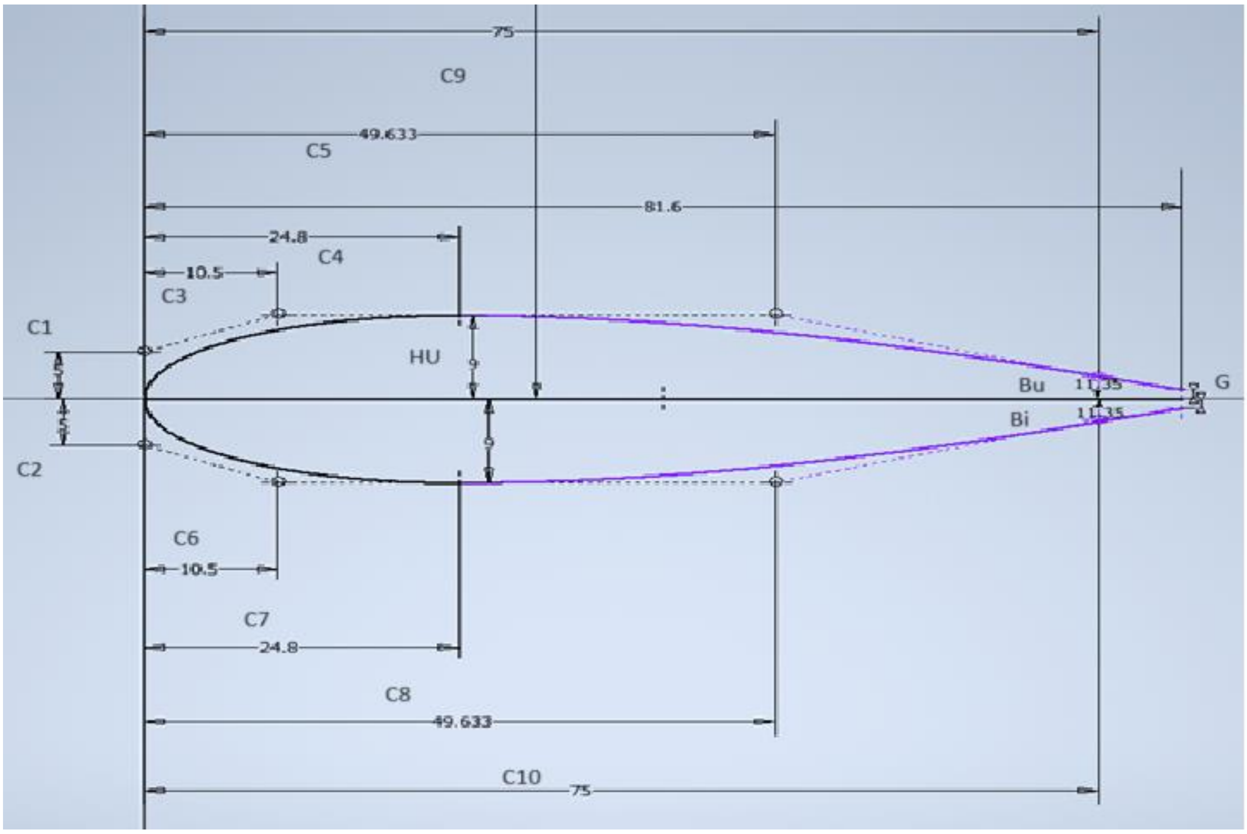


Figure 44 Aerofoil created by using Cubic Bezier Curve

From the developed aerofoil, certain parameters list for an aerofoil is created as follows,

Table 12 Parameters of Aerofoil

Parameters	Variables
Leading Edge	
Upper Nose Fraction	C1
Lower Nose Fraction	C2
Upper Side Curve	
Upper Thickness	HU
Upper Front Fraction	C3
Maximum Thickness Distance	C4
Upper Back Fraction	C5
Lower Side Curve	
Lower Thickness	HL
Lower Front Thickness	C6
Maximum Thickness Distance	C7
Lower Back Thickness	C8
Trailing edge	
Trailing edge Gap	G
Upper Trailing edge wedge angle	Bu
Lower Trailing edge wedge angle	Bl
Upper Trailing edge Fraction	C9
Lower Trailing edge Fraction	C10

For, figure 54 the design of the blade is made by the original values given by VAWT-X Energy for method, pitch, height, and taper.

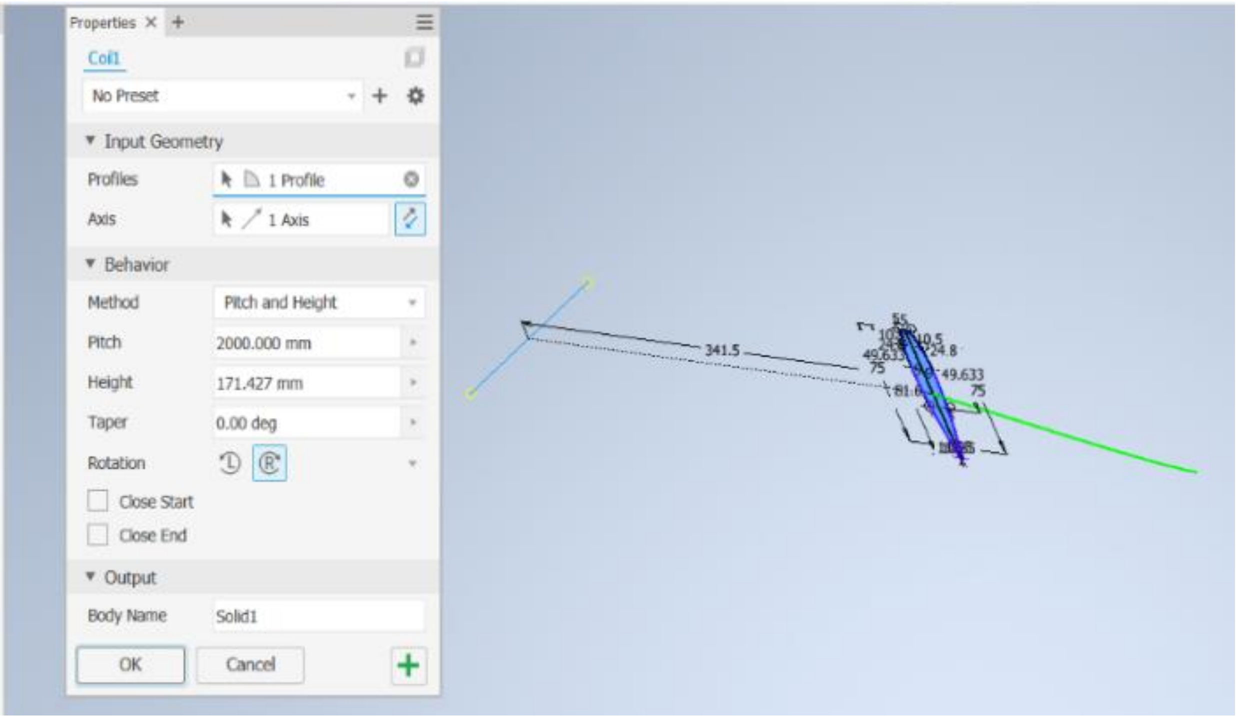


Figure 45 properties used for coil feature in inventor to create the helical blade surface.

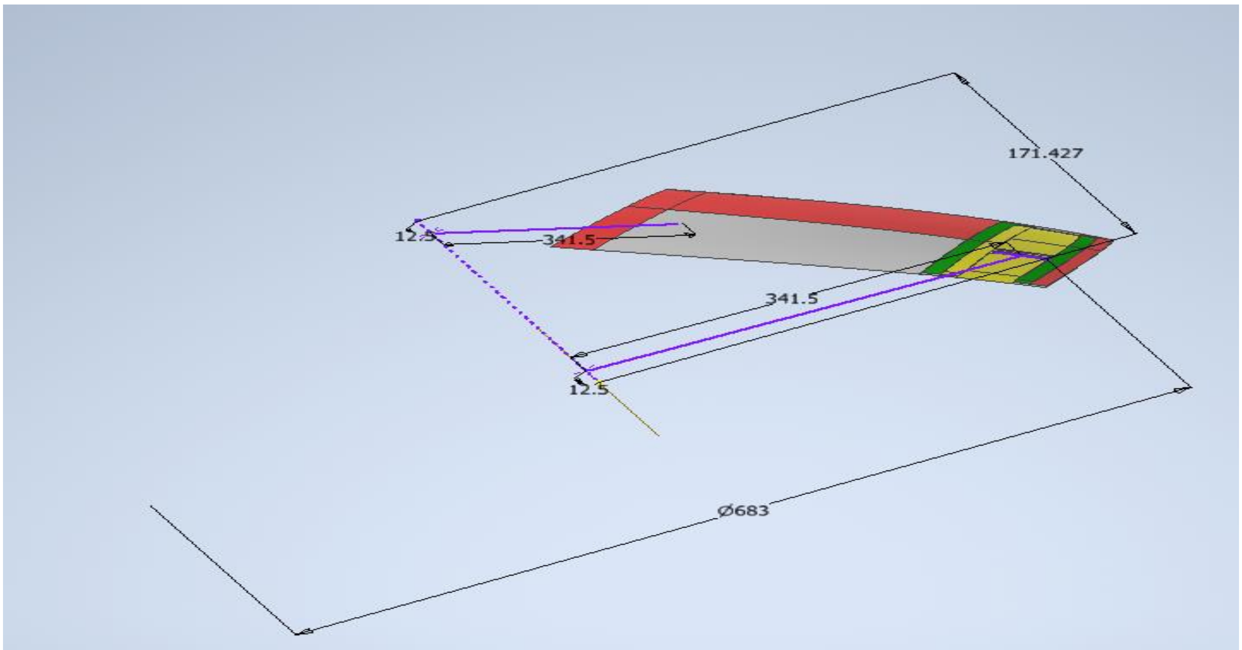


Figure 46 3D sketch Drawing for creating the holes.

By the use of 3D sketch, the points for the hole were identified, as the shape of the blade is helical and so it was helpful to overlap with the other section of the blade for blade assembly. So that the blade section could overlap within desired parts as can be seen in figure 56.

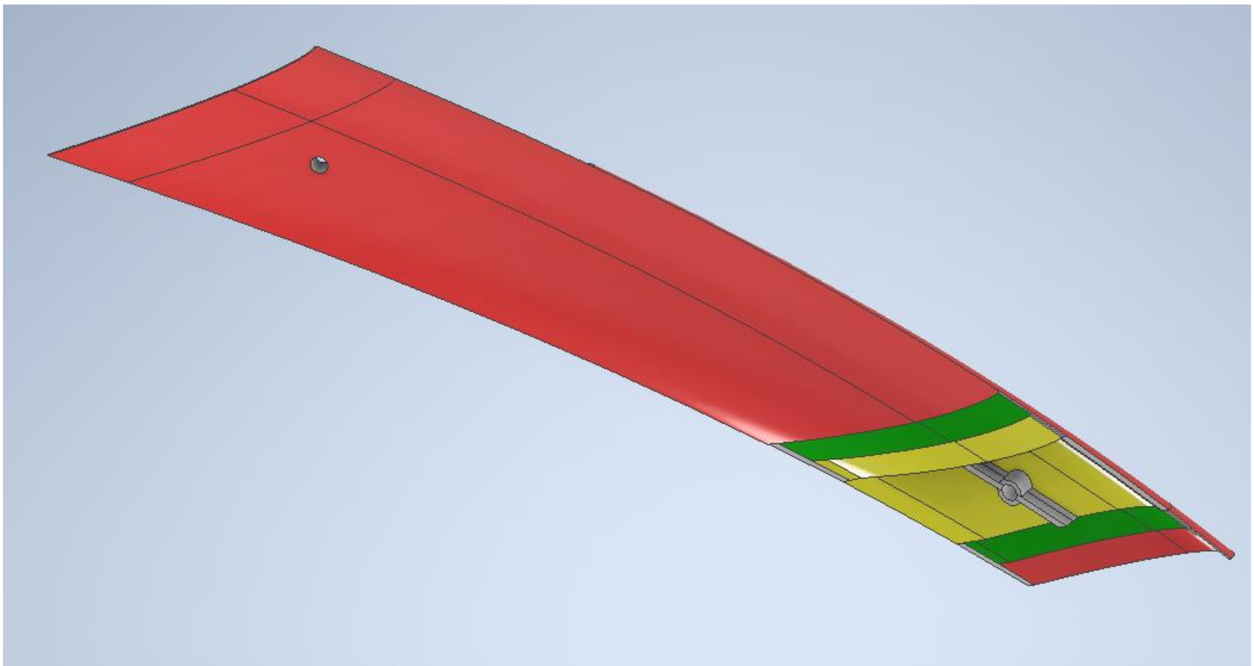


Figure 47 Front view of Blade

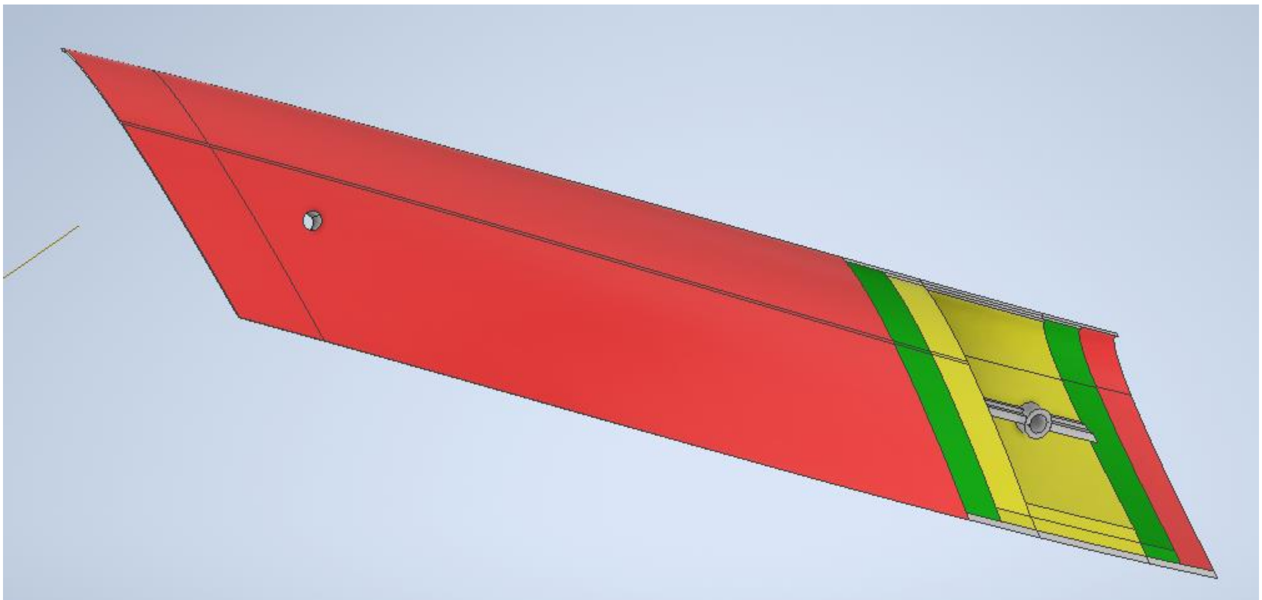


Figure 48 Back View of Blade

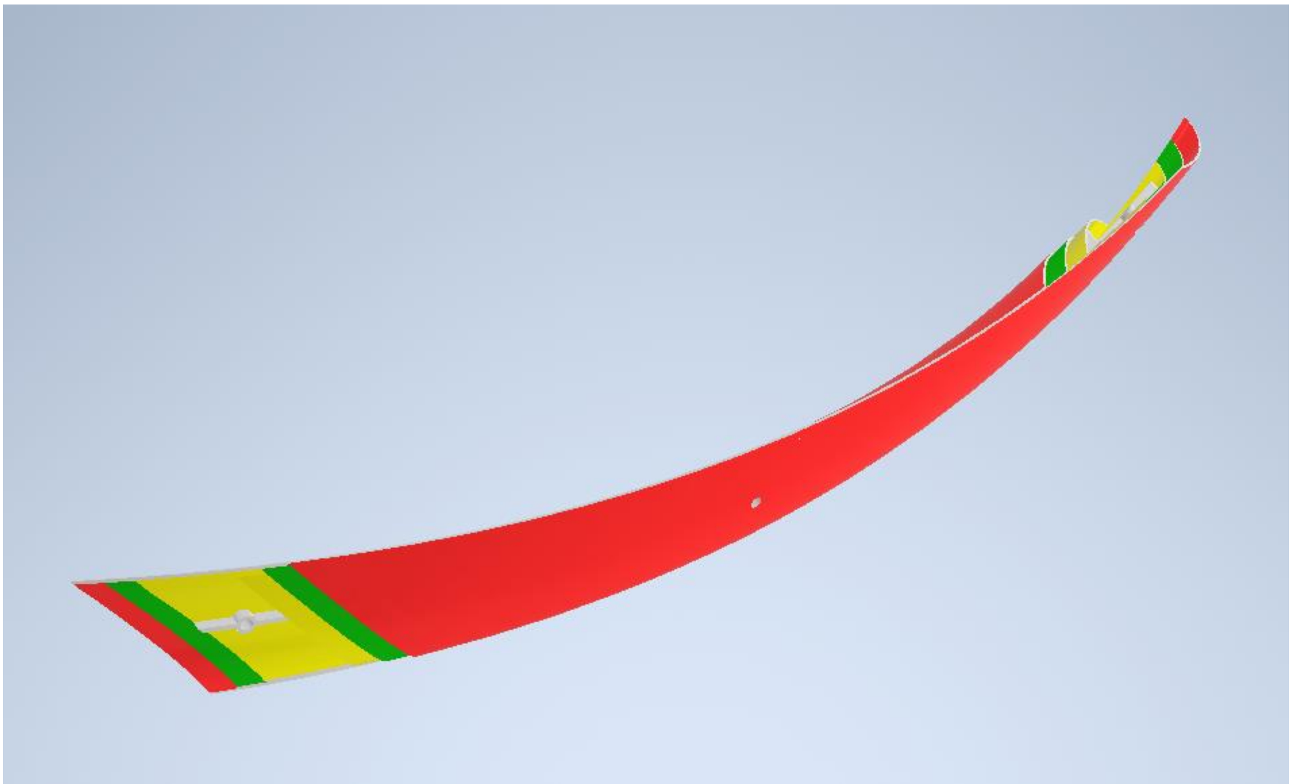


Figure 49 Assembly of two blades.

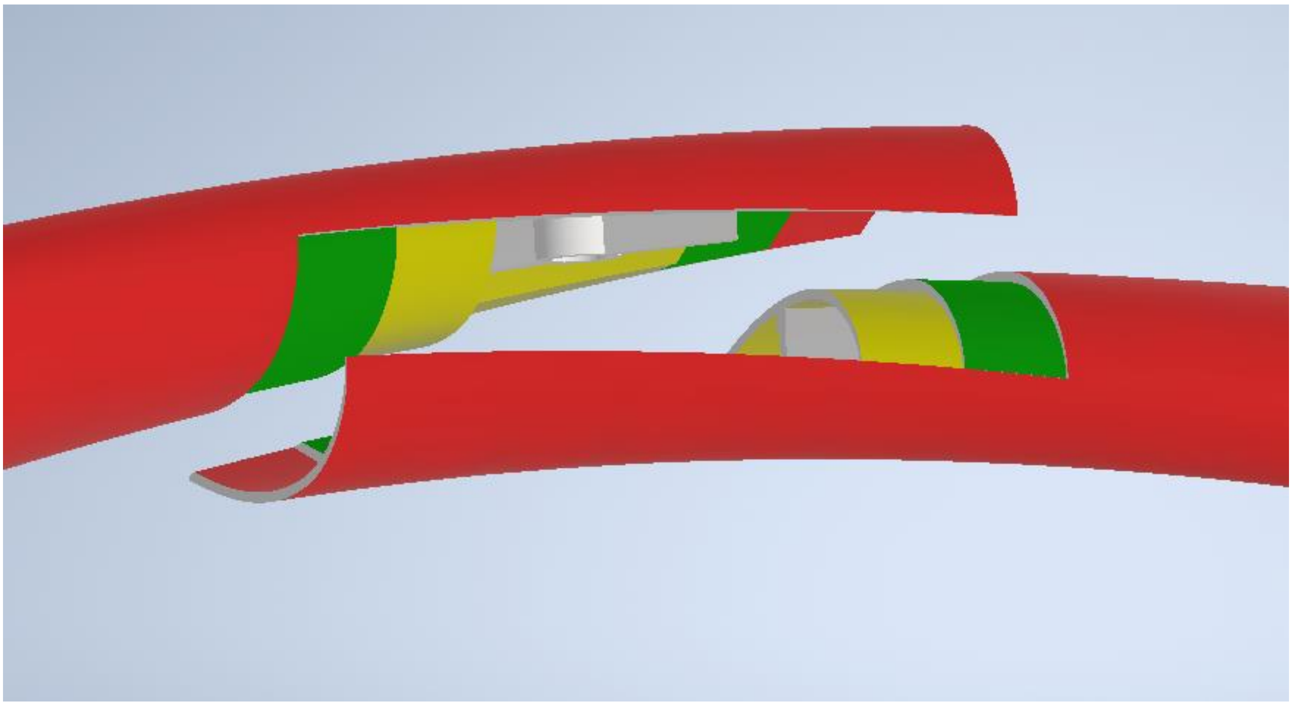


Figure 50 Lap joint assembly for 2 blades

Appendix B: Engineering drawings of the blade and Mould & its parts.

In this section the engineering drawings for conceptual blade design and mould design for each parts are provided.

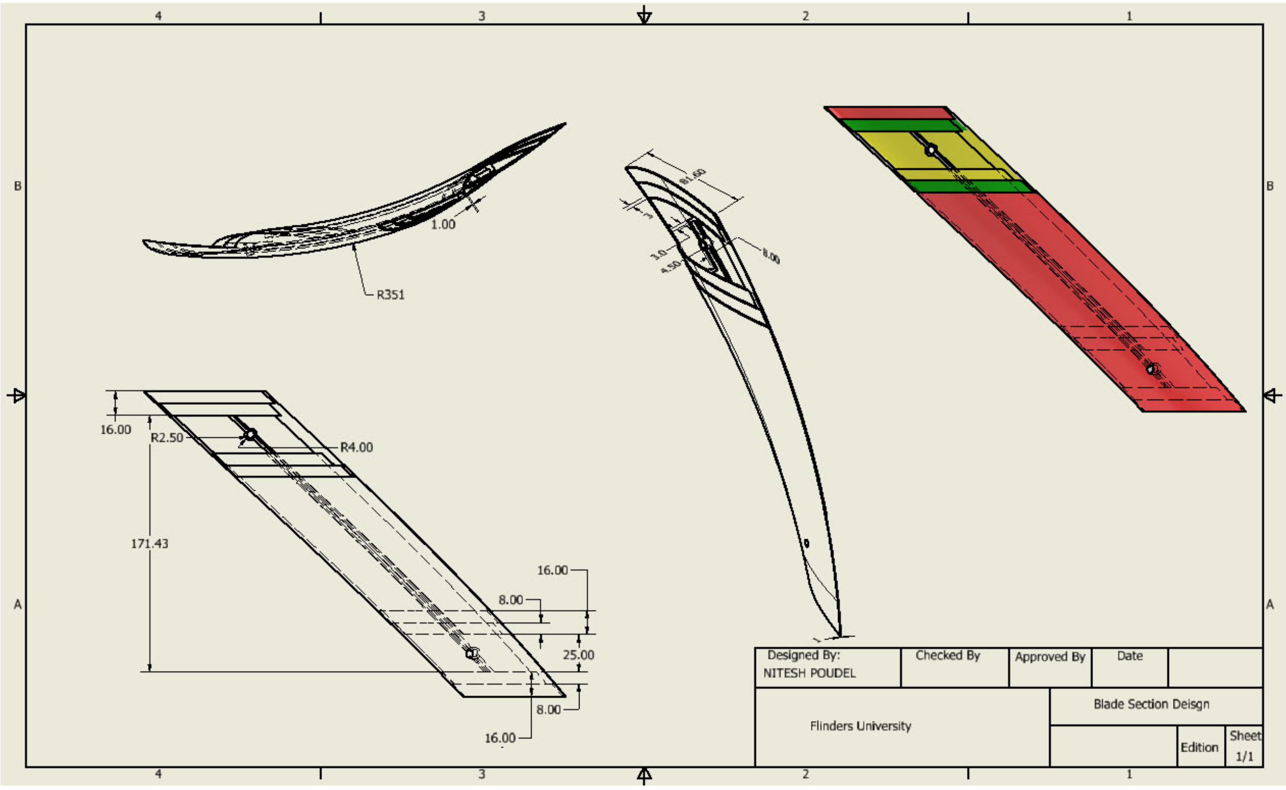


Figure 51 Engineering drawing for the conceptual design of blade

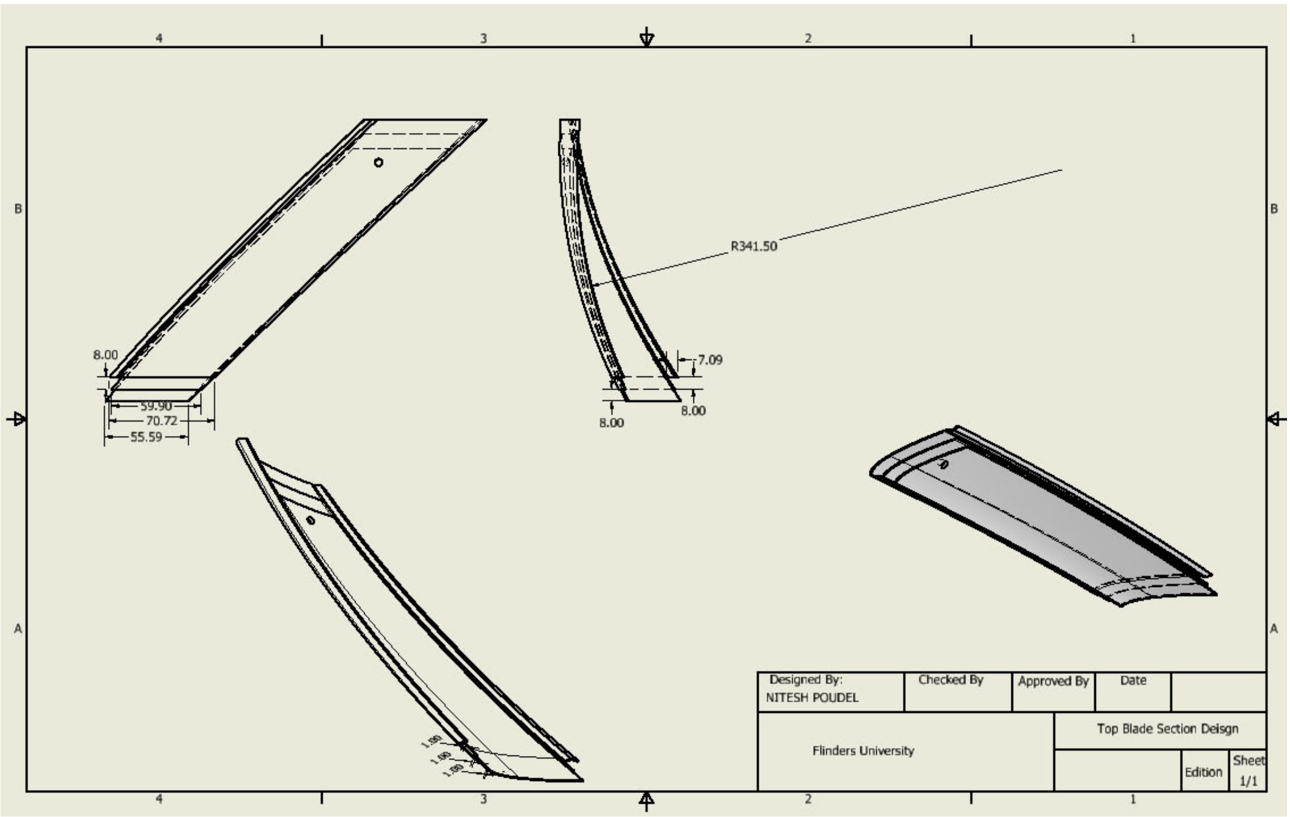


Figure 52 Engineering design for Top Blade with manufacturing approach

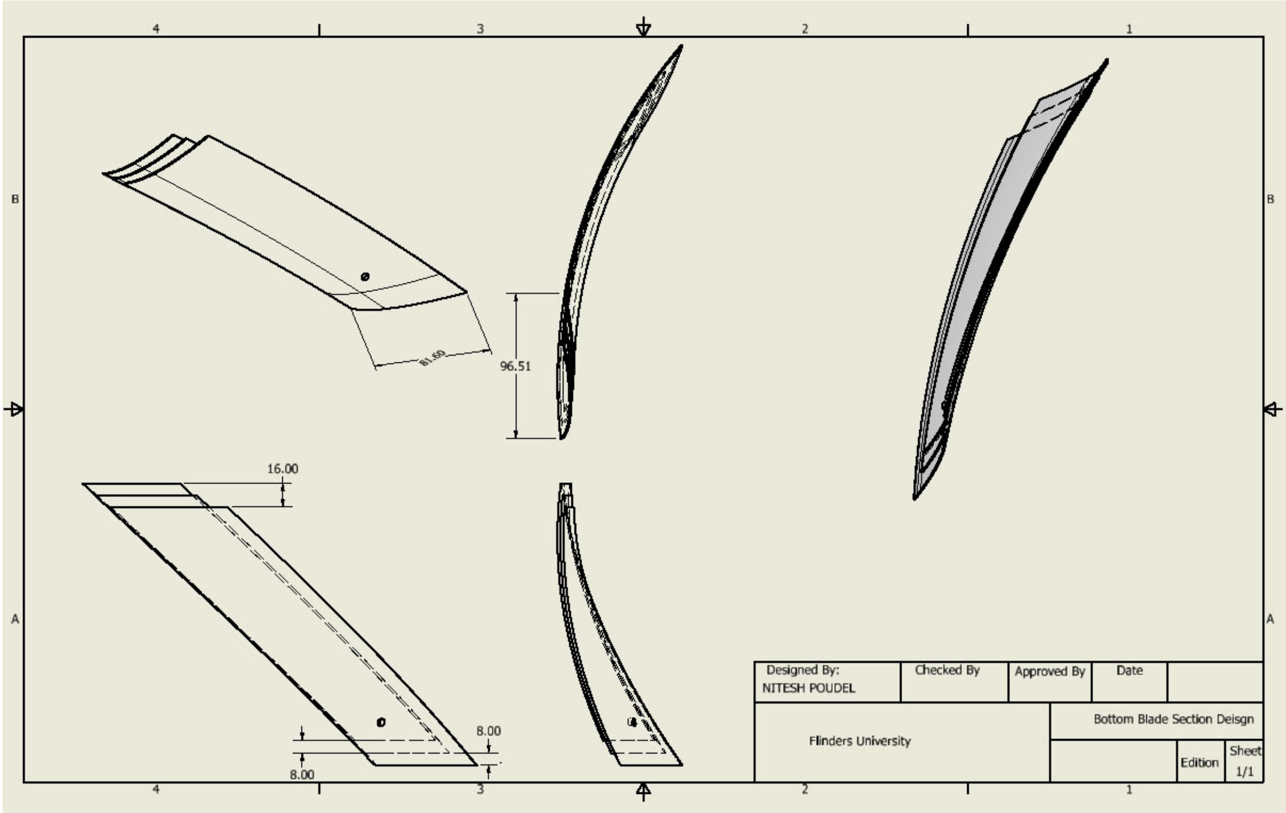


Figure 53 Engineering design for Bottom Blade with manufacturing approach

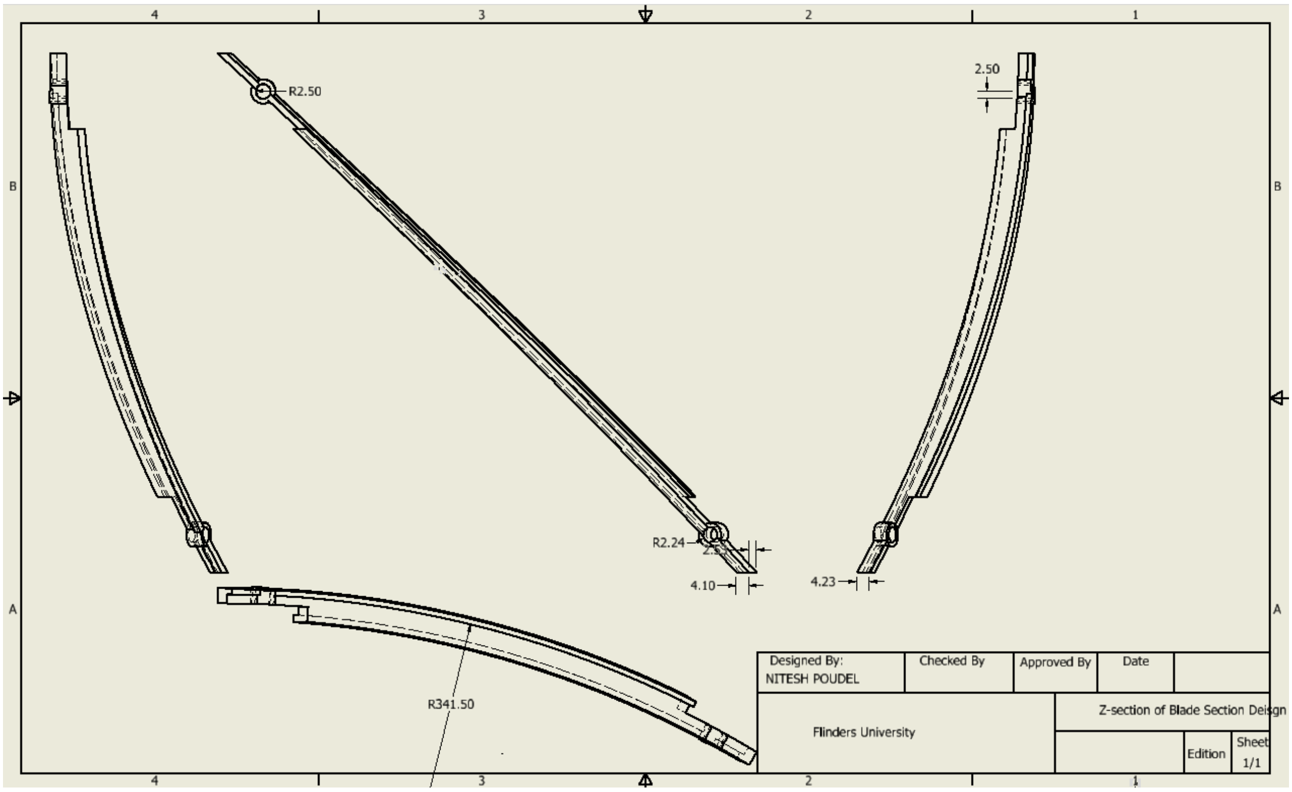


Figure 54 Engineering design for Z-section

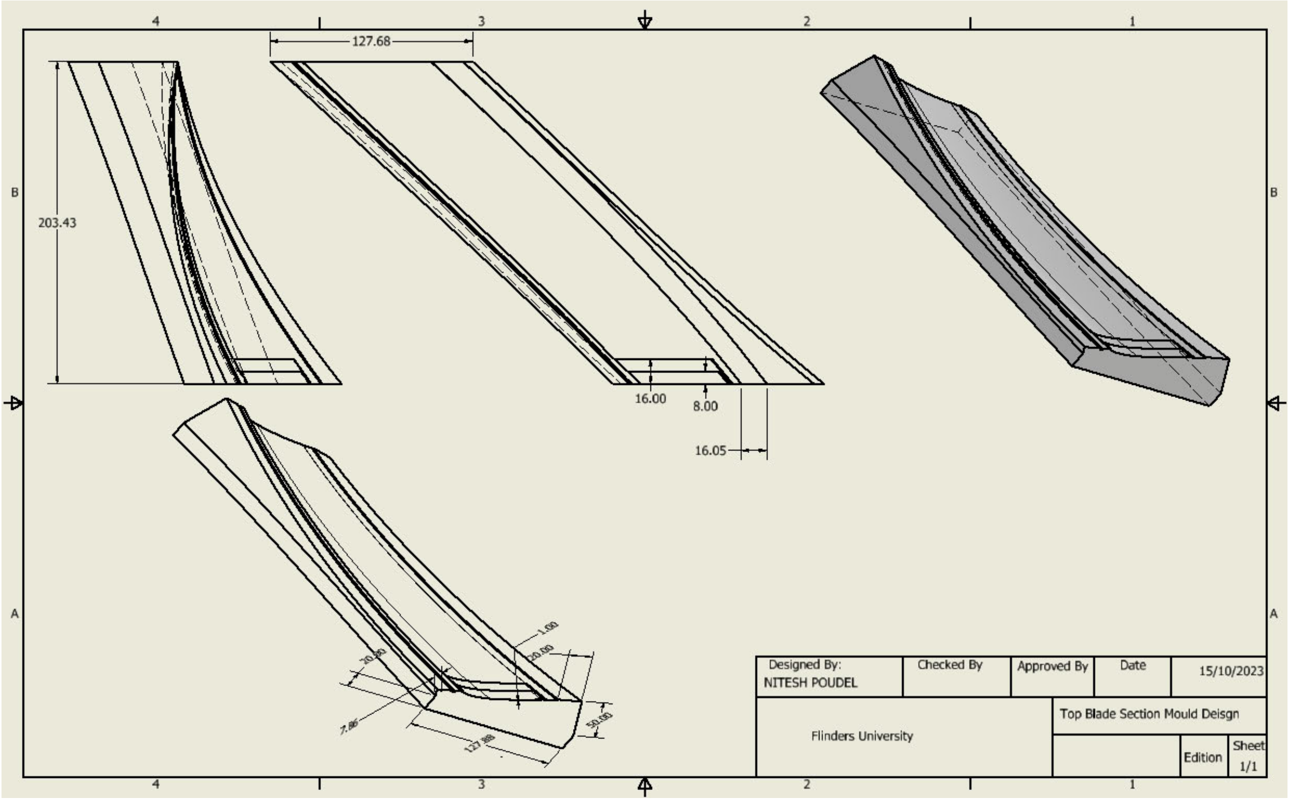


Figure 55 Engineering Drawing for Top Mould Base

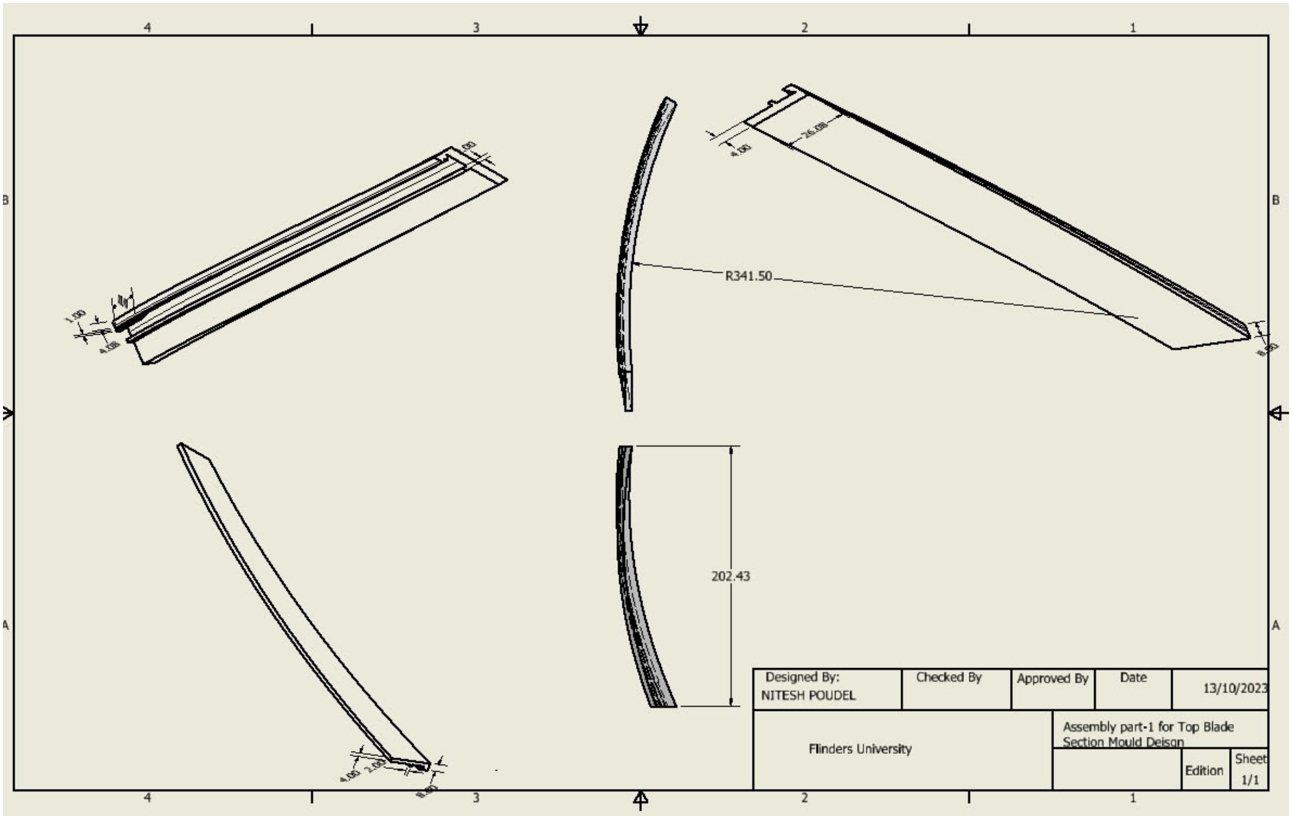


Figure 56 Assembly part-1 for Top Blade Section Mould Design

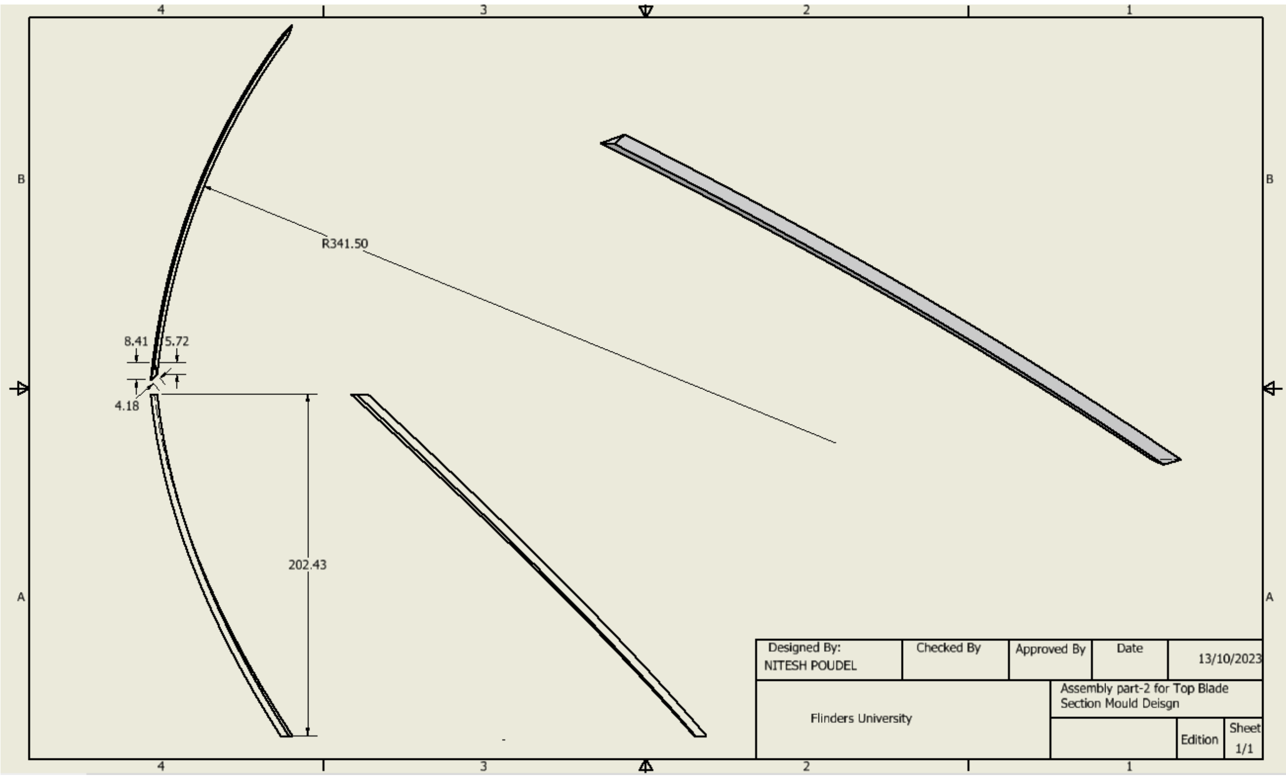


Figure 57 Assembly part-2 for Top Blade Section Mould Design

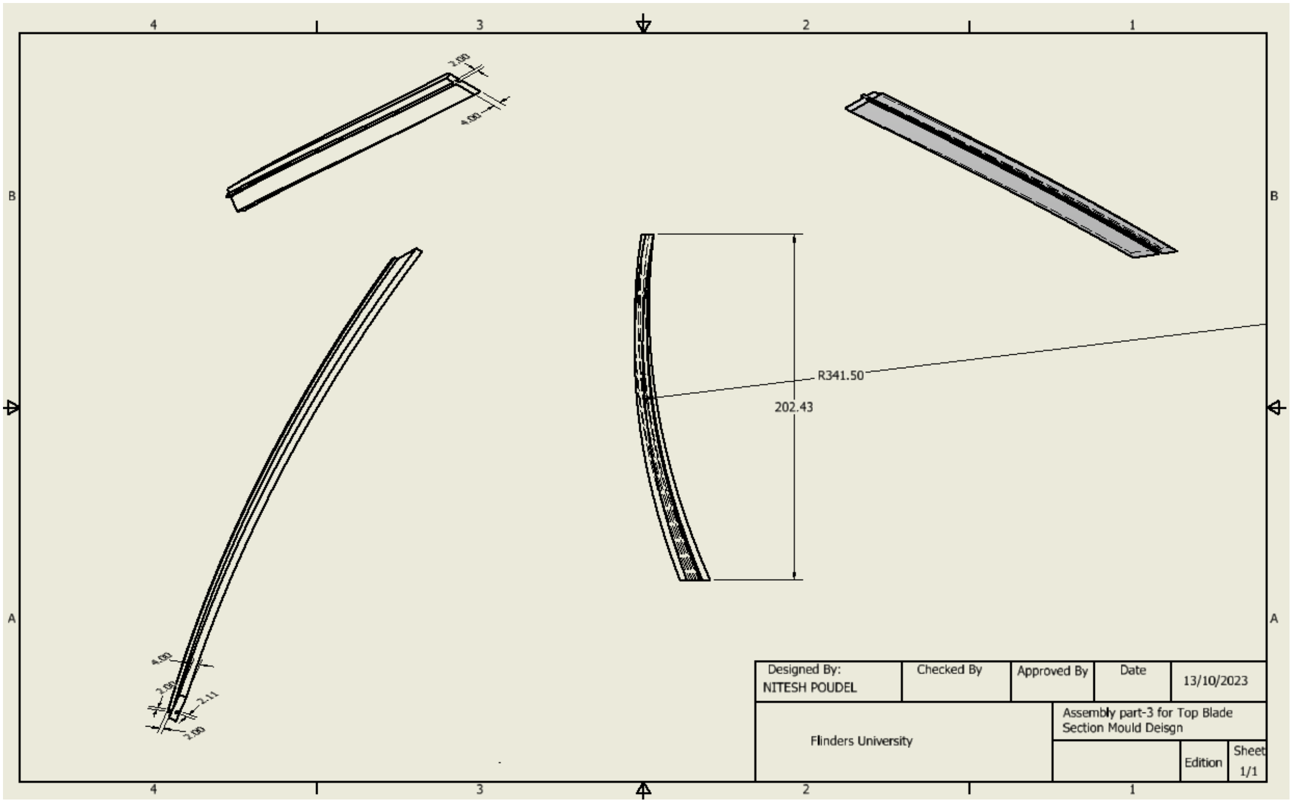


Figure 58 Assembly part-3 for Top Blade Section Mould Design

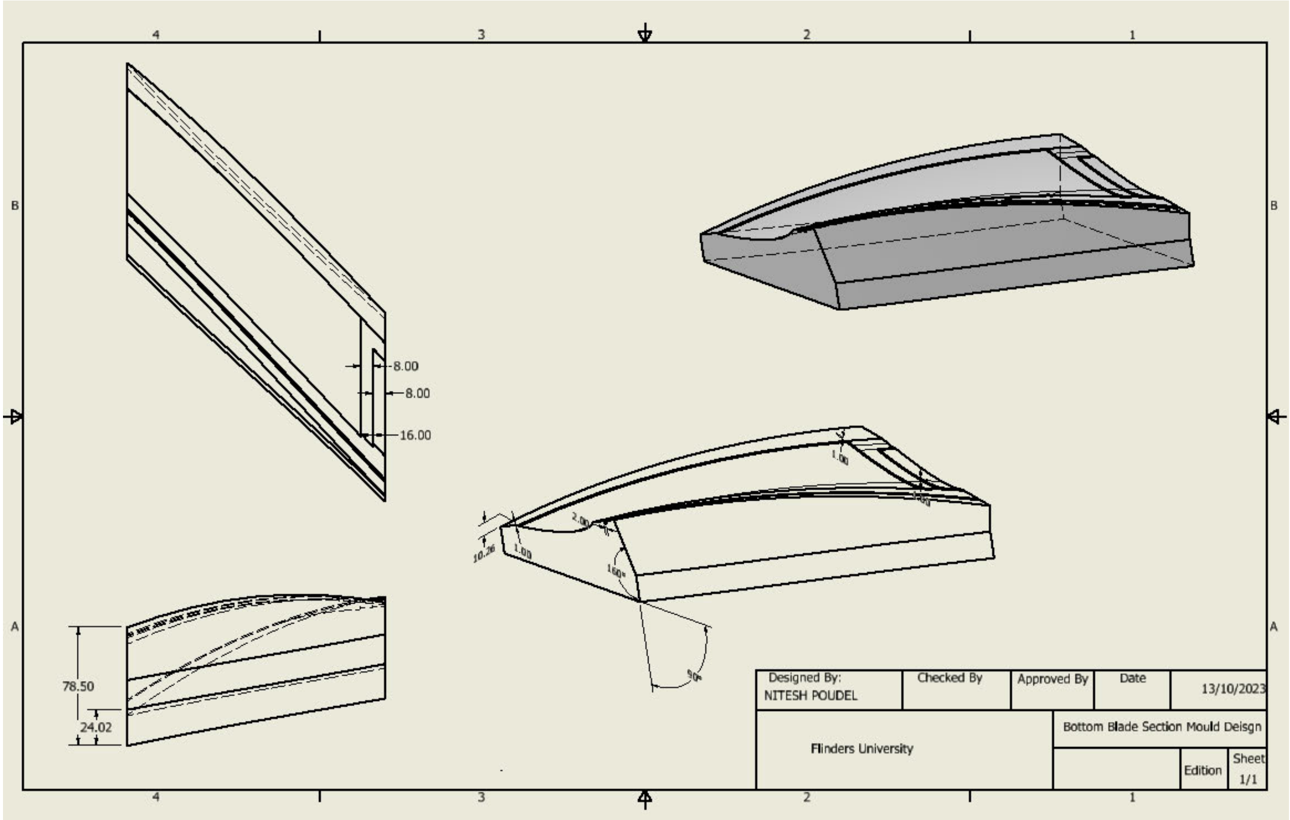


Figure 59 Engineering design of Bottom Blade section Mould

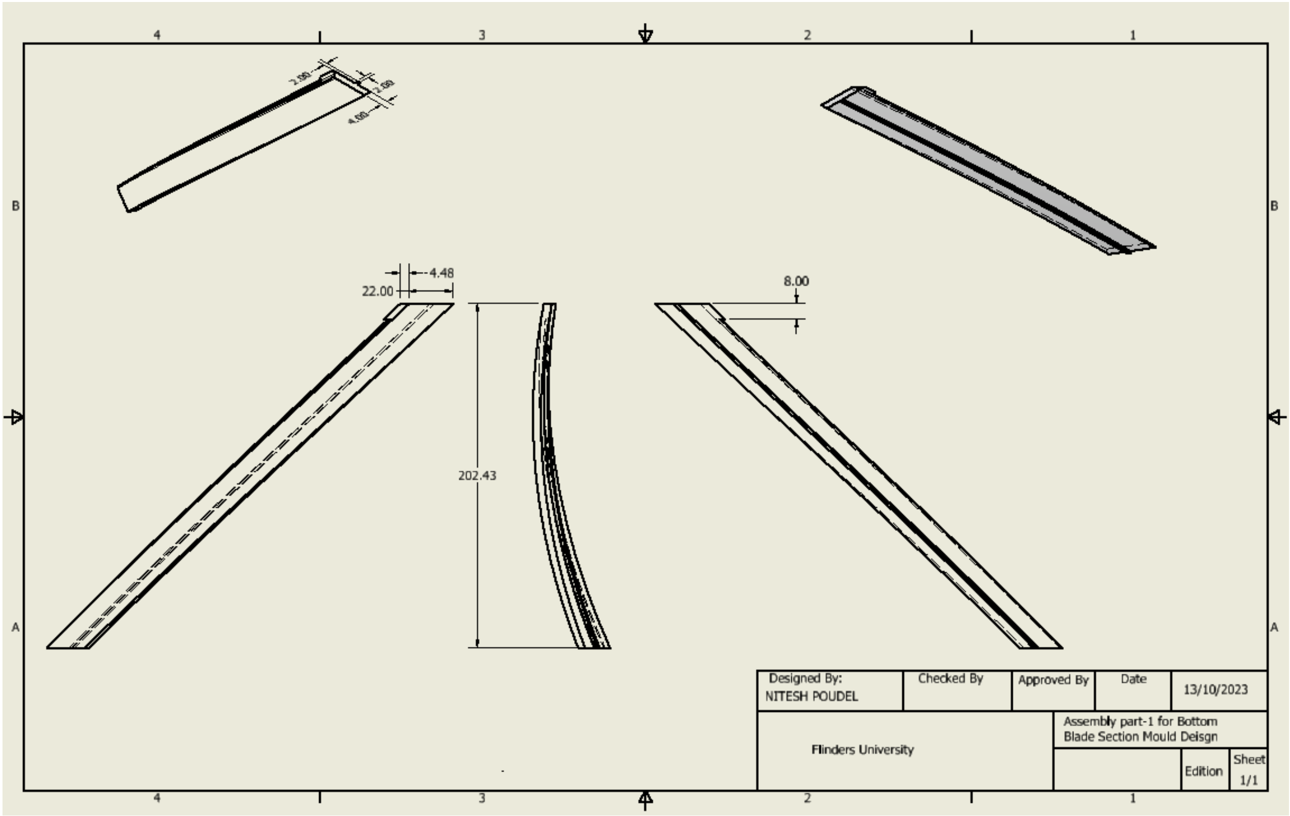


Figure 60 Assembly part-1 for Bottom Blade Section Mould Design

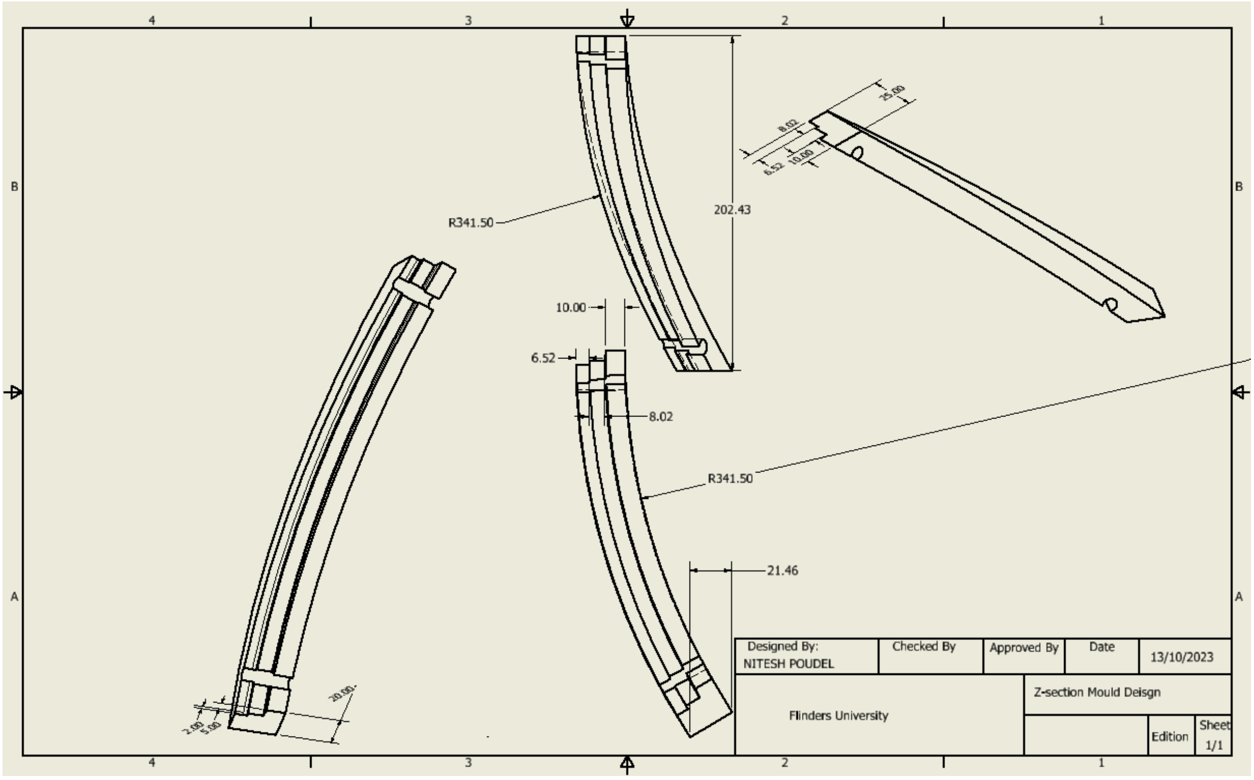


Figure 61 Engineering drawing for Z-section Mould

Appendix C: Decision Matrix for Manufacturing Approach

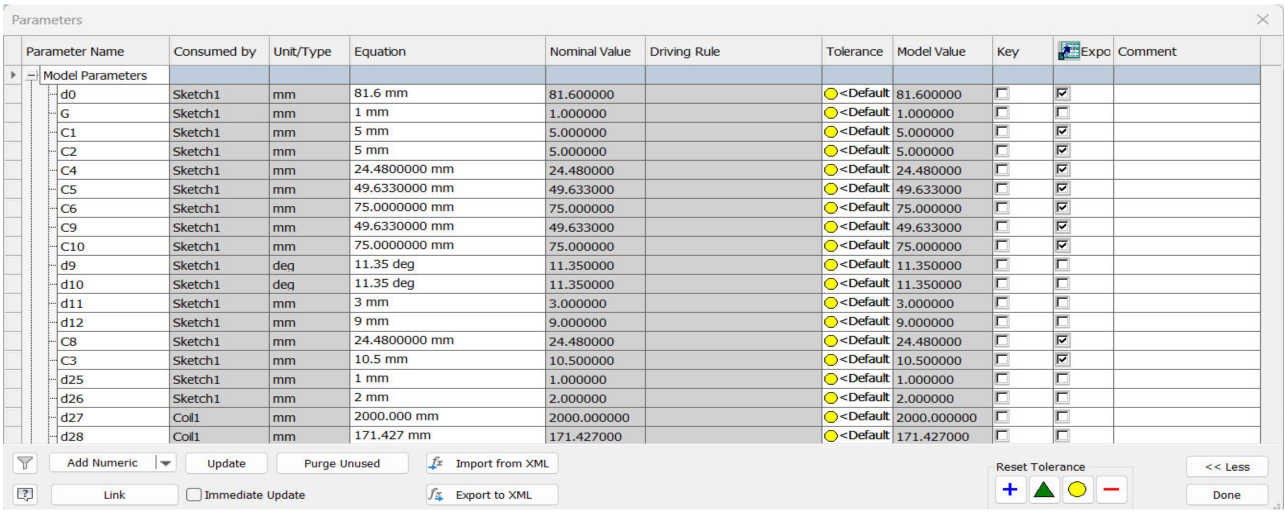
The following table represents the decision matrix for the manufacturing approach through which the vacuum Assisted Resin Infusion Method was selected. Another reason for selecting this technique was because the VAWT-X energy is also leaning toward the vacuum infusion technique therefore it would help the company to a certain extent by this research paper with a design automation approach.

Table 13 Decision matrix for manufacturing approach

Criteria	Weight	Wet hand layup	Prepreg technology	Vacuum Resin Transfer	Vacuum Assisted Resin Infusion	Centrifugal Moulding	Filament winding
Strength	0.2	Medium	High	Medium	High	Low	Medium
Weight	0.2	Low	High	Medium	Medium	High	High
Low Cost	0.2	High	High	High	High	Low	Medium
Production speed	0.1	Low	High	Medium	Medium	High	Medium
Complexity	0.2	Low	High	Medium	Medium	Low	Low
Quality control	0.1	Low	Medium	Medium	High	Low	Medium

Appendix D: Linking interface for parameters of Blade and Mould.

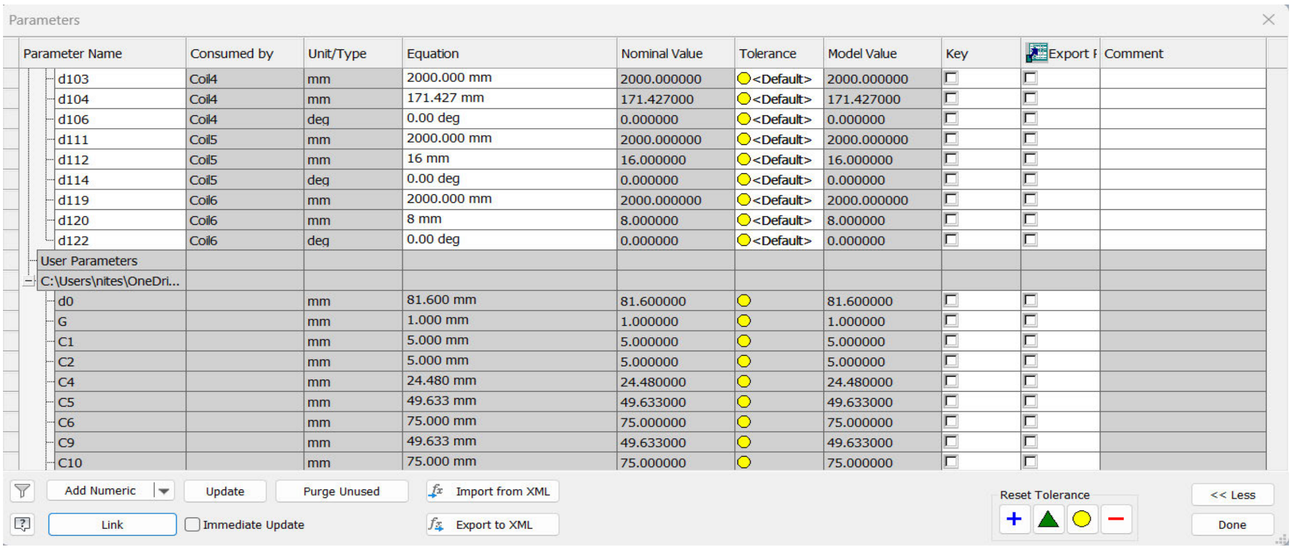
The figures in this section just represents the interface for linking of the two component parameters.



Parameters

Parameter Name	Consumed by	Unit/Type	Equation	Nominal Value	Driving Rule	Tolerance	Model Value	Key	Expo	Comment
Model Parameters										
d0	Sketch1	mm	81.6 mm	81.600000		<Default	81.600000	☐	☑	
G	Sketch1	mm	1 mm	1.000000		<Default	1.000000	☐	☐	
C1	Sketch1	mm	5 mm	5.000000		<Default	5.000000	☐	☑	
C2	Sketch1	mm	5 mm	5.000000		<Default	5.000000	☐	☑	
C4	Sketch1	mm	24.4800000 mm	24.480000		<Default	24.480000	☐	☑	
C5	Sketch1	mm	49.6330000 mm	49.633000		<Default	49.633000	☐	☑	
C6	Sketch1	mm	75.0000000 mm	75.000000		<Default	75.000000	☐	☑	
C9	Sketch1	mm	49.6330000 mm	49.633000		<Default	49.633000	☐	☑	
C10	Sketch1	mm	75.0000000 mm	75.000000		<Default	75.000000	☐	☑	
d9	Sketch1	deg	11.35 deg	11.350000		<Default	11.350000	☐	☐	
d10	Sketch1	deg	11.35 deg	11.350000		<Default	11.350000	☐	☐	
d11	Sketch1	mm	3 mm	3.000000		<Default	3.000000	☐	☐	
d12	Sketch1	mm	9 mm	9.000000		<Default	9.000000	☐	☐	
C8	Sketch1	mm	24.4800000 mm	24.480000		<Default	24.480000	☐	☑	
C3	Sketch1	mm	10.5 mm	10.500000		<Default	10.500000	☐	☑	
d25	Sketch1	mm	1 mm	1.000000		<Default	1.000000	☐	☐	
d26	Sketch1	mm	2 mm	2.000000		<Default	2.000000	☐	☐	
d27	Coil1	mm	2000.000 mm	2000.000000		<Default	2000.000000	☐	☐	
d28	Coil1	mm	171.427 mm	171.427000		<Default	171.427000	☐	☐	

Figure 62 Parameters table for blade design in inventor software



Parameters

Parameter Name	Consumed by	Unit/Type	Equation	Nominal Value	Tolerance	Model Value	Key	Export P	Comment
d103	Coil4	mm	2000.000 mm	2000.000000	<Default>	2000.000000	☐	☐	
d104	Coil4	mm	171.427 mm	171.427000	<Default>	171.427000	☐	☐	
d106	Coil4	deg	0.00 deg	0.000000	<Default>	0.000000	☐	☐	
d111	Coil5	mm	2000.000 mm	2000.000000	<Default>	2000.000000	☐	☐	
d112	Coil5	mm	16 mm	16.000000	<Default>	16.000000	☐	☐	
d114	Coil5	deg	0.00 deg	0.000000	<Default>	0.000000	☐	☐	
d119	Coil6	mm	2000.000 mm	2000.000000	<Default>	2000.000000	☐	☐	
d120	Coil6	mm	8 mm	8.000000	<Default>	8.000000	☐	☐	
d122	Coil6	deg	0.00 deg	0.000000	<Default>	0.000000	☐	☐	
User Parameters									
C:\Users\nites\OneDri...									
d0		mm	81.600 mm	81.600000		81.600000	☐	☐	
G		mm	1.000 mm	1.000000		1.000000	☐	☐	
C1		mm	5.000 mm	5.000000		5.000000	☐	☐	
C2		mm	5.000 mm	5.000000		5.000000	☐	☐	
C4		mm	24.480 mm	24.480000		24.480000	☐	☐	
C5		mm	49.633 mm	49.633000		49.633000	☐	☐	
C6		mm	75.000 mm	75.000000		75.000000	☐	☐	
C9		mm	49.633 mm	49.633000		49.633000	☐	☐	
C10		mm	75.000 mm	75.000000		75.000000	☐	☐	

Figure 63 Adding parameters to user interface section for linking blade and mould parameters.