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Fuzzy Multi-Criteria Decision-Making Model for Supplier Evaluation and Selection in a Wind Power Plant Project

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Abstract: In order to meet ambitious growth targets in the medium term, Vietnam must continue exploiting traditional energy sources. In the longer term, Vietnam has to develop a strategy and roadmap for the development of new energy sources. In these new energy sources, wind energy has emerged as a viable option. Given the geographic conditions of a locality with a long coastline and high winds that are fairly distributed all year, many wind-power plants are being built in Vietnam. One of the most important pieces of equipment in a wind-power plant is the wind turbine. The wind turbine suppliers' selection is a complex and multicriteria decision-making (MCDM) process that can reduce the costs of procuring equipment and aid in receiving products on time. Many studies have applied the MCDM model to various fields of science and engineering. One of the fields that the MCDM approaches have been applied to is the supplier selection problem. Supplier selection is an important issue of the MCDM model. Especially in a renewable energy project, decision-makers have to evaluate both natural and society factors. Although some researchers have reviewed the applications of the MCDM model in wind turbine supplier selection, limited work has focused on this problem in a fuzzy environment. Therefore, in this work, the authors propose a fuzzy MCDM model for the wind turbine supplier selection process under fuzzy environment conditions. In the first step, all factors for wind turbine supplier selection are identified by supply chain operations reference (SCOR) metrics and the results from a review of the literature. A fuzzy analytic network process (FANP) model is applied for determining the weight of all the criteria in the second stage, and the technique for order preference by similarity to an ideal solution (TOPSIS) model is used to rank all the potential suppliers in the final stage. As a result, Decision-Making Unit 010 (DMU010) becomes an optimal option for the wind turbine supplier selection processes. The contribution of this research is to develop new hybrid fuzzy MCDM approaches for wind turbine supplier selections. Furthermore, this work presents useful guidelines for wind turbines as well as provides a guideline for supplier selection in other industries.

Keywords: FMCDM; wind turbine; supplier selection; SCOR metrics; FANP; TOPSIS

1. Introduction

Thirty years ago, the Vietnamese government was forced to change its economic policy. The inefficiencies of the economic system led to deteriorating living conditions in the 1980s. During the sixth congress party in December 1986, the communist party decided to reform the economic system, called Doi Moi (renovation). The political elite opted for a gradual change of the economy, without changing the political system. The economic development induced by the reforms was remarkable. The living conditions of the Vietnamese have improved drastically as a consequence of the high growth rates. Despite economic and social success since the introduction of the reforms, Vietnam has now reached a distinctive moment [1]. As the living standards of the population increase, the level of economic production becomes increasingly modern, the demand for energy increases, and satisfying this demand is a real challenge for most nations. Since the Doi Moi period, there has been a surge in electricity demand, while the supply capacity has been limited in development. If this momentum continues, power shortage will remain a constant concern for the electricity industry as well as other industries in Vietnam.

Hydropower is considered clean electricity, which helps in reducing greenhouse gases. With favorable geographic conditions of a locality with a long coastline and high winds that are fairly distributed all year, Vietnam has many favorable conditions for investment in the development of wind energy sources. Thus, many wind-power plants are being built in Vietnam, and one of the most important pieces of equipment of a wind power plant is the wind turbine.

Wind turbines are manufactured in a series of vertical and horizontal shafts. The smallest turbines are used for applications such as charging batteries for auxiliary power for boats, caravans, and traffic signals. Larger steam turbines can be used to contribute to domestic electricity while selling unused electricity to service providers through the grid. Large turbines, called wind farms, are becoming increasingly important renewable energy sources and are used by many countries as part of a strategy to reduce the dependence on fossil fuels. An assessment declared that, by 2009, the wind had the "lowest relative greenhouse gas emissions, lowest water consumption, and the most favorable social impacts" compared with photovoltaic, hydropower, geothermal heat, coal, and gas [2].

Wind turbines are typically inexpensive. They will produce between two and six cents per kilowatt hour, which makes them one of the lowest-priced renewable energy sources [3]. Thus, as the technology required for wind turbines continues to improve, prices will also fall. Also, there is no competitive market for wind power, as the wind does not have any cost. [3] The main cost of wind turbines is the installation process, which averages $48,000 to $65,000. However, the energy obtained from the turbines will offset the installation costs as well as provide almost free energy for many years to come [4].

Thus, wind turbine supplier selection is naturally a critical issue for wind energy companies and governments when they build new wind farms [5]. Therefore, the authors propose a fuzzy multicriteria decision-making multicriteria decision-making (FMCDM) model for wind turbine supplier selection processes. In the first step, all main criteria and sub-criteria for wind turbine supplier selection are identified by supply chain operations reference (SCOR) metrics and the results from a review of the literature. A fuzzy analytic network process (ANP) model is applied for determining the weight of all the criteria in the second stage, and all potential suppliers will be ranked by The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) model in the final stage.

The main goal of this research is to present fuzzy MCDM approaches for wind turbine supplier selections based on qualitative and quantitative factors. The primary objectives of this work also propose useful guidelines for supplier selection in general and wind turbine supplier selection in particular.

The remainder of the paper provides background materials to assist in the development of the MCDM model. Then, a hybrid SCOR-FANP-TOPSIS approach is proposed to select the best wind turbine supplier from 10 potential locations. Discussions and contributions of this research are presented at the end of this paper.

2. Literature Review

Previous work has applied MCDM approaches to supplier selection in many fields of science and engineering, such as Gupta et al. [6] who applied the ANP model for supplier selection in the automation industry. Significant suppliers play an important role in the competitive market, so in this work, each potential supplier is ranked by the ANP model. Adhikary et at. [7] used the Multi-Criteria Optimization Technique for ranking turbine suppliers for a small hydro project. This paper aimed to evaluate the applicability of the multi-criteria optimization to decision makers during the small hydropower project planning and development. Samut [8] applied the integrated fuzzy analytic network process (FANP) and the mixed integer goal programming (MIGP) model to single wind turbine suppliers in the wind power plant projects. This study contributed to the literature both the establishment of specific criteria and proposed an integrated model which allowed for the selection of the best suppliers of wind turbines and similar project-based productions.

Yang and Li [9] studied the selection of equipment suppliers for the Wind Power Generation engineering, procurement and construction (EPC) Project. Dinmohammadi and Jeng et al. [10] proposed the α-Fraction First Strategy for Hierarchical Model in Wireless Sensor Networks. The model was finally applied to determine the most suitable wind turbine technology transfer strategy among four options of reverse engineering, technology skills training, turn-key contracts, and technology licensing for the renewable energy sector of Iran, and the results were compared with those obtained by classical decision-making models. Wang et al. [11] proposed an MCDM model for renewable energy plant location selection. Wang and Tsai [12] presented the MCDM model using hybrid fuzzy analytic hierarchy process (FAHP) and data envelopment analysis (DEA) for solar panel supplier selection. Lee et al. [13] proposed a hybrid to select suitable turbines when developing a wind farm. Chen et al. [14] introduced the solar-wind generation system, and next developed its critical success criteria. Patlitzianas et al. [15] proposed an MCDM model for assessing the environment of renewable energy suppliers in the European Union (EU).

Nüt et al. [16] used the ANP model for evaluating the most suitable energy resources in Turkey. Lee et al. [17] introduced an MCDM method, with the incorporation of analytic hierarchy process (AHP) and the benefits, opportunities, costs, and risks concept for selecting a wind farm project. Cristóbal [18] proposed a MCDM model for selecting the renewable energy project. Kolios et al. [19] proposed an MCDM method for comparing support structures of offshore wind turbines. Wang et al. [20] proposed a hybrid FANP and Data Envelopment Analysis (DEA) model for supplier selection. Nguyen et al. [21] presented an MCDM model using hybrid FANP and TOPSIS for solid waste to energy plant location selection. Wang et al. [11] used the DEA, FAHP, and TOPSIS model for solar power plant location selection. Beside. Wang et al. [22] introduced an MCDM model for renewable energy plants location selection.

Kaur et al. [23] proposed a linear program for integrated supplier selection. Lamba et al. [24] considered carbon emissions in a big data environment. Dubey et al. [25] proposed a framework for the green supply chain. The study empirically tested the research calls of various researchers and extended them to green supply chain networks. Their findings support aninstitutional theory. Lamba et al. [26] integrated decisions for supplier selection and lot-sizing considering different carbon emission regulations in a big data environment. The model provides an optimal supplier selection and lot-sizing policy along with carbon emissions. Carter and Dresner [27] analyzed the purchasing's role in environmental management—cross-functional development of grounded theory. The findings resulted in an inductive study leading to theory grounded in the data but related to extant findings and was based on case studies that tap the perspectives of purchasing managers and the managers in multiple, additional functional areas with whom they interact when initiating environmental projects. Ciaramella et al. [28] proposed a Bayesian-Based Neural Network model for solar photovoltaic power forecasting. Perera et al. [29] surveyed machine learning techniques for the supporting of renewable energy generation and integration. The studies reviewed in this paper analyzes the different machine learning techniques used for supporting the generation of renewable energy and more importantly their integration into the power grid. Cavone et al. [30] proposed a game-theoretical design technique for multi-stage supply chains under the uncertainty environment. Ho et al. [31] reviewed the literature of the multi-criteria decision-making approaches for supplier evaluation and selection. This research not only provides evidence that the multi-criteria decision-making approaches are better than the traditional cost-based approach but also aids researchers and decision makers in applying the approaches effectively. Govindan et al. [32] reviewed the literature of the multi-criteria decision-making approaches for green supplier evaluation, and the selection of the goal and purpose of this paper was to analyze the research in international scientific journals and international conference proceedings that focus on green supplier selection. Kahraman et al. [33] used fuzzy analytic hierarchy processes (AHP) to select the best supplier firm providing the most satisfaction of the criteria determined.

3. Materials and Methods

3.1. Research Development

In this research, the authors present a fuzzy MCDM model, including SCOR metrics and FANP and TOPSIS models, to select the optimal suppliers for wind turbines. Three steps are involved in this research, as shown in Figure 1.

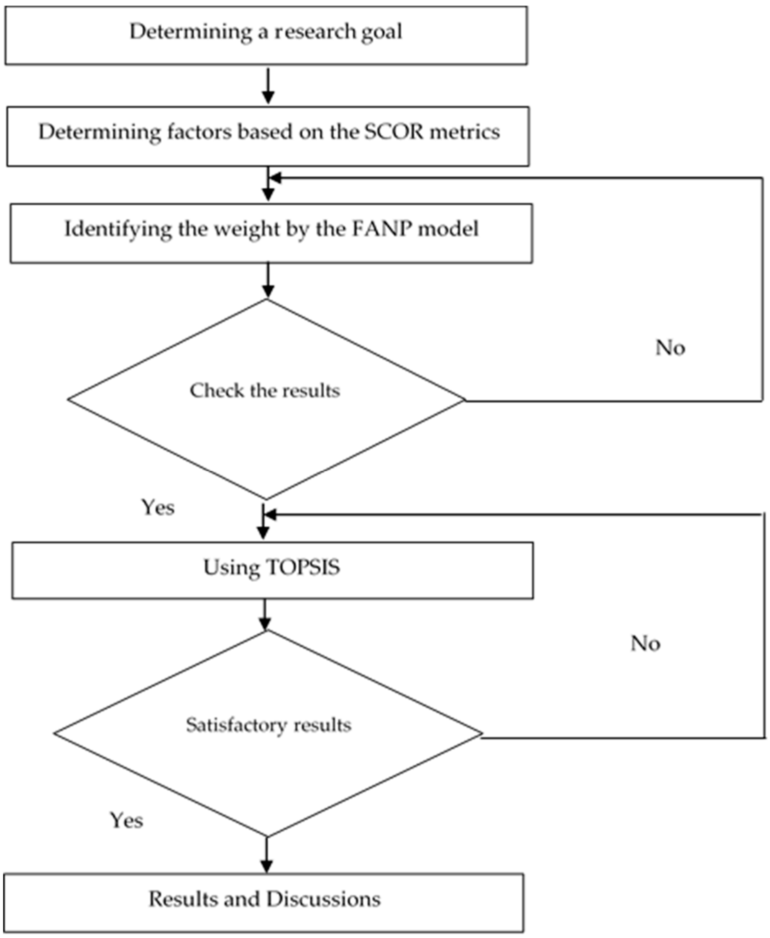

Figure 1. The research methodology.

Step 1: Evaluating and selecting the criteria based on the SCOR metrics

In this step, all main criteria and sub-criteria for wind turbine supplier selection will be identified. The key criteria and sub-criteria are built based on the SCOR metrics and the results from the literature review.

Step 2: Applying a fuzzy ANP approach

A fuzzy ANP approach is one of the most useful tools for solving complex issues of MCDM, with a connection with various qualitative and quantitative factors. The weight of all the criteria and sub-criteria will be identified by the FANP model.

Step 3: Implementing the TOPSIS model

The TOPSIS method has become a popular tool for solving multicriteria decision problems (MCDM). The main idea of TOPSIS is to evaluate options by simultaneously measuring the distance from the options to the positive ideal solution PIS and the negative ideal solution NIS. Based on the weight of all the criteria, which were defined by the ANP model in Step 2, the authors applied the TOPSIS model for ranking the suppliers listed in this stage.

3.2. *Methodology*

Although some researchers have reviewed of the applications of the MCDM model in wind turbine supplier selection, very few studies have focused on this problem in a fuzzy environment. In this research, the authors proposed a fuzzy MCDM model including Supply Chain Operations Reference (SCOR) metrics, a fuzzy analytic network process (FANP) model, and the technique for order preference by similarity to an ideal solution (TOPSIS) model for supplier selection.

SCOR metrics are categorized into five performance attributes: reliability, responsiveness, agility, costs, and asset management efficiency. The Fuzzy Analytic Network Process (FANP) method is a widely used multi-criteria method to handle the interaction among the criteria and linguistic variable, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method, which was originally developed by Ching-Lai Hwang and Yoon in 1981 with further developments by Yoon in 1987, and Hwang, Lai and Liu in 1993. TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution (PIS) and the longest geometric distance from the negative ideal solution (NIS). More detail about the SCOR metrics, the FANP model, and the TOPSIS approaches are shown in Sections 3.2.1–3.2.4.

3.2.1. Supply Chain Operations Reference (SCOR) Metrics

SCOR was proposed by Theodore et al. [34,35]. The SCOR reference sourcebook consists of five main sections which are shown in Figure 2. The performance or metrics section of the SCOR focuses on understanding the outcomes of the supply chain and consists of two types of elements: Performance Attributes and Metrics, and introduces the concept of Process/Practice Maturities.

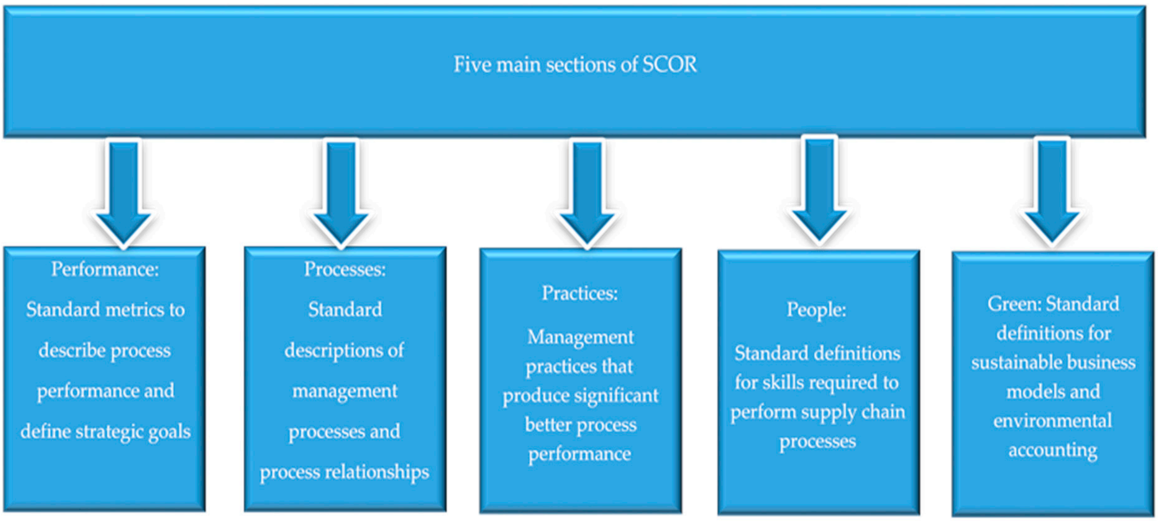

Figure 2. Five main sections of the SCOR.

A performance attribute is a grouping or categorization of metrics used to express a specific strategy. An attribute itself cannot be measured; it is used to set a strategic direction. Metrics measure the ability to achieve these strategic directions. The SCOR recognizes the five performance attributes: reliability, responsiveness, agility, cost, and assets. The performances attributes of the SCOR metrics are shown in Figure 3.

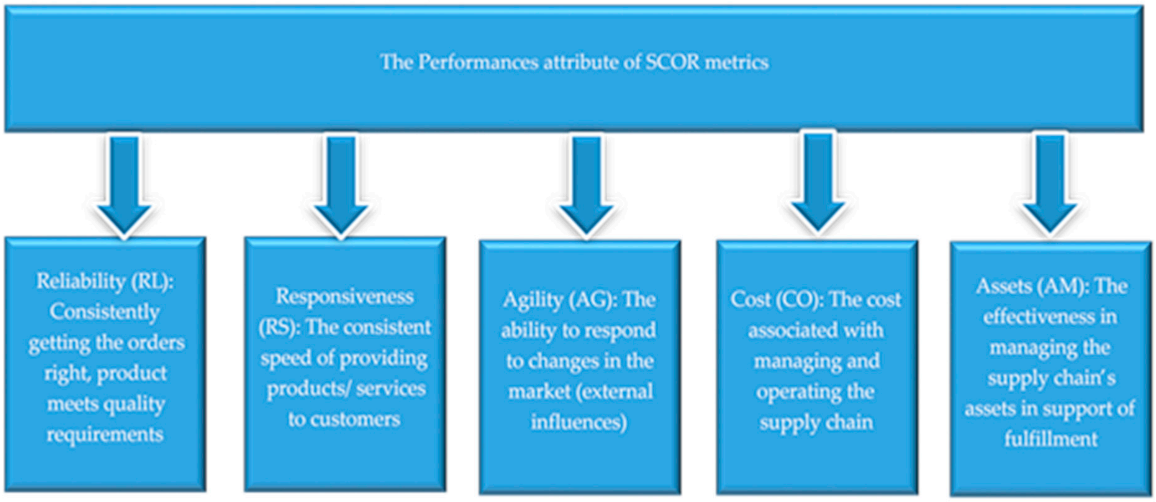

Figure 3. Performance attributes of the SCOR metrics.

3.2.2. Fuzzy Sets and Fuzzy Number

The Triangular Fuzzy Number (TFN) can be defined as (q, w, e), where q, w, and e $(q \leq w \leq e)$ are parameters indicating the smallest, the promising, and the largest value in the TFN, respectively. The TFN is shown in Figure 4.

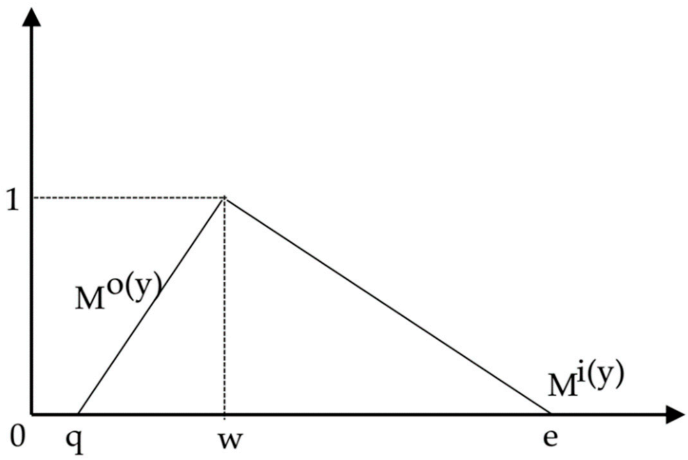

Figure 4. Triangular Fuzzy Number.

Triangular Fuzzy Number: A fuzzy number $\widetilde{M} = (q, w, e)$ is called triangular fuzzy number if its membership function is given by:

$$\mu\left(\frac{x}{\widetilde{M}}\right) = \begin{cases} 0, & x < w, \\ \frac{x-q}{w-q} & q \leq x \leq w, \\ \frac{e-x}{e-w} & w \leq x \leq e, \\ 0, & x > e. \end{cases} \tag{1}$$

Consider two positive triangular fuzzy numbers $M_1 = (q_1, w_1, e_1)$ and $M_2 = (q_2, w_2, e_2)$. The basic calculations of fuzzy numbers are shown in:

$$\widetilde{M} = (M^{o(y)}, M^{i(y)}) = [q + (w - q)y,\ e + (w - e)y], y \in [0, 1] \tag{2}$$

$o(y)$, $i(y)$ indicates both the left side and the right side of a fuzzy number as:

$$\begin{aligned}
(q_1,\ w_1,\ e_1) + (q_2,\ w_2,\ e_2) &= (q_1 + q_2,\ w_1 + w_2, e_1 + e_2) \\
(q_1,\ w_1,\ e_1) - (q_2,\ w_2,\ e_2) &= (q_1 - q_2,\ w_1 - w_2, e_1 - e_2) \\
(q_1,\ w_1,\ e_1) \times (q_2,\ w_2,\ e_2) &= (q_1 \times q_2,\ w_1 \times w_2, e_1 \times e_2) \\
\frac{(q_1,\ w_1,\ e_1)}{(q_2,\ w_2,\ e_2)} &= (q_1/q_2,\ w_1/w_2, e_1/e_2)
\end{aligned} \tag{3}$$

3.2.3. Analytic Network Process (ANP)

ANP is a development of the AHP model [36]. The model of ANP (Analytic Network Process) is in the form of a network hence the interactions between each element on the same factor, or the elements of different factors can be seen.

- Calculation of the Consistency Index (CI):

$$CI = (\lambda max\text{-}q)/(q\text{-}1). \tag{4}$$

where CI: Consistency Index and q: is the number of compared elements.

- Calculation of the Consistency Ratio (CR), using a random index is as following:

$$CR = CI/UI. \tag{5}$$

where UI = random index (CI of the randomly generated pairwise comparison matrix). Random index are shown in Table 1.

Table 1. Random index.

Matrix Size (q)	UI Value
1.0	0.00
2.0	0.00
3.0	0.58
4.0	0.90
5.0	1.12
6.0	1.24
7.0	1.32
8.0	1.41
9.0	1.45
10.0	1.49

- Formation of the supermatrix which is the result of the priority vector from the paired comparisons between clusters including goal, criteria, sub-criteria, and alternatives.

3.2.4. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)

The results of the analysis in some of studies using the TOPSIS method shows that quality evaluation indicators affect the results of the evaluation, hence the selection of the precise indicator is very important [37]. Thus, this study uses the TOPSIS method to verify the accuracy of the ANP model. The procedure of the TOPSIS method consists of the steps as follows [38,39].

Determining the TOPSIS Needs Performance Ranking in Every Ai Option Over Every Normalized Cj Factor

This can be seen from the formula below:

$$e_{ij}\frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^{2}}}. \tag{6}$$

with I = 1,2, ... m; and j = 1,2, ... n.

Calculate the Normalized Weighted Decision Matrix

$$S_{ij} = W_i e_{ij}. \tag{7}$$

with i = 1,2, ... m and j = 1,2, ... n.

Calculate PIS A^+ Matrix and NIS A^- Matrix

$$\begin{aligned} A^+ &= s_1^+,\ s_2^+, \ldots, s_n^+; \\ A^- &= s_1^-,\ s_2^-, \ldots, s_n^-; \end{aligned} \tag{8}$$

where s_j^+ is Max s_{ij} if j is an advantage factor and Max s_{ij} if j is a cost factor; s_j^- is Min s_{ij} if j is an advantage factor and Min s_{ij} if j is a cost factor.

Identifying the Gap between the Values of Each Options with the PIS Matrix and NIS Matrix

Options to PIS:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \left(s_i^+ - s_{ij}\right)^2};\ i = 1, 2, \ldots, m. \tag{9}$$

Options to NIS:

$$D_i^- = \sqrt{\sum_{j=1}^{m} \left(s_{ij} - s_i^-\right)^2};\ i = 1, 2, \ldots, m. \tag{10}$$

where D_i^+ is the distance to the PIS for I option and D_i^- is the distance to the NIS.

Calculating the Preference Value for Every Alternative (G_i)

$$G_i = \frac{D_i^-}{D_i^- + D_i^+} \quad i = 1,\ 2,\ \ldots,\ m. \tag{11}$$

4. Case Study

Existing coal, oil, and gas resources in the near future will become exhausted; therefore, so many countries are now focused on developing wind resources. The price of electricity generated from wind power is roughly equivalent to that of the electricity generated from traditional fossil fuels. Wind energy resources are the newest and most powerful sources of energy in the world today. Wind power at sea is converted into electricity by wind turbines and is manufactured with a longer lifespan suited to this environment's extreme conditions. Therefore, the development of wind energy in Vietnam towards the objective of mitigating the impacts of climate change is one of the solutions considered feasible today.

In addition, Vietnam is a tropical monsoon country, so the wind in many regions in Vietnam is considered abundant. Vietnam has the greatest potential for this kind of energy, according to surveys in Thailand, Vietnam, Laos, and Cambodia on wind energy, conducted by the World Energy Agency and the World Bank. Thus, the government facilitates many renewable energy projects to invest in its development. One of the most important pieces of equipment of a wind power plant is the wind turbine. In wind farm projects, selecting a wind turbine supplier is a complex decision, requiring the decision-maker to consider quantitative and qualitative factors.

To overcome these issues, the authors propose a fuzzy MCDM model for the wind turbine supplier selection process. In the first step, all main criteria for wind turbine supplier selection are identified by the SCOR metrics and the results from the literature review. A fuzzy ANP model is applied for identifying the weights of criteria in the second stage, and the TOPSIS model is used to rank all potential suppliers in the final stage.

In this case study, the authors considered the Wind Power Plant project in the Binh Thuan Province, Vietnam. According to the plan, the project would build and install 60 wind power stations (or turbines), increasing the total capacity of the Binh Thuan Wind Power Plant to 120 MW. A project manager wanted to buy all the wind turbines manufactured with a special stainless steel structure, 80 m height, 4 m diameter, weighing over 200 tons, 42 m special plastic propeller, and with a self-folding control system to avoid damage to heavy storms. Ten potential suppliers (decision-making units [DMUs]) were selected by interviewing experts based on their delivery time, product capacity, supplier's location, unit price, etc. The authors considered 10 suppliers:

$$\text{Supplier} - i\ (\text{DMU}i),\ \text{where}\ i = 1, \ldots, 10.$$

Based on the SCOR metrics and experts' option, the ANP structure was built and is shown in Figure 5.

Main Criteria	Subcriteria
1.Reliability (RL)	RL.1.1. Perfect order fulfillment (BOF)
	RL.1.2. Quantity deliveries (QUD)
	RL.1.3. Capability compatibility (CCO)
2. Responsiveness (RE)	RE.1.1. Order fulfillment cycle time (OFC)
	RE.1.2. Supplier corrective action request (SCR)
	RE.1.3. Resolution time (RET)
3. Agility (AG)	AG.1.1 Upside supply chain flexibility (USF)
	AG.1.2. Supply chain upside adaptability (SUA)
	AG.1.3. Downside supply chain adaptability (DSA)
4. Cost (CO)	CO.1.1. Material costs (MOS)
	CO.1.2. Transportation Costs (TRC)
	CO.1.3. Supplier management costs (SMS)
5. Asset Management Efficiency (AM)	AM.1.1. Cash to cash cycle time (CCT)
	AM.1.2. Return on supply chain fixed assets (RFA)
	AM.1.3. Return on working capital (RWC)

Figure 5. The FANP structure.

The fuzzy comparison matrix of the goal is shown in Table 2.

Table 2. The fuzzy comparison matrices for the goal.

Criteria	AG	AM	CO	RE	RL
AG	(1,1,1)	(1,1,1)	(3,4,5)	(1,2,3)	(3,4,5)
AM	(1,1,1)	(1,1,1)	(2,3,4)	(1,2,3)	(3,4,5)
CO	(1/3,1/4,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)	(1/3,1/2,1)
RE	(1/3,1/2,1)	(1/3,1/2,1)	(2,3,4)	(1,1,1)	(2,3,4)
RL	(1/3,1/4,1/2)	(1/3,1/4,1/2)	(1,2,3)	(1/4,1/3,1/2)	(1,1,1)

We have

$\alpha = 0.5$ and $\beta = 0.5$.
$g_{0.5,0.5}(\overline{a_{AM,CO}}) = [(0.5 \times 2.5) + (1 - 0.5) \times 3.5] = 3$
$f_{0.5}(L_{AM,CO}) = (3 - 2) \times 0.5 + 2 = 2.5$
$f_{0.5}(U_{AM,CO}) = 4 - (4 - 3) \times 0.5 = 3.5$
$g_{0.5,0.5}(\overline{a_{CO,AM}}) = 1/3$

The real number priority when comparing the main criteria pairs are shown in Table 3.

Table 3. Real number priority.

Criteria	AG	AM	CO	RE	RL
AG	1	1	4	2	4
AM	1	1	3	2	4
CO	1/4	1/3	1	1/3	$\frac{1}{2}$
RE	1/2	1/2	3	1	3
RL	1/4	1/4	2	1/3	1

Calculation of the maximum individual values are as follows:

$MT1 = (1 \times 1 \times 4 \times 2 \times 4)^{1/5} = 2$
$MT2 = (1 \times 1 \times 3 \times 2 \times 4)^{1/5} = 1.89$
$MT3 = (1/4 \times 1/3 \times 1 \times 1/3 \times 1/2)^{1/5} = 0.43$
$MT4 = (1/2 \times 1/2 \times 3 \times 1 \times 3)^{1/5} = 1.18$
$MT5 = (1/4 \times 1/4 \times 2 \times 1/3 \times 1)^{1/5} = 0.53$
$\sum MT = 6.03$
$\omega_1 = \frac{2}{6.03} = 0.33$
$\omega_2 = \frac{1.89}{6.03} = 0.31$
$\omega_3 = \frac{0.43}{6.03} = 0.07$
$\omega_4 = \frac{1.18}{6.03} = 0.20$
$\omega_5 = \frac{0.53}{6.03} = 0.09$

$$\begin{bmatrix} 1 & 1 & & 4 \quad 2 & 4 \\ 1 & 1 & & 3 \quad 2 & 4 \\ 1/4 & 1/3 & 1 & 1/3 & 1/2 \\ 1/2 & 1/2 & 3 & 1 & 3 \\ 1/4 & 1/4 & 2 & 1/3 & 1 \end{bmatrix} x \begin{bmatrix} 0.33 \\ 0.31 \\ 0.07 \\ 0.20 \\ 0.09 \end{bmatrix} = \begin{bmatrix} 1.68 \\ 1.61 \\ 0.37 \\ 1 \\ 0.46 \end{bmatrix}$$

$$\begin{bmatrix} 1.68 \\ 1.61 \\ 0.37 \\ 1 \\ 0.46 \end{bmatrix} / \begin{bmatrix} 0.33 \\ 0.31 \\ 0.07 \\ 0.20 \\ 0.09 \end{bmatrix} = \begin{bmatrix} 5.09 \\ 5.19 \\ 5.29 \\ 5 \\ 5.11 \end{bmatrix}$$

the authors get $n = 5$, so:

$$\lambda_{max} = \frac{5.09 + 5.19 + 5.29 + 5 + 5.11}{5} = 5.136$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{5.136 - 5}{5 - 1} = 0.034$$

To calculate CR value, we get $RI = 1.12$ with $n = 5$.

$$CR = \frac{CI}{RI} = \frac{0.034}{1.12} = 0.03$$

Because $CR = 0.03 \leq 0.1$, there was no need for it to be re-evaluated. After evaluating the interaction between all the criteria in the FANP model, the results from Microsoft Excel are shown in Table 4.

Table 4. Results of the FANP model.

No	Sub-Criteria	Weight
1	BOF	0.0704
2	QUD	0.0747
3	CCO	0.0715
4	OFC	0.0931
5	SCR	0.0416
6	RET	0.0906
7	USF	0.0805
8	SUA	0.1917
9	DSA	0.1596
10	MOS	0.0406
11	TRC	0.0384
12	SMS	0.0455
13	CCT	0.0009
14	RFA	0.0007
15	RWC	0.0005

The normalized matrices, determined by the TOPSIS model, are shown in Table 5.

Table 5. The normalized matrix.

	DMU-1	DMU-2	DMU-3	DMU-4	DMU-5	DMU-6	DMU-7	DMU-8	DMU-9	DMU-10
BOF	0.2882	0.3294	0.3705	0.3705	0.2470	0.2470	0.3294	0.2882	0.3705	0.2882
QUD	0.2816	0.3218	0.3218	0.2816	0.2816	0.3620	0.2414	0.3218	0.3620	0.3620
CCO	0.2892	0.3305	0.3305	0.3305	0.2479	0.2892	0.3718	0.2892	0.2892	0.3718
OFC	0.3360	0.2940	0.3360	0.3360	0.2940	0.3360	0.3360	0.2940	0.2520	0.3360
SCR	0.2654	0.3097	0.3097	0.3539	0.2654	0.3097	0.3981	0.3097	0.3097	0.3097
RET	0.3316	0.3731	0.3316	0.2902	0.3316	0.2902	0.2902	0.2902	0.2902	0.3316
USF	0.3824	0.2974	0.3399	0.2974	0.2549	0.3399	0.2974	0.2974	0.3399	0.2974
SUA	0.2902	0.3316	0.2902	0.2902	0.3316	0.2902	0.3316	0.2902	0.3316	0.3731
DSA	0.3724	0.3310	0.3310	0.3310	0.3310	0.2897	0.3310	0.2897	0.2483	0.2897
MOS	0.3052	0.3052	0.3052	0.3488	0.2616	0.3924	0.3052	0.3052	0.2616	0.3488
TRC	0.3336	0.3753	0.2919	0.2502	0.2919	0.3753	0.2919	0.3753	0.2502	0.2919
SMS	0.3577	0.3180	0.3577	0.3180	0.2385	0.3180	0.2782	0.3577	0.3180	0.2782
CCT	0.3490	0.2714	0.3102	0.3102	0.2327	0.3490	0.3102	0.3490	0.3102	0.3490
RFA	0.3456	0.3072	0.3456	0.3072	0.2688	0.3456	0.3072	0.3456	0.2688	0.3072
RWC	0.3530	0.3530	0.3530	0.3138	0.2353	0.3138	0.2746	0.2746	0.3138	0.3530

5. Results and Discussion

Nowadays, numerous renewable energy sources are being exploited, including solar, wind, geothermal, and biomass [40]. With advances in science and technology, along with inevitable world trends, renewable energies are being studied and increasingly used. Wind energy is one of the most important sources of renewable energy that will increasingly contribute to the world's energy output. Vietnam is an ideal country for investment and expansion of wind power production capacity, thanks to the highly skilled labor force and the future development of the energy sector.

Equipment supplier selection is an important issue in renewable energy projects in that a decision-maker must consider qualitative and quantitative factors. Choosing the right equipment supplier is one of the key success factors of renewable energy projects in general and wind energy projects in particular.

Many studies have used the MCDM model in various fields of science and engineering. Further, although studies have reviewed the applications of MCDM approaches in wind turbine supplier selection, few have focused on this problem in a fuzzy environment. In this research, the author proposed an MCDM model using hybrid SCOR metrics, FANP, and TOPSIS for wind turbine suppliers for wind power projects in Vietnam. Ten suppliers were considered and judged based on five criteria and 15 sub-criteria. In the first stage of this work, all important criteria are identified based on the SCOR metrics, and a FANP model is used to define the weight of each criterion. To overcome the disadvantages of using a FANP model, this process has been corrected by the TOSIS model in the final stage. This is the main contribution of this study from a theoretical point. In addition, this research provides a useful guideline for wind turbine supplier selection in many countries, and in practice, a guideline for supplier selection in related industries as well. Per the results shown in Table 6 and Figure 6, DMU010 is an optimal wind turbine supplier for wind power projects in Vietnam. One of the limitations of this research is that it does not perform a sensitivity analysis; however, the authors will do so in future research.

Table 6. PIS and NIS value from TOPSIS model.

	Di+	**Di-**
DMU001	0.0253	0.0225
DMU002	0.0178	0.0239
DMU003	0.0174	0.0263
DMU004	0.0205	0.0242
DMU005	0.0321	0.0160
DMU006	0.0263	0.0216
DMU007	0.0207	0.0290
DMU008	0.0258	0.0166
DMU009	0.0234	0.0254
DMU010	0.0176	0.0304

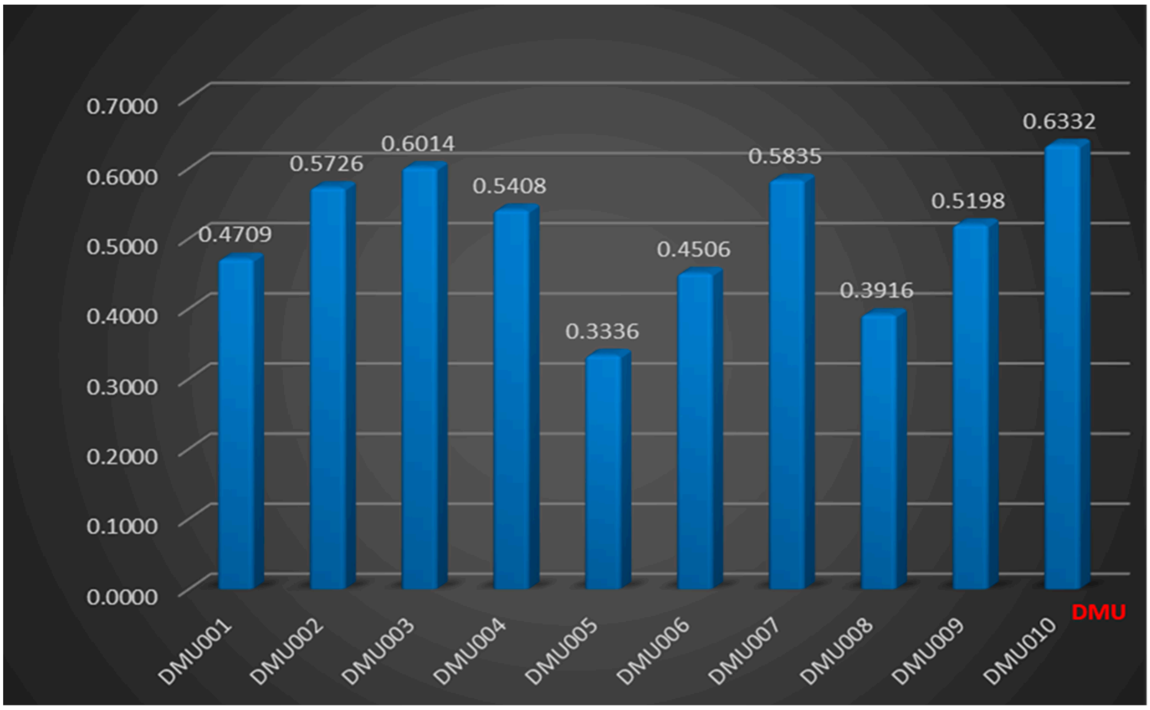

Figure 6. Final ranking score.

6. Conclusions

Nowadays, exploiting renewable energies not only helps to overcome the exhaustion of fossil fuel sources and save energy but also contributes to reducing environmental pollution. Vietnam is an ideal country for investment and expansion of wind power production capacity, thanks to its high-skilled labor force and the future development of the energy sector. In wind power energy projects, equipment supplier selection is an important issue in that a decision-maker must consider qualitative and quantitative criteria. Thus, wind turbine supplier selection involves multicriteria decision-making.

This is why the author proposed an MCDM model for wind turbine supplier selection in this research. In the first step, all main criteria and sub-criteria for wind turbine supplier selection are identified by the SCOR metrics and the results from the literature review. A FANP model is applied for determining the weight of all the criteria in the second stage, and the TOPSIS model is used to rank all the potential suppliers in the final stage. As a result, DMU010 become an optimal option for wind turbine supplier selection processes.

The contribution of this study is presented in a multicriteria decision-making model (MCDM) for wind turbine supplier selection in Vietnam under a fuzzy environment, and no previous research has applied this proposed model for wind turbine supplier selection in Vietnam. Especially, all the criteria affecting the supplier selection process are defined based on the SCOR metrics. This paper also resides in the evolution of a new approach that is flexible and practicable to the decision-maker. This research provides a useful guideline for wind turbine supplier selection in many countries as well as a guideline for supplier selection in related industries.

In addition, this research can be broadened, creating a premise for applying supplier selection in other industries and in particular extending the model for the evaluation and selection of suppliers in future research.

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