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A comparative study based on neutrosophic numbers and the Indeterminate VIKOR method for the selection of three types of vertical axis wind turbines adapted to the conditions of Peru

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Abstract. The use of vertical axis wind turbines to electrify homes without electricity in the Peruvian region of Junín is essential to address the challenges of climate change and move towards a more sustainable and environmentally friendly future. The objective was set to compare three types of wind turbines, these are Darrieus H, Savonius, and Windside concerning to the wind speeds that occur in the Junín region. This is because the operation of these wind turbines in this region is not yet known. The following procedure was tracked: first, the design was made and then it was experimented in the wind tunnel laboratory of the Faculty of Electrical and Electronic Engineering of the National University of Central Peru. In the study, we took into account that there is indeterminacy in the variable wind speed among others, which is why we adapted the traditional variables to the use of neutrosophic numbers. Additionally, we carried out a comprehensive study that includes other variables for decision-making. To select the best complete option we asked a group of 3 experts for their evaluations according to several criteria and we used the VIKOR method for intervals adapted to neutrosophic numbers.

Keywords: Wind turbines, electrification, winds, electrical power, neutrosophic numbers, Indeterminate VIKOR method.

1 Introduction

The possibility of increasing electricity production without polluting the environment can be achieved using wind fields. This is one of the techniques that has had the greatest advancement and research over the last decades.

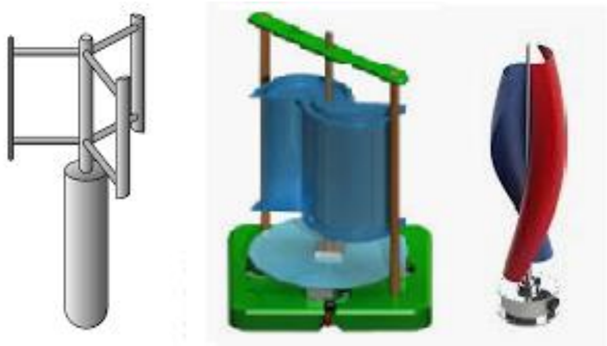
Vertical axis wind turbines have low performance due to the shape of the blades, which is the reason for carrying out several studies so that these elements can capture a greater amount of air mass, taking into account that the transformation of air into kinetic energy must be carried out on the rotor, which is made up of the blades and the hub.

The theory that governs this study is based on the conversion of kinetic energy into mechanical. But obtaining a super wind generator is almost impossible because according to Betz's law, it is not possible to capture the entire mass of air or otherwise the wind turbine would not be able to rotate. The airfoil is obtained through a genetic algorithm optimization of an objective function that maximizes the aerodynamic performance of the airfoils, providing better structural rigidity compared to a NACA design that is thinner.

The most used vertical axis wind turbines are Darrieus, Savonius, and Windside due to their easy construction and assembly. They are currently used in urban homes in Europe, but in Peru this technology is only recently known. That is why it is important to determine which of these three types of wind turbines best adapt to the climatic and physical conditions of the Junín region. The present investigation consists of studying which of the three wind turbine models has the best performance at high speeds and low speeds in isolated homes in the region.

Figure 1 contains schematic representations of the Darrieus H, Savonius, and Windside wind turbines.

Figure 1. Schemes of the three types of wind turbines studied, from left to right: Darrieus H, Savonius, and Windside type.



To meet this purpose, we carried out experiments on models of wind turbines built to scale to be tested in wind tunnels of the Faculty of Electrical and Electronic Engineering of the National University of Central Peru. When studying this type of phenomenon, it is not enough to determine the operation of the devices at a constant speed, because the wind has speed variations that can be abrupt. That is why, instead of working with precise values of the variables to be studied, we prefer to use neutrosophic numbers that allow us to include the indeterminacy that exists in this type of studies ([1,2]). Neutrosophic numbers are defined in the form of $a + bI$, where $a, b \in \mathbb{R}$, a is the determined part and bI is the indeterminate part, I is a symbolic element that represents indeterminacy, although it can also be equated to a numerical interval so that the calculations are replaced with values in the form of intervals instead of values in the form of scalars.

On the other hand, we have 3 experts to determine which of the three types of generators is optimal. This is a decision-making problem that is not simple because in addition to the technological component that consists of obtaining the greatest energy gain, there are also other variables to take into account for the selection, such as the durability of the equipment, and its efficiency, maintenance cost, among others. All of these variables are also indeterminate.

For decision-making, we use the Indeterminate VIKOR method, which is a variation of VIKOR for intervals [3]. The VIKOR originally emerged as a model for multi-criteria decision-making where experts evaluate alternatives for certain criteria, comparing them with ideal values, both positive and negative [4]. A ranking is formed of the alternatives that best satisfy these conditions. On the other hand, the interval-valued VIKOR generalizes the classical method to an indeterminacy framework, where uncertainty and indeterminacy are considered in decision-making, and we adapt this method to the case of data in the form of neutrosophic numbers. In scientific literature we can read other generalizations of VIKOR technique [5-10].

In this paper a materials and methods section where the basic notions of neutrosophic numbers are recalled, and also the VIKOR method for data in the form of interval numbers. Next, we present a section called The Study where the theoretical details of the study carried out and the obtained results appear, particularly the equations used in the experiment. We end the article with the conclusions.

2 Materials and Methods

A *neutrosophic number* N has the following form:

$N = a + bI$, where a is the *determinate* (sure) part of N, and bI is the *indeterminate* (unsure) part of N.

The arithmetic operations between these numbers are summarized below:

Given $N_1 = a_1 + b_1 I$ and $N_2 = a_2 + b_2 I$, which are two neutrosophic numbers, some operations between them are defined as follows, [1, 2, 11, 12]:

$N_1 + N_2 = a_1 + a_2 + (b_1 + b_2)I$ (Addition)

$N_1 - N_2 = a_1 - a_2 + (b_1 - b_2)I$ (Difference)

$N_1 \times N_2 = a_1 a_2 + (a_1 b_2 + b_1 a_2 + b_1 b_2)I$ (Product)

$\frac{N_1}{N_2} = \frac{a_1 + b_1 I}{a_2 + b_2 I} = \frac{a_1}{a_2} + \frac{a_2 b_1 - a_1 b_2}{a_2(a_2 + b_2)} I$ (Division)

We have I is a constant such that $I^2 = I$, $0 \cdot I = 0$, $\underbrace{I + I + \cdots + I}_{n\ times} = nI$, and $I^{-1}$is undefined

In general, we have the following definition:

Definition 1: ([13-15]) Let R be a ring. The *neutrosophic ring* ⟨R ∪ I⟩ is also a ring, generated by R and I under the operation of R, where I is a neutrosophic element that satisfies the property $I^2 = I$. Given an integer n, then, n+I and nI are neutrosophic elements of ⟨R ∪ I⟩ and in addition $0 \cdot I = 0$. Also, I^{-1}, the inverse of I is not defined.

E.g., a neutrosophic ring is ⟨ℤ ∪ I⟩ generated by ℤ, which is the set of integers.

We use the following interval-valued arithmetic when we convert I in the interval:

Given $I_1 = [a_1, b_1]$ and $I_2 = [a_2, b_2]$ we have the following operations between them (see [16, 17-18-19-20]):

1. $I_1 \le I_2$ if and only if $a_1 \le a_2$ and $b_1 \le b_2$.
2. $I_1 + I_2 = [a_1 + a_2, b_1 + b_2]$ (Addition);
3. $I_1 - I_2 = [a_1 - b_2, b_1 - a_2]$ (Subtraction),
4. $I_1 \cdot I_2 = [\min\{a_1 \cdot b_1, a_1 \cdot b_2, a_2 \cdot b_1, a_2 \cdot b_2\}, \max\{a_1 \cdot b_1, a_1 \cdot b_2, a_2 \cdot b_1, a_2 \cdot b_2\}]$ (Product),
5. $I_1/I_2 = I_1 \cdot (1/I_2) = \{a/b: a \in I_1, b \in I_2\}$, always that $0 \notin I_2$ (Division).
6. $\sqrt{I} = [\sqrt{a}, \sqrt{b}]$, always that $a \ge 0$ (Square root).
7. $I^n = \underbrace{I \cdot I \cdots I \cdot I}_{\text{n times}}$

The de-neutrosophication process was introduced by Salmeron and Smarandache [1], which converts a neutrosophic number into one numerical value. This process provides a range of numbers for centrality using as a base the maximum and minimum values of $I = [a_1, a_2]$, based on Equation 1:

$$\lambda([a_1, a_2]) = \frac{a_1 + a_2}{2} \tag{1}$$

The VIKOR method is specified below for data in the form of intervals, which can be treated as data in the form of neutrosophic numbers [3]:

We have to input the Table shown below:

	C_1	C_2	⋯	C_n
A_1	$[f_{11}^L, f_{11}^U]$	$[f_{12}^L, f_{12}^U]$	⋯	$[f_{1n}^L, f_{1n}^U]$
A_2	$[f_{21}^L, f_{21}^U]$	$[f_{22}^L, f_{22}^U]$	⋯	$[f_{2n}^L, f_{2n}^U]$
⋯	⋯	⋯	⋯	⋯
A_m	$[f_{m1}^L, f_{m1}^U]$	$[f_{m2}^L, f_{m2}^U]$	⋯	$[f_{mn}^L, f_{mn}^U]$

Where $A_1, A_2, \ldots, A_m$ are the alternatives to choose one of them, $C_1, C_2, \ldots, C_n$ are the criteria by which to evaluate the alternatives, $f_{ij} \in [f_{ij}^L, f_{ij}^U]$ is the evaluation of the alternative A_i with respect to the criterion C_j that is not known exactly what it is except that it belongs to the given interval. This interval can be expressed in the form of neutrosophic numbers such as $[f_{ij}^L, f_{ij}^U] = f_{ij}^L + (f_{ij}^U - f_{ij}^L)I$, where $I = [0, 1]$.

In addition, there is a vector of weights $W = [w_1, w_2, \ldots, w_n]$ for each of the criteria. The steps to track are the following:

A) Determine the positive ideal solution (PIS) in Equation 2 and the negative ideal solution (NIS) in Equation 3.

$$A^* = \{f_1^*, \ldots, f_n^*\} = \{(max_i\, f_{ij}^U | j \in K) \text{ or } (min_i\, f_{ij}^L | j \in J)\}, j = 1,2, \ldots, n. \tag{2}$$

$$A^- = \{f_1^-, \ldots, f_n^-\} = \{(min_i\, f_{ij}^L | j \in K) \text{ or } (max_i\, f_{ij}^U | j \in J)\}, j = 1,2, \ldots, n. \tag{3}$$

Where K is associated with the benefit criteria and J is associated with the cost criteria.

B) The intervals $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$ are calculated as shown below:

$$S_i^L = \sum_{j \in K} w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) + \sum_{j \in K} w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right) \; i = 1, \ldots, m \tag{4}$$

$$S_i^U = \sum_{j \in K} w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) + \sum_{j \in K} w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right) \; i = 1, \ldots, m \tag{5}$$

$$R_i^L = max\left\{w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) | j \in K, w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right) | j \in J\right\} \; i = 1, \ldots, m \tag{6}$$

$$R_i^U = max\left\{w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) | j \in K, w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right) | j \in J\right\} \; i = 1, \ldots, m \tag{7}$$

C) Calculate the interval $Q_i = [Q_i^L, Q_i^U]$; i = 1,2,…, m; such that:

$$Q_i^L = v\left(\frac{S_i^L - S^*}{S^- - S^*}\right) + (1-v)\left(\frac{R_i^L - R^*}{R^- - R^*}\right) \quad (8)$$

$$Q_i^U = v\left(\frac{S_i^U - S^*}{S^- - S^*}\right) + (1-v)\left(\frac{R_i^U - R^*}{R^- - R^*}\right) \quad (9)$$

Where:

$$S^* = min_i\, S_i^L,\ S^- = max_i\, S_i^U \quad (10)$$

$$R^* = min_i\, R_i^L,\ R^- = max_i\, R_i^U \quad (11)$$

v means the strategy weight of the majority of the criteria or the maximum of the group utility. It is assumed $v = 0.5$.

D) According to the classical VIKOR method, an alternative that has a minimum Q_i is the best alternative and is taken as a trade-off solution. However, in this method Q_i is an interval. Therefore, an order relation between intervals is used as indicated in the next step:

E) Suppose we have two intervals $[a^L, a^U]$ and $[b^L, b^U]$, to determine the minimum between them we have the following cases:

(1) If the two intervals do not have intersections, the minimum of them is the one with the lowest values. That is, when $a^U \leq b^L$, then the minimum is taken as $[a^L, a^U]$.

(2) If both intervals are the same, then both are taken with equal importance.

(3) When $a^L \leq b^L < b^U \leq a^U$, the minimum interval is taken as: if $\alpha(b^L - a^L) \geq (1-\alpha)(a^U - b^U)$ then $[a^L, a^U]$ is the minimum, otherwise $[b^L, b^U]$ is the minimum.

(4) When $a^L < b^L < a^U < b^U$, if $\alpha(b^L - a^L) \geq (1-\alpha)(b^U - a^U)$, then $[a^L, a^U]$ is the minimum, otherwise $[b^L, b^U]$ is the minimum.

Here α is introduced as an optimistic level of the decision-maker with $\alpha \in (0,1]$, a decision-maker with a higher alpha value is considered more optimistic than a decision-maker with a lower one. A rational decision maker has an $\alpha = 0.5$.

3 The study

We worked with speeds ranging from 4 m/s to 7 m/s. It is important to indicate that the simulation was carried out with wind turbines of 53cm high and 20cm wide. This reference dimension was taken due to the size of the wind tunnel. The maximum speeds of the region were also considered as reference. It is the province of Junín located at more than 3000 meters above sea level, with average wind speeds of 7 m/s and air mass densities of 909 $Kg.m^{-3}$.

From the point of view of modeling the physics of wind turbines, the following equations are used:

Betz's law is taken into account, which indicates that it is not possible to capture the entire air mass or otherwise the wind turbine would not be able to rotate. This law is modeled by the equation:

$$P = 0.20 D_I^2 v_e^3 \quad (12)$$

Where:

D_I is the Diameter [meters] of the wind turbine,

V_e is the undisturbed wind speed [meters/seconds],

The axial intromission factor (a_{xi}) measures the reduction in the undisturbed speed of the wind when passing through the actuator disc and is expressed by the following equation:

$$a_{xi} = \frac{v_e - v_{avg}}{v_e} \quad (13)$$

Where:

v_e is the undisturbed wind speed [meters/seconds],

v_{avg} is the speed of the air through the actuator disc [meters/seconds].

The vertical axis wind turbine is a machine that is installed very close to the ground, consequently the expense in assembly and maintenance is minimal, and it does not even have an orientation system because it is omnidirectional. The disadvantage of this type of wind turbine is efficiency.

In the Savonius type wind turbine the rotor is simple and is made up of split hollow cylinders that rotate in the direction of least resistance. The Darrieus wind turbine is the most successful machine on the market. It has more efficiency than the Savonius but is not better than the horizontal axis wind turbine. It is shaped like a jump rope that has greater centrifugal force. The problem with this type of machine is starting, so it needs an initial impulse, but if it manages to start, it begins to provide power. The Windside type wind turbine is similar to the Savonius rotor, the difference is the use of the aerodynamic concept, which allows the efficiency of a horizontal axis to be approximated, see Figure 1.

For the experiment, the simulation of prototypes of three vertical axis technologies was carried out, based on the DL WIND-B wind tunnel. An instrument was created to collect data on electricity generation, wind speeds and others. The torque and speed of the wind turbine were analyzed.

The results are shown in the Figures that follow, starting with the comparison of speeds of the different wind turbines.

Figure 2. Comparison of power in the axis for different wind speeds.

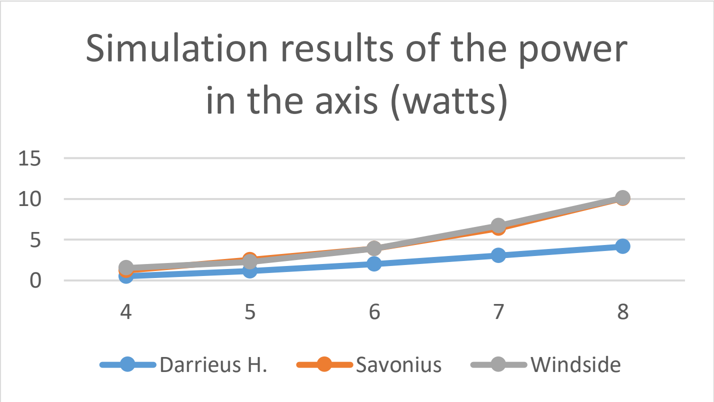


Figure 3. Neutrosophic histogram of power in the axis simulation results. The determined part appears in blue and the indeterminate part in orange.

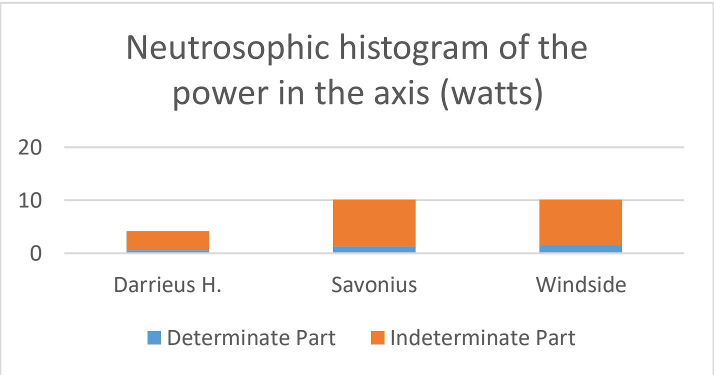


Figure 2 represents the measured axis power for wind speeds between 4m/s and 8m/s for the three types of wind turbines. Figure 3 represents the neutrosophic histogram of the on-axis power of the wind turbines. Recall that a neutrosophic histogram like the neutrosophic numbers contains a determinate part (represented in blue in Figure 3) and an indeterminate part (represented in orange).

Table 1 contains more details of the experiment results.

Table 1. Comparison of power generation of the three wind turbines.

Wind turbine model	**Aerodynamic coefficient**	**Air density (kg.m $^{-3}$)**	**Area (m^2)**	**Relative air speed (m/s)**	**Theoretical power in the axis (watts)**	**Power in the axis with simulation (watts)**
Darrieus H.	1.33	0.909	0.106	4	0.61	0.52
				5	1.19	1.13
				6	2.05	1.98
				7	3.26	3.05
				8	4.86	4.14

Wind turbine model	Aerodynamic coefficient	Air density (kg.m $^{-3}$)	Area (m^2)	Relative air speed (m/s)	Theoretical power in the axis (watts)	Power in the axis with simulation (watts)
Savonius	23	0.909	0.14045	4	1.39	1.22
				5	2.72	2.53
				6	4.70	3.89
				7	7.46	6.41
				8	11.14	10.08
Windside	2.35	0.909	0.11	4	1.11	1.52
				5	2.18	2.25
				6	3.76	3.89
				7	5.97	6.72
				8	8.91	10.12

From the previous results we have that for the Darrieus H. the power generated is $[0.52, 4.14] = 0.52 + 3.62I$; for the Savonius it is $[1.22, 10.08] = 1.22 + 8.86I$ and for the Windside it is $[1.52, 10.12] = 1.52 + 8.6I$. Therefore it is evidently preferred the Windside concerning the power, closely followed by Savonius. As for speeds of wind of 5m/s Savonius generated more power than Windside we compared the averages of the powers in both and the results were 4.826 Watts for the Savonius and 4.9 Watts for the Windside, so it confirms the decision made that the latter is the one that generates the most current electric.

However, this is only one factor, there are others like the efficiency of each of the models, the maintenance cost, in addition to the current power it generates and the durability.

We evaluate the three types of wind turbines $A_1 =$ Darrieus H., $A_2 =$ Savonius, and $A_3 =$ Windside for $C_1 =$ Power, $C_2 =$ Efficiency, $C_3 =$ Maintinance cost, $C_4 =$ Durability. The evaluations are shown in Table 2.

Table 2. Evaluation of the three types of wind turbines with respect to four criteria, namely: Power, Efficiency, Maintenance cost, and Durability.

Wind turbine	C_1(Watts)	C_2(%)	C_3(% initial cost)	C_4(Years)
Darrieus H.	$0.52 + 3.62I$	$30 + 10I$	$1 + I$	$20 + I$
Savonius	$1.22 + 8.86I$	$10 + 7I$	$1 + I$	$25 + 5I$
Windside	$1.52 + 8.6I$	$11 + 7I$	$1 + I$	$25 + 4I$

3 experts were hired, who were asked to determine the weights of each of the 4 criteria for decision making. $W = [w_1, w_2, w_3, w_4]$. Among them, they reached a consensus such that $w_1 = 0.2$, $w_2 = 0.3$, $w_3 = 0.2$, $w_4 = 0.3$. Note that the values of the weights are in the interval $[0, 1]$ and satisfy the condition $\sum_{j=1}^{4} w_j = 1$.

From Equations 2 and 3 we have:

$A^* = \{f_1^*, f_2^*, f_3^*, f_4^*\} = \{10.12, 40,1,30\}$, $A^- = \{f_1^-, f_2^-, f_3^-, f_4^-\} = \{0.52,10,2,20\}$.

Then, the intervals $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$ are calculated with the help of Equations 4-7:

$S_1 = [0.39458, 0.8]$, $R_1 = [0.39458, 0.8]$; $S_2 = [0.23083,0.83542\ ]$, $R_2 = [0.23083,0.83542]$; $S_3 = [0.25, 0.81917]$, $R_3 = [0.25,0.81917]$.

From Equations 8-11 it is calculated:

$Q_1 = [0.27084, 0.94141] = 0.27084 + 0.67057I$, $Q_2 = [0, 1] = I$, and $Q_3 = [0.031707, 0.973122] = 0.031707 + 0.94142I$.

According to the order defined in the algorithm for $\alpha = 0.5$, there is, Q_2 is the minimum, followed by Q_3, and ends Q_1.

That is, according to a more complete analysis, the Savonius model is preferred, then Windside, and finally Darrieus H.

Conclusion

Neutrosophic tools, such as neutrosophic numbers were used to model the indeterminacy that exists in the ranges of variation in wind speeds, which implies changes in the watts of electrical energy generation. A simulation of three types of wind turbines was carried out in a wind tunnel, these are: Darrieus H., Savonius and Windside. As a result, the Windside vertical axis wind turbine is the one that has the best performance and generates greater power compared to the other wind turbines that were studied.

On the other hand, we use the VIKOR Indeterminate decision-making method, which basically consists of the VIKOR algorithm for interval numbers, adapted to neutrosophic numbers. The 3 types of wind turbines were compared with respect to 4 criteria, which are: Power, Efficiency, Maintinance cost, and Durability. Three experts served as support to assign weights to each of the criteria. The result is that the Savonius type is preferred over the others.

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