MULTIPLE LINEAR REGRESSION AND MULTI-CRITERIA OPTIMIZATION OF BLADE ROOT DIMENSIONS OF A SMALL WIND TURBINE

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Small wind turbine blades of 2.5 m in length (sixteen models with four levels of root length, width and thickness) are simulated in ANSYS Mechanical R18.1. The analysis of variance results suggested an alternative root dimension's range for improved strength. Hence, new data for 512 blade models is generated through multiple linear regressions. Among them, most favorable fourteen blades are evaluated using three Multi-Criteria Decision-Making (MCDM) techniques including Weighted Addition Method, Weighted Product Method and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and their rankings are well-aligned. The best-compromised solution from the new data is found to be better than the simulation results.

Keywords: MCDM, regression, small wind turbine, TOPSIS

1. Introduction

The design of wind turbine blades is a complex process in all aspects [1]. It begins with the aerodynamic design of the main blade body and concludes with the structural design of the blade root, which connects to the hub. Aerodynamic design may pass through various activities such as selection or design of airfoils, computational and/or experimental evaluation of airfoil if designed newly and computational analysis of the full blade [2, 3]. The strength design of wind turbine blades involves various considerations, including the selection and/or development of materials, manufacturing processes, cost, gyroscopic effects, and computational and/or experimental evaluation of strength, as well as the design of the blade root [4-7].

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Figure 1 shows the portions of the wind turbine blade in which the region from root to tip needs more focus on aerodynamic considerations and near root airfoils to root portion needs more focus on structural considerations. Most of the Small Wind Turbine (SWT) blades research articles available are related to airfoil design, aerodynamic evaluation of blade, static and fatigue analysis of the SWT blades materials [8-13].

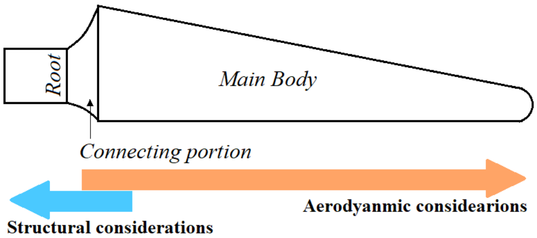


Fig. 1. Aerodynamic and structural design considerations for Wind Turbine Blade

Though the design of blade roots has not been the focus of many researchers and relatively little research is available in the literature, it is practically one of the most important parts of any wind turbine blade. The root design of a variable-pitch blade is considerably more complicated compared to that of a fixed-pitch blade [14-16]. However, the design of a fixed-pitch blade is equally important, as it affects the strength, weight and cost of the blades, in addition to influencing the starting aerodynamic behavior [17, 18].

Small wind turbine blade models having 1.1 m in length made from different materials are evaluated using multi-dimensional optimization [8]. Experimental and computational results of stresses induced in the blade main body are presented for a one kW wind turbine blade of 1.5 m length [9]. The significance of appropriate blade root design was identified and a 1.82 m long blade with root portion made of steel having 0.1 m length and 0.06 m diameter was studied [10]. A five kW variable pitch SWT blade of 2.5 m length with 0.3 m long root portion was simulated in ANSYS. Loads of range 3.3 kg to 8.3 kg were applied and stresses induced in the blade body and root were calculated [11]. Habali and Saleh evaluated static strength of a 5 m long SWT blade with 0.45 m hub radius made from glass fiber reinforced polymer [12].

A detailed parametric study of different rectangular root dimensions on blade mass, stresses and deformation was studied using analysis of variance (ANOVA) for sixteen blade models (fixed pitch, 2.5 m long, B01 to B16) [17]. In the aforementioned study four levels of root parameters such as length (l_b), width (w_b) and thickness (t_b) were considered. The previous study [17], suggested the use of Multi-Criteria Decision-Making (MCDM) technique to decide an appropriate solution. From now this study will be mentioned as the reference study and its data as reference data, in the current research paper. Hence, the current research work builds upon the reference study and includes the determination of the widest ranges of eight level parameters (512 blade models) calculated through Multiple Linear Regression (MLR). Among these, the most favorable 14 blade models (M001 to M014) were further ranked using three multi-criteria decision making techniques.

2. Methodology

2.1. Limitation of Previous Models

In the reference study, sixteen blade models were simulated in the software ANSYS Mechanical R18.1 and the effect of blade root dimensions on their strengths was analyzed. The change in root dimensions not only affects the strengths of the blade but also influences the blade mounting flange weight. In the current research a simplified flange structure is considered for the mounting of blades as shown in Fig. 2. The wind turbine rotor considered for this study includes three blades mounted on a flange. Hence, the total mass of the rotor is the sum of the masses of three blades and a flange. It has already been found that the blade mass increases with increasing any dimensional parameter of the blade root.

The length (l_f) and width (w_f) of flanges are considered equal to the root length (l_b) and root width (w_b) of the blade. Hence, the blade root resting area ($l_f \times w_f$) is equal to the flap-wise area of the blade root ($l_b \times w_b$). This indicates that the flange mass increases with the length and width of blade root and independent of blade root thickness. The outer radius, R_f of flange increases with an increase in root length. After a certain level the radius R_C is also controlled by the root width to avoid intersections with blade roots. While calculating the mass, the thickness of all flanges is kept the same and equal to 30 mm. These flanges can be manufactured using any suitable aluminium alloy materials whose density is taken as 2700 kg/m^3. All the flanges are considered to be manufactured using laser cutting process and its cost depends on the outer dimensions of the flange.

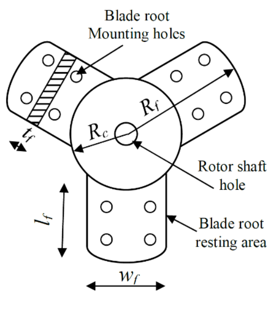


Fig. 2. Nomenclature of the blade mounting flange

The rotor cost includes the cost of three blades and a flange. For all sixteen blade models, these costs were calculated. The values of deflection, main body stresses and root stresses were taken from a reference study. Values of rotor mass and rotor cost were calculated as discussed earlier in previous paragraph. All the five characteristics - rotor mass (m_R), deflection (δ), main body stresses (σ_m), root stresses (σ_r) and rotor cost (C_R) are shown in Table 1. Some values were appropriately rounded off. From Table 1, it was found that all main body stress values are less than or equal to 96 MPa. For the blade models with 15 and 20 mm root thickness (8 models out of 16), root stress values are greater than or equal to 96 MPa. Since wind turbine blades are subjected to cyclic stresses lower stress values are always desirable. It is also observed from the table that the range of reference root length, root width and root thickness (l_b, w_b and t_b) needs to be modified to get improved blade strength.

Table 1

Physical and Mechanical Characteristics of Reference Blades / Rotors (col. 6-8 from [17])

Blade Model	l_b (mm)	w_b (mm)	t_b (mm)	m_R (kg)	δ (mm)	σ_m (MPa)	σ_r (MPa)	C_R ($)
B03	300	225	15	40.131	1580	79	170	250
B06	250	200	15	34.999	1629	79	156	222
B13	200	175	15	30.666	1749	96	167	198
B16	150	150	15	27.017	1801	79	205	178
B01	250	225	20	39.193	1566	79	164	246
B02	300	200	20	38.920	1555	79	106	247
B14	150	175	20	29.773	1719	96	118	193
B15	200	150	20	29.651	1685	96	130	195
B04	300	175	25	37.334	1545	79	88	241
B05	250	150	25	32.345	1578	79	96	213
B09	200	225	25	37.860	1634	96	75	239
B11	150	200	25	33.013	1618	79	82	212
B07	300	150	30	35.407	1539	79	85	233
B08	150	225	30	36.214	1637	96	52	231
B10	200	200	30	36.755	1620	96	61	235
B12	250	175	30	36.440	1558	79	65	236
Min	150	150	15	27	1539	79	52	178
Max	300	225	30	40	1801	96	205	250
Diff.	150	75	15	13	262	18	153	72
Avg.	225	188	23	35	1626	85	114	223

2.2. Modified Models Using Multiple Linear Regression

Multiple linear regression technique was applied to the simulated reference data and five equations were obtained for rotor mass (m_R), deflection (δ), main body stresses (σ_m), root stresses (σ_r) and rotor cost (C_R). Here suffix '*r*' is used for blade root and '*R*' for rotor.

$$m_R = 2.6615 + 0.0427 \times l_b + 0.0964 \times w_b + 0.1951 \times t_b \tag{1}$$

$$\delta = 2139.78 - 1.0112 \times l_b - 0.7083 \times w_b - 6.8305 \times t_b \tag{2}$$

$$\sigma_m = 94.36935 - 0.0863 \times l_b + 0.0333 \times w_b + 0.1801 \times t_b \tag{3}$$

$$\sigma_r = 314.6652 + 0.0114 \times l_b - 0.1961 \times w_b - 7.4140 \times t_b \tag{4}$$

$$C_R = 41.6169 + 0.2582 \times l_b + 0.4865 \times w_b + 1.4285 \times t_b \tag{5}$$

To get better solutions, eight levels of blade root length, width and thickness were considered as shown in Table 2. The new lower root dimensional limits for l_b, w_b and t_b are 200, 170, and 20 mm, compared to the reference values of 150, 150, and 15 mm. Similarly, new upper limit values (340, 240 and 34 mm) are significantly different than the reference values (300, 225 and 30 mm). Using Eqs.1 to 5, m_R, δ, σ_m, σ_r and C_R were calculated for all possible 8^3 = 512 models.

Table 2

Blade root parameters with 8 levels

Parameter	Levels (8 for each)
Root length (l_b)	200, 220, 240, 260, 280, 300, 320, 340
Root width (w_b)	170, 180, 190, 200, 210, 220, 230, 240
Root thickness (t_b)	20, 22, 24, 26, 28, 30, 32, 34

2.3. Data Selection and MCDM

For long life, improved functioning, and economy, low values of m_R, δ, σ_m, σ_r and C_R are desirable. The data obtained for these 512 models were selected on this basis. The data for individual parameters that are equal to or less than individual average values were omitted and only favorable 14 blade models were found suitable for further evaluation. These 14 models (alternatives) are compared using three different multi-criteria decision-making techniques.

2.4. Weighted Addition Method (WAM)

Here, alternative's ranking is obtained using three simple steps [19].

Step 1. In this case all output parameters are non-beneficial and normalized matrix is obtained using Eq. 6.

$$m_{ij(Norm)} = M_i^- / m_{ij} \tag{6}$$

Where, i = 1, 2, 3 … N (Number of Alternatives = N), j = 1, 2 … M (Number of Attributes = M), M_i^- = Minimum value from i^{th} non-beneficial attribute, m_{ij} = performance measure, $m_{ij(Norm)}$ = normalized value of m_{ij}.

Step 2. Performance index (P_i) is obtained by adding the products of normalized value (m_{ij}) and allotted weightage of the attribute (W_{ij}) using Eq. 7.

$$P_i = \sum_{j=1}^{M} m_{ij(Norm)} \times W_{ij} \tag{7}$$

Step 3. The higher P_i values are the better ranking.

2.5. Weighted Product Method (WPM)

WPM is similar to WAM and only uses Eq. 8 instead of Eq. 7 [19]. (Number of Attributes = M)

$$P_i = \prod_{j=1}^{M} \left[\left(m_{ij} \right)_{Norm} \right]^{W_{ij}} \tag{8}$$

2.6. TOPSIS Method

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the most preferred multi-criteria optimization methods. The nearest to best likely solution and farthest to worst likely decision can be obtained using the steps followed by Garmode et al. [19].

Step 1: Preparation of data table and obtaining a normalized decision matrix (R_{ij}) using Eq. 9.

$$R_{ij} = m_{ij} \Big/ \left[\sum_{j=1}^{M} m_{ij}^2 \right]^{1/2} \tag{9}$$

Step 2: Use Eq. 10 to generate the weighted normalized matrix (V_{ij}).

$$V_{ij} = W_i \times R_{ij} \tag{10}$$

Step 3: From Eq. 11 to 14, ideal best ($+^{ve}$), and ideal worst ($-^{ve}$) solutions.

Where, i = 1, 2, 3 ….. N, J = beneficial attributes, J^0 = non-beneficial attributes,

V_j^+ = the best ideal value, V_j^- = the worst ideal value

$$V^{+}=\left\{\left(\frac{\sum_{i}^{\max} v_{ij}}{i} \in J\right),\left(\frac{\sum_{i}^{\min} v_{ij}}{i} \in J^{o}\right)\right\} \tag{11}$$

$$V^{+}=\left\{V_{1}^{+}, V_{2}^{+}, V_{3}^{+} \ldots\ldots, V_{m}^{+}\right\} \tag{12}$$

$$V^{-}=\left\{\left(\frac{\sum_{i}^{\min} v_{ij}}{j} \in J\right),\left(\frac{\sum_{i}^{\max} v_{ij}}{j} \in J^{o}\right)\right\} \tag{13}$$

$$V^{-}=\left\{V_{1}^{-}, V_{2}^{-}, V_{3}^{-} \ldots\ldots, V_{m}^{-}\right\} \tag{14}$$

Step 4: Eqs. (15) and (16) give the best separation size for individual alternatives.

$$S_{i}^{+}=\left\{\sum_{j=1}^{M}\left(V_{ij}-V_{j}^{+}\right)^{2}\right\}^{0.5} \tag{15}$$

$$S_{i}^{-}=\left\{\sum_{j=1}^{M}\left(V_{ij}-V_{j}^{-}\right)^{2}\right\}^{0.5} \tag{16}$$

Step 5: Determine the relative closeness of the alternative to the ideal solution (P_i) from Eq. (17)

$$P_{i}=S_{i}^{-} \Big/ \left(S_{i}^{+}+S_{i}^{-}\right) \tag{17}$$

Step 6: The higher to lower ranking is obtained by arranging P_i in descending order indicates best to worst solutions.

3. Results

As mentioned in the second section values of rotor mass, deflection, main body stresses, root stresses and rotor cost were obtained for 512 models through Multiple Linear Regression. Instead of presenting the complete data, a summary is provided in Table 3.

Table 3

Summary of 512 blade models obtained through multiple linear regression

	l_b (mm)	w_b (mm)	t_b (mm)	m_R (kg)	δ (mm)	σ_m (MPa)	σ_r (MPa)	C_R ($)
Min	200	170	20	31.490	1394	74	18	205
Max	340	240	34	46.946	1681	91	137	295
Diff.	140	70	14	15.456	286	17	119	90
Avg.	270	205	27	39.218	1537	83	77	250
Number of values > Avg				257	256	269	262	256

3.1. Reduced data for MCDM

The difference between the maximum and minimum values of these output parameters is significant. Additionally, evaluating such large datasets is a challenging and complex task. As these 512 blade models are derived from the same equations, they exhibit repetitive patterns and most data-reduction techniques do not provide acceptable solutions. Therefore, it was decided to use a simplified and basic-reduction technique. Knowing the benefits of lower values of all output parameters, blade models with individual output parameter (m_R, δ, σ_m, σ_r and C_R) values exceeding the average were omitted during the reduction process. This screening ensures the removal of non-satisfactory blade models.

The number of blade models omitted from further processing due to having fewer favorable attributes than average is shown in Fig. 3. For instance, 213 blades with three attributes below average were excluded from further analysis. Similarly, 211 blades with two attributes below average were excluded from further analysis. Thirty blade models were omitted because one output parameter was below the average value, ensuring that no significant data was excluded.

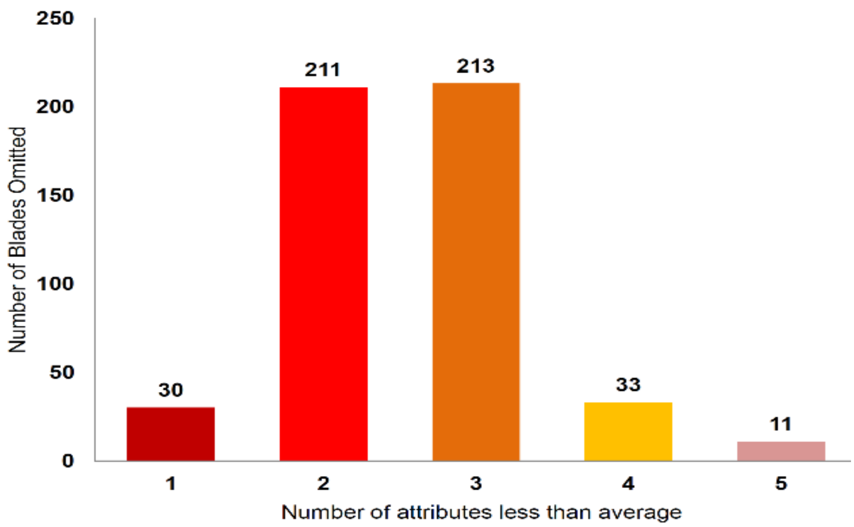


Fig. 3. Number of omitted blades based on a number of non-favored attributes

By omitting these non-favorite attributes, only 14 models were finalized, as shown in Table 4. It is observed that the finalized data is satisfactory and covers a favorable range of input and output parameters. The new blade models, labeled M001 to M014, are clearly distinguished from the reference models B01 to B16.

Table 4

Finalized 14 blade models for MCDM

Blade Model	l_b (mm)	w_b (mm)	t_b (mm)	m_R (kg)	δ (mm)	σ_m (MPa)	σ_r (MPa)	C_R ($)
M001	280	170	30	36.856	1531	81	62	239
M002	280	170	32	37.246	1518	82	47	242
M003	280	170	34	37.637	1504	82	32	245
M004	280	180	30	37.820	1524	82	60	244
M005	280	180	32	38.210	1511	82	45	247
M006	280	190	28	38.394	1531	82	73	246
M007	280	190	30	38.784	1517	82	58	249
M008	300	170	28	37.319	1525	79	77	242
M009	300	170	30	37.710	1511	80	62	245
M010	300	170	32	38.100	1497	80	47	247
M011	300	180	28	38.284	1518	80	75	247
M012	300	180	30	38.674	1504	80	60	249
M013	320	170	28	38.173	1505	77	77	247
M014	320	170	30	38.563	1491	78	63	250
Min	280	170	28	36.856	1491	77	32	239
Max	320	190	34	38.784	1531	82	77	250
Diff.	40	20	6	1.928	40	5	45	10
Avg.	293	176	30	37.984	1513	80	60	246

3.2. WAM and WPM Ranking

Following the procedure mentioned in subsections 2.4 and 2.5, the normalized values, performance index and rankings obtained from the weighted addition method and weighted product method are presented in Table 5 for M001 to M014 models. In this research, equal weightage of 0.2 was applied to all attributes for all multi-criteria decision-making applications.

3.3. TOPSIS method Ranking

Following the procedure mentioned in subsection 2.6 the normalized values, performance index and rankings obtained from TOPSIS are presented in Table 6 for M001 to M014 models.

Table 5

Normalized data, performance index and rankings of M001 to M014 models by WAM and WPM

Blade Model	m_R	δ	σ_m	σ_r	C_R	WAM		WPM	
						P_i	Rank	P_i	Rank
M001	1.000	0.974	0.953	0.522	1.000	0.890	5	0.865	5
M002	0.990	0.982	0.949	0.686	0.988	0.919	2	0.910	2
M003	0.979	0.991	0.945	1.000	0.977	0.978	1	0.978	1
M004	0.975	0.978	0.949	0.539	0.980	0.884	8	0.863	7
M005	0.965	0.987	0.945	0.716	0.969	0.916	4	0.910	3
M006	0.960	0.974	0.950	0.444	0.972	0.860	14	0.826	14
M007	0.950	0.983	0.945	0.558	0.961	0.879	10	0.861	8
M008	0.988	0.978	0.978	0.420	0.990	0.871	11	0.830	11
M009	0.977	0.987	0.974	0.521	0.979	0.887	6	0.863	6
M010	0.967	0.996	0.969	0.683	0.968	0.917	3	0.908	4
M011	0.963	0.982	0.974	0.431	0.971	0.864	13	0.827	13
M012	0.953	0.991	0.970	0.537	0.960	0.882	9	0.861	10
M013	0.965	0.991	1.000	0.419	0.970	0.869	12	0.828	12
M014	0.956	1.000	0.995	0.519	0.959	0.886	7	0.861	9

Table 6

Normalized data, performance index and rankings of M001 to M014 models by TOPSIS method

Blade Model	m_R	δ	σ_m	σ_r	C_R	P_i	Rank
M001	0.052	0.054	0.054	0.054	0.052	0.346	8
M002	0.052	0.054	0.054	0.041	0.053	0.665	3
M003	0.053	0.053	0.055	0.028	0.053	0.919	1
M004	0.053	0.054	0.054	0.052	0.053	0.383	6
M005	0.054	0.053	0.054	0.039	0.054	0.702	2
M006	0.054	0.054	0.054	0.064	0.054	0.100	11
M007	0.055	0.054	0.054	0.051	0.054	0.422	5
M008	0.053	0.054	0.053	0.067	0.053	0.078	13
M009	0.053	0.053	0.053	0.054	0.053	0.338	9
M010	0.054	0.053	0.053	0.041	0.054	0.660	4
M011	0.054	0.054	0.053	0.065	0.054	0.068	14
M012	0.054	0.053	0.053	0.053	0.054	0.377	7
M013	0.054	0.053	0.052	0.067	0.054	0.078	12
M014	0.054	0.053	0.052	0.054	0.054	0.335	10

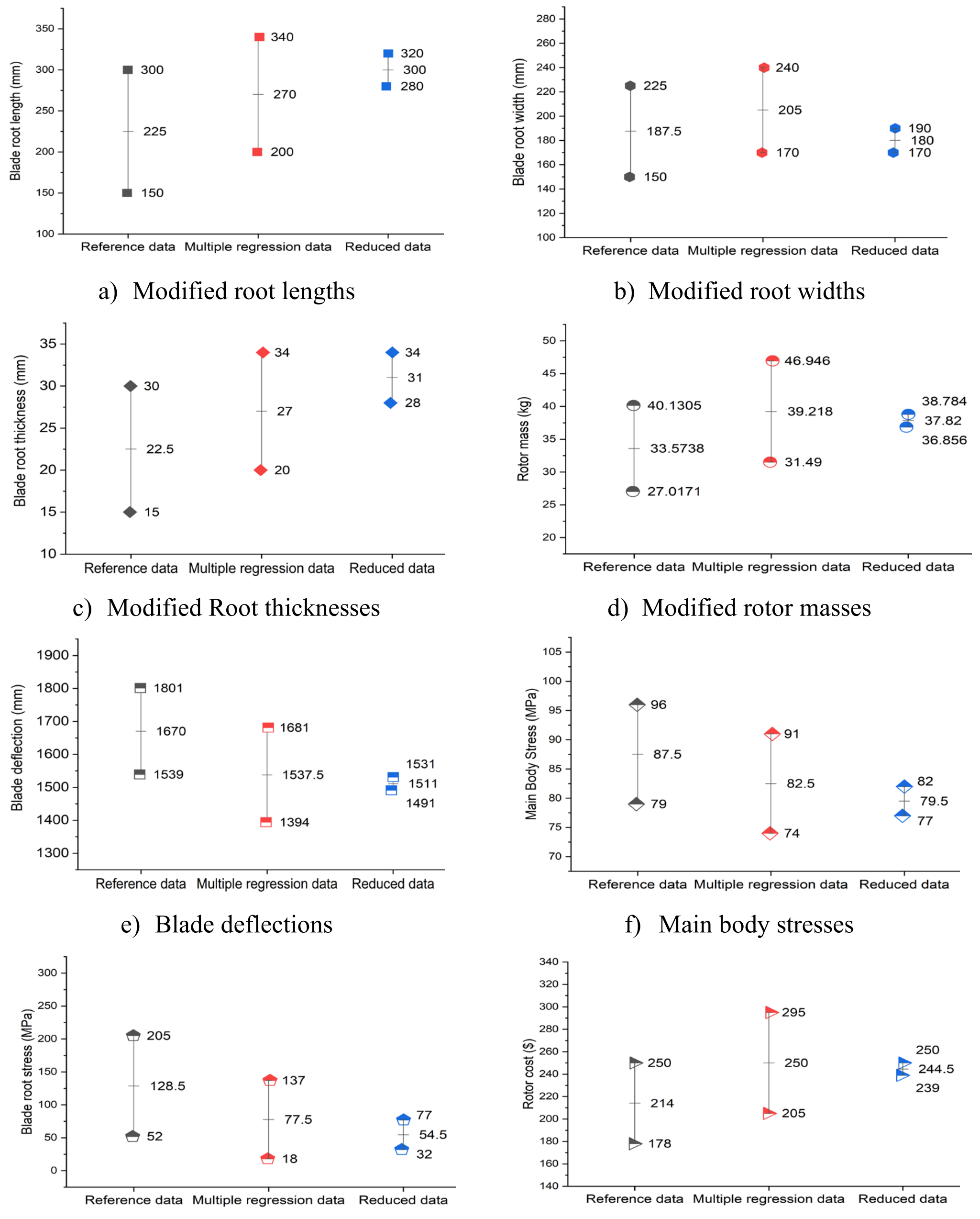
4. Discussion

By identifying the limitations of the reference data, a new dataset was prepared using multiple linear regressions. Non-favorable blades were then omitted from the new dataset. The maximum and minimum values of various input and output parameters are illustrated in Fig. 4 (a) to (h). The average values shown in these figures are based on the minimum and maximum values. It is clearly observed that the selected favorable data values span a much narrower range compared to the reference and multiple regression data values. These reduced data values suggest a directive range of input parameters where output parameters are significantly favorable. Figure 4 (a) to (c) suggests the ranges of 280-320 mm, 170-190 mm and 28-30 mm for l_b, w_b and t_b respectively. These suggested ranges align well with our previous work limitation discussed in [17]. Therefore, the selected favorable data is considered appropriate, and suitable for further optimization process.

Currently, several MCDM techniques are available and widely applied to various engineering research problems. The rankings obtained by these techniques often differ, making it necessary to evaluate them for consistency. Figure 5 presents the graphical view of the rankings determined using WAM, WPM, and TOPSIS. A well-acceptable agreement is observed among the rankings derived from different methods. Blade model M003 appears as the best-compromised solution among the 14 models (M001 to M014), with l_b, w_b and t_b values of 280, 170 and 34 mm respectively. Rotor mass (m_R), deflection (δ), main body stresses (σ_m), root stresses (σ_r) and rotor cost (C_R) for M003 blades are 37.637 kg, 1504 mm, 82 MPa, 32 MPa and $ 245 respectively.

It is important to compare these results with reference data. Weighted addition and weighted product methods were also applied for the reference blade models B01 to B16 as shown in Table 1, with equal weightage of 0.2. From this analysis, the B08 model is identified as the best-compromised solution among the 16 models B01 to B16. In the B008 model, l_b, w_b and t_b values are 150, 225 and 30 mm respectively, and m_R, δ, σ_m, σ_r and C_R are 36.214 kg, 1637 mm, 96 MPa, 52 MPa and $ 231 respectively.

In blade model M003, values m_R and C_R are increased by 4 % and 6%, respectively, and values δ, σ_m and σ_r are reduced by 8 %, 15 % and 38 % respectively. The blade root stress, already declared as the most influencing variable, is found to be significantly reduced. Additionally, deflection and main body stresses are considerably reduced. Expecting longer life and safe working of a wind turbine blade with reduced stress and deformation is a well-accepted solution on compromising a small increase in weight and cost of the rotor. Hence, the new blade model dimensions obtained through multiple linear regressions and further refined using multi-criteria optimization provide a better solution with improved structural strength.



a) Modified root lengths

b) Modified root widths

c) Modified Root thicknesses

d) Modified rotor masses

e) Blade deflections

f) Main body stresses

g) Blade root stresses

h) Modified rotor costs

Fig. 4. Changes in blade root dimensions and output parameters at various stages

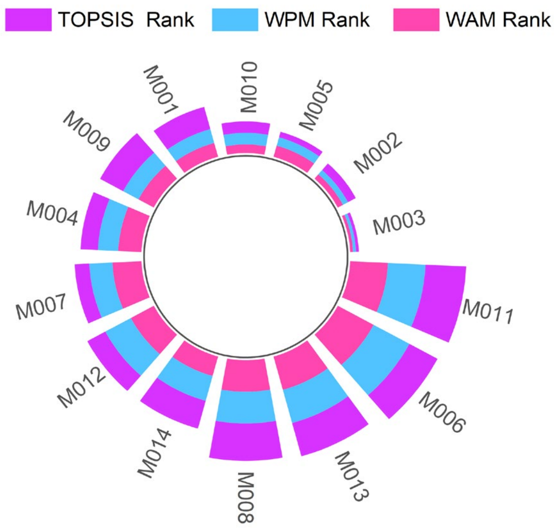


Fig. 5. Comparative illustration of different MCDM rankings

5. Conclusions

This research was initiated by examining the limitations of sixteen blade models simulated in ANSYS Mechanical R18.1, each with varying root dimensions, to identify the need for improved blade root dimensions that could provide enhanced structural strength. Equations resulting from multiple linear regressions of sixteen simulated models were used to generate a broader dataset of 512 blade models. Through further multi-criteria optimization, the research identified the best-compromised blade root dimensions for a small wind turbine blade of 2.5 m length. This approach enabled the identification of optimal root dimensions without requiring computational analysis of all possible models. Rankings obtained through WAM, WPM and TOPSIS showed strong agreement for most new blade models (M001 to M014). The suggested best-compromised model, M003, demonstrated a significant improvement in structural strength (with reduced deflection, main body stresses, and root stresses) on compromising a minor increase in mass and cost.

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