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An Integrated Multi-Criteria Decision Making Model for Evaluating Wind Farm Performance

He-Yau Kang [1], Meng-Chan Hung [2], W. L. Pearn [2], Amy H. I. Lee [3,* and Mei-Sung Kang [4]

[1] Department of Industrial Engineering and Management, National Chin-Yi University of Technology, Taichung 411, Taiwan; E-Mail: kanghy@ncut.edu.tw

[2] Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu 300, Taiwan; E-Mails: vivi_mon100@yahoo.com.tw (M.-C.H.); wlpearn@mail.nctu.edu.tw (W.L.P.)

[3] Department of Technology Management, Department of Industrial Management, Chung Hua University, Hsinchu 300, Taiwan

[4] Department of Electrical Engineering, Kao Yuan University, Kaohsiung 821, Taiwan; E-Mail: kmswmy@cc.kyu.edu.tw

* Author to whom correspondence should be addressed; E-Mail: amylee@chu.edu.tw; Tel.: +886-3-5186582; Fax: +886-3-5186575.

Abstract: The demands for alternative energy resources have been increasing exponentially in the 21st century due to continuous industrial development, depletion of fossil fuels and emerging environmental consciousness. Renewable energy sources, including wind energy, hydropower energy, geothermal energy, solar energy, biomass energy and ocean power, have received increasing attention as alternative means of meeting global energy demands. After Japan's Fukushima nuclear plant disaster in March 2011, more and more countries are having doubt about the safety of nuclear plants. As a result, safe and renewable energy sources are attracting even more attention these days. Wind energy production, with its relatively safer and positive environmental characteristics, has evolved in the past few decades from a marginal activity into a multi-billion dollar industry. In this research, a comprehensive evaluation model is constructed to select a suitable location for developing a wind farm. The model incorporates interpretive structural modeling (ISM), benefits, opportunities, costs and risks (BOCR) and fuzzy analytic network process (FANP). Experts in the field are invited to contribute their expertise in evaluating the importance of the factors and various aspects of the wind farm evaluation

problem, and the most suitable wind farm can finally be generated from the model. A case study is carried out in Taiwan in evaluating the expected performance of several potential wind farms, and a recommendation is provided for selecting the most appropriate wind farm for construction.

1. Introduction

Depletion of fossil fuels, increasing industrial development and emerging environmental consciousness have all increased the demand for alternative energy resources in the 21st century. Due to Japan's devastating earthquake and tsunami and the subsequent nuclear plant disaster in March 2011, fears of possible radiation and casualties resulting from nuclear plant malfunction have increased. With the protests of environmental groups, more and more countries are closing or planning to close their nuclear plants. Thus, a good alternative energy resource must not only be renewable with zero or little air pollutants and greenhouse gases, but it should also be safe for the World. When comparing different types of renewable energy sources, various aspects, such as cost, greenhouse gas emissions, radiological and toxicological exposure, occupational health and safety, domestic energy security, employment, and social impacts, must all be considered [1]. In addition, the outputs of natural and renewable energy sources are strongly affected by geographical factors and weather conditions, which cause the fluctuations in power quantity, frequency and voltage [2]. Therefore, different countries and places may be more suitable to develop different types of renewable energy sources than others.

The development of wind energy technologies and the decreases in wind power production costs have accelerated wind energy production in the past decade, with an annual growth rate around 30% and currently generating about 1.5% of global electricity [1,3]. With the heavy dependence of local wind energy resources and grid connection, the development of a wind farm involves several important stages: early prospecting of suitable sites, wind mapping at the potential site and conceptual wind farm design, micro-siting of turbines and optimization, risk assessment, planning of certification towers, post-construction performance analysis, and operation [4]. In addition, a comprehensive evaluation of related factors, such as wind energy policy and economical feasibility, must also be carried out [3].

The evaluation of different renewable energy sources or the evaluation of renewable energy projects/sites are multi-criteria decision making (MCDM) problems because advantages and disadvantages of renewable energy alternatives based on multiple criteria must be taken into account. MCDM methods, such as analytical hierarchy process (AHP), analytic network process (ANP), technique for order preference by similarity to the ideal solution (TOPSIS), preference ranking organization method for enrichment of evaluations (PROMETHEE), multi-attribute utility theory (MAUT), multi-objective decision making (MODM), ELECTRE, VIKOR, and decision support systems, have been used in the evaluation of renewable energy projects [5,6]. The applications of MCDM to renewable energy problems include renewable energy project planning, geothermal

projects, solar energy projects, hydro-site selection, wind farm projects, *etc*. [6]. Operationally, the assessment must deal with criteria that are difficult to define and that may be quantitative or qualitative [7]. In order to include the vagueness, ambiguity and subjectivity of human judgment, fuzzy set theory can also be adopted to express the linguistic terms using membership functions [5,7].

Depending heavily on imported fossil fuels, Taiwan faces the problems caused by its increasing energy consumption and the scarcity of global fuel energy resources. Taiwan is encountering energy shortages, escalating fuel prices, pollution emissions and environmental issues. Because of its unique geographic characteristics, Taiwan could develop wind farms at various locations on the island. Therefore, the development of wind power technology and the usage of wind energy source are important for the sustainable economic development of the country. However, this development needs to consider important aspects such as political issues, technologies, costs and societal environments. With a tremendous investment in capital, time and effort, the selection of the most appropriate place for constructing a wind farm is a very complicated task. In consequence, wind farm evaluation problem is a MCDM problem which involves the assessments of different factors in an uncertain environment.

Although wind farm selection is not a new research topic, this research, in the authors' understanding, is the first one that examines the interrelationship of the criteria in the decision making process by adopting interpretive structural modeling (ISM) and that considers the benefits, opportunities, costs and risks (BOCR) merits by using a fuzzy analytic network process (FANP). The rest of this paper is organized as follows: Section 2 reviews the related methodologies, and Section 3 develops an integrated MCDM model for evaluating wind farm performance. In Section 4, the model is applied to a case study in Taiwan. Some concluding remarks are offered in the last section.

2. Methodologies

2.1. Interpretive Structural Modeling (ISM)

Interpretive structural modeling (ISM), first proposed by Warfield, can be used to understand complex situations and to put together a course of action for solving a problem [8–10]. First, a map of the complex relationships among elements can be prepared by calculating a binary matrix, called relation matrix [11]. A question such as "Does criterion x_i affect criterion x_j?" is asked. If the answer is yes, then $\pi_{ij} = 1$; otherwise, $\pi_{ij} = 0$. Transitivity is considered to calculate a reachability matrix next. Finally, the operators of the Boolean multiplication and addition are applied to obtain a final reachability matrix, which can reflect the convergence of the relationship among the elements. ISM has been applied in various fields, and some recent works are presented in Table 1.

Table 1. Recent works on ISM.

Authors	Theories or Applications
Sahney *et al.* [12]	To propose an integrated framework for quality in education by applying SERVQUAL, quality function deployment, ISM and path analysis.
Agarwal *et al.* [13]	To understand the characteristics and interrelationship of variables in an agile supply chain.
Thakkar *et al.* [14]	To develop a balanced scorecard (BSC) framework using cause and effect analysis, ISM and ANP for performance measurement.

Table 1. *Cont.*

Authors	Theories or Applications
Faisal *et al.* [15]	To employ ISM to identify various information risks that could impact a supply chain and to present a risk index to quantify information risks.
Kannan and Haq [16]	To understand the interactions of criteria and sub-criteria that are used to select the supplier for the built-in-order supply chain environment.
Qureshi *et al.* [17]	To model the logistics outsourcing relationship variables to enhance shippers' productivity and competitiveness in logistical supply chain.
Singh *et al.* [18]	To construct a structural relationship of critical success factors for implementing advanced manufacturing technologies.
Upadhyay *et al.* [19]	To use content analysis, nominal group technique (NGT) and ISM to develop a hierarchy framework for quality engineering education.
Thakkar [20]	To propose an integrated mathematical approach based on ISM and graph theoretic matrix for evaluating buyer-supplier relationships.
Vivek *et al.* [21]	To establish changing emphasis of the core, transactional and relational specificity constructs in offshoring alliances.
Yang *et al.* [22]	To study the relationships among the sub-criteria and use integrated fuzzy MCDM techniques to study the vendor selection problem.
Wang *et al.* [23]	To analyze the interactions among the barriers to energy-saving projects in China.
Chidambaranathan *et al.* [24]	To develop the structural relationship among supplier development factors and to define the levels of different factors based on their dependence power and mutual relationships.
Kannan *et al.* [25]	To construct a multi-criteria group decisionmaking (MCGDM) model through ISM and fuzzy technique for order preference by similarity to ideal solution (TOPSIS) to guide the selection process of best third-party reverse logistics providers.
Mukherjee and Mondal [26]	To examine relevant issues in managing the remanufacturing technology for an Indian company.
Feng *et al.* [27]	To propose a hybrid fuzzy integral decision-making model, which integrates factor analysis, ISM, Markov chain, fuzzy integral and the simple additive weighted method, for selecting locations of high-tech manufacturing centers.
Lee *et al.* [28]	To determine the interrelationship among the critical factors for technology transfer of new equipment in high technology industry and apply the FANP to evaluate the technology transfer performance of equipment suppliers.
Lee *et al.* [29]	To determine the interrelationship among the criteria in a conceptual model to help analyze suitable strategic products for photovoltaic silicon thin-film solar cell power industry.
Lee *et al.* [30]	To propose an integrated model, which applies ISM to understand the interrelationship among criteria, for evaluating various technologies for a flat panel manufacturer.

2.2. Fuzzy Analytic Network Process (FANP)

Analytic hierarchy process (AHP) was introduced by Saaty in 1980 as a multi-criteria decision support methodology [31]. AHP is widely used in a variety of fields and has been successfully applied to many practical decision-making problems. The basic assumption of AHP is to decompose the decision making process into a linear top-to-bottom and the elements in each level are independent. However, each individual criterion may not be absolutely independent to others, and dependence and feedback usually exit. In order to deal with the limitations of AHP, Saaty [32] proposed an analytic network process (ANP) approach, which is a generalization of AHP. ANP approach replaces

hierarchies with networks, in which the relationships between levels are not easily represented as higher or lower, dominated or being dominated, directly or indirectly [33]. After evaluating the importance of all factors, including goal, cluster, criteria and alternatives through pairwise comparisons, a "supermatrix" is formed. A weighted supermatrix is formed next to ensure column stochastic; that is, the sum of the elements in each column is equal to one [32]. Finally, a limit supermatrix is calculated to obtain final solutions. ANP has also been applied successfully to project selection, strategic decision, scheduling, and so on. The procedures of FANP are basically as follows [27,30]:

1. Decompose the problem into a network. The overall objective is in the first level. The second level includes criteria, and there might be sub-criteria under each criterion. The dependences and feedback among criteria and among sub-criteria are considered. The last level includes the alternatives that are under evaluation.

2. Prepare a questionnaire based on the constructed network, and ask experts to fill out the questionnaire. Consistency index and consistency ratio for each comparison matrix are calculated to examine the consistency of each expert's judgment [31]. If the consistency test is not passed, the original values in the pairwise comparison matrix must be revised by the expert.

3. Transform the scores of pairwise comparison into fuzzy numbers.

4. Aggregate the results from Step 3. The fuzzy positive reciprocal matrix can be defined as:

$$\widetilde{A}^k = \left[\tilde{a}_{ij} \right]^k \tag{1}$$

where: $\widetilde{A}^k$: a positive reciprocal matrix of decision maker k;

$\tilde{a}_{ij}$: relative importance between decision elements i and j;

$\tilde{a}_{ij} = 1, \forall i = j$ and $\tilde{a}_{ij} = \dfrac{1}{\tilde{a}_{ji}}, \forall i, j = 1, 2, \ldots, n$.

If there are k experts, each pairwise comparison between two criteria has k positive reciprocal trapezoid fuzzy numbers. Geometric average approach is applied to aggregate multiple experts' responses, and the aggregated fuzzy positive reciprocal matrix is:

$$\widetilde{A}^* = \left[\tilde{a}_{ij}^{\ *} \right] \tag{2}$$

5. Defuzzy the synthetic trapezoid fuzzy numbers $\tilde{a}_{ij}^{\ *} = \left(x_{ij}, y_{ij}, z_{ij}, \upsilon_{ij} \right)$ into crisp numbers.

6. Form pairwise comparison matrices using the defuzzificated values, and calculate priority vector for each pairwise comparison matrix.

$$\mathbf{A} \cdot w = \lambda_{\max} \cdot w \tag{3}$$

where $\mathbf{A}$ is the matrix of pairwise comparison, w is the eigenvector, and $\lambda_{\max}$ is the largest eigenvalue of $\mathbf{A}$.

7. Form an unweighted supermatrix, as shown in Figure 1.

8. Form a weighted supermatrix to ensure column stochastic.

9. Calculate the limit supermatrix by taking the weighted supermatrix to powers so that the supermatrix converges into a stable supermatrix. Obtain the priority weights of the alternatives from the limit supermatrix.

Figure 1. Generalized supermatrix [27].

2.3. Benefits, Opportunities, Costs and Risks (BOCR)

The benefits, opportunities, costs and risks (BOCR) concept, also proposed by Saaty, is one of the general theories of the ANP [30,32]. Four sub-networks, benefits, opportunities, costs and risks, can be constructed in a network. In benefits (B) and opportunities (O) sub-networks, pairwise comparison questions ask which alternative is most beneficial or has the best opportunity under a factor [30]. In risks (R) and costs (C) subnets, the pairwise comparison questions ask which alternative is riskiest or costliest under a factor.

After the priority of each alternative under each merit sub-network is calculated, the priorities of the alternative under the four merits are further combined to get a single outcome for each alternative. There are five different ways to combine the scores of each alternative under the four merits, and the relative priority, P_i, for each alternative is [30,34]:

1. Additive:

$$P_i = bB_i + oO_i + c[(1/C_i)_{\text{Normalized}}] + r[(1/R_i)_{\text{Normalized}}] \tag{4}$$

   where B_i, O_i, C_i and R_i represent respectively the synthesized results of alternative i under merit B, O, C and R, and b, o, c and r are respectively normalized weights of merit B, O, C and R.

2. Probabilistic additive:

$$P_i = bB_i + oO_i + c(1 - C_i) + r(1 - R_i) \tag{5}$$

3. Subtractive:

$$P_i = bB_i + oO_i - cC_i - rR_i \tag{6}$$

4. Multiplicative priority powers:

$$P_i = B_i^b \, O_i^o \, [(1/C_i)_{\text{Normalized}}]^c \, [(1/R_i)_{\text{Normalized}}]^r \tag{7}$$

5. Multiplicative:

$$P_i = B_iO_i/C_iR_i \tag{8}$$

3. An Integrated Model for Evaluating Wind Farm Performance

A systematic FANP model incorporated with ISM and BOCR is proposed to help evaluate the performance of wind farms. The proposed steps are as follows:

Step 1. Form a committee of experts in the wind farm industry to define the wind farm evaluation problem.

Step 2. Construct a control network for the problem. A control network, as depicted in Figure 2, contains strategic criteria and four merits, benefits (B), opportunities (O), costs (C) and risks (R).

Figure 2. The control network [35].
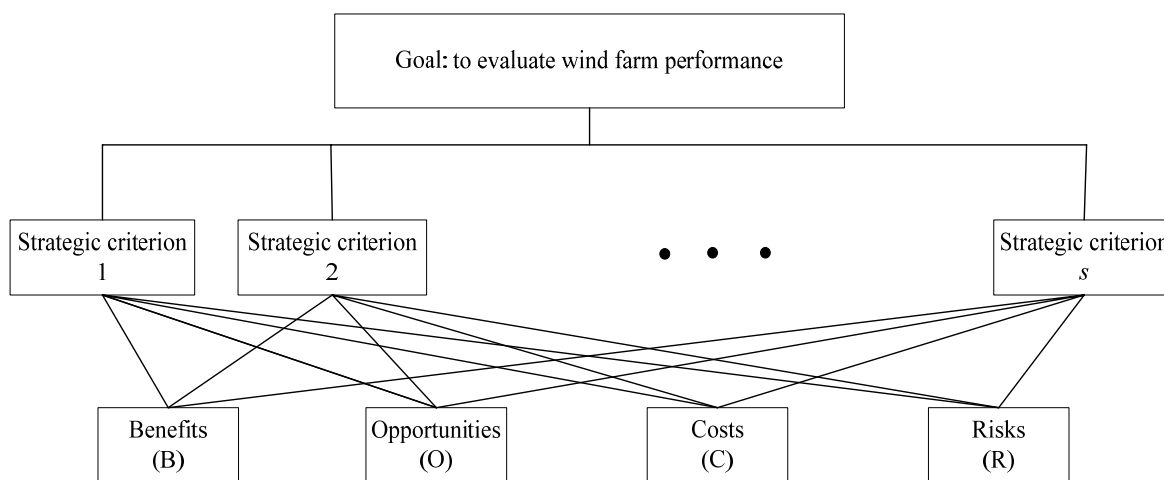
Step 3. Prepare a questionnaire to collect experts' opinions based on the control network. Experts are asked to pairwise compare the strategic criteria using seven different linguistic terms, as depicted in Figure 3. The linguistic variables of pairwise comparison of each part of the questionnaire from each expert are transformed into trapezoid fuzzy numbers. Experts are also asked to determine the ranking of each merit (B, O, C, R) on each strategic criterion by a seven-step scale, as depicted in Figure 4.

Figure 3. Membership function of fuzzy numbers for relative importance/performance.
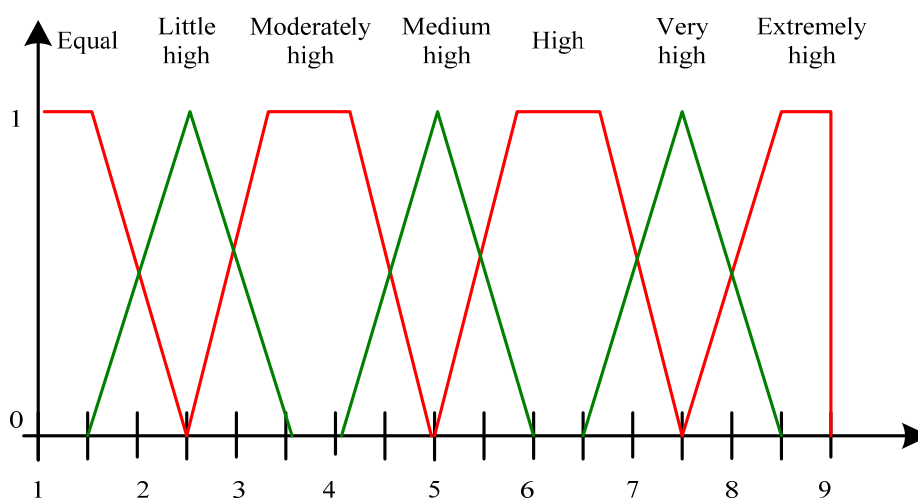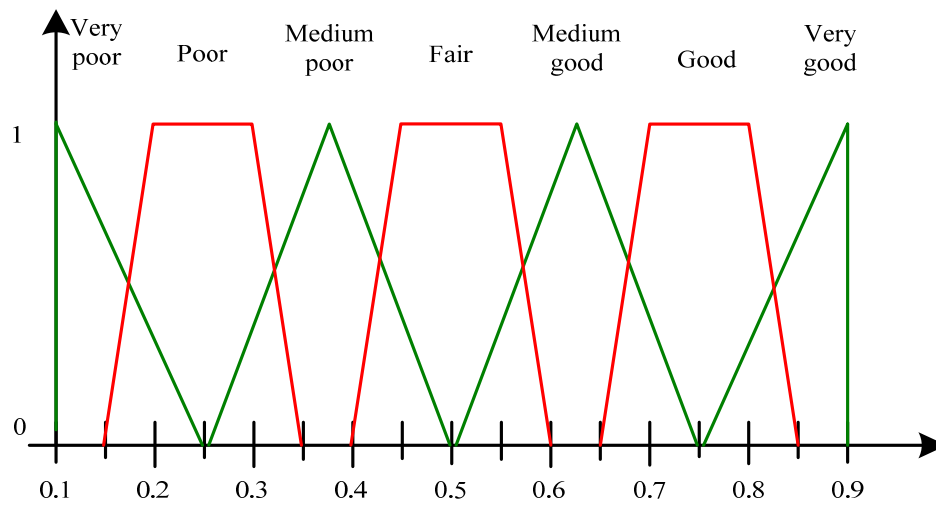
Figure 4. Membership function of fuzzy numbers for ranking.

Step 4. Determine the priorities of the strategic criteria. Geometric average approach is employed next to aggregate experts' responses, and a synthetic trapezoid fuzzy number is resolved:

$$\tilde{r}_{ij} = \left(\tilde{a}_{ij1} \otimes \tilde{a}_{ij2} \otimes ...... \otimes \tilde{a}_{ijk} \right)^{1/k} \tag{9}$$

where $\tilde{a}_{ijk}$ is the pairwise comparison value between strategic criterion i and j determined by expert k.

Defuzzy each fuzzy number $\tilde{r}_{ij}$ into a crisp number r_{ij} using Yager [36] ranking method:

$$r_{ij} = \int_0^1 \tfrac{1}{2} \left((\tilde{r}_{ij})_\alpha^L + (\tilde{r}_{ij})_\alpha^U \right) d\alpha \tag{10}$$

The α-cuts of the fuzzy numbers are shown in Table 2.

The aggregated pairwise comparison matrix is:

$$\mathbf{W_s} = \begin{bmatrix} 1 & r_{12} & \cdots & \cdots & \cdots & \cdots & r_{1j} \\ \dfrac{1}{r_{12}} & 1 & \cdots & \cdots & \cdots & \cdots & r_{2j} \\ \vdots & \vdots & 1 & \cdots & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & 1 & r_{ij} & \cdots & \cdots \\ \vdots & \vdots & \vdots & \dfrac{1}{r_{ij}} & 1 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & 1 & \cdots \\ \dfrac{1}{r_{1j}} & \dfrac{1}{r_{2j}} & \cdots & \cdots & \cdots & \cdots & 1 \end{bmatrix} \tag{11}$$

Derive priority vector for the aggregated comparison matrix as follows:

$$\mathbf{W_s} \times w_s = \lambda_{max} \times w_s \tag{12}$$

where $\mathbf{W_s}$ is the aggregated comparison matrix, w_s is the eigenvector, and λ_{max} is the largest eigenvalue of $\mathbf{W_s}$.

Table 2. α-cuts of fuzzy numbers.

$\tilde{a}$	$(\tilde{a})_\alpha^L$	$(\tilde{a})_\alpha^U$
$\tilde{a}_{VH} = (7.5, 8.5, 9, 9)_{L\text{-}R}$	$(\tilde{a}_{VH})_\alpha^L = 7.5 + \alpha$	$(\tilde{a}_{VH})_\alpha^U = 9$
$\tilde{a}_{H} = (6.5, 7.5, 7.5, 8.5)_{L\text{-}R}$	$(\tilde{a}_{H})_\alpha^L = 6.5 + \alpha$	$(\tilde{a}_{H})_\alpha^U = 8.5 - \alpha$
$\tilde{a}_{MH} = (5, 5.75, 6.75, 7.5)_{L\text{-}R}$	$(\tilde{a}_{MH})_\alpha^L = 5 + 0.75\,\alpha$	$(\tilde{a}_{MH})_\alpha^U = 7.5 - 0.75\,\alpha$
$\tilde{a}_{M} = (4, 5, 5, 6)_{L\text{-}R}$	$(\tilde{a}_{M})_\alpha^L = 4 + \alpha$	$(\tilde{a}_{M})_\alpha^U = 6 - \alpha$
$\tilde{a}_{ML} = (2.5, 3.25, 4.25, 5)_{L\text{-}R}$	$(\tilde{a}_{ML})_\alpha^L = 2.5 + 0.75\,\alpha$	$(\tilde{a}_{ML})_\alpha^U = 5 - 0.75\,\alpha$
$\tilde{a}_{L} = (1.5, 2.5, 2.5, 3.5)_{L\text{-}R}$	$(\tilde{a}_{L})_\alpha^L = 1.5 + \alpha$	$(\tilde{a}_{L})_\alpha^U = 3.5 - \alpha$
$\tilde{a}_{VL} = (1, 1, 1.5, 2.5)_{L\text{-}R}$	$(\tilde{a}_{VL})_\alpha^L = 1$	$(\tilde{a}_{VL})_\alpha^U = 2.5 - \alpha$

Step 5. Examine the consistency property of the aggregated comparison matrix. If an inconsistency is found, the experts are asked to revise the part of the questionnaire, and the calculations in Step 3 and 4 are done again. The consistency index (CI) and consistency ratio (CR) are defined as [31,32]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{13}$$

$$CR = \frac{CI}{RI} \tag{14}$$

where *n* is the number of items being compared in the matrix, and RI is random index. After the consistency test is passed, the priorities of the strategic criteria are confirmed.

Step 6. Determine the importance of each merit (B, O, C, R) with respect to each strategic criterion. Based on the feedback of the questionnaires from the experts from Step 3, geometric average approach is applied to aggregate experts' responses. Each fuzzy number is then defuzzified into a crisp number by Yager ranking method.

Step 7. Determine the priorities of the merits. Calculate the priority of a merit by multiplying the importance of the merit on each strategic criterion from Step 6 with the priority of the respective strategic criterion from Step 4 and summing up the calculated values for the merit. Normalize the calculated values of the four merits, and obtain the priorities of benefits, opportunities, costs and risks, that is, b, o, c and r, respectively.

Step 8. Decompose the wind farm evaluation problem into a network with four sub-networks. With literature review and experts' opinions, we can construct a network in the form as in Figure 5. Four merits (B, O, C, R) must be considered in achieving the overall goal, and a sub-network is formed for each of the merits. For example, for the benefits (B) sub-network, there are criteria that are related to the achievement of the benefits of the ultimate goal, and the lowest level contains the wind farms that are under evaluation.

Figure 5. The BOCR with ISM network.
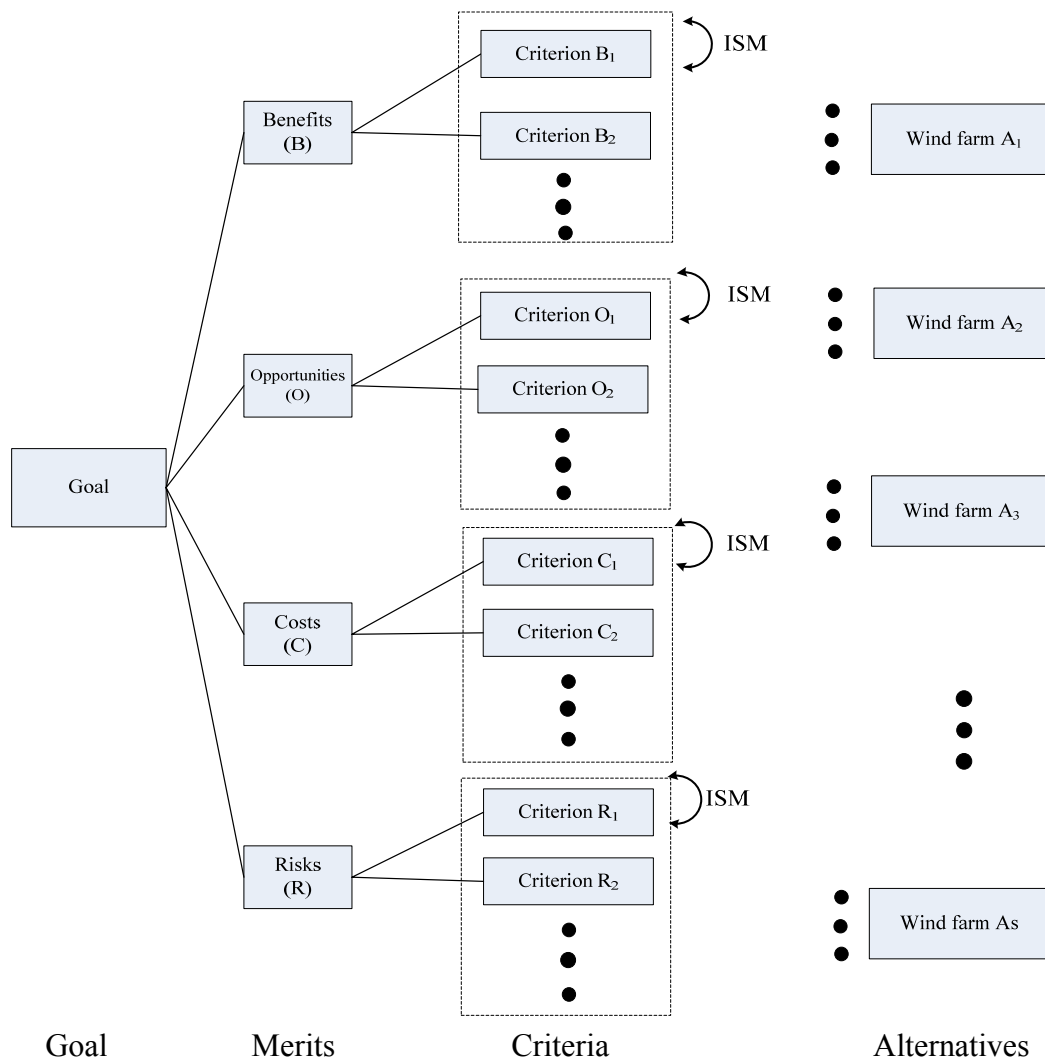
Step 9. Construct adjacency matrix (*i.e.*, relation matrix) for the criteria under each merit. For each merit *M*, establish relation matrix $\mathbf{D}_M$, using the criteria identified in Step 8, to show the contextual relationship among the criteria. Experts, through a questionnaire or the Delphi method, are invited to identify the contextual relationship between any two criteria, and the associated direction of the relation. The relation matrix $\mathbf{D}_M$ is presented as follows:

$$
\mathbf{D}_M = \begin{array}{c} \\ x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_j \\ \vdots \\ x_n \end{array} \begin{array}{cccccc} x_1 & x_2 & \cdots & x_i & \cdots & x_j & \cdots x_n \end{array} \left[\begin{array}{cccccc} 0 & \pi_{12M} & \cdots & \cdots & \cdots & \pi_{1nM} \\ \pi_{21M} & 0 & & & & \pi_{2nM} \\ \vdots & & \ddots & & \pi_{ijM} & \vdots \\ \vdots & & & \ddots & & \vdots \\ \vdots & & \pi_{jiM} & & 0 & \vdots \\ \pi_{n1M} & \pi_{n2M} & \cdots & \cdots & \cdots & 0 \end{array} \right], \; i=1,2,\ldots,n; \; j=1,2,\ldots,n \qquad (15)
$$

where π_{ijM} denotes the relation between criteria x_i and x_j, and $\pi_{ijM} = 1$ if x_j is reachable from x_i,; otherwise, $\pi_{ijM} = 0$.

Step 10. Develop initial reachability matrix for each merit and check for transitivity. The initial reachability matrix $\mathbf{R}_M$ is calculated by adding $\mathbf{D}_M$ with the unit matrix $\mathbf{I}$:

$$\mathbf{R}_M = \mathbf{D}_M + \mathbf{I} \tag{16}$$

Step 11. Develop final reachability matrix $\mathbf{R}_M^*$ for each merit. The transitivity of the contextual relation means that if criterion x_i is related to x_j and x_j is related to x_p, then x_i is necessarily related to x_p. Under the operators of the Boolean multiplication and addition (*i.e.*, $0 \times 0 = 0$, $1 \times 0 = 0 \times 1 = 0$, $1 \times 1 = 1$, $0 + 0 = 0$, $1 + 0 = 0 + 1 = 1$, $1 + 1 = 1$), a convergence can be met:

$$\mathbf{R}_M^* = \mathbf{R}_M^q = \mathbf{R}_M^{q+1}, q > 1 \tag{17}$$

$$\mathbf{R}_M^* = \begin{matrix} & \begin{matrix} x_1 & x_2 & \cdots & x_i & \cdots & x_j & \cdots x_n \end{matrix} \\ \begin{matrix} x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_j \\ \vdots \\ x_n \end{matrix} & \begin{bmatrix} \pi_{11M}^* & \pi_{12M}^* & \cdots & \cdots & \cdots & \pi_{1nM}^* \\ \pi_{21M}^* & \pi_{22M}^* & & & & \pi_{2nM}^* \\ \vdots & & \ddots & & \pi_{ijM}^* & \vdots \\ \vdots & & & \ddots & & \vdots \\ \vdots & & \pi_{jiM}^* & & \ddots & \vdots \\ \pi_{n1M}^* & \pi_{n2M}^* & \cdots & \cdots & \cdots & \pi_{nnM}^* \end{bmatrix} \end{matrix}, \ i = 1,2,\ldots,n; \ j = 1,2,\ldots,n \tag{18}$$

where π_{ijM}^* denotes the impact of criterion x_i to criterion x_j under merit M.

Step 12. Construct a sub-network for each merit based on the final reachability matrix for the merit.

Step 13. Employ a questionnaire to collect experts' opinions on the BOCR with ISM network. Formulate a questionnaire based on the network in Figure 5 and the sub-networks constructed in Step 12 to pairwise compare the importance of the criteria under each merit, and the interdependence among the criteria under each merit. The expected relative performance of the alternatives under each criterion is determined by the experts using seven different linguistic terms, as depicted in Figure 3.

Step 14. Calculate the relative priorities under each merit sub-network. A similar procedure as in Steps 4 and 5 is applied to establish relative importance weights of the criteria with respect to the same upper-level merit, the interdependence of the criteria with respect to the same upper-level merit, and the expected relative performance of alternatives with respect to each criterion.

Step 15. Calculate the priorities of alternatives for each merit sub-network. Using the priorities obtained from Step 14, form an unweighted supermatrix for merit M, as depicted in Figure 6, where w_{cm}^M is a vector that represents the impact of merit M on the criteria, $\mathbf{W}_{cc}^M$ indicates the interdependency of the criteria, $\mathbf{W}_{ac}^M$ is a matrix that represents the impact of criteria on each of the alternatives, and $\mathbf{I}$ is the identity matrix. A weighted supermatrix and a limit supermatrix for each sub-network can be calculated by ANP, which is proposed by Saaty [32]. The priorities of the alternatives under each merit are calculated by normalizing the alternative-to-goal column of the limit supermatrix of the merit.

Step 16. Calculate overall priorities of the alternatives by synthesizing priorities of each alternative under each merit from Step 15 with corresponding normalized weights *b, o, c* and *r*

from Step 7. There are five ways to calculate the overall priority of each alternative under B, O, C and R, as shown in Equations (4) to (8) [34].

A case study of a wind farm evaluation problem is presented next to examine the practicality of the proposed model. The results shall provide a comprehensive framework and guidance to practitioners in evaluating the performance of wind farms.

Figure 6. Unweighted supermatrix for merit *M*.

$$
\begin{array}{c}
\begin{array}{ccc}
\text{Merit } M & \text{Criteria} & \text{Alternatives}
\end{array} \\
\begin{array}{c}
\text{Merit } M \\ \\ \text{Criteria} \\ \\ \text{Alternatives}
\end{array}
\left[
\begin{array}{ccccccccccc}
I & \vdots & & & & & \vdots & & & & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
w_{cm}^{M} & \vdots & & \mathbf{W}_{cc}^{M} & & & \vdots & & & & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
& \vdots & & \mathbf{W}_{ac}^{M} & & & \vdots & & I & & \\
& \vdots & & & & & \vdots & & & &
\end{array}
\right]
\end{array}
$$

4. Case Study

The proposed model is used to evaluate the expected wind farm performance in Taiwan. With a literature review and interviews with the domain experts, the control network and the BOCR with ISM network are constructed, as shown in Figure 7.

Figure 7. The network for the case.
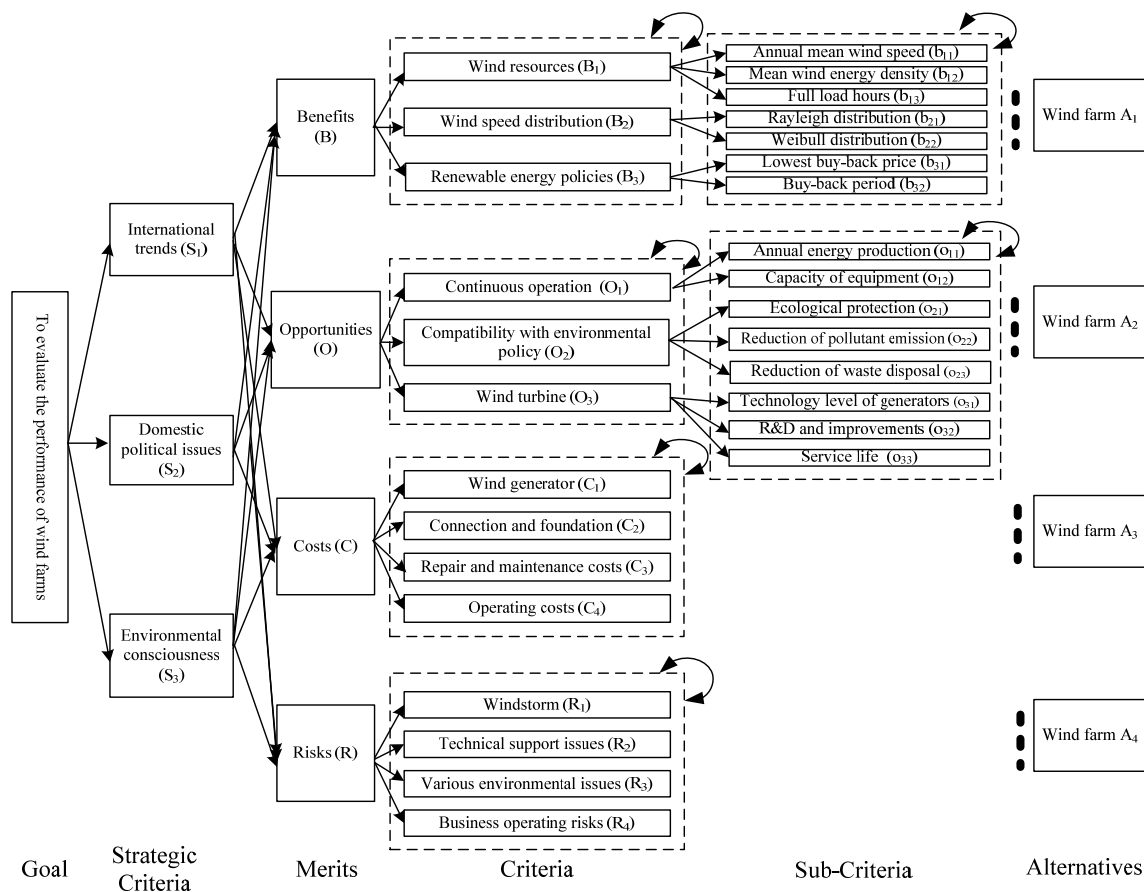
There are three strategic criteria, namely, international trends, domestic political issues and environmental consciousness. International trends include the trends, accords and commitments among nations in renewable energy, climate change prevention and sustainable development. Domestic political issues concern with the consensus among leaders' opinions for wind farm energy and national development. Environmental consciousness indicates the gradually emerging consciousness of human beings about environmental degradation due to industrialization and the use of fossil fuels. Under each merit, there are a number of criteria. For example, the benefits that can be obtained from operating a wind farm need to consider wind resources, wind speed distribution and renewable energy policies. Under the benefits and opportunities merits, there are sub-criteria under each criterion. The definitions of the criteria and sub-criteria are shown in Table 3.

Table 3. Definitions of the criteria and sub-criteria.

Merits	Criteria/Sub-criteria	Definition
Benefits	(B_1) Wind resources	Estimation of energy production of a wind farm.
	(b_{11}) Annual mean wind speed	Annual average (mean) wind speed for a given location (meters per second, m/s)
	(b_{12}) Mean wind energy density	Wind power density, measured in watts per square meter, indicating how much energy is available at the site for conversion by a wind turbine.
	(b_{13}) Full load hours	Average hours of full load of a wind turbine per year.
	(B_2) Wind speed distribution	Estimation of the distribution of wind speeds throughout the year
	(b_{21}) Rayleigh distribution	The Rayleigh distribution may be used as a model for wind speed. It can estimate the energy recovered by a wind turbine.
	(b_{22}) Weibull distribution	The Weibull distribution may be used to describe the variations in wind speeds.
	(B_3) Renewable energy policies	The utility company and the wind farm have an agreement on the buy back of electricity supplied by a wind farm.
	(b_{31}) Lowest buy-back price	The utility company offers a lowest buy-back price to buy back electricity.
	(b_{32}) Buy-back period	The utility company offers to buy back electricity in a specified duration of time.
Opportunities	(O_1) Continuous operation	The continuous and reliable operation of the wind farm.
	(o_{11}) Annual energy production	Expected annual energy generated from the wind farm.
	(o_{12}) Capacity of equipment	Expected capacity of equipment after deducting downtime and maintenance time.
	(O_2) Compatibility with environmental policy	The degree of convergence between the environmental policy and the operation of the wind farm.
	(o_{21}) Ecological protection	The ecological benefits obtained from the wind farm in generating energy compared to traditional energy sources.
	(o_{22}) Reduction of pollutant emission	The reduction of pollutant emission, such as CO_2 and SO_2, from the wind farm in generating energy compared to traditional energy sources.
	(o_{23}) Reduction of waste disposal	The reduction of waste, which can damage the environment from the wind farm in generating energy, compared to traditional energy sources.

Table 3. *Cont.*

Opportunities	(O_3) Wind turbine	The expected operation of wind turbines.
	(o_{31}) Technology level of generators	Technology that can be obtained from operating generators.
	(o_{32}) R&D and improvements	R&D level and improvements that can be achieved in the equipment other than generators.
	(o_{33}) Service life	Expected useful life of wind turbines.
Costs	(C_1) Wind generator	The cost of wind generators.
	(C_2) Connection and foundation	The cost of connection and foundations in constructing wind turbines.
	(C_3) Repair and maintenance costs	Repair and maintenance costs incurred in operating the wind farm.
	(C_4) Operating costs	Operating costs of the wind farm in generating energy.
Risks	(R_1) Windstorm	The severity of windstorms may disable the operation of the wind farm.
	(R_2) Technical support issues	Local technical problems may arise because some equipment is purchased overseas.
	(R_3) Various environmental issues	The negative impacts of the wind farm to the environment, such as bird deaths, aesthetics and noise.
	(R_4) Business operating risks	Risks arising from the execution of the wind farm's business functions, and including the risks arising from the people, systems, processes and financial conditions.

To ensure anonymity, the four wind farms under evaluation are identified as wind farm A_1, A_2, A_3 and A_4. Experts in the industry are asked to fill out the questionnaire. The three strategic criteria are pairwise compared by each expert using seven different linguistic terms shown in Figure 3. An aggregated pairwise comparison matrix is prepared. For example, the pairwise comparison between S_1 and S_2 by the experts are "little high", "moderately high", "equal", "little high", "moderately high" and "equal". The fuzzy numbers are (1.5, 2.5, 2.5, 3.5), (2.5, 3.25, 4.25, 5), (1, 1, 1.5, 2.5), (1.5, 2.5, 2.5, 3.5), (2.5, 3.25, 4.25, 5) and (1, 1, 1.5, 2.5). The aggregated trapezoid fuzzy number is $(1.554, 2.010, 2.517, 3.524) = ((1.5 \times 2.5 \times 1 \times 1.5 \times 2.5 \times 1)^{1/6}, (2.5 \times 3.25 \times 1 \times 2.5 \times 3.25 \times 1)^{1/6},$ $(2.5 \times 4.25 \times 1.5 \times 2.5 \times 4.25 \times 1.5)^{1/6}, (3.5 \times 5 \times 2.5 \times 3.5 \times 5 \times 2.5)^{1/6})$. The fuzzy aggregated pairwise comparison matrix for the strategic criteria is:

$$\tilde{\mathbf{W}}_S = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \end{array} \begin{bmatrix} (1, 1, 1, 1) & (1.554, 2.010, 2.517, 3.524) & (1.357, 1.481, 2.123, 3.150) \\ (1.554, 2.010, 2.517, 3.524)^{-1} & (1, 1, 1, 1) & (1.145, 1.357, 1.778, 2.797) \\ (1.357, 1.481, 2.123, 3.150)^{-1} & (1.145, 1.357, 1.778, 2.797)^{-1} & (1, 1, 1, 1) \end{bmatrix}$$

The Yager ranking method is applied next to prepare a defuzzified comparison matrix. For example, with the synthetic trapezoid fuzzy number for the comparison between S_1 and S_2 of (1.554, 2.010, 2.517, 3.524), the defuzzified comparison between S_1 and S_2 is 2.401. The defuzzified aggregated pairwise comparison matrix is:

$$\mathbf{W}_S = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \end{array} \begin{array}{ccc} S_1 & S_2 & S_3 \\ \begin{bmatrix} 1.000 & 2.401 & 2.028 \\ 0.416 & 1.000 & 1.769 \\ 0.493 & 0.565 & 1.000 \end{bmatrix} \end{array}$$

The priority vector and λ_{max} of the defuzzified aggregated pairwise comparison matrix for the strategic criteria are calculated:

$$w_s = \begin{array}{c} S_1 \\ S_2 \\ S_2 \end{array} \begin{bmatrix} 0.521 \\ 0.278 \\ 0.201 \end{bmatrix}, \ \lambda_{max} = 3.061$$

The importance of each merit to each strategic criterion is determined next. The experts' opinions are collected using a seven-level linguistic scale, and a trapezoid fuzzy number is used to represent the assigned value. Geometric average method is applied to aggregate experts' opinions, and the Yager ranking method is used to defuzzify the fuzzy numbers. The aggregated fuzzy weights of the three merits on strategic criteria are shown in Table 4. Based on the priorities of strategic criteria and the crisp weights of the four merits from Table 5, the overall priorities of the four merits are calculated. Finally, as shown in the last column of Table 5, the normalized priorities of the four merits are obtained: benefits (*b*), 0.423; opportunities (*o*), 0.268; costs (*c*), 0.186; and risks (*r*), 0.124.

Table 4. Aggregated fuzzy weights of the merits on strategic criteria.

	S_1	S_2	S_3
Benefits	(0.715, 0.828, 0.865, 0.883)	(0.682, 0.761, 0.832, 0.866)	(0.546, 0.683, 0.714, 0.782)
Opportunities	(0.292, 0.398, 0.398, 0.531)	(0.464, 0.590, 0.590, 0.696)	(0.507, 0.597, 0.624, 0.726)
Costs	(0.178, 0.247, 0.323, 0.394)	(0.247, 0.323, 0.370, 0.472)	(0.368, 0.485, 0.485, 0.608)
Risks	(0.114, 0.126, 0.144, 0.280)	(0.208, 0.262, 0.343, 0.419)	(0.178, 0.247, 0.323, 0.394)

Table 5. Normalized priorities of the merits (*b*, *o*, *c*, *r*).

	S_1 (0.521)	S_2 (0.278)	S_3 (0.201)	Overall priorities	Normalized priorities
Benefits	0.823	0.785	0.681	0.784	0.423
Opportunities	0.405	0.585	0.613	0.497	0.268
Costs	0.285	0.353	0.487	0.345	0.186
Risks	0.166	0.308	0.285	0.229	0.124

ISM is applied next to determine the interrelationship among the criteria with the same upper-level merit. Delphi method is applied first to generate a relation matrix under each merit. The relation matrix among the criteria under benefits, $\mathbf{D}_B$, is:

$$\mathbf{D}_B = \begin{array}{c} \\ B_1 \\ B_2 \\ B_3 \end{array} \begin{array}{ccc} B_1 & B_2 & B_3 \\ \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{array}$$

By adopting Step 10, the initial reachability matrix $\mathbf{R}_B$ for the criteria under benefits is:

$$\mathbf{R}_B = \mathbf{D}_B + \mathbf{I} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{R}_B{}^* = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Based on $\mathbf{R}_B^*$, the interrelationship among the four criteria under benefits can be depicted as in Figure 8. The direction of an arrow signifies dependence, and a two-way arrow represents the interdependency between two criteria. The same procedure can be carried out for determining the interrelationship among the criteria under opportunities, costs and risks, respectively.

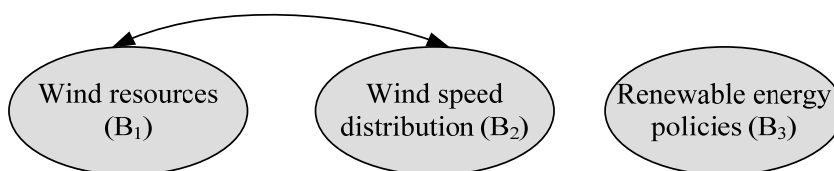**Figure 8.** Interrelationship among criteria under benefits.

Table 6. Unweighted supermatrix for the benefits merit.

	g	B_1	B_2	B_3	b_{11}	b_{12}	b_{13}	b_{21}	b_{22}	b_{31}	b_{32}	A_1	A_2	A_3	A_4
g	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B_1	0.27877	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0
B_2	0.22280	0.5	05	0	0	0	0	0	0	0	0	0	0	0	0
B_3	0.49843	0	0	1	0	0	0	0	0	0	0	0	0	0	0
b_{11}	0	0.28488	0	0	0.22621	0.18215	0.19164	0.19093	0.18169	0	0	0	0	0	0
b_{12}	0	0.21740	0	0	0.20656	0.20430	0.19180	0.20233	0.19414	0	0	0	0	0	0
b_{13}	0	0.49772	0	0	0.19884	0.20703	0.19651	0.19591	0.19073	0	0	0	0	0	0
b_{21}	0	0	0.5	0	0.18704	0.19211	0.20832	0.21735	0.21517	0	0	0	0	0	0
b_{22}	0	0	0.5	0	0.18136	0.21440	0.21174	0.19347	0.21827	0	0	0	0	0	0
b_{31}	0	0	0	0.75	0	0	0	0	0	1	0	0	0	0	0
b_{32}	0	0	0	0.25	0	0	0	0	0	0	1	0	0	0	0
A_1	0	0	0	0	0.34747	0.32230	0.50355	0.22361	0.46891	0.23058	0.25058	1	0	0	0
A_2	0	0	0	0	0.13922	0.13743	0.14563	0.23300	0.15262	0.18832	0.24913	0	1	0	0
A_3	0	0	0	0	0.33228	0.37174	0.22574	0.20282	0.25823	0.44495	0.20642	0	0	1	0
A_4	0	0	0	0	0.18103	0.16852	0.12508	0.34058	0.12023	0.13615	0.23986	0	0	0	1

Based on the network in Figure 7, and the interrelationship among the criteria under the four merits, a pairwise comparison questionnaire is prepared, and the experts are complete the questionnaire. The opinions are aggregated, and aggregated pairwise comparison matrices are prepared. The Yager ranking method is applied next to prepare defuzzified comparison matrices, and the priority vectors of the defuzzified aggregated pairwise comparison matrices are calculated. These priority vectors are entered into the designated places in an unweighted supermatrix. For example, the unweighted

supermatrix for the benefits merit is as shown in Table 6. To make the matrix stochastic, a weighted supermatrix is formed, as shown in Table 7. Finally, by taking the weighted supermatrix to a large power, a limit supermatrix is obtained, as shown in Table 8. The priorities of the alternatives can be seen from the (4,1) block of the limit supermatrix. That is, the priorities for wind farm A_1, A_2, A_3 and A_4 are 0.30741, 0.18374, 0.32702 and 0.18183, respectively.

Table 7. Weighted supermatrix for the benefits merit.

	g	B_1	B_2	B_3	b_{11}	b_{12}	b_{13}	b_{21}	b_{22}	b_{31}	b_{32}	A_1	A_2	A_3	A_4
g	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B_1	0.13939	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0
B_2	0.11140	0.25	2.5	0	0	0	0	0	0	0	0	0	0	0	0
B_3	0.24922	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0
b_{11}	0	0.14244	0	0	0.11311	0.09108	0.09582	0.09547	0.09085	0	0	0	0	0	0
b_{12}	0	0.10870	0	0	0.10328	0.10215	0.09590	0.10117	0.09707	0	0	0	0	0	0
b_{13}	0	0.24886	0	0	0.09942	0.10352	0.09826	0.09796	0.09537	0	0	0	0	0	0
b_{21}	0	0	0.25	0	0.09352	0.09606	0.10416	0.10868	0.10759	0	0	0	0	0	0
b_{22}	0	0	0.25	0	0.09068	0.10720	0.10587	0.09674	0.10914	0	0	0	0	0	0
b_{31}	0	0	0	0.375	0	0	0	0	0	0.5	0	0	0	0	0
b_{32}	0	0	0	0.125	0	0	0	0	0	0	0.5	0	0	0	0
A_1	0	0	0	0	0.17374	0.16115	0.25178	0.11181	0.23446	0.11529	0.12529	1	0	0	0
A_2	0	0	0	0	0.06961	0.06872	0.07282	0.11650	0.07631	0.09416	0.12457	0	1	0	0
A_3	0	0	0	0	0.16614	0.18587	0.11287	0.10141	0.12912	0.22248	0.10321	0	0	1	0
A_4	0	0	0	0	0.09052	0.08426	0.06254	0.17029	0.06012	0.06807	0.11993	0	0	0	1

Table 8. Limit supermatrix for the benefits merit.

	g	B_1	B_2	B_3	b_{11}	b_{12}	b_{13}	b_{21}	b_{22}	b_{31}	b_{32}	A_1	A_2	A_3	A_4
g	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{11}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{21}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{22}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{31}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b_{32}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_1	0.30741	0.38711	0.36839	0.23558	0.35998	0.34858	0.43827	0.29738	0.42069	0.23058	0.25058	1	0	0	0
A_2	0.18374	0.15834	0.17125	0.20352	0.15013	0.14949	0.15395	0.19777	0.15762	0.18832	0.24913	0	1	0	0
A_3	0.32702	0.27555	0.26099	0.38532	0.30595	0.32464	0.25132	0.24003	0.2674	0.44495	0.20642	0	0	1	0
A_4	0.18183	0.17900	0.19937	0.17558	0.18394	0.1773	0.15646	0.26481	0.15429	0.13615	0.29386	0	0	0	1

Table 9 shows the relative performance of alternatives under each merit. Under the benefits merit, A_3 performs the best, with a priority of 0.32702, followed by A_1 with 0.30741 and A_2 with 0.18374. Under the opportunities merit, A_1 performs the best with a priority of 0.35528, followed by A_3 with

0.31219. Under the costs merit, A_3 is the least costly with a normalized reciprocal priority of 0.29497, followed by A_4 with 0.29233. Under the risks merit, the least risky alternative is A_1 with a normalized reciprocal priority of 0.26763, followed by A_3 with 0.25718 and A_4 with 0.24416. The results show that A_3 ranks the first under the benefits and costs merits, while A_1 ranks the first under the opportunities and risks merits. With varied performances of the alternatives under different merits, the overall performance ranking of the four alternatives is unknown.

Table 9. Priorities of alternatives under the four merits.

Merits	Benefits	Opportunities	Costs			Risks		
Priorities	0.423	0.268	0.186			0.124		
Alternatives	Normalized	Normalized	Normalized	Reciprocal	Normalized Reciprocal	Normalized	Reciprocal	Normalized Reciprocal
A_1	0.30741	0.35528	0.30827	3.24391	0.19629	0.23282	4.29516	0.26763
A_2	0.18374	0.18714	0.27960	3.57654	0.21641	0.26970	3.70782	0.23103
A_3	0.32702	0.31219	0.20514	4.87472	0.29497	0.24228	4.12746	0.25718
A_4	0.18183	0.14540	0.20699	4.83115	0.29233	0.25520	3.91850	0.24416

The final ranking of the alternatives is calculated by the five methods, additive, probabilistic additive, subtractive, multiplicative priority powers and multiplicative, to aggregate the scores of each alternative under B, O, C and R. The results are as shown in Table 10. The priority of wind farm A_1 by the five methods are given here as an example:

Additive:

$$0.423 \times 0.30741 + 0.268 \times 0.35528 + 0.186 \times 0.19629 + 0.124 \times 0.26763 = 0.29494$$

Probabilistic additive:

$$0.423 \times 0.30741 + 0.268 \times 0.35528 + 0.186 \times (1 - 0.30827) + 0.124 \times (1 - 0.23282) = 0.44904$$

Subtractive:

$$0.423 \times 0.30741 + 0.268 \times 0.35528 - 0.186 \times 0.30827 - 0.124 \times 0.23282 = 0.13904$$

Multiplicative priority powers:

$$0.30741^{0.423} \times 0.35528^{0.268} \times 0.19629^{0.186} \times 0.26763^{0.124} = 0.28863$$

Multiplicative:

$$0.30741 \times 0.35528 / (0.30827 \times 0.23282) = 1.52171$$

Table 10. Final priorities of alternatives.

| Methods	Additive		Probabilistic additive		Subtractive		Multiplicative priority powers		Multiplicative	
Alternatives	Priorities	Ranking	Priorities	Ranking	Priorities	Ranking	Priorities	Ranking	Priorities	Ranking
A_1	0.29494	2	0.44904	2	0.13904	2	0.28863	2	1.52171	2
A_2	0.19678	4	0.35243	4	0.04243	4	0.19550	3	0.45598	4
A_3	0.30875	1	0.46380	1	0.15380	1	0.30720	1	2.05410	1
A_4	0.20053	3	0.35574	3	0.04574	3	0.19370	4	0.50049	3

Under all the five methods of synthesizing the scores of alternatives, A_3 ranks the first, and A_1 ranks the second. However, note that A_2 and A_4 may have different rankings. To examine the robustness of the outcomes under the five methods, a sensitivity analysis is carried out next by changing the priorities of the merits. The sensitivity analysis can be carried out using the software Super Decisions [34]. The results from the additive method are as shown in Figure 9. Figures 9(1), 9(2), 9(3) and 9(4) show the sensitivity analysis graphs when the priority of benefits, opportunities, costs and risks changes, respectively. Depending on changes of the priorities of the merits, the best wind farm may change as a result. Under the current priorities of benefits, opportunities, costs and risks, the best alternative is A_3. No matter how much the priority of benefits (*b*) changes from 0.423, the best alternative is still A_3. The original priority of opportunities (*o*) is 0.268. When *o* increases to 0.503, the best alternative will change from A_3 to A_1. When the priority of costs (*c*) decreases from the original 0.186 to 0.078, the best alternative will change to A_1. Finally, when the original priority of risks (*r*) of 0.124 increases to 0.7, the most suitable alternative becomes A_1. Nevertheless, the likelihood that *o*, *c* or *r* has a very big change is small. Therefore, the current solution is rather robust.

The importance of criteria and sub-criteria in making the wind farm selection decision should be understood by management. Table 11 shows the relative priorities of criteria and sub-criteria under the four merits. Under the benefits merit, the most important sub-criterion, out of a total of seven criteria, is *lowest buy-back price*, with a priority of 0.37382. This means that the major benefit concern for selecting the wind farm is the *lowest buy-back price* for the power generated. The second and third sub-criteria are *full load hours* (0.13875) and *buy-back period* (0.12461). Under the opportunities merit, *ecological protection* (0.19380) is the most important sub-criterion, and *technology level of generators* (0.16067) ranks the second. Under the costs merit, *wind generator* (0.34982) is the major concern, followed by *connection and foundation* (0.31905). Under the risks merit, *windstorm* (0.35521) is what the firm worries most about since it may affect the operation of the wind farm.

Table 11 also shows the integrated priorities of criteria (for those that do not have sub-criteria) and sub-criteria, and their respective rankings. Among all the factors, *lowest buy-back price*, with an integrated priority of 0.15813 in the network, is the most important concern in selecting a wind farm. Other important factors include the cost of *wind generator*, the cost of *connection and foundation*, *full load hours*, and *buy-back period*.

The performance of alternatives with respect to each criterion can be understood by checking the (4,2) block of the limit supermatrix. For example, the relative performances of A_1 to A_4 under *wind resources* (B_1) are shown in the first column of the (4,2) block of the limit supermatrix for the benefits merit in Table 8, and they are 0.38711, 0.15834, 0.27555 and 0.17900, respectively. In addition, the performances of alternatives with respect to each sub-criterion are shown in the (4,3) block of the limit supermatrix. The relative performances of A_1 to A_4 under *annual mean wind speed* (b_{11}) are shown in the first column of the (4,3) block in Table 8, and they are 0.35998, 0.15013, 0.30595 and 0.18394, respectively. Table 12 summarizes the performance priorities of the alternatives under various criteria and sub-criteria.
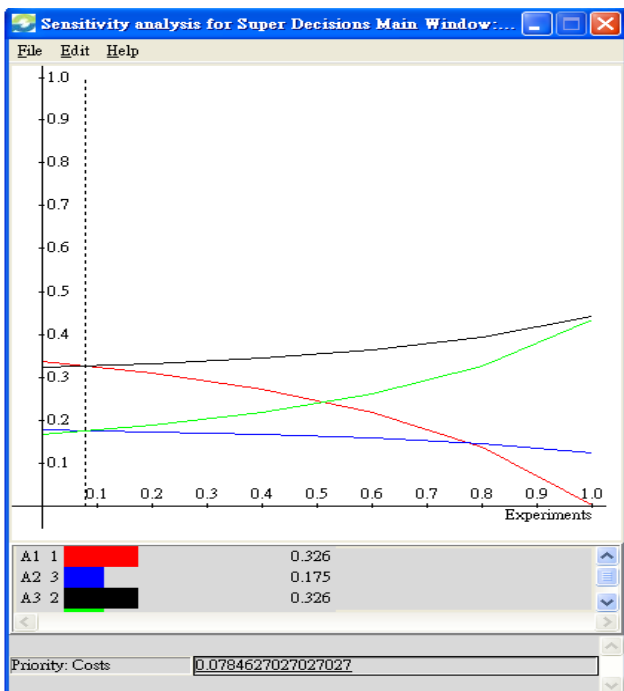
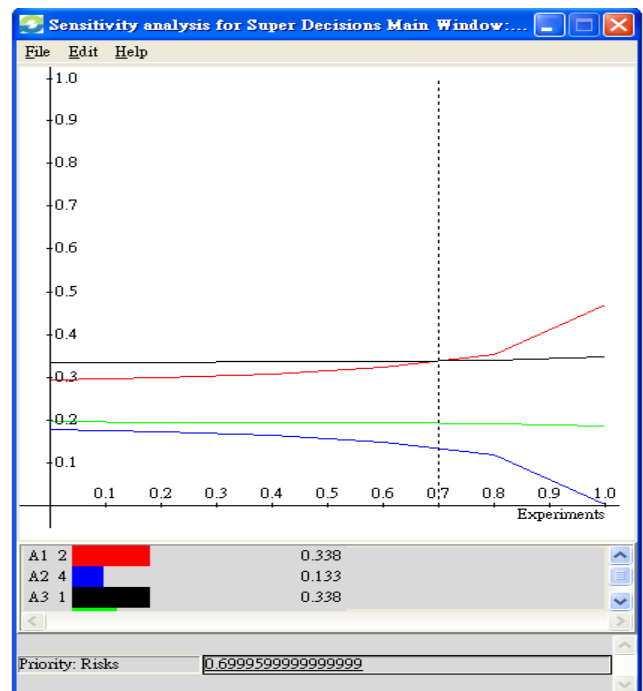**Figure 9.** Sensitivity analysis under the additive method.
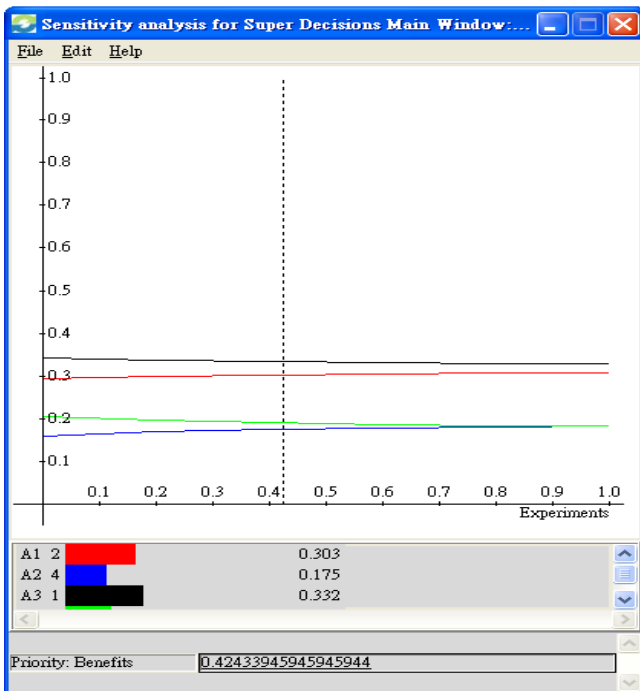
(**1**) Changes in the priority of benefits.
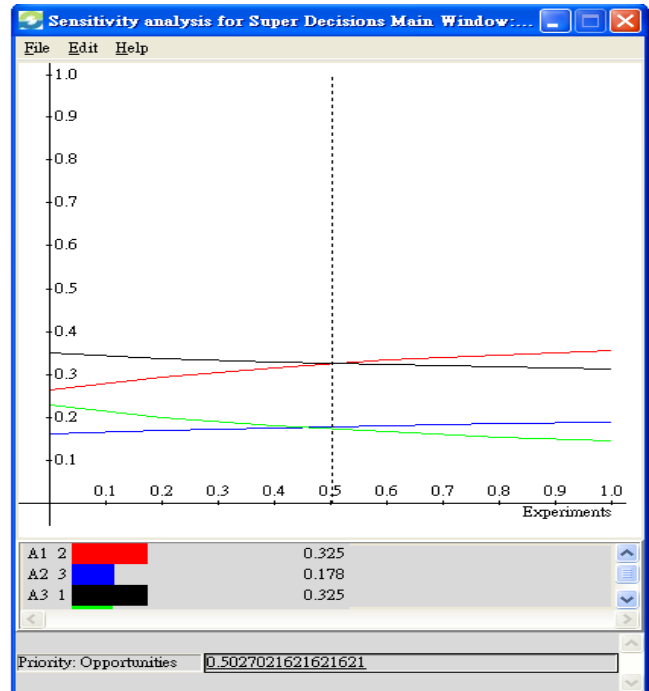
(**2**) Changes in the priority of opportunities.

(**3**) Changes in the priority of costs.

(**4**) Changes in the priority of risks.

Table 11. Priorities of criteria and sub-criteria.

Merits	Criteria/Sub-criteria	Criterion priorities	Sub-criterion priorities	Integrated priorities under the merit	Integrated priorities in the network	Integrated ranking
Benefits (0.423)	(B_1) Wind resources	0.27877				
	(b_{11}) Annual mean wind speed		0.28488	0.07942	0.03359	15
	(b_{12}) Mean wind energy density		0.21740	0.06060	0.02563	20
	(b_{13}) Full load hours		0.49772	0.13875	0.05869	4
	(B_2) Wind speed distribution	0.22280				
	(b_{21}) Rayleigh distribution		0.5	0.11140	0.04712	7
	(b_{22}) Weibull distribution		0.5	0.11140	0.04712	7
	(B_3) Renewable energy policies	0.49843				
	(b_{31}) Lowest buy-back price		0.75	0.37382	0.15813	1
	(b_{32}) Buy-back period		0.25	0.12461	0.05271	5
Opportunities (0.268)	(O_1) Continuous operation	0.19855				
	(o_{11}) Annual energy production		0.5	0.09928	0.02661	18
	(o_{12}) Capacity of equipment		0.5	0.09928	0.02661	18
	(O_2) Compatibility with environmental policy	0.45456				
	(o_{21}) Ecological protection		0.42634	0.19380	0.05194	6
	(o_{22}) Reduction of pollutant emission		0.32536	0.14790	0.03964	12
	(o_{23}) Reduction of waste disposal		0.24830	0.11287	0.03025	16
	(O_3) Wind turbine	0.34689				
	(o_{31}) Technology level of generators		0.46316	0.16067	0.04306	10
	(o_{32}) R&D and improvements		0.29177	0.10121	0.02712	17
	(o_{33}) Service life		0.24507	0.08501	0.02278	21
Costs (0.186)	(C_1) Wind generator	0.34982		0.34982	0.06507	2
	(C_2) Connection and foundation	0.31905		0.31905	0.05934	3
	(C_3) Repair and maintenance costs	0.21789		0.21789	0.04053	11
	(C_4) Operating costs	0.11325		0.11325	0.02106	22
Risks (0.124)	(R_1) Windstorm	0.35521		0.35521	0.04405	9
	(R_2) Technical support issues	0.27870		0.27870	0.03456	14
	(R_3) Various environmental issues	0.29620		0.29620	0.03673	13
	(R_4) Business operating risks	0.06988		0.06988	0.00867	23

Table 12. Priorities of alternatives with respect to each criterion and sub-criterion.

Criteria/Sub-criteria	A_1	A_2	A_3	A_4
(B_1) Wind resources	0.38711	0.15834	0.27555	0.17900
(b_{11}) Annual mean wind speed	0.35998	0.15013	0.30595	0.18394
(b_{12}) Mean wind energy density	0.34858	0.14949	0.32464	0.1773
(b_{13}) Full load hours	0.43827	0.15395	0.25132	0.15646
(B_2) Wind speed distribution	0.36839	0.17125	0.26099	0.19937
(b_{21}) Rayleigh distribution	0.29738	0.19777	0.24003	0.26481
(b_{22}) Weibull distribution	0.42069	0.15762	0.2674	0.15429

Table 12. *Cont.*

Criteria/Sub-criteria	A_1	A_2	A_3	A_4
(B_3) Renewable energy policies	0.23558	0.20352	0.38532	0.17558
(b_{31}) Lowest buy-back price	0.23058	0.18832	0.44495	0.13615
(b_{32}) Buy-back period	0.25058	0.24913	0.20642	0.29386
(O_1) Continuous operation	0.34600	0.17919	0.32437	0.15044
(o_{11}) Annual energy production	0.35839	0.17069	0.31497	0.15595
(o_{12}) Capacity of equipment	0.33366	0.18756	0.33857	0.14021
(O_2) Compatibility with environmental policy	0.36703	0.19597	0.30328	0.13372
(o_{21}) Ecological protection	0.39645	0.17855	0.29645	0.12855
(o_{22}) Reduction of pollutant emission	0.35099	0.22272	0.29646	0.12983
(o_{23}) Reduction of waste disposal	0.33752	0.19084	0.32393	0.14772
(O_3) Wind turbine	0.34595	0.17930	0.31958	0.15517
(o_{31}) Technology level of generators	0.37304	0.15305	0.32974	0.14417
(o_{32}) R&D and improvements	0.35755	0.16966	0.31569	0.15711
(o_{33}) Service life	0.28075	0.24087	0.28543	0.19295
(C_1) Wind generator	0.34959	0.35074	0.16062	0.13904
(C_2) Connection and foundation	0.27363	0.23576	0.21463	0.27598
(C_3) Repair and maintenance costs	0.31317	0.25176	0.25198	0.18310
(C_4) Operating costs	0.26878	0.23694	0.22580	0.26849
(R_1) Windstorm	0.23451	0.26127	0.23302	0.27120
(R_2) Technical support issues	0.22807	0.25092	0.24515	0.27587
(R_3) Various environmental issues	0.24346	0.26973	0.26681	0.22000
(R_4) Business operating risks	0.19806	0.38736	0.17392	0.24067

5. Conclusions

Energy has been recognized as one of the most important resources for economic development. As fossil fuels continue to deplete exponentially, renewable energy, which is generated from natural resources such as sunlight, wind, rain, tides and geothermal heat, has been recognized as the last resort for future economic development. The selection of the most suitable renewable energy investment projects requires that multiple decision makers be involved in the process. Traditional single-criterion decision-making is no longer capable of solving the problem since energy investment decisions are inherently multi-objective in nature. Therefore, multi-criteria decision making methods are becoming popular in helping governments and companies in evaluating energy sector plans, policies, projects and site selections issues, *etc*.

In this research, a decision analysis model for selecting the most suitable wind farm is proposed. The factors to be considered to achieve the goal are identified first through literature review and interviews with experts, and they are used to construct a network with four merits: benefits, opportunities, costs and risks (BOCR). By adopting interpretive structural modeling, the interrelationships among criteria under each merit are determined. After questionnaires are filled out by decision makers, a fuzzy analytic network process is used to calculate the importance of the criteria and to evaluate the expected overall performance of the wind farm projects. With the implementation of the model, the most suitable project can be selected for development.

The proposed MCDM model can consider the advantages and disadvantages of wind farms based on multiple criteria, and it can also examine the interrelationships between the criteria. In addition, it can incorporate the vagueness, ambiguity and subjectivity of different decision makers. The model can also be tailored as required to help evaluate other renewable energy projects.

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