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Research article

Implementation of multi-criteria decision method for selection of suitable material for development of horizontal wind turbine blade for sustainable energy generation

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ABSTRACT

The material selection process for producing a horizontal axis wind turbine blade for sustainable energy generation is a vital issue when using Nigeria as a case study. Due to the challenge faced with the low wind speed variations. However, this paper focuses on implementing MCDM for the material selection process for a suitable material for developing a horizontal wind turbine blade. This paper used a quantitative research approach using AHP and TOPSIS multi-criteria decision method. The study put into consideration the environmental conditions for the material selection process when designing the questionnaire. The authors extracted the data used for the selection process from the 130 research questionnaire distributed to materials engineers and renewable energy professionals. This research considered four alternatives that is, aluminum alloy, stainless steel, glass fiber, and mild steel to determine the best material for the wind turbine blade. Also, the model has four criteria and eight sub-criteria used for developing the pair-wise matrix and the performance score used for the ranking process of the alternatives. The result shows that a consistency index of 0.056 and a consistency ratio of 0.062 gotten via the AHP method is workable for material selection practice. 78%, 43%, 67%, and 25% are the performance scores for the four alternatives via the TOPSIS techniques. In conclusion, aluminum alloy is the best material, followed by glass fibre. Therefore, the decision-makers recommended aluminum alloy; hence, manufacturers should apply aluminum alloy to develop the wind turbine blade for sustainable energy generation.

1. Introduction

Nigerians have been making use of fossil fuel as a major source of energy generation for over a hundred decays. But, the energy generated from fossil fuel has become a problem because it causes environmental pollution and Ozone layer depletion (Akuru et al., 2017). Renewable energy is the only source that will end this ecological pollution during power generation via fossil fuel. And substituting fossil fuel consumption depends on the rapid development of renewable electricity (Scarlat et al., 2015; Zervos, 2009). The European Union (EU) In 2020, aimed to make use of renewable energy sources via the wind to produce most of their electricity. Wind energy has advantages over other sources of developing power because it's free from environmental pollutions. The EU intends to achieve a wind energy growth rate of 21% from 2020 (Scarlat et al.,

2018). Electrical energy is significant for developing countries because it has vital effects on their nation's economy. The manufacturing company in Nigeria, both small and large-scale industries, need a stable power to run their day-to-day business (Lechner and Boli, 2020). Nigeria generate 4,000 MW and does not supply the demand of the consumers. The nation has been facing an electrical crisis, which has affected the economic stability. And to keep the financial stability of the country, the decision-makers need to move towards renewable energy for electricity supply. The specific focus is wind energy as a replacement for fossil fuel because the power generated from wind is friendly and does not affect the ozone layer. It is worth knowing that electricity generated from the wind is affordable and is a clean energy generation (Vidadili et al., 2017). Power generating via the wind turbine will aid the nation in achieving a sustainable development goal (Fayomi et al., 2018).

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The challenge faced is because of the wind speed in Nigeria varies from 3 m/s to 9.5 m/s. The wind speed is among the low wind speed region (Oyewole and Aro, 2018). For the wind speed to develop sustainable electricity, the material used must be able to work under low wind speed (Okokpujie et al., 2018a,b,c,d). Literature has proven that horizontal wind turbines can work under low wind speed when compared with the vertical axis wind turbine (El Khchine et al., 2019). Hence, this research is focusing on the horizontal wind turbine blade. The manufacturer makes the horizontal axis wind turbine with several parts and components such as the shaft, hub, blade, gearbox, brake, and the generator. Every part has its functionality. The wind blade is a significant part that has a great influence on producing power from the wind. So, studying the materials used for developing wind turbine blades has become a serious issue because of the failure rate recorded from literature (Chehouri et al., 2016; Chou and Tu, 2011; Shafiullah et al., 2013). As depicted in Figure 1. Chou et al. (2013) carried out a study of the

failure rate of a horizontal wind turbine. The authors discovered that the highest rate of failure occurs at the blade section of 20%, as shown in Figure 2.

Lee et al. (2015) also carried out an experimental analysis of the wind turbine downtime and the cost of maintenance in service. The result shows that the blade has a 30% cost and 34% downtime, as presented in Figure 3.

The wind turbine blade is vital, and the material selection process cannot be over-emphasized. It worth knowing that the blade material choice is a serious problem facing the manufacturing industry. The wind turbine blade is one of the most significant parts of the turbine (Njiri and Soeffker, 2016). Blades are used to translate the wind energy into mechanical energy via the wind turbine blade, which causes a rotational force on the shaft. Then the shaft transmits the rotational force into electrical power via the generator. Wind blades are essential components of the wind turbine, not because they convert the wind kinetic energy. But the failure of one blade will lead to malfunctioning and causes a total

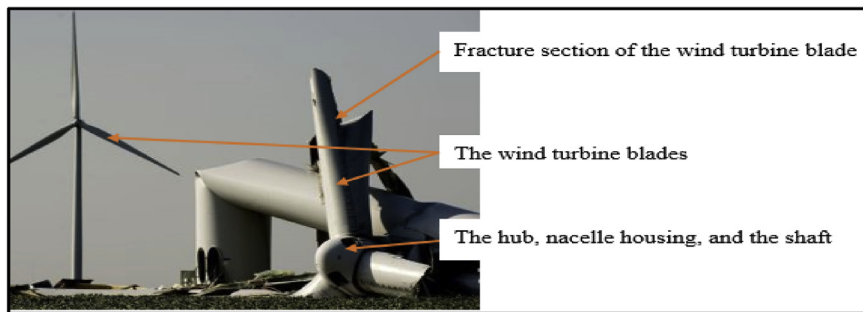


Figure 1. Failure of wind turbine blade during operation. Source: <http://stopthesethings.com>.

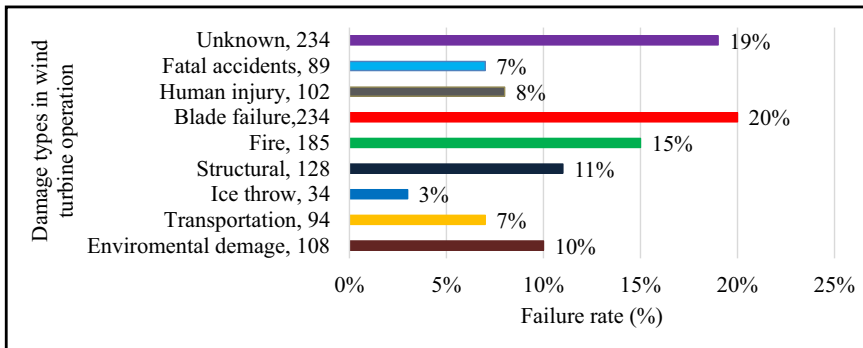


Figure 2. Analysis of the damage types and failure rate that occurs during wind turbine operation.

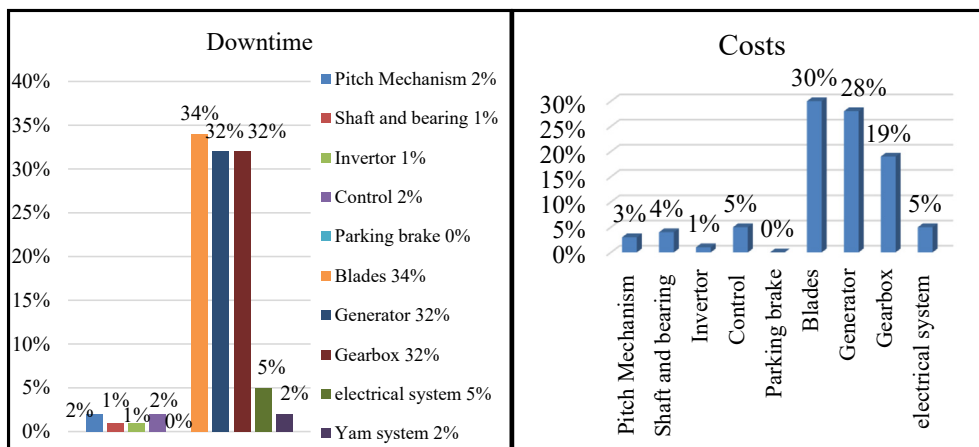


Figure 3. The analytical review of the downtime and cost-effectiveness of a wind turbine.

operational stoppage of the wind turbine (Odia et al., 2016). Turbine blades convert the kinetic energy from the wind by creating a lift because of its curvature shape. The large and the thinning curve section generates low air pressure and high air pressure. To enable the air to flow through the blade, causing the blade to rotate. This explains the airfoil shape of the blade, as shown in Figure 4.

Due to the complexity of the blade, the materials for the blade development. Should be machine-able, durable, high corrosion resistance, high wear rate resistance, high strength to lightweight ratio, and, most of all, cost-effective. These are the motives why researchers are carrying out studies using different methods to investigate the choice of material for designing wind turbine blades (Nwoke et al., 2017; Okokpujie et al., 2018a,b,c,d). There are various techniques to carry out the material selection process; however, this study focus on the Multi-criteria decision method (MCDM).

MCDM is a unique tool used to solve complex problems in engineering and other fields of life that deal with the issues of choice (Huang et al., 2011). This method helps in breaking down the problem into smaller sections, and the decision maker's analyses it to resolve the issues with reasonable solutions. MCDM is consistent, very simple to apply, and has several methods. i.e., AHP, DEA-CCR model, entropy method, EDAS, FAHP, TOPSIS, TOPSIS using Excel, and WASPA (Fatemi and Rezaei-Moghaddam, 2019; Almeida, 2019). Researchers use these methods either to solve the issues of choices of location, supply chain, and materials selections for the design of mechanical systems (Zavadskas and Turskis, 2011).

The decision-makers break down the problems into smaller sections, and the analysis of the solutions relies upon experience and observational of professional. AHP always ask that individuals in the essential administration process should handle the issue (Zhang et al., 2019). It is fundamental that anchoring each vital segment related to the topic inside the dynamic framework. The review structure is the procedure from the best objectives to the administrative perspective. The measurement criteria and sub-criteria rely upon the alternative measured (Wang et al., 2019). The development of the pair-wise matrix carried out with a pecking ask, and data gathering is to merge the wise relationships. And choose the general importance of the segments in each measurement (Ansari et al., 2019; Hwang et al., 2016; Gugliuzza and Drioli, 2013). The criteria and sub-criteria are not likewise fundamental to each other and sometimes does not decide each part in the same hierarchy of judgment. AHP gives an illustrative method that joins the evaluations of the alternatives and criteria by a social event related to the essential authority. AHP, add the two segments of the pair-wise examination for diminishing the sensible multi-faceted nature of an investigation (Wang et al., 2009).

Incorporates norms are adequate by Satty (2008); Tučník and Bureš (2016). Set pair-wise study, encompasses the three positions:

- associating a connection at each choice at a pecking ask starting from the second measurement and working,
- addressing the relative burdens for each segment of the dynamic framework,

- testing the consistency extent to check the consistency of the judgment.

A lot of engineering selections techniques make use of MCDM to solve problems that need urgent decisions making. Ohunakin and Saracoglu (2018) used five multi-criteria methods in studying a suitable location site for solar plants for power generation. The result shows that the MCDA method used was sound for the study since solar energy is one of the profitable renewable energy for sustainability. Also, Saracoglu et al. (2018) work on a related review of the selection of solar energy local sites. Masebinu et al. (2018) applied MCDA in resolving solid waste recovery from a fraction of organic products. The model could fix the problem and help in providing environmental sustainability. Mayaki et al. (2018) used MCDA in selecting a suitable site for wind farm development in Nigeria. Therefore, the need to carry out more material selection process on the wind turbine blade for sustainable development of wind energy in Nigeria. This will lead to an increase in the productivity rate of the Nigerian economic (Orisanmi et al., 2017; Okokpujie et al., 2017; Yekini et al., 2018; Dunmade et al., 2018). And also ignite the industrial revolution and development of more research concept with the wind energy (Azeta et al., 2016; Onawumi et al., 2018; Ongbali et al., 2018; Udo et al., 2018; Okokpujie et al., 2018a,b,c,d). Rashedi et al. (2012) applied multiple constraint objectives to study a material selection of the towel and the blade. The selected criteria are mass concentrations of carbon footprint and epoxy concentrations. The authors do the study to determine a suitable material. By investigating epoxy-carbon fibre composite to determine either it will be a suitable material for developing the blade and towel sections of the wind turbine. The result shows that the best material composite is epoxy-carbon composite of 74% mass, 17% carbon footprint with 30% energy reduction. And the material produces 78% weights, 26% of carbon and energy. But it has a high rate of 67% cost. The authors noticed that the study has challenges because of the material and its properties the manufacturers supplied.

Babu et al. (2006) work on the material choice process for a vertical wind turbine blade applying fuzzy linguistic limits with the TOPSIS method. The study considers five materials, including carbon fibres, Steel, Aluminum, Aramid fibres, and electrical glass. The authors select these materials based on the property of the content, stiffness (GPA), tensile strength (Mpa), density (g/cm³), elongation at break (%), and highest temperature of the component. From the result, the decision maker's selected Aramid fibres because of the materials property it owned. However, the decision-maker could not settle for that; they looked into the compressive strength, poor machinability and poor environmental stability of the Aramid fibres and concluded by chosen carbon fibre over Aramid fibres. From the study, the TOPSIS and fuzzy linguistic method aid in the material choice process. Therefore, the investigation bears some limitations to an extent because the authors only considered the properties of the alternatives. The researchers did not put into consideration the weather condition at which the wind turbine blade will work. So, the need to review the flexibility, brutality,

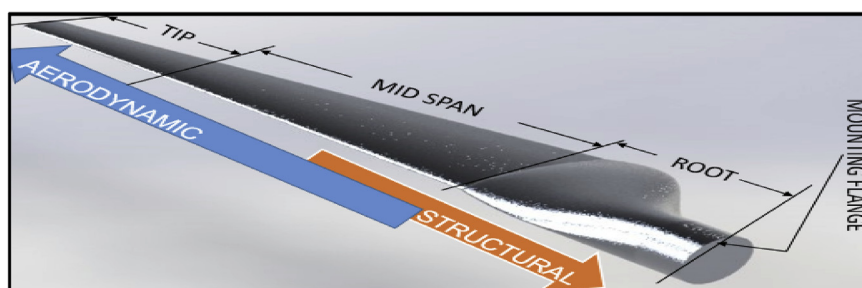


Figure 4. The aerofoil shape of the wind turbine blade.

durability, corrosion rate, cost of the material, and availability of the materials, and this is the research focus of this study.

From history, a lot of scientists have carried out a study of a selection of area using MCDM for building a wind farm in Nigeria. However, materials selection of the wind turbine blades has not given concentration. And the wind speed of these locations needs aerofoil shape and excellent blade material that can withstand high humidity and work under low airspeed. The specific focus of this study is to implement MCDM to investigate for aluminum alloy, stainless steel, glass fibre, and mild steel for producing wind turbine blades. The novelty of this study attributed to the knowledge of experts in material science and renewable energy used for the material selection process. Through a good design questionnaire with a rigorous literature survey on material selection. Therefore, this research focus on implementing MCDM for selecting suitable material for developing a horizontal wind turbine blade for the sustainability of electricity generation via the wind turbine.

2. Method

This section comprises the methods used for investigating a suitable material for developing a wind turbine blade. This research work applied the quantitative research approach for the material selection of the blade for low wind speed areas in Nigeria. The justifying of the quantitative research approach is the fact that the research deals with the numerical analysis of data gotten from questionnaires and literature. However, the study used the AHP and TOPSIS techniques for developing the pair-wise matrix and the rating of the four (4) alternatives. The authors analysed the criteria according to the present situation at the time of the research, price/cost per 1 kg at a price in the market. Also, the corrosion resistance rate (in terms of air or oxygen attack), weight, and the durability level. With a scale of 1–5, such as 5 = excellent; 4 = very good; 3 = good; 2 = satisfactory; 1 = poor. After getting the ideas from material science and renewable energy engineers, the authors interpret their opinions into numerical data. An applied the AHP and TOPSIS methods to achieve the ratings and the performance evaluation of the four alternatives. Under this section, entails the explanations of the data collection process, AHP, TOPSIS, framework, Descriptions of the goal, criteria, sub-criteria, the alternatives, and the Consistency study. The authors used Excel 2016 software for the mathematical calculations by applying the formulae from AHP and TOPSIS method.

2.1. Data collection

This research used a quantitative strategy for the investigation through a concentrated optional information. And got the required, optional information from consultations of literature and constructed questionnaire. Distributed the questionnaires to the materials science engineers at Aluminum roll mill company, Ajaokuta Steel Company Limited and Nigeria foundry limited. By implementing a total number of 130 research questionnaires. The complete information from professionals' ideas through the questionnaire was used to get data and ratings of the decisions.

2.2. Method descriptions of the analytical hierarchy process

Analytical hierarchy process (AHP), the first step, is the pair-wise matrix, and developing the model is by comparing one criterion to the other within the four criteria's. When two criteria have the same significance, they will have a score equal to one (1). The decision-makers scored the criterion that is more significant than one high using the scoring scale. At the end of the process, ratings were used to determine the final decision with the TOPSIS techniques.

Starting at the top point of the chain of command and working down, it breaks the savvy match relationship at a dimension down to various square frameworks $B = [b_{ij}]_{n \times n}$. The study has four (4) alternative, and four significant criteria's, hence, the developed matrix is 4 by 4 matrix, as shown in Eq. (1).

$$\begin{bmatrix} b_{11} & b_{12} & b_{13} \dots & b_{1n} \\ b_{21} & b_{22} & b_{23} \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & b_{n3} \dots & b_{nn} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \dots & b_{1n} \\ \frac{1}{b_{12}} & b_{22} & b_{23} \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{b_{1n}} & \frac{1}{b_{1n}} & \frac{1}{b_{23}} \dots & b_{nn} \end{bmatrix} \quad (1)$$

Therefore, Eq. (2) showed the reciprocal properties.

$$b_{ji} = \frac{1}{b_{ij}} \quad (2)$$

AHP recommends the use of a relative importance scale from 1 to 9 for the decision to develop the pair-wise matrix. However, designing all pair-wise comparison matrices, the vector weights, $\omega = [\omega_1, \omega_2, \dots, \omega_n]$ is calculated on the foundation of Saaty's eigenvector technique (Saaty, 2008). is calculated on the foundation of Saaty's eigenvector technique (Saaty, 2008). The calculation of the weights encompasses two steps. First, the normalized pair-wise comparison matrix, $B = [b_{ij}]_{n \times n}$, by Eq. (3), and then the calculated weights by Eq. (4) (Benitez et al., 2007).

$$\hat{b}_{ij} = \frac{b_{ij}}{\sum_{i=1}^n b_{ij}} \quad (3)$$

determined the weight computation as follows

$$\hat{\omega}_{ij} = \frac{\sum_{j=1}^n \hat{b}_{ij}}{n} \quad (4)$$

Assuming for all that. i and $j = 1, 2, 3, \dots, n$.

Eq. (5) gives the correlation between the vector weights, w , and the pair-wise comparison matrix b exits.

$$B * \omega = \lambda_{max} * \omega \quad (5)$$

The λ_{max} value is a significant validating factor in AHP and used as a situation index to screen information by determining the consistency ratio (CR) of the average vector. To determine the CR and the CI for all the matrix of order n Eq. (6) used.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

Therefore, determined the CR by applying Eq. (5)

$$CR = \frac{CI}{RI} \quad (7)$$

where RI is the random consistency indices value gotten from a randomly produced pair-wise evaluation matrix, applying the RI matrix of the order of 1–10 presented in Table 3. If $CR \geq 0$, then the comparisons are satisfactory. However, if $CR \leq 0.1$, the values of the ratio shows that the matrix has inconsistent judgments.

2.3. TOPSIS method

For the evaluation of horizontal wind turbine blade selection, the study used the TOPSIS technique. TOPSIS is a method used in MCDM to resolving world problems adequately (Bid and Siddique, 2019; Nikas et al., 2018). TOPSIS efforts are to specify the best alternative that has the shortest distance from the best ideal value and the furthest distance from the worst ideal value. The positive value or solution is minimizing the cost criteria and maximize the profit criteria (Dos Santos et al., 2019). However, the negative value is the opposite of a positive value. In the TOPSIS technique, applied the specific scores for all the alternative gotten from the criteria evaluation to develop the vector-matrix, normalized matrix, and weighted normalized matrix. By taking into action the ratings of all criteria, best, and worst ideal solutions (Zavadskas et al., 2016). Also, equating the distance factor of individual alternatives, however, achieved the ranking order of the other options.

TOPSIS process for decision making is as follows:

Step 1: Development of the normalized decision matrix of definite and non-positive criteria for the material selection process of the wind turbine blade. Hence Eq. (8) gives the normalized decision equation.

$$\bar{b}_{ij} = \frac{b_{ij}}{\sqrt{\sum_{j=1}^n b_{ij}^2}} \quad (8)$$

where, $j = 1,2,3,\dots$; $i = 1,2,3,\dots,n$, \bar{b}_{ij} and b_{ij} are the vectors and original normalized matrix.

Step 2: Develop the weighted normalized decision matrix by multiplying the weights ω_j of assessment criteria with the normalized decision matrix b_{ij} by developing the weighted model using Eq. (9).

$$V_{ij} = \bar{b}_{ij} \times \omega_j \quad (9)$$

Step 3: Calculate the positive ideal value and the negative ideal value for the various materials involved in this study. The authors use the excel 2016 software with Eqs. (10) and (11) to determine the ideal value.

Where V_j^+ this is the positive ideal value for the criteria,

$$V_{ij} = \text{the maximum value} \quad (10)$$

$$V_j^- \text{ the negative ideal value for the criteria. } V_{ij} = \text{the minimum value} \quad (11)$$

Step 4: Implementing the excel software to calculating the Euclidean distance of the ideal best (Ed+) and ideal worst (Ed-) using Eqs. (12) and (13) for the material selection process of the wind turbine blade.

$$Ed^+ = \left[\sum_{j=1}^n (V_{ij} - V_j^+)^2 \right]^{0.5} \quad (12)$$

$$Ed^- = \left[\sum_{j=1}^n (V_{ij} - V_j^-)^2 \right]^{0.5} \quad (13)$$

Step 5: Calculate the performance score for the selection process of each alternative. However, using Eq. (14) to test the best choice with excellent performance score during the material selection process for the wind turbine blade.

$$P_s = \frac{Ed_i^-}{Ed_i^+ + Ed_i^-} \quad (14)$$

Step 6: Ranking the alternatives.

Ranking the alternatives according to the maximum values of the performance score for the four choices, respectively.

2.4. Developing the framework system

MCDM encompass five major sections, such as to determine:

- Goal
- The opinions of the decisions makers
- The selection for the alternatives
- Sub criteria evaluation
- The final output of the combination of choice with the criteria

Three models used in the AHP for basic reasoning are according to the accompanying:

- Disintegration: sorting out the parts of the issue into a hierarchy of leadership,
- Near decisions: making a network of pair-wise connections of all segments in measurement with detail to each related sector in the analysis
- Union of needs: figuring the overall demand of the divisions at any rate of frequency of the pecking request (that is, the decisions).

The choice of criteria is significant for the assessment process and acknowledged with comprehensive literature in the introduction. Since knowing the goal, criteria, and alternatives, this paper focused on four types of criteria that are price/cost (B1), lightweight (B2), corrosion resistance (B3), durability (B4). And the four (4) alternative materials selected are aluminum alloy (AA), stainless steel (SS), glass fiber (GF) and mild steel (MS). Figure 5. Shows the decision framework of AHP, with the detail descriptions of the assessment criteria presented in Table 2.

2.5. Descriptions of the goal, criteria, sub-criteria and the alternatives

Wind turbine makes use of the wind to generate electrical power by the rotation of the blades. For some decades, the manufacturers used wood to develop wind turbine blades. But due to its composition, such as

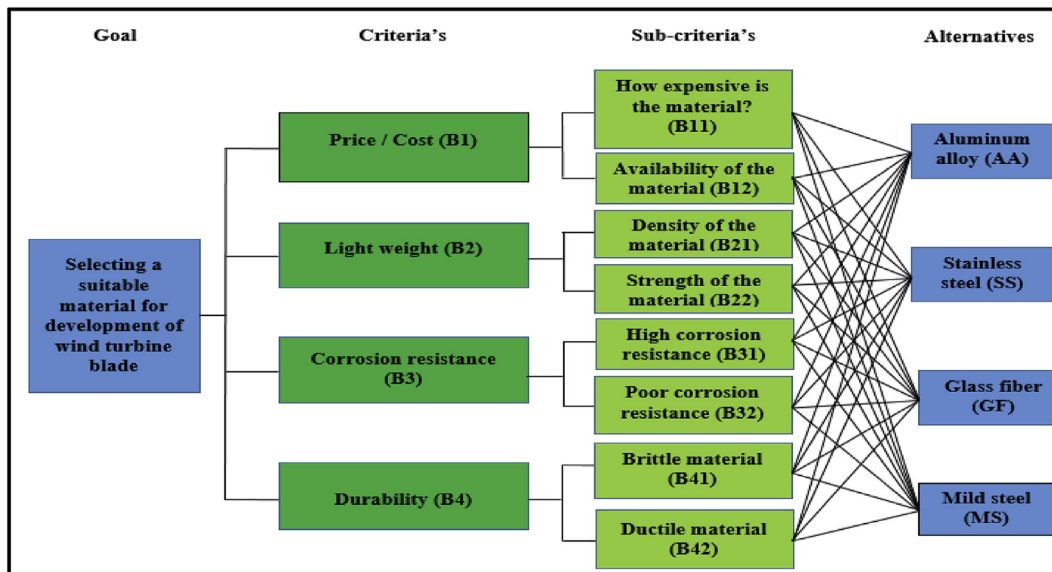


Figure 5. Breaking down the problem into Hierarchy by building the decision framework.

Table 1. Evaluation of sub-criteria and the corresponding description.

Sub-criteria No	Sub-criteria	Descriptions
B ₁₁	Expensive	One of the essential criteria is cost, how cheap or costly it is the material in the marketplace.
B ₁₂	Availability	The material availability can also influence the cost of the wind turbine blade, which will either increase the price of the wind blade or reduces the price.
B ₂₁	The density of the material	In developing a wind turbine blade, the density is very significant as the density affects the weight to strength ratio.
B ₂₂	Strength of the material	The strength of the material is a compulsory factor in designing the wind turbine blade. Is the metal durable, or does it have an excellent hardness property?
B ₃₁	The high corrosion resistance material	Corrosion is an essential property to select covers for the development of a wind turbine blade because the wind turbine blade operates in a moist condition, where there is a need to fight corrosion. So the material needs to have high corrosion resistance, and the materials must be able to withstand the attack from the air or oxygen within the environment.
B ₃₂	The poor corrosion resistance material	A material with weak corrosion resistance is not too fit for wind turbine blade design
B ₄₁	Brittle material	The durability of the material in operations is an important issue. If the material is brittle, it can fail with little or no warning. Leading to the full stoppage of the horizontal wind turbine, and it can be disastrous.
B ₄₂	Ductile material	The ductility of the component is a serious issue because some components transit from ductile to brittle under some force or pressure.

its high sensitivity to moisture, which causes the material to fail with little or no warning occurs for alternatives. However, metals like stainless steel, aluminum alloy, glass fiber, and mild steel a replacement for wood.

Goal: Selecting a suitable material for the development of a horizontal wind turbine blade, that can perform in a low wind speed region in Nigeria.

Criteria: There are four main criteria selection purposes for wind turbine blade development. These include B1: price/cost, B2: Light-weight, B3: corrosion resistance, B4 durability. They are also important as the eight (8) sub-criteria.

Sub-criteria: Table 1 shows the eight significant factors in this decision process and their description.

The alternatives: This section describes the four options selected for this study.

Aluminum alloy (AA): is an alloy that contains about 85% of aluminum as the predominant metal. The specific alloying elements are magnesium, copper, tin, zinc, silicon, and manganese. There is two types of aluminum alloy, which are casting alloys and wrought alloys, which are in two categories knowing as heat-treatable and non-heat-treatable. Aluminum rolling mill in Ota Ogun State Nigeria developed the aluminum 6061-T9 alloys and provided it for this study. The alloys contained a high percentage of chromium with excellent mechanical properties. The manufacturing companies used aluminum alloy for designing engineering components and for structural applications, where the design need high corrosion resistance and lightweight to strength

Table 2. Random inconsistency indices for n = 10.

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

Table 3. Relative ranking scale Satty (2008).

The intensity of Relative Importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Extreme importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
1/3, 1/5, 1/7, 1/9	Reciprocal for inverse comparison

ratio materials. Aluminum alloy metals have a thin protective layer of oxide that covers the surface, which protects the aluminum from being an attack by air.

Stainless steel (SS): are alloys materials, also known as inox steel that contained 10.5% of chromium and a maximum of 1.2% of carbon by mass. The 316s applied in this research is well notable for their high corrosion resistance, and they are used to develop home appliances, construction materials, and industrial equipment. They are heavier when compared with aluminum alloy. Stainless steel reacts with air to form metallic oxides or hydroxides, which contain some corrosion products. Applying stainless steel is a good idea in developing a wind turbine blade, but stainless steel will react with air, and it will increase the failure rate of the blade.

Glass fiber (GF): contains various excellent fibers of glass, and they also have good mechanical, chemical, and thermal properties during engineering operations. Most glass fiber reinforcement is from electrical glass, which has excellent heat resistance and electrical property. Glass fiber possesses high strength, adequate stiffness, and proper density. However, the glass fiber has little fire resistance during operations.

Mild steel (MS): are metals developed from the mixture of iron ore and coal. During the extraction of the iron ore and coal from the earth, they are further melted in a blast furnace to produce mild steel. Mild steel is very cheap and locally used for many applications. The disadvantage of mild steel is that mild steel gets rust quickly that is, has weak resistance to corrosion, but can be heat-treated and easy to machine.

2.6. Consistency analysis using AHP

Consistency study is calculating the C, R, C, I while adopting the R, I from Satty (1990). Tables 2 and 3 show the R, I values and the relative ranking scale to generate the pair-wise comparison matrix.

3. Result and discussion

In order to determine a suitable material for the blade, the author defined the pair-wise comparison matrix, and rate the criteria according to the relative scale from extreme importance to equal importance. The normalized pair-wise model, total pair-wise model, is used to divide each interest, and Eq. (4) is used for the average weight of the pair-wise matrix, as shown in Tables 4, 5, and 6.

To determine the Consistency Analysis of the pair-wise comparison matrix, using Eqs. (6), (7), and (8). Table 7 present the weight of the four criteria chosen for this selection process.

$$\lambda_{max} = \frac{\sum_{j=1}^n \hat{\omega}_{ij}}{n} \tag{15}$$

Therefore, since the proportion of the inconsistency of the consistency ratio is less than 0.1, that means the developed pair-wise comparison

Table 4. Developing the pair-wise comparison matrix using AHP method for the four (4) criteria.

Criteria	Price/cost (B1)	Lightweight (B2)	Corrosion resistance (B3)	Durability (B4)
Price/cost (B1)	1	7	5	9
Lightweight (B2)	0.14	1	0.33	3
Corrosion resistance (B3)	0.2	3	1	4
Durability (B4)	0.11	0.33	0.25	1

Table 5. Pair-wise comparison matrix total in column.

Criteria	Price/cost (B1)	Lightweight (B2)	Corrosion resistance (B3)	Durability (B4)
Price/cost (B1)	1	7	5	9
Lightweight (B2)	0.14	1	0.33	3
Corrosion resistance (B3)	0.2	3	1	4
Durability (B4)	0.11	0.33	0.25	1
Total	1.45	11.33	6.58	17

Table 6. Normalization of the pair-wise comparison matrix.

Criteria	Price/cost (B1)	Lightweight (B2)	Corrosion resistance (B3)	Durability (B4)
Price/cost (B1)	0.687	0.617	0.759	0.529
Lightweight (B2)	0.098	0.088	0.050	0.176
Corrosion resistance (B3)	0.137	0.264	0.151	0.235
Durability (B4)	0.076	0.029	0.037	0.058
Total	1.453	11.333	6.583	17

Table 7. The detailed result of the consistency analysis for the pair comparison matrix.

Criteria	B1	B2	B3	B4	weighted sum value	Criteria weight	Consistency Measure
B1	0.648	0.723	0.986	0.455	2.815	0.648	4.341
B2	0.092	0.103	0.065	0.151	0.413	0.103	4.002
B3	0.129	0.31	0.197	0.202	0.839	0.197	4.255
B4	0.072	0.034	0.049	0.051	0.206	0.051	4.076
						λ_{max}	4.168
						CI	0.056
						CR	0.062

Table 8. The vector normalization matrix for the four alternative using the four criteria.

Criteria	Price/Cost (₦)	Light-weight (density) (g/cm3)	Corrosion resistance	Durability
Aluminum Alloy (AA)	2000	2.7	5	4
Stainless steel (SS)	2038	7.7	4	5
Glass fibre (GF)	1940	2.62	3	1
Mild steel (MS)	1800	7.85	1	2
Column total	7778	20.87	13	12

matrix is consistent for the four alternatives. The result has proven that the judgment of the ranking decision is accurate; this result is in line with the analysis from Hama et al. (2019). The authors applied MCDM in location selection of a decentralized treated wastewater unit. In this study, the decision-marker used the weight criteria for the decision-making process. Figure 6 shows the weighted criteria value for the four selected criteria for the selection of the material for the wind turbine blade.

3.1. Ranking the alternatives using TOPSIS techniques

After determining the criteria weight with the AHP, the study applied the TOPSIS technique to rank the selected alternatives. Therefore, Table 8 shows the normalized vector matrix.

Figures 7 and 8 show the performance analysis of the four alternatives using the selected criteria, including prices/cost, lightweight, corrosion resistance, and durability. The illustrations depict the ideals from the professional, i.e., the material scientist and renewable energy researchers, as it pertained to the areas of the functional ability of the alternatives. And also, as it relates to the durability, corrosion resistance, and strength to a lightweight ratio and density of the materials. Another

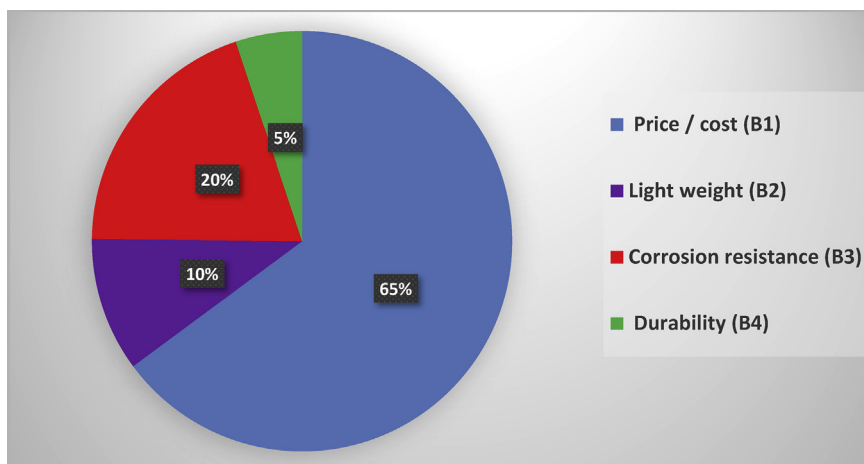


Figure 6. Criteria weight value for the four most critical selected criteria for the wind turbine blade material.

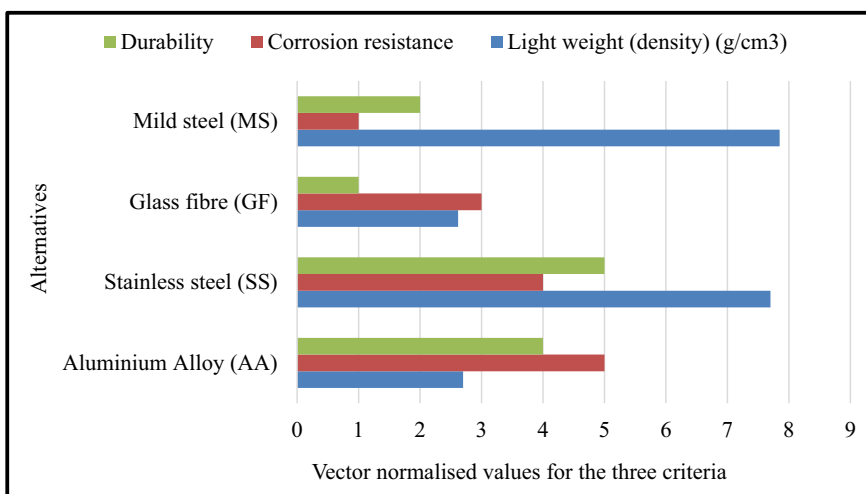


Figure 7. The analysis of the alternatives with the vector normalised values.

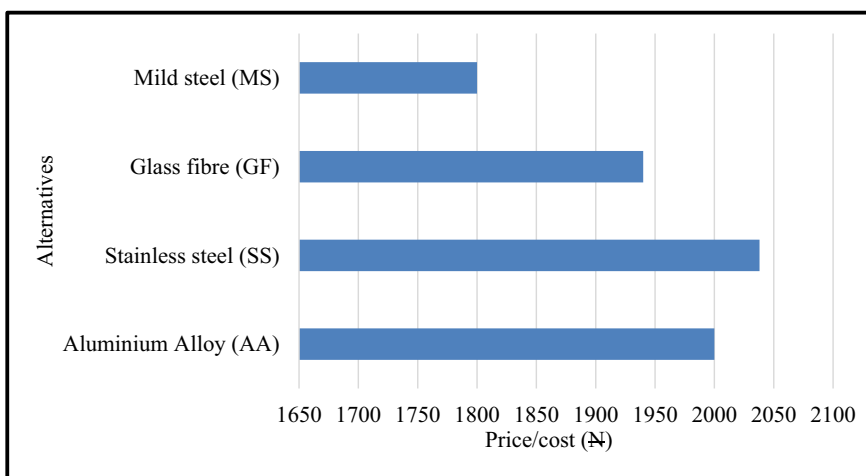


Figure 8. The prices of the four alternatives at the time of the research investigation.

significant consideration of this study is the price/cost of the alternatives. Here, putting economic factors in place, there is a need to have a moderate cost-related material for the design of the wind turbine blade. From Figure 8 and Table 8, the stainless steel has the highest cost of ₦2038 per kg as at the time of the survey of the price in the market. Followed by aluminum 6061-T9 alloy with ₦2000, glass fiber ₦1940, and mild steel ₦1800, respectively. Glass fiber and mild steel are cheap when compared with the others.

The data extracted from the questionnaire to develop the pair-wise matrix, C. I and C. R using the AHP method to translate into the normalized decision matrix using Eq. (8). Also, Eq. (9) applies to determine the ideal best and the ideal worst for the four alternatives. Hence the Euclidean distance of the ideal best (Ed⁺), ideal worst (Ed⁻), using Eqs. (12), (13), and (14) to analyze the performance score for the final ranking of the alternatives. Tables 9, 10, 11, and 12 gives the results, respectively.

Table 9. The normalized decision matrix with the criteria and the alternatives.

Criteria	Price/Cost (₦)	Lightweight (density) (g/cm3)	Corrosion resistance	Durability
Aluminum Alloy (AA)	0.513	0.232	0.700	0.589
Stainless steel (SS)	0.523	0.662	0.420	0.737
Glass fibre (GF)	0.498	0.225	0.560	0.147
Mild steel (MS)	0.462	0.675	0.140	0.294

Table 10. The weighted normalized decision matrix with the criteria and the alternatives.

Criteria	Price/Cost (₦)	Lightweight (density) (g/cm3)	Corrosion resistance	Durability
Aluminum Alloy (AA)	0.332	0.023	0.137	0.030
Stainless steel (SS)	0.339	0.068	0.082	0.037
Glass fibre (GF)	0.322	0.023	0.110	0.007
Mild steel (MS)	0.299	0.069	0.027	0.015

Table 11. The calculation of the best ideal value and the ideal worst value.

V ⁺	0.299	0.023	0.137	0.037
V ⁻	0.339	0.069	0.027	0.007

Table 12. The Euclidean distance (Ed⁺) ideal best (Ed⁻) ideal worst and the performance score used for the ranking.

Criteria	Ed ⁺	Ed ⁻	Ps _i	Rank
Aluminum Alloy (AA)	0.034	0.121	0.780	1
Stainless steel (SS)	0.081	0.062	0.435	3
Glass fibre (GF)	0.046	0.096	0.671	2
Mild steel (MS)	0.121	0.040	0.248	4

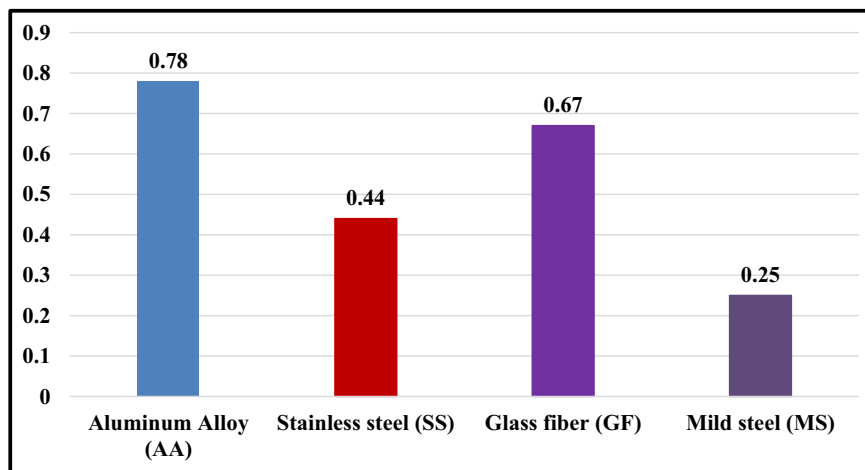


Figure 9. The performance value analysis of the alternatives materials for the wind turbine blade.

The significant of the normalized decision matrix, CR, CI, RI, Euclidean distance, and ideal best analysis is to determine the performance of the four alternatives criteria. Figure 9 shows the result of the MCDM in selecting a suitable material for the development of a wind turbine blade. Aluminum 6061-T9 alloy has the best performance value of 0.78, followed by glass fiber of 0.67, stainless steel and mild steel of 0.44, and 0.25. From the result analysis, it shows that aluminum 6061-T9 alloy is the suitable material needed to develop the wind turbine blade due to its excellent chemical and mechanical properties.

However, from this study, 6061-T9 aluminum alloy has excellent durability, high corrosion resistance, and strength to weight ratio. It is also lighter than steel in terms of weight, which give aluminum alloy advantage over steel when it concerns the development of a wind turbine blade. This result is in line with the observation made by Asodariya et al. (2018) in a related study. The authors carried out performance analysis on speed ratio, weld-ability, and walkability of aluminum alloy. The result confirmed that aluminum alloy has high functional speed, walk-ability, and weld-ability to form the aerofoil shape of the wind turbine blade. This result also contradicts the observation from Babu et al. (2006), in their study, they considered pure aluminum, steel, carbon fibers, aramid fibers, and electrical glass. The result from the analysis and the decision made by the decision-makers approved carbon fiber is the best alternatives. The authors did not consider that carbon fiber is rigid and can fail with little or no warming during operation when used for the wind turbine blade development. And the manufacturers cannot restructure the material of carbon fibers, unlike aluminum 6061-T9 alloy. There is a clear difference with the shape of the blade for the vertical wind turbine and horizontal wind turbine blade. The aerofoil shape of the horizontal wind turbine blade is complex. The material needed must have excellent walkability, weld-ability, machinability, ductility, and equipment that cannot react with air.

4. Conclusion

The study carried out the material selection process of a wind turbine blade development using the AHP and TOPSIS in MCDM. The result from the four alternatives, i.e., aluminum alloy, stainless steel, glass fiber, and mild steel, shows that aluminum alloy has the highest performance value of 78%. Followed by 67% glass fiber, 44% stainless steel, and 25% mild steel. After carrying out extensive research, the authors recommended that manufacturers of wind turbine blade should apply aluminum 6061-T9 alloy for development. Because aluminum 6061-T9 alloy has excellent resistance to corrosion, durable, high strength to weight ratio, and cannot react with air. Another uniqueness of this aluminum 6061-T9 alloy is that it has other elements present in its composition that make the material function under the moistures condition. The element is magnesium,

copper, tin, zinc, silicon, and manganese. Aluminum alloy can be further heat-treated to increase the mechanical properties and thermal stability of the wind turbine blade.

Declarations

Author contribution statement

I. P. Okokpujie: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

U. C. Okonkwo: Conceived and designed the experiments; Performed the experiments.

C. A. Bolu, O. S. Ohunakin, A. A. Atayero: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

M. G. Agboola: Performed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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