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REVERSE ENGINEERING AND MODIFICATION OF WIND TURBINE BLADE THROUGH 3D SCANNING AND CFD 6DOF ANALYSIS

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ABSTRACT

Efforts to increase the potential of low-speed wind energy can be achieved by optimizing blade shape. Reverse engineering is a method used to replicate components that will be developed or produced domestically, thereby reducing import value and wait times for ordering components. In this study, blades from foreign production will be tested through reverse engineering using a Scan-arm 3D Scanner. The result of the 3D scanning process, which is in the form of a point cloud, is processed with Rev Eng software to form a mesh. Then, the geometry data in mesh form is exported in .stl format for further processing in CAD software. The geometry modification process is carried out for optimization. The results of the modification process are then analyzed using CFD (Computational Fluid Dynamics) with the 6 degrees of freedom method. The torque and rotational speed obtained from the CFD analysis are used to calculate the theoretical mechanical power. The aim of this research is to modify the blade obtained through reverse engineering. By using the latest technology in the field of reverse engineering, the modification process is conducted to obtain blade geometry that can operate at low wind speeds. The Detailed Engineering Design (DED) data from each blade modification serves as a reference for the production/manufacturing of the reverse-engineered blade. The reverse engineering process can accelerate product design and development. By using a 3D scanner, complex geometric shapes that are difficult to interpret can be accurately digitized. In the reverse engineering process of the turbine blades, two modified variants were made. From the results of the CFD 6DoF method simulation, it was found that variant 1 had better aerodynamic properties than the original with changes in twist and an increase in the blade tip width. Meanwhile, variant 2, with modifications only to the twist angle, showed worse performance.

Keywords Wind turbine; reverse engineering; design; energy;
Paper type Research paper

INTRODUCTION

The application of technology in the field of renewable energy is a significant challenge, especially for Indonesia, which has more than 17,000 islands. The move towards a green energy transition requires a systematic approach to reduce the risk of green inflation. To meet the electricity needs across Indonesia, implementing off-grid wind turbine renewable energy systems is a potential option. However, wind speeds in Indonesia vary, generally at relatively low speeds, ranging from 4-6 m/s across the country. The potential for wind energy with speeds of 6-8 m/s occurs along the coast of Java, but only during certain months [1]. Therefore, for wind turbines to operate optimally throughout the year, a comprehensive wind turbine design suited to low wind conditions is necessary. The design must use readily available materials and prioritize ease of periodic maintenance, especially in remote areas.

Efforts to increase the potential of low-speed wind energy can be achieved by optimizing blade shape. Several studies in previous years have focused on blade geometry design. The development of vertical turbine blades by applying overlap and helix models has aimed to achieve a relatively high initial rotation speed [2]. Further analysis using the 6 degrees of freedom CFD method has been conducted on vertical wind turbines with combined Savonius-Darrieus blades [3]. Development efforts continued with horizontal wind turbines, which have a higher efficiency value compared to vertical axis types. Innovation in adding bent tips to horizontal wind turbines made from PVC was found to increase torque by up to 200% [4]. In 2023, the focus shifted to maximizing turbine blade geometry using airfoil and twist angle configurations, with composite materials as the base [5],[6]. A

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prototype of a horizontal wind turbine with mahogany wood blades was built in collaboration with P.T. PLN in Palang Tuban, successfully generating up to 10 kW of electricity. However, recent studies showed that there was a significant difference between the mechanical power and the generator power produced.

The reverse engineering method is used to replicate components that will be developed or produced domestically, thereby reducing import costs and shortening the lead time for component orders [7]. In this study, blades from foreign production will undergo reverse engineering using a Scan-arm 3D Scanner. The result of the 3D scanning process, in the form of a point cloud, is processed with Rev Eng software to form a mesh. Then, the geometry data in mesh form is exported in .stl format for further processing in CAD software. The geometry modification process is carried out for optimization. The results of the modification process are then analyzed using CFD with the 6 degrees of freedom method. The torque and rotational speed obtained from the CFD analysis are used to calculate the theoretical mechanical power [8], [9], [10]. The aim of this research is to modify the blades resulting from reverse engineering. Using the latest technology in reverse engineering, modifications are made to obtain blade geometry that can operate at low wind speeds. The mechanical power values obtained from CFD serve as a reference for data comparison. The Detailed Engineering Design (DED) data from each blade modification serves as a reference for the production/manufacture of reverse-engineered blades.

METHOD

The scanning process uses the Faro Quantum Max. The point cloud parameters are set with a resolution of 0.25 mm, and a clip plane height of 0.2 mm is applied. The conversion process utilizes Rev Eng 2022.3 software with settings as shown in Figure 3.2. The conversion method involves two steps: point filtering and mesh generation, using the "Detailed Object" setting template.

Figure 1. Original Turbine Blade

The reverse engineering process in this study involves a wind turbine blade purchased from China, as shown in Figure 1. This blade has an aerodynamic shape with a smooth surface and is equipped with two holes at one end, which are used for mounting or attaching it to the turbine hub. The blade's design is thin and tapers towards the tip, a common characteristic of wind turbine blades to optimize efficiency in capturing wind energy. The reverse engineering process of this blade involves analyzing its shape, dimensions, materials, and other design features to thoroughly understand its technical and functional specifications, allowing for replication or modification according to local needs or standards. The blade has a long, thin, and tapered shape, designed to maximize wind capture [11]. For low wind speeds, a blade with a larger surface area and an optimal angle of attack is crucial. The analysis focuses on modifying this shape to improve efficiency under low wind conditions, such as widening the blade profile or adjusting the angle of attack.

Figure 2. 3D Scanning Processes

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The 3D scanning process is carried out using a Faro Scan Arm in the Reverse Engineering Laboratory of the Mechanical Engineering Department at Polinema. The scanning process requires special precision to produce a point cloud with a low error rate. Figure 2 shows the 3D scanning process of the blade.

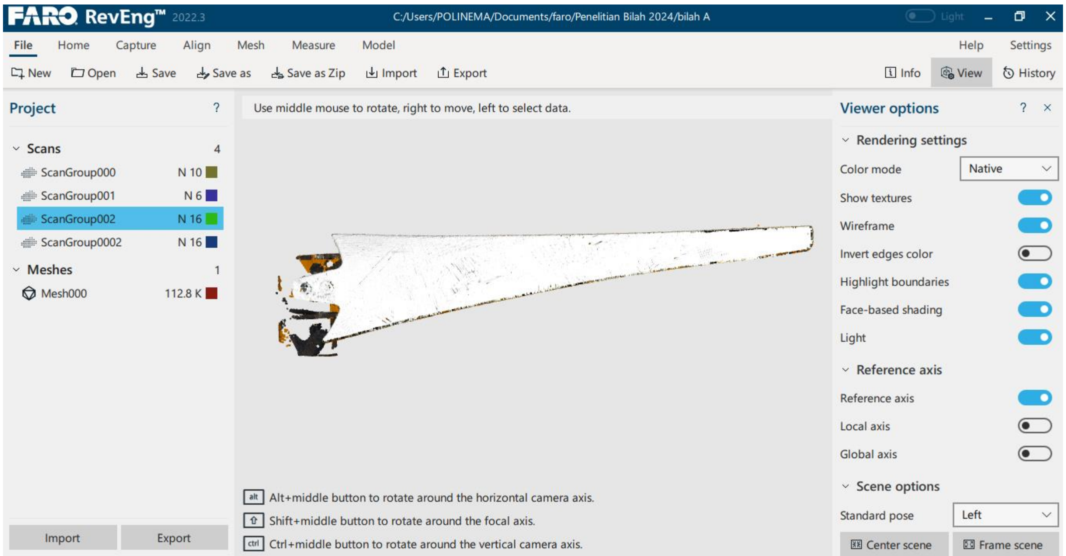

Figure 3. 3D Scanning Processes

The result of the 3D scanning process is a point cloud, as seen in Figure 3. The 3D scanner captures the contour colors. With an accuracy setting of 0.01 mm, the number of points in the point cloud is necessary for the blade's thin geometry. Some errors due to shadowing were manually removed to produce a more optimal mesh generation.

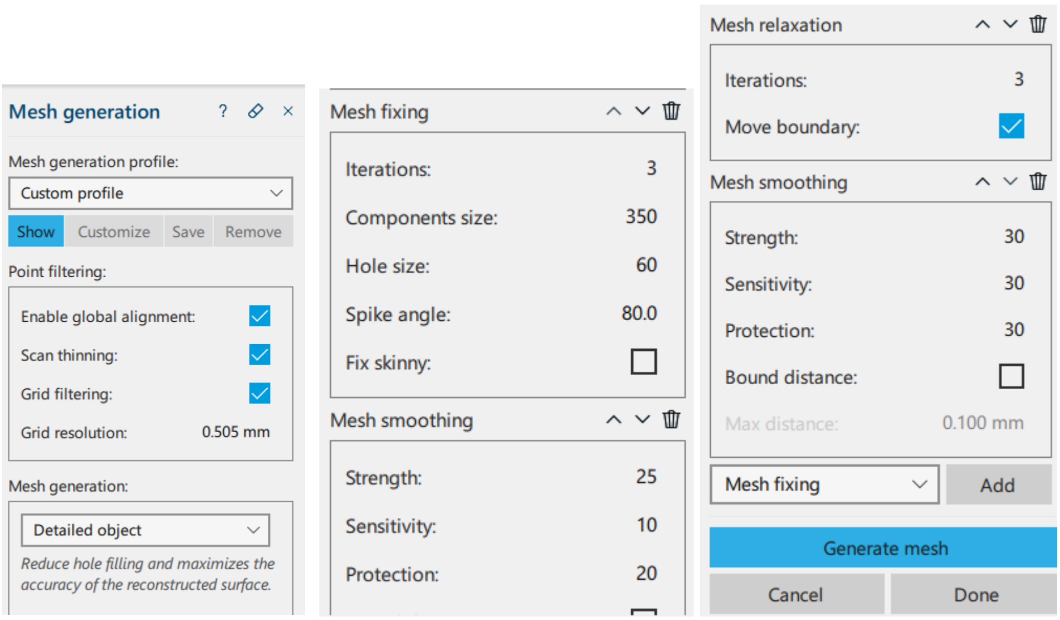

Figure 4. Mesh generation parameters

Figure 4 displays the user interface of software used to generate a 3D mesh from the 3D scan data of the blade. A 3D mesh is a digital representation of an object's surface, consisting of a collection of points (vertices) connected by lines (edges) to form polygons (faces). The setting stage is the core of the mesh generation process. By adjusting several parameters, the mesh quality can be optimized according to needs.

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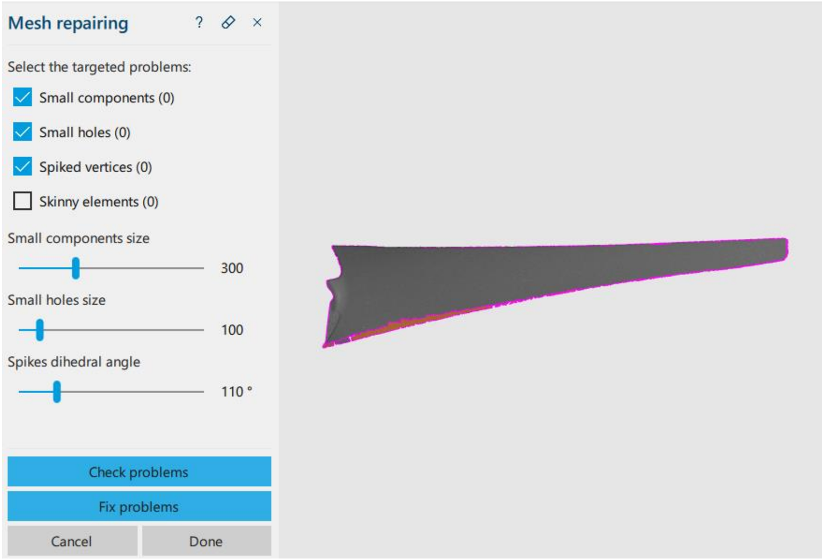
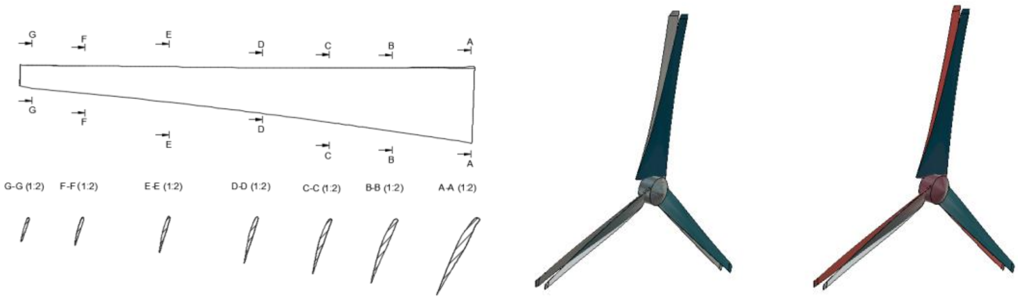


Figure 5. Mesh fixing steps

The figure 5 shows the mesh repairing process for the wind turbine blade model, which was generated in the previous mesh generation stage. Mesh repairing is a crucial step in 3D modeling to ensure that the digital model is ready for further analysis or production, such as fluid flow simulation or fabrication via 3D printing. The goal of the mesh repairing process is to ensure that the generated mesh is free from defects that could reduce the quality of analysis or prototype fabrication [12]. The turbine blade model being repaired will have improved mesh quality, making it more reliable for simulating wind turbine performance in low-wind conditions like those in Indonesia. After the repair process is completed, the digital model will be ready for the next steps in the reverse engineering or simulation process. In this study, modifications were made to the geometry of the object resulting from the 3D scanning process. Modifications were made to the blade width and twist angle, while the airfoil profile and blade length remained based on the 3D scan results. Variant 1 widens the blade tip by 50 mm with a twist angle of 25°. Variant 2 uses a twist angle of 5° without widening the airfoil.



(a) (b) (c)

Figure 6. (a) Cut drawing of original wind turbine. (b) Comparison of original design with variant 1. (c) Comparison of original design with variant 2

The figure 6(a) shows the appearance of the wind turbine blade tapering from the root (section G) to the tip (section A). This is a common shape for wind turbine blades, where the blade is thicker at the root for structural strength and thinner at the tip to reduce drag and improve aerodynamic efficiency. In the side view, several blade cross-sections are taken at specific points along the blade (G, F, E, D, C, B, A). Labels like G-G, F-F, and so on indicate the cross-section locations from the side view. The cross-sections show changes in the aerodynamic shape of the blade profile. At the root (G-G), the blade profile appears thicker, while at the tip (A-A), the blade profile becomes thinner and more curved. This illustrates a typical aerodynamic design where the root must be strong to withstand structural loads, while the tip must be aerodynamic to optimize wind flow.

The overall view shows the effect of tapering, where the blade gradually becomes slimmer toward the tip. This design balances structural strength and aerodynamic efficiency while reducing the twisting moment caused by wind at the blade tip. The blade design in variant 1 is optimized to

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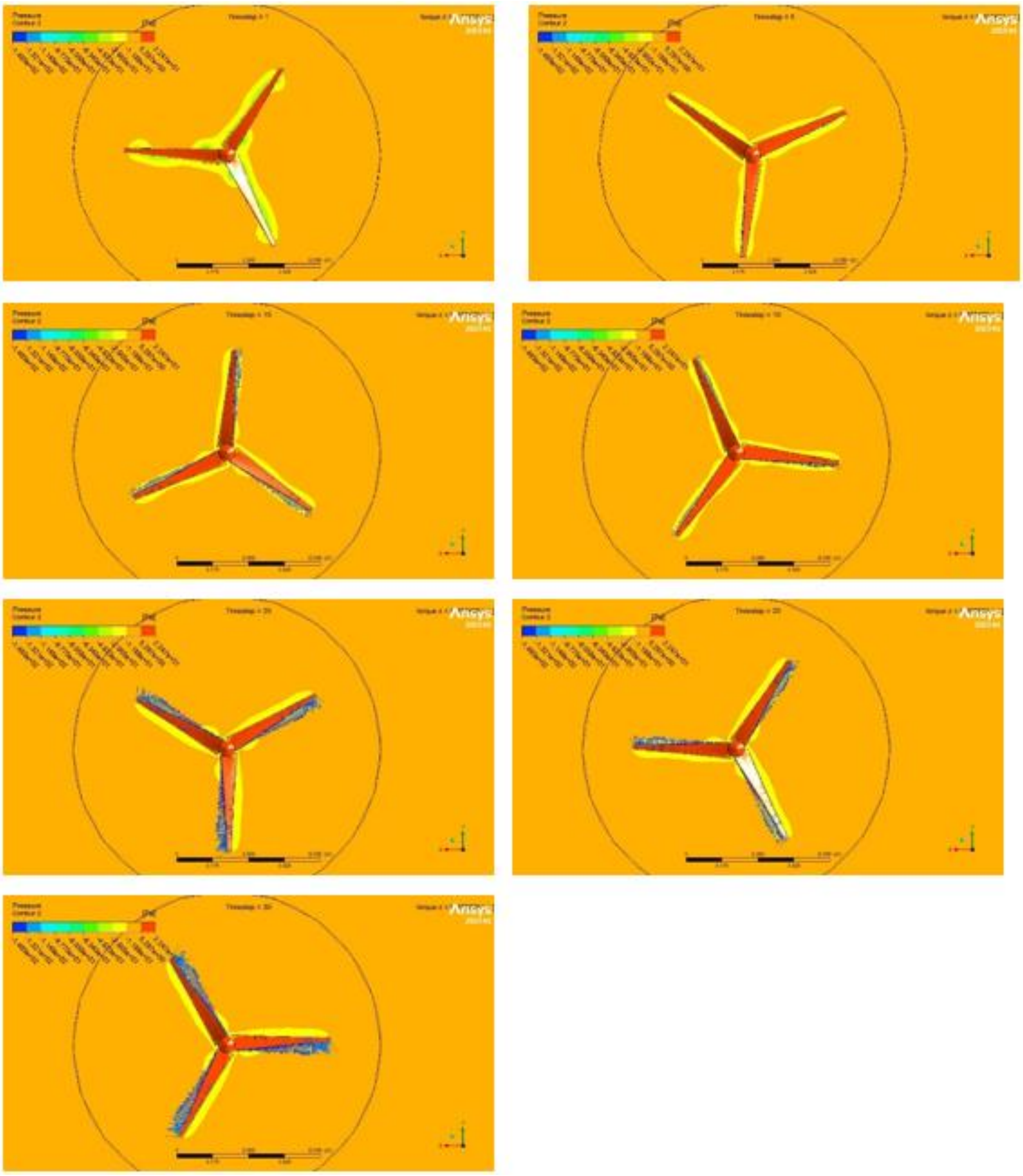
increase lift or reduce drag during rotation. A thicker or thinner blade profile in certain areas affects the airflow passing over the blade, which can increase torque and rotational speed of the turbine. Variant 2 uses a twist angle of 5° without widening the airfoil. The change in the twist angle aims to improve the cut-in wind speed, which is the minimum wind speed at which the turbine can start rotating.

DISCUSSION

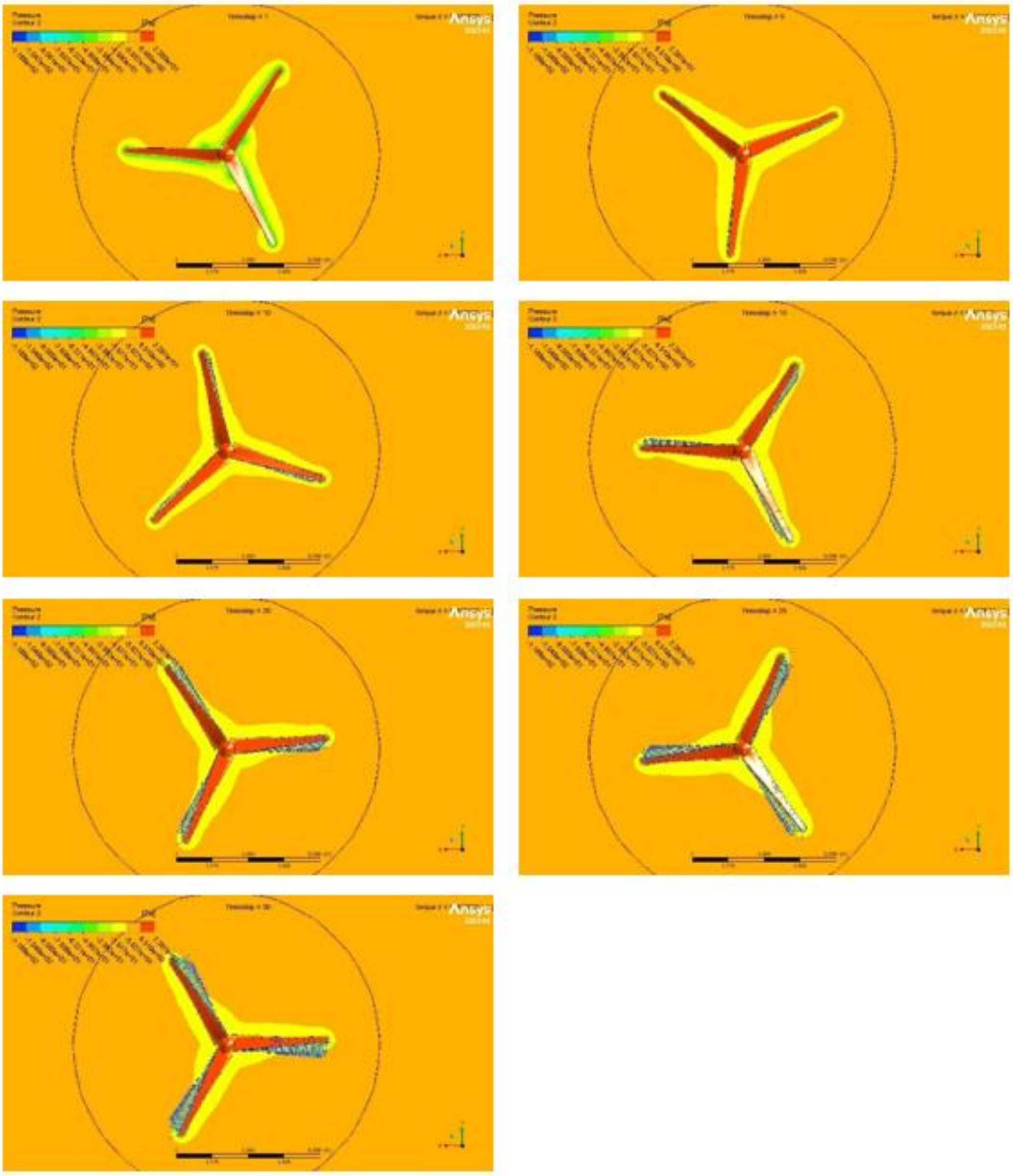
CFD Results

The simulation was conducted transiently, with wind speed at the inlet set to 6 m/s. Using the 6DoF method, the turbine's rotation due to wind impact can be analyzed. The turbine's rotation was observed from a stationary condition until the turbine reached motion within a 30-second time frame.

Data from each timestep were exported and divided into several .jpg files for observation. A deeper analysis was conducted on the pressure in the fluid region surrounding the turbine and the fluid flow speed in the area hitting the turbine.



(a)



(b)

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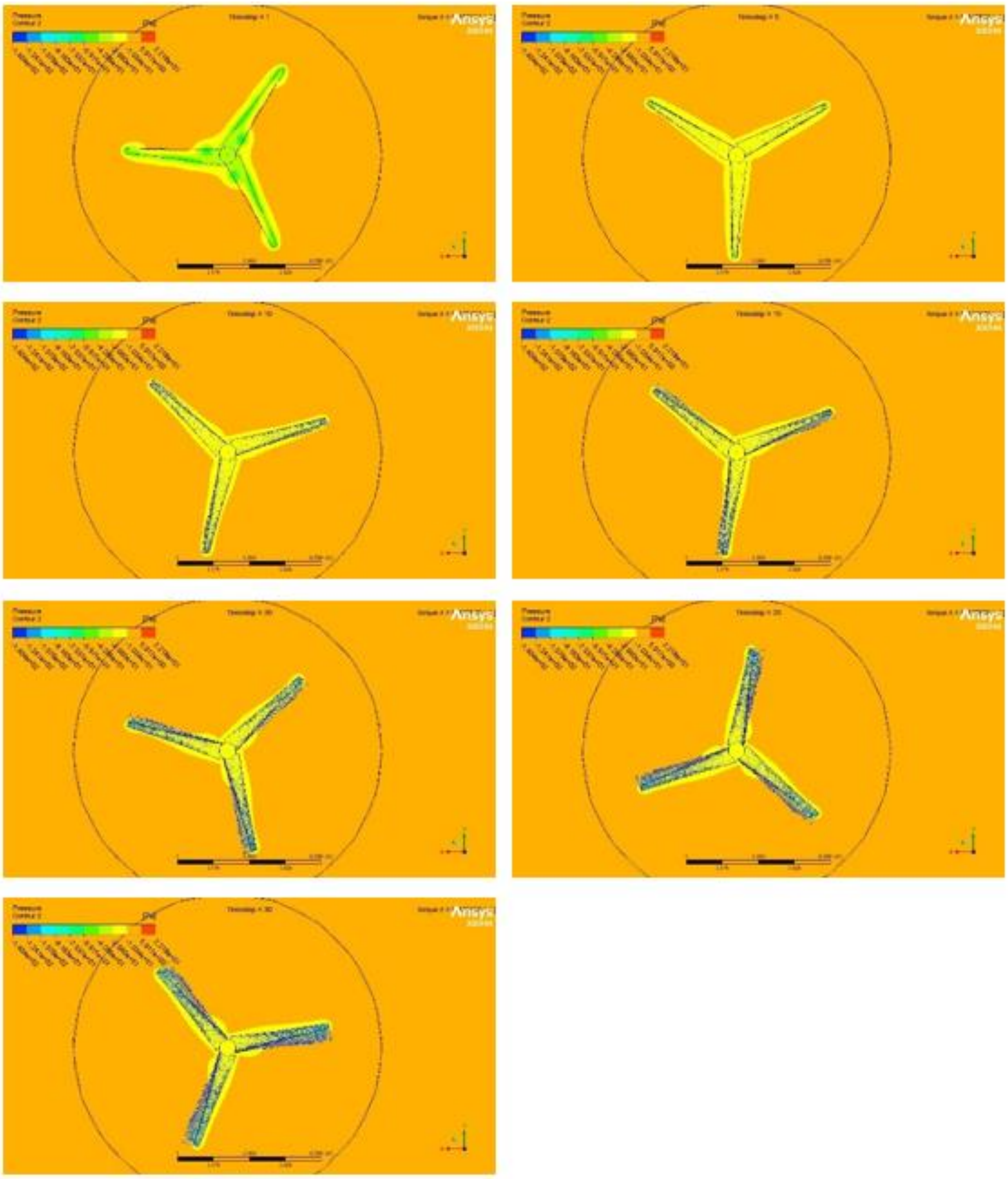

(c)

Figure 7. 6DoF simulation result in 0, 5, 10, 15, 20, 25 and 30 second. (a) original (b) variant 1 (c) variant 2

The simulation results plotted show the pressure contours in the fluid region affected by the turbine. Geometrically, the turbine rotates clockwise, showing lower pressure areas in the regions the turbine has passed. The colors on the blades depict the distribution of pressure or wind flow speed generated by the turbine's rotation. Brighter colors (yellow) represent areas with higher wind flow speed or pressure, while darker colors indicate lower pressure or reduced wind flow.

In each image, the color distribution along the blades gradually changes, indicating a shift in wind flow dynamics over time (with a 5-second interval between each image). Each image shows changes in the distribution of pressure and wind speed around the blades, which could be due to variations in local wind speed or the turbine's aerodynamic response to a constant wind speed of 6 m/s. Uneven pressure distribution along the blades provides insights into the turbine's performance and efficiency. Parts of the blades experiencing higher pressure contribute more to the generated wind power, while areas with lower pressure experience drag forces.

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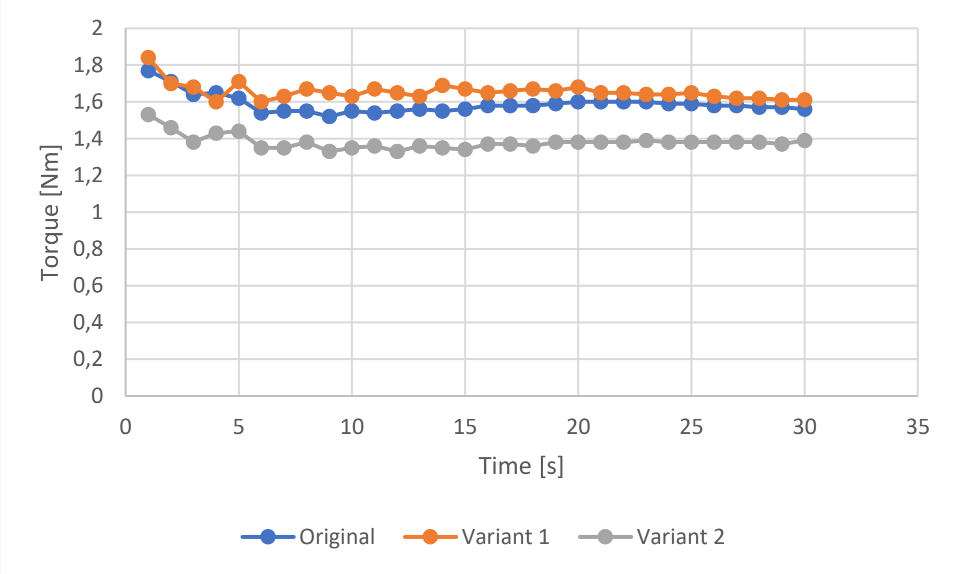

Figure 8. Torque values for each turbine geometry variation over time

Figure 8 shows a comparison of torque (in Newton-meters, Nm) for three wind turbine design variations (Original, Variant 1, and Variant 2) over a time span of 0 to 30 seconds. At the start of the simulation (0 seconds), all variations show higher torque, with Variant 1 slightly leading (~1.8 Nm), followed by the Original (~1.7 Nm), and Variant 2 with the lowest initial torque (~1.5 Nm). The torque quickly decreases in the first few seconds before stabilizing.

After around 10 seconds, all three variations stabilize at a nearly constant torque. Both the Original and Variant 1 settle at around 1.6 Nm, indicating similar performance in generating rotational force. In contrast, Variant 2 stabilizes at a lower torque of around 1.4 Nm, indicating less rotational force compared to the other two variations.

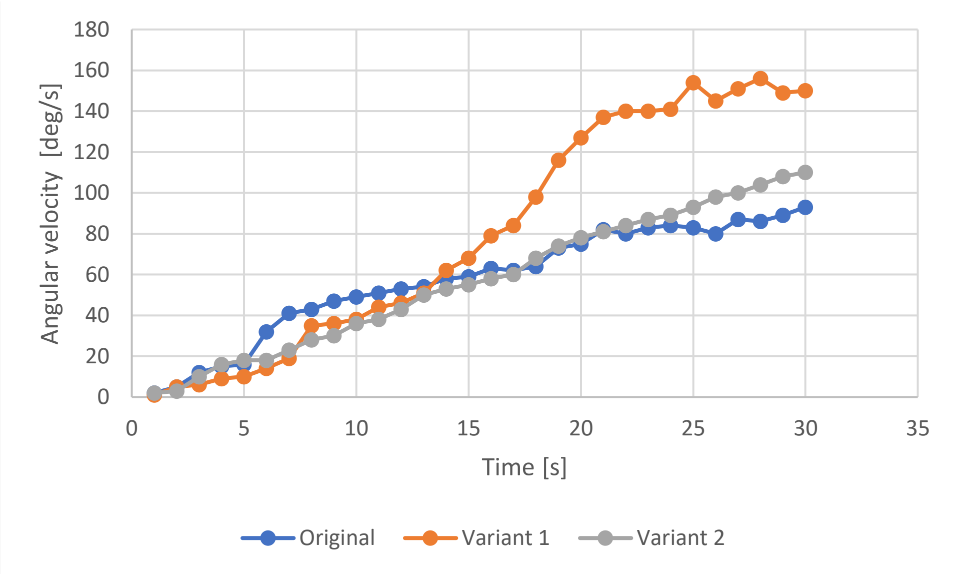

Figure 9. Tangential Velocity for Each Turbine Geometry Variation Over Time

Figure 9 compares angular velocity (in degrees per second) for the three wind turbine designs (Original, Variant 1, and Variant 2) over the time span of 0 to 30 seconds. Variant 1 experiences the fastest increase in angular velocity, reaching about 160 degrees per second at 25 seconds and then stabilizing around that value. A significant increase is noticeable after 5 seconds, showing that the turbine requires time to build stable rotational momentum. Compared to the Original (blue line), Variant 1 (orange line) performs better, with a higher angular velocity at nearly every time point after 5 seconds. Variant 2 (gray line) also outperforms the Original but does not reach the peak performance of Variant 1, with a maximum angular velocity of around 130 degrees per second.

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Variant 1 reaches peak performance (around 160 degrees per second) and stabilizes after 25 seconds. This indicates that the design of Variant 1 is more efficient at harnessing wind speed (6 m/s as mentioned earlier) compared to the Original and Variant 2. The stable torque suggests that despite differences in angular velocity, the torque generated by the Original and Variant 1 is nearly identical once the turbine reaches stable speed. This means that although Variant 1 produces a higher angular velocity, the force required to rotate the turbine remains comparable to the Original. Since power output is a function of both torque and angular velocity ($P = T \times \omega$), the higher angular velocity of Variant 1 will result in greater power output than the Original.

CONCLUSION

From the results of this research, several conclusions can be drawn:
The reverse engineering process can accelerate product design and development. Using a 3D scanner allows for the accurate digitization of complex geometric shapes that are difficult to interpret. The reverse engineering process applied to the wind turbine blades, with modifications to two variants, demonstrated through CFD simulation using the 6DoF method that Variant 1 exhibits better aerodynamic properties than the original, with changes in twist angle and the addition of blade tip width. In contrast, Variant 2, which only modified the twist angle, showed poorer performance.

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