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ORIGINAL PAPER

Integration of fuzzy ANP and fuzzy TOPSIS for evaluating carbon performance of suppliers

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Abstract Previous studies have proven that enterprises addressing green supply chain management problem may produce an apparent improvement to their stockholder interests. According to the report of Kearney (Carbon Disclosure Project: supply chain report 2010. CDP, London, 2010), more than 80 % of the carbon emissions are generated from the suppliers' activities in a company's performance. Many members of the project claimed that they will reassess their suppliers as soon as possible. Therefore, to combine the carbon management issue and supplier evaluating problem turns to be a very crucial work. Therefore, this study intends to develop a framework of the supplier evaluating process for carbon management by integrating fuzzy ANP and fuzzy TOPSIS approaches. Thirteen criteria of carbon management under four dimensions were identified by literature review and modified according to the opinion of seven experts in the environmental department. The model result in a case company shows that three of the most important criteria are "carbon governance," "carbon policy" and "carbon reduction targets." The proposed hybrid methodology has great ability to explain the vagueness of decision maker's expression and better discrimination power to evaluate suppliers in carbon management.

Keywords Supplier evaluation · Fuzzy ANP · Fuzzy TOPSIS · Carbon management

Introduction

Over the past decade, green supply chain management (GSCM) has obtained increasing attention, yet the growing importance of GSCM is mainly led by constantly deteriorating of the environment (Srivastava 2007). However, the practice of GSCM is not only about being kind to the environment. As matter of fact, firms that trying to solve problems related to GSCM get apparent improvement on their profit (Sheu et al. 2005). The main purpose of GSCM is to reduce environmental pollution from upstream to downstream in purchasing raw materials, manufacturing, distribution, selling products and obsolescing products (Kuo et al. 2010). Thus, it indicates that the suppliers play critical roles in firm's success. Therefore, firms should embrace a supplier evaluation and selection model in determining an appropriate long-term partnership (Hsu et al. 2013).

A report conducted by Kearney (2010) indicates that only 14 % of the greenhouse gas (GHG) emissions are generated from direct operational activities of a company. The rest of the 86 % of GHG emissions are generated from other indirect activities, which means the activities from the suppliers in the supply chain. Likewise, 39 % of the carbon disclosure project members respond that they would soon deselect the suppliers that do not measure and manage their carbon emissions. It is crucial to link carbon management in GSCM with supplier selection practice as soon as possible. However, the literature that addressed carbon management in supplier selection of GSCM is rare (Hsu et al. 2013; Shaw et al. 2012).

The supplier selection issue is one of the multi-criteria decision-making (MCDM) problems. This study integrates

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two MCDM approaches: analytic network process (ANP) and technique for order preference by similarity to ideal solution (TOPSIS). ANP is applied to determine the relative weights of multiple evaluation criteria, while the TOPSIS approach is used to rank competing alternatives in terms of their overall performance. However, these approaches are highly depending on the experiences of the experts. Yet the linguistic expressions of the experts are usually with fuzziness or vagueness. Therefore, this study utilizes fuzzy set theory that was proposed by Zadeh (1965). The theory enables decision makers to handle the ambiguities during the process of the linguistic assessment of the data (Büyüközkan and Çifçi 2012a, b).

The first objective of this study is to identify the criteria of supplier selection in carbon management with respect to GSCM. Then, this study will try to develop a framework of the supplier selection process in carbon management using fuzzy ANP and fuzzy TOPSIS approaches that can be referred by the application in electronic industry. For the purpose of evaluation, an internationally well-known high-tech company provided the related data.

The remainder of this paper is organized as follows. "Literature review" section discusses some related backgrounds and approaches by reviewing literature. "Materials and methods" section presents the proposed supplier selection and evaluation model, while the model evaluation results are illustrated in "Results and discussion" section. Finally, the concluding remarks are made in "Conclusion" section.

Literature review

This section will discuss some backgrounds related to this study, including GSCM, supplier selection, ANP and TOPSIS.

Green supply chain management

In response to governmental regulations and increasing public awareness of the effect of industrial production on the environment, organizations start taking major initiatives to transform their supply chain processes. These environmental issues have received increasing attention in recent years. Additionally, supply chain operations with sustainable consideration have also become an important issue (Büyüközkan and Çifçi 2012a, b). Environmental pollution issue and industrial development are thus combined together with supply chain management and contribute to GSCM (Hsu et al. 2013).

The scope of GSCM practices implementation in the literature ranges from green purchasing to integrated life cycle management. (Sarkis et al. 2011). GSCM can be defined as integrating environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers and end-of-life management of the product after its useful life (Srivastava 2007). Green sustainable supply chain management considers the management of materials, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, economic, environmental and social into account, which are derived from customer and stakeholders' requirements (Seuring and Müller 2008).

In GSCM, suppliers and customers work together to reduce the environmental impact of production processes and products and to exchange technical information. The firm and the suppliers share a mutual willingness to learn about each other's operations and to set goals in order to limit their environmental impact. A well-integrated GSCM has to involve a coordinated flow of materials and information between suppliers, manufacturers and customers, and implements product postponement and mass customization in the supply chain (Tseng 2011). Shang et al. (2010) indentified six dimensions of GSCM including green manufacturing and packaging, environmental participation and green marketing, suppliers, stock and eco-design. It shows that a greater degree of integration between suppliers and customers in the supply chain results in a greater competitive advantage (Tseng 2011).

Supplier selection

Supplier selection is one of the most important components of production and logistics management for many companies. The selecting process mainly involves evaluation of different alternative suppliers based on different criteria. This process is essentially considered as a multi-criteria decision-making (MCDM) problem which is affected by different criteria including price, quality, performance, technical capability and delivery (Önüt and Soner 2008).

The supplier selection issue has been discussed for many years. Due to the governmental regulations and the raising environmental consciousness, the focus of this topic has turned into green. The green supplier selection problem can be defined as a classical supplier selection problem in which, among others, also environmental criteria are taken into account in order to select and monitor suppliers' performances (Genovese et al. 2010). Rao (2002) described GSCM as involving screening suppliers based on the environmental performance of companies and those who meet certain environmental regulations and standards. Supplier selection in GSCM is clearly a critical activity in purchasing management, because firm environmental sustainability and ecological performance can be demonstrated by its suppliers.

The four-step procedure of supplier selection proposed by (De Boer et al. 1998) is (1) problem definition, (2) formulation of criteria, (3) qualification and (4) choice. Dickson (1966) conducted a survey and presented 23 different criteria to be considered so as to perform an appropriate supplier performance evaluation. Hu (2004) analyzed 24 papers published after 1991 and discovered that price, quality, production capacity and delivery remain as the most important attributes of supplier evaluation techniques. To be more practical during suppliers selecting, Çelebi and Bayraktar (2008) presented 37 criteria and advanced a theory that integration of neural network and data envelopment analysis for evaluating suppliers under incomplete information of evaluation criteria. These criteria are further divided into four dimensions, cost, quality, delivery and service. In addition, some research studied the criteria of green supplier evaluation in order to meet the environmental and governmental regulations. Noci (1997) used an analytic hierarchy process (AHP) model to support decision makers in the selection of the most effective supplier from an environmental point of view. Four dimensions were reported including green competencies, current environmental efficiency, supplier's green image and net life cycle cost. Totally, there are thirteen criteria.

Although Noci (1997) suggested a preliminary framework that identifies measures for assessing environmental performance, Humphreys et al. (2003) believed that only a little emphasis was placed on environmental cost. Hence, he proposed other more mature criteria for selection process. They include the following dimensions: environmental pollutant effects cost, environmental improvement cost, management competencies, green image, design for environment, environmental management systems and environmental competencies.

Green supplier selection problem might be limited in exploring the broad environmental criteria of either quantitative or qualitative property with regard to environment cost, production process, products and management system in the past literature. However, the importance of managing hazardous substance is increasing recently. Thus, many enterprises have tried to consider this issue when determining suitable suppliers. Therefore, Hsu and Hu (2009) presented criteria of supplier selection which incorporate the issue of hazardous substance management (HSM). This study considers the following five dimensions: procurement management, R&D management, process management, incoming quality control and management system. In addition, firms in different industry sectors begin to recognize carbon issue as one of the critical factors in GSCM since very high percentage of carbon emissions are produced in the total supply chain. However, carbon management in supplier selection is rarely explored. For that reason, Hsu et al. (2013) presented 13 criteria specially for carbon management. These criteria include carbon governance, carbon policy, carbon reduction targets, carbon risk assessment, training-related carbon management, life cycle cost management, measures of carbon management, involvement in initiatives for carbon management, management systems of carbon information, supplier collaboration, carbon accounting and inventory, carbon verification, and carbon disclosure and report.

Supplier evaluation and selection is a multi-criteria decision-making problem that has been studied extensively, and the related literature has proposed a number of supplier selection approaches in the past decade.

AHP introduced by Saaty (1980) has been applied to supplier selection. AHP is designed to handle those decision environments in which subjective judgments are inherent in the decision-making process. The advantage of AHP is to systematically and carefully evaluate the importance of each criterion in relation to the others in a hierarchical manner. Barbarosoglu and Yazgac (1997) applied an AHP model to solve the supplier selection problem for the Turkish electromotor manufacturer. Chan (2003) presented an AHP with interactive selection model. Interactive selection model is used first to identify interactions and the valid data collection methods for minimizing the effect of qualitative factors. Then, AHP is applied to generate the best possible suppliers. Levary (2008) applied AHP approach to evaluate and rank the potential suppliers or the so-called reliability chain. However, although AHP can check the consistency of an individual's judgment, it is not always achieved a sufficient consistency. Furthermore, AHP is not able to handle the correlation between the criteria (Levary 2008). Thus, Saaty (1996) modified AHP and presented a novel approach, analytical network process (ANP), which is able to consider the correlation between the criteria. ANP was also applied to solve supplier selection problems (Bayazit 2006; Gencer and Gürpinar 2007).

Besides AHP and ANP, DEA was also applied to supplier selection. DEA, which is a mathematical programming technique that calculates the relative efficiencies of multiple decision-making units (DMUs) based on multiple inputs and outputs yet does not require prior assumed weights on inputs and outputs, was introduced by Charnes et al. (1978). Liu et al. (2000) introduced a DEA approach for evaluating the overall performance of suppliers with a strategic orientation of being able to reduce the number of suppliers. Wu and Blackhurst (2009) purposed an extended DEA model to evaluate and rank suppliers. The model incorporates a range of virtual standards and weight constraints to enhance the discriminatory ability of DEA. Falagario et al. (2012) used a cross-efficiency DEA to solve the decision-making problem of supplier selection.

Decision-making trial and evaluation laboratory (DEMATEL) is a comprehensive tool for building and analyzing a structural model involving casual relationships between complex factors. It was used to solve a group of complicated and intertwined problems (Gabus and Fontela 1973). Hsu et al. (2013) utilized DEMATEL approach to recognize the influential criteria of carbon management in green supply chain and causal relationships between the evaluation criteria of supplier selection. Chang et al. (2011) used fuzzy DEMATEL to evaluate supplier performance in electronic industry. Supratik et al. (2012) integrated DEMATEL with quality function deployment to select the most suitable supplier.

Besides using a single method for supplier selection, some studies also have employed hybrid methods for supplier selection. Shaw et al. (2012) presented an integrated approach using fuzzy AHP and fuzzy multi-objective linear programming for selecting the appropriate supplier in the supply chain addressing the carbon issue. Fuzzy AHP is applied first to analyze the weights of the multiple factors. Then, they exploit the weights into fuzzy multi-objective linear programming for supplier selection and quota assignation. Lin (2012) adopted fuzzy ANP and fuzzy multi-objective linear programming to solve supplier selection problem. Fuzzy ANP is used to identify the suppliers rank and combine fuzzy multi-objective linear programming to select the best suppliers for achieving the optimal order allocation. Liou et al. (2013) proposed a fuzzy integral-based model using DEMATEL combined with ANP and VIKOR. DEMATEL is applied to determine the effect on each criterion, and ANP was adopted to calculate the weights of the criteria. Finally, VIKOR are applied to transform the performance values into weighed gaps.

Applications of ANP to green supply chain management

Saaty (1996) purposed the ANP to surmount the limitation of AHP. The limitation of AHP is that it does not allow the elements of hierarchical model to have dependence and feedback between each involved element. ANP allows interdependence interaction between involved elements that can be criteria and alternatives. ANP is not limited by the independent assumption happened between the criteria of a decision and the alternatives of that decision, or simply among the criteria or among the alternatives themselves. As a consequence, the importance of criteria determines the importance of the alternatives. That is, the preference of one element may be changed depending on the control criterion. Further, ANP shows the interdependencies with feedback in the structure which has two-way arrows and connected cycles of its clusters like a network instead of level hierarchy in AHP.

The ANP approach is capable of handling interdependent relationships between elements by obtaining the composite weights through the development of a "supermatrix." The supermatrix is a two-dimensional matrix:

1. Control hierarchy: It means the interaction between criteria and sub-criteria. It includes the goal of the problem, criteria and sub-criteria, each criterion and sub-criteria are independent at the same level. The weight of criteria in control hierarchy can evaluate by AHP approach.
2. Network hierarchy: It indicates the relationship between elements and clusters, and criteria interaction. It composes the weights of criteria in control hierarchy and becomes the supermatrix.

The supermatrix must first be reduced to a matrix, each of whose columns sums to unity, resulting in a column stochastic matrix. Interaction in the supermatrix may be measured according to several different criteria. To display and relate the criteria, we need a separate control hierarchy that includes the criteria and priorities. For each criterion, a different supermatrix of impacts is developed, and in terms of that criterion, the clusters are compared according to their relative impact on each other cluster, thus developing priorities to weight the block matrices of eigenvector columns under that cluster in the supermatrix. The result matrix is known as the weighted supermatrix. It needs to be stochastic to derive meaningful limiting priorities.

ANP has been applied to GSCM in some studies. Hsu and Hu (2009) used an ANP to select suppliers incorporating the issue of GSCM with respect to 19 criteria. Criteria of HSM competence were considered the requirements of hazardous substance for environmental regulations. Dou et al. (2013) introduced a gray ANP model to identify green supplier development programs (GSD) that would improve suppliers' performance. The model applied ANP to calculate the weights of criteria and rank of GSD programs. Then, the gray aggregation method was used to evaluate suppliers' involvement propensity in various GSD programs. Büyüközkan and Çifçi (2011) developed an approach for sustainable supplier selection based on fuzzy ANP considering incomplete preference relations. Criteria were evaluated by experts' opinions, and missing values were estimated by incomplete preference relations. Then, fuzzy ANP was applied to identify the optimal supplier. In addition, Büyüközkan and Çifçi (2012a, b) also proposed a hybrid model for evaluating green suppliers. Relation dependence from fuzzy DEMATEL was applied to fuzzy ANP. Then, fuzzy ANP could obtain weights of the criteria. Finally, fuzzy TOPSIS was used to rank the alternatives.

Applications of TOPSIS to green supply chain management

TOPSIS was presented by Hwang and Yoon (1981) to solve multi-criteria decision-making (MCDM) problems. It improved the concept of displaced ideal solution presented by Zelany (1974). It has been proved to be one of the best MCDM methods in addressing the rank reversal issue, which is the change in the ranking of alternatives when a non-optimal alternative is introduced (Zanakis et al. 1998).

The basic idea of TOPSIS method is that the most optimal alternative should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution (Chen and Hwang 1992; Hwang and Yoon 1981). This method assumes that every criterion is monotone increasing or monotone decreasing. The positive ideal solution stands for a solution that maximizes the benefit criteria and minimizes the cost criteria, while the negative ideal solution minimizes the benefit criteria and maximizes the cost criteria (Opricovic and Tzeng 2004). That is, the positive ideal solution is composed of all best values attainable from the criteria, and the negative ideal solution consists of all worst values attainable from the criteria (Wang and Chang 2007).

TOPSIS was also applied to GSCM. However, TOPSIS was not used individually. It was always integrated with other methods. Azadnia et al. (2012) introduced an integrated approach to solve sustainable supplier selection problem. Fuzzy AHP was applied to obtain the weights of criteria for sustainable supplier selection. Then, self-organizing map neural network was utilized to cluster the suppliers based on their scores regarding each criterion. Finally, TOPSIS was used twice to rank the suppliers within the best cluster. Kannan et al. (2013) presented an integrated approach for selecting the green suppliers and allocating the optimum order quantities. Fuzzy AHP and TOPSIS were used to assign criteria weight and rank all alternative suppliers. Then, a weighted max–min fuzzy multi-objective model was constructed to determine the order quantity. Objective of the model was to maximize the total value of purchasing and to minimize the total cost of purchasing. Govindan et al. (2013) introduced a fuzzy approach for supplier selection decisions with consideration of sustainability criteria based on the triple bottom line concept. Fuzzy TOPSIS was used to aggregate the ratings and generate an overall performance score.

Materials and methods

"Literature review" section has demonstrated that the supplier selection procedure would straightly affect the environmental sustainability and the ecological performance of firms. Thus, it is an important part in the GSCM. This section proposes a fuzzy MCDM method for green supplier selection illustrated in Fig. 1. It consists of three steps:

1. The Delphi method for determining the criteria,
2. Fuzzy ANP method for obtaining the weights of each criterion and
3. Fuzzy TOPSIS method for ranking the alternatives.

Basically, the Delphi method is used to determine the important criteria first by domain experts. Then, these important criteria are applied to develop the fuzzy ANP structure. From fuzzy ANP, it can provide the weight for each criterion. These weights will be used by fuzzy TOPSIS in order to make the supplier selection. The detailed discussion for each step is as follows.

Delphi method

This step intends to determine the most significant criteria and collect the corresponding factors that are considered for the green supplier selection. Considering the criteria of green supplier selection in carbon management is a narrow

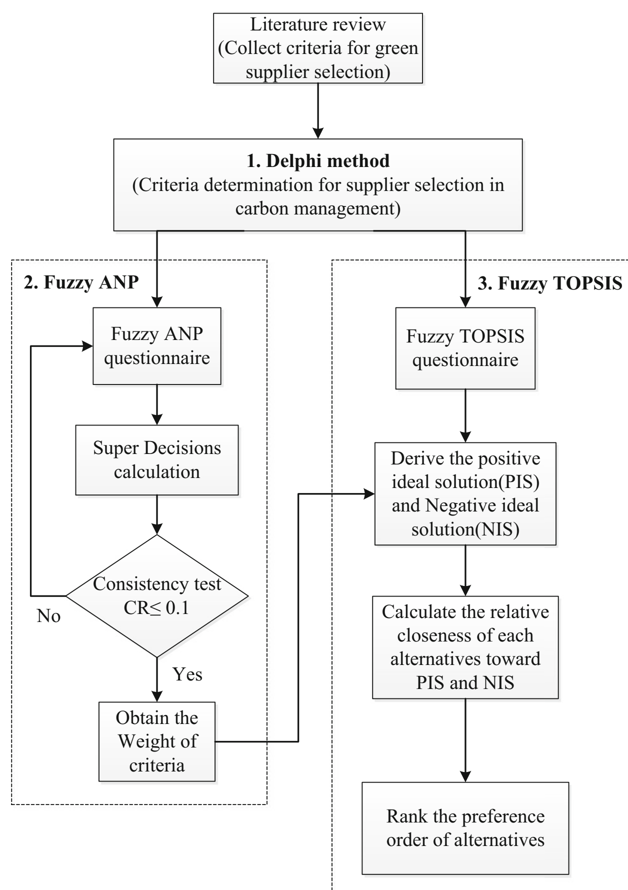


Fig. 1 Fuzzy MCDM supplier selection framework

field, and it would need professionals to get involved. Delphi method therefore becomes the first choice. Delphi method is adopted to collect data from a series of expert panels that consist of purchasing managers or appropriate people for related industries or academics. Descriptions of the steps are listed below:

1. Literature research.
2. Assemble an expert panel.
3. Questionnaire design: The form of questionnaire uses Likert scale to exhibit importance of each criterion. The importance and their scores can be divided into five levels: “very important, 5”; “important, 4”; “general, 3”; “unimportant, 2”; and “very unimportant, 1.”
4. Pretest and distribute questionnaire.
5. Analyze the first-round answers.
6. Design and distribute the second-round questionnaire with the result of the first-round questionnaire, experts are encouraged to change their previous answers referring others’ answers.
7. Analyze the second-round answers and delete criteria with a lower score.
8. Determine the green supplier selection criteria.

Fuzzy ANP

In order to measure the relationship or the relative importance between criteria determined by the expert panel, this step utilizes a fuzzy ANP approach to obtain the weights of each criterion through pair comparison analysis by experts.

Fuzzy theory was developed by Zadeh (1965) to solve problems with descriptions of activities and observations which are imprecise, uncertain or fuzzy in decision-making problem related to complicate systems. The evaluation given by experts or decision makers on qualitative criteria of a certain object is always expressed in linguistic expressions instead of crisp values, based on experience and expertise. Such linguistic evaluations are vague, which makes further analysis is hard to compute. Therefore, fuzzy set theory can be implemented to measure ambiguous concepts associated with human’s subjective judgments. In fuzzy logic, each number between 0 and 1 indicates a partial truth, whereas crisp sets correspond to binary logic [0,1] (Lin 2013).

Some important definitions of fuzzy set theory are listed below (Lin 2013). Let X be the universe of discourse and $X = \{x1, x2, x3, \ldots, xn\}$. A fuzzy set $\tilde{A}$ of X is a set of order pairs:

$$\left\{\left(x1, f\tilde{A}(x1), (x2, f\tilde{A}(x2)), (xn, f\tilde{A}(xn)\right)\right\}, \quad (1)$$

where $f\tilde{A} : X \to [0, 1]$. is the membership function of A and $f\tilde{A}(Xi)$ stands for the membership degree of xi in $\tilde{A}$.

The related definitions are described as follows.

Definition 1 When X is a continuous rather than a countable or finite set, the fuzzy set $\tilde{A}$ is denoted as $\tilde{A} = {}^{f\tilde{A}(xi)}/_{(x)}$, where $x \in X$.

Definition 2 When X is a countable or finite set, the fuzzy set $\tilde{A}$ is represented as $\tilde{A} = \sum {}^{\text{if}\,\tilde{A}(xi)}/_{(x)}$, where $xi \in X$.

Definition 3 A fuzzy set $\tilde{A}$ of the universe of discourse X is normal when its membership function $f\tilde{A}(x)$ satisfies $\max \tilde{f}A(x) = 1$.

Definition 4 A fuzzy number is a fuzzy subset in the universe of discourse X that is not convex but also normal.

Definition 5 The fuzzy α-cut $\tilde{A}$ and strong α-cut $\tilde{A}\alpha+$ of the fuzzy set $\tilde{A}$ in the universe of discourse X are defined by

$$\begin{aligned} \tilde{A}\alpha &= \left\{xi | f\tilde{A}(xi) \geq \alpha, xi \in X\right\}, \quad \text{where } \alpha \in [0,1] \\ \tilde{A}\alpha+ &= \left\{xi | f\tilde{A}(xi) \geq \alpha, xi \in X\right\}, \quad \text{where } \alpha \in [0,1] \end{aligned} \quad (2)$$

Definition 6 A fuzzy set $\tilde{A}$ of the universe of discourse X is convex if and only if every $\tilde{A}\alpha$ is convex, that is, $\tilde{A}\alpha$ is a close interval of R. It can be written as

$$\tilde{A}\alpha = [P1(\alpha), P2(\alpha)], \quad \text{where } \alpha \in [0,1] \quad (3)$$

Definition 7 A triangular fuzzy number (TFN) can be defined as a triplet ($a1$, $a2$, $a3$); the membership function of the fuzzy number $\tilde{A}$ is defined as:

$$f_{\tilde{A}}(x) = \begin{cases} 0, & x \prec a1 \\ \dfrac{(x - a1)}{a2 - a1}, & a1 \leq x \leq a2 \\ \dfrac{(a3 - x)}{a3 - a2}, & a2 \leq x \leq a3 \\ 0, & x \succ a3 \end{cases}. \quad (4)$$

Let $\tilde{A}$ and B be two TFN parameterized by the triplet ($a1$, $a2$, $a3$) and ($b1$, $b2$, $b3$), respectively, and then, the operational laws of these two TFNs are as follows:

$$\begin{aligned} \tilde{A}(+)\tilde{B} &= (a1, a2, a3)(+)(b1, b2, b3) = (a1 + b1, a2 + b2, a3 + b3) \\ \tilde{A}(-)\tilde{B} &= (a1, a2, a3)(-)(b1, b2, b3) = (a1 - b1, a2 - b2, a3 - b3) \\ \tilde{A}(\times)\tilde{B} &= (a1, a2, a3)(\times)(b1, b2, b3) = (a1b1, a2b2, a3b3) \\ \tilde{A}(\div)\tilde{B} &= (a1, a2, a3)(\div)(b1, b2, b3) = (a1/b1, a2/b2, a3/b3) \end{aligned} \quad (5)$$

Since fuzzy set theory is similar to human being’s thinking, it was integrated with ANP and TOPSIS. The fuzzy ANP contains the following steps:

Step 1: Construct ANP network framework. When constructing the network of ANP, we assemble an expert panel with five managers in risk management and environmental safety and health (ESH) management department from industry and two environmental science professors to discuss the ANP framework.

Step 2: Design and distribute fuzzy ANP questionnaire. This study applies the method proposed by Chen and Hwang (1992) and designs five semantic word sets (equally important, fairly important, important, very important and extremely important) to collect the responses of expert panel on each question. Then, transform these 1–9 scales into TFN as shown as follows:

1. Equally important: 1 = (1,1,1),
2. Middle point: 2 = (1,2,3),
3. Fairly important: 3 = (2,3,4),
4. Middle point: 4 = (3,4,5),
5. Important: 5 = (4,5,6),
6. Middle point: 6 = (5,6,7),
7. Very important: 7 = (6,7,8),
8. Middle point: 8 = (7,8,9) and
9. Extremely important: 9 = (8,9,10).

Equation (6) is used to perform calculations.

$$\tilde{a}_{ij} = \left(1/_n\right) \otimes \left(\tilde{a}_{ij}^1 \otimes \tilde{a}_{ij}^2 \otimes \cdots \otimes \tilde{a}_{ij}^n\right), \tag{6}$$

where $\tilde{a}_{ij}$ is the integrated TFN, and $\tilde{A}_{ij}^n$ is the response of nth expert for ith criterion toward jth criterion. It can be represented as TFN as follows:

$$\tilde{a}_{ij} = \left[l_{ij}, m_{ij}, u_{ij}\right], \tag{7}$$

$$l_{ij} = \left[\sum_{k=1}^{n} l_{ij}^k\right] \Big/ n, \tag{8}$$

$$m_{ij} = \left[\sum_{k=1}^{n} m_{ij}^k\right] \Big/ n, \text{ and} \tag{9}$$

$$u_{ij} = \left[\sum_{k=1}^{n} u_{ij}^k\right] \Big/ n, \tag{10}$$

where l represents the lower bound of TFN, m represents the middle bound of TFN, and u represents the upper bound of TFN.

Step 3: Establish a pairwise comparison matrix and obtain the relative weights. This study introduces TFNs to represent the semantic ranking of expert panel and integrates the measurement of importance for all question results.

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \cdots & \tilde{a}_{1j} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{i1} & \cdots & \tilde{a}_{ij} \end{bmatrix} \tag{11}$$

The corresponding fuzzy weight of each comparison matrix is calculated by the logarithmic least squares method (Büyüközkan and Çifçi 2012a, b; Önüt and Soner 2008) as follows:

$$\tilde{W}_k = \left(w_k^l, w_k^m, w_k^u\right), \quad k = 1, 2, \ldots, m \tag{12}$$

$$w_i^s = \frac{\left[\prod_{j=1}^{n} a_{kj}^s\right]^{1/n}}{\sum_{i=1}^{n}\left[\prod_{j=1}^{n} a_{ij}^m\right]^{1/n}}, \quad s \in \{l, m, u\} \tag{13}$$

Then, the center of gravity is employed to defuzzify the fuzzy weights as follows:

$$F_i = \frac{\left[\left(w_i^u - w_i^l\right) + \left(w_i^m - w_i^l\right)\right]}{3} + w_i^l, \tag{14}$$

where F_i represents a weight of ith criterion in the fuzzy pair comparison matrix.

After calculation, the results are fed to Super Decisions software to generate the initial supermarkets for calculating the relative weights.

Step 4: Consistence test: If $A > B$ and $B > C$, we can infer that $A > C$. This is called "transitive law" in mathematics. After establishing the pairwise comparison and evaluate eigenvector, it is necessary to check whether the "consistency ratio" (*CR*) of pairwise compare matrix conforms the transitive law. *CR* and *CI* are defined as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \text{ and} \tag{15}$$

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}. \tag{16}$$

CI is consistency index, RI is random index, and n is the number of criteria.

$$\begin{cases} \mathrm{CI} = 0; & \text{Full compliance with consistency} \\ \mathrm{CI} > 0; & \text{Not in full compliance with consistency} \\ \mathrm{CR} \leq 0.1; & \text{Acceptable consistency} \end{cases}$$

If the consistency ration is not in full compliance, it is necessary to correct or adjust the result from the pairwise comparison.

Fuzzy TOPSIS

After obtaining the weight of each criterion by fuzzy ANP approach, the next step is to adopt the fuzzy TOPSIS method as the ranking method for the alternatives. The fuzzy TOPSIS method also introduces TFN and linguistic variable with five semantic word sets (very high, high, medium, low and very low) to collect the response of experts on each question. The fuzzy TOPSIS method consists of following steps (Chen 2000):

Step 1: Construct the fuzzy decision matrix $\tilde{D}$ for m criteria for n alternatives: $\tilde{x}_{ij} = \left(a_{ij}, b_{ij}, c_{ij}\right)$ represents the transformed TFNs from linguistic terms. $\tilde{D}$ is represented as follows:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{17}$$

Step 2: Calculate the normalized fuzzy decision matrix $\tilde{R}$ as follows:

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m \times n}. \tag{18}$$

The normalized $\tilde{r}_{ij}$ is calculated as:

$$\tilde{r}_{ij} = \left[\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right] \tag{19}$$

$$c_j^* = \max c_{ij}. \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n. \tag{20}$$

To avoid the effect of outliers, TOPSIS needs to normalize the decision matrix.

Step 3: Calculate the weighted normalized decision matrix $\tilde{V}$: In this study, the weights are obtained from previous fuzzy ANP approach. The weighted normalized value $\tilde{v}_{ij}$ is calculated as follows:

$$\tilde{V}_{ij} = w_i r_{ij}, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n \text{ and} \tag{21}$$

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{\min}, \tag{22}$$

where w_i is the weight of the ith criterion and $\sum_{i=1}^{m} w_i = 1$.

Step 4: Determine the fuzzy positive ideal solution A^* and fuzzy negative ideal solution A^-.

$$A^* = \left(\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*\right) \tag{23}$$

$$A^- = \left(\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\right) \tag{24}$$

where $v_j^* = (1, 1, 1)$ and $v_j^- = (0, 0, 0)$, $j = 1, 2, \ldots, n$.

Step 5: Calculate the distance of each alternative using A^* and A^- as follows:

$$D_j^* = \sum_{i=1}^{m} d\left(\tilde{v}_{ij}, \tilde{v}_i^*\right), \quad j = 1, 2, \ldots, n \tag{25}$$

$$D_j^- = \sum_{i=1}^{m} d\left(\tilde{v}_{ij}, \tilde{v}_i^-\right), \quad j = 1, 2, \ldots, n \tag{26}$$

where

$$d\left(\tilde{A}, \tilde{B}\right) = \sqrt{\frac{1}{3}\left[(a1 - b1)^2 + (a2 - b2)^2 + (a3 - b3)^2\right]}. \tag{27}$$

Step 6: Calculate the relative closeness to the positive ideal solution: The relative closeness of the alternative A_i with respect to A^* is defined as:

$$RC_j^* = \frac{D_j^-}{D_j^* + D_j^-}, \quad j = 1, 2, \ldots, \text{n}. \tag{28}$$

Step 7: Rank the preference order: The index values of RC_i^* lie between 0 and 1. The larger index value means closer to a positive ideal solution for alternatives.

Results and discussion

After presenting the proposed hybrid MCDM method for green supplier selection, this section will employ a case company to demonstrate the proposed method. The case study is based on an electronic company that is a pioneer in the LEDs industry. As one of the largest technology companies listed on the Taiwan Stock Exchange, the case company committed to develop eco-friendly manufacturing and focused on cooperating with green suppliers in Taiwan.

Criteria for supplier selection in carbon management

In this study, there are two steps for constructing supplier selection criteria under carbon management practice. First, collect green supplier selection criteria from the previous literature and then implement the Delphi method. The questionnaire uses a Likert scale to show the importance of each criterion. The importance can be divided into five levels: "very important, 5"; "important, 4"; "general, 3"; "unimportant, 2"; and "very unimportant, 1." The questionnaire for Delphi method was distributed to seven experts in the area of environmental science for different industries and to two experts from academy. After two run of survey, the result already has been consistent.

According to the results of the questionnaires, four criteria "establishment of carbon emission factor," "carbon disclosure and report," "energy management system (ISO 50001)," "information system" and "supplier collaboration" are deleted. In addition, one criterion "risk assessment for low carbon requirement" is added. Finally, there are 13 criteria for supplier selection in carbon management as shown in Table 1.

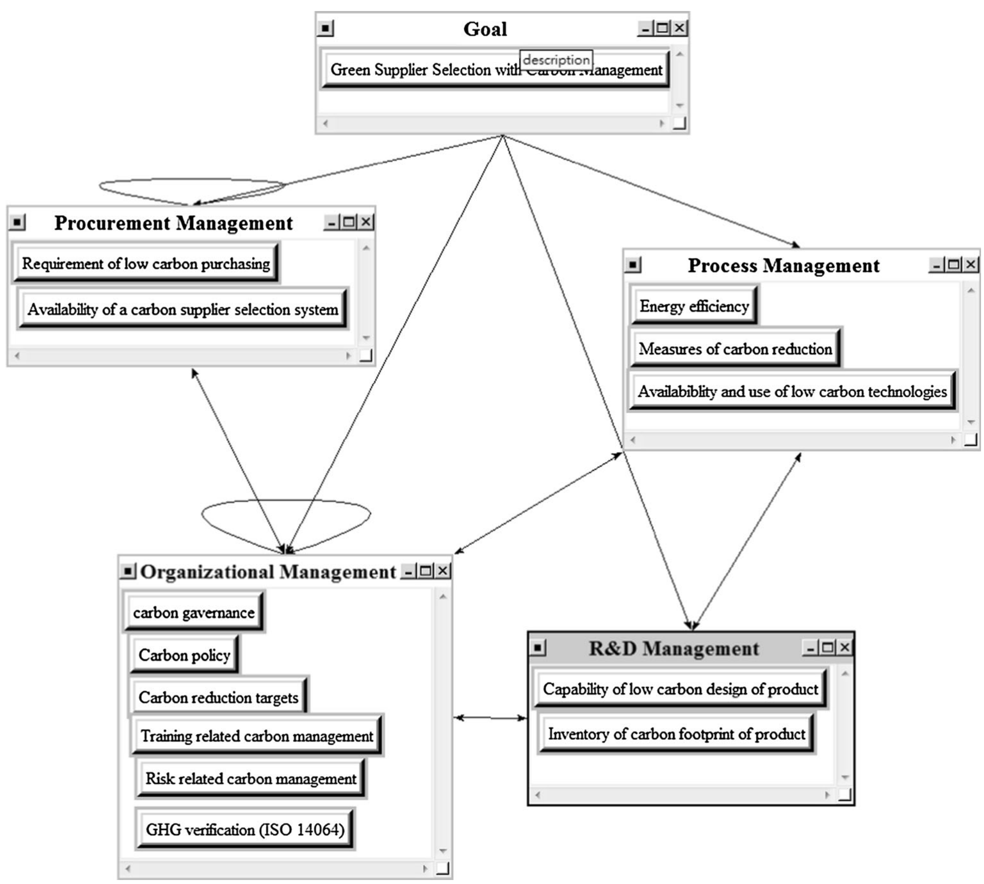
Generate criteria weights by ANP

After settling down the criteria for the supplier selection model, the expert panel is gathered to build the ANP structure. Since the pairwise comparison process will be performed using Super Decisions software, the experts need to be asked to describe the dependences and feedbacks between each involved criterion and dimension. Through this process, an ANP model with feedback system is constructed as shown in Fig. 2.

Table 1 Criteria for supplier selection in carbon management with respect to GSCM

Dimensions	Criteria	Explanation
Organizational management	Carbon governance (C1)	Supplier has a responsible department to handle carbon management
	Carbon policy (C2)	Supplier has explicit policy or plan about carbon management
	Carbon reduction targets (C3)	Supplier has set clear goals for carbon emission reduction target
	GHG verification (ISO 14064) (C4)	Supplier achieves ISO 14064 regulation
	Risk assessment for low carbon requirement (C5)	Supplier has a risk assessment for low carbon requirement from government or her clients
	Training-related carbon management (C6)	Supplier implements carbon management training to its staffs
Process management	Availability and use of low carbon technologies (C7)	Whether to apply low carbon technologies or not
	Energy efficiency (C8)	Electricity consumption is low or efficient of suppliers
	Measures of carbon reduction (C9)	Supplier is monitoring and measuring its carbon emission quantity
Procurement management	Availability of a carbon supplier selection system (C10)	Supplier has its own reliable supplier selection system
	Requirement of low carbon purchasing (C11)	Supplier has low carbon regulation for its raw material purchasing
R&D management	Capability of low carbon design (C12)	Assessing whether supplier has the ability to design low carbon product
	Inventory of carbon footprint of product (C13)	Supplier implements carbon footprint inventory and calculating

Fig. 2 ANP model



Then, the pairwise comparison questionnaires are designed based on the ANP mode. According to the pair comparison result gathering from the experts, the pair comparison matrix can be generated. Table 2 shows the pair comparison matrix for one of the experts.

In this step, the consistency of questionnaire results ($CI \leq 0.1$) has to be tested in advance. Then, transform the expert's judgment into TFNs. We can obtain the fuzzy judgment matrix as shown in Table 3.

By using a fuzzy number merging method, the fuzzy judgments of all experts can be integrated and an integrated matrix can be generated as shown in Table 4.

After generating the defuzzified weights of every fuzzy pair comparison matrix, all the weights are imported back in Super Decisions software again to run the final weights for each selected supplier selection criteria with respect to carbon management.

In Super Decisions software, it can automatically run the ANP process and generate the supermatrix. By assigning the defuzzified weights directly to each comparison matrix,

Table 2 Paired comparison matrix between dimensions

	Organizational management	Process management	Procurement management	R&D management
Organizational management	1.000	2.000	4.000	7.000
Process management	0.500	1.000	2.000	5.000
Procurement management	0.250	0.500	1.000	3.000
R&D management	0.143	0.200	0.333	1.000

Table 3 Fuzzy paired comparison matrix between dimensions

	Organizational management	Process management	Procurement management	R&D management
Organizational management	(1.000, 1.000, 1.000)	(1.000, 2.000, 3.000)	(3.000, 4.000, 5.000)	(6.000, 7.000, 8.000)
Process management	(4.000, 5.000, 6.000)	(1.000, 1.000, 1.000)	(1.000, 2.000, 3.000)	(4.000, 5.000, 6.000)
Procurement management	(0.200, 0.250, 0.333)	(0.333, 0.500, 1.000)	(1.000, 1.000, 1.000)	(2.000, 3.000, 4.000)
R&D management	(0.125, 0.143, 0.167)	(0.167, 0.200, 0.250)	(0.250, 0.333, 0.500)	(1.000, 1.000, 1.000)

Table 4 Integrated fuzzy paired comparison matrix between dimensions

	Eigen vectors	Normalized fuzzy weights	Defuzzified weights
Organizational management	(2.034, 2.599, 3.163)	(0.387, 0.495, 0.602)	0.494
Process management	(1.103, 1.413, 1.766)	(0.210, 0.269, 0.336)	0.272
Procurement management	(0.542, 0.736, 0.946)	(0.103, 0.140, .180)	0.141
R&D management	(0.420, 0.509, 0.627)	(0.080, 0.097, 0.119)	0.099

Table 5 Weighted supermatrix of supplier selection in carbon management

	Goal	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Goal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.09	0.00	0.23	0.23	0.00	0.38	0.50	0.00	0.00	0.00	0.60	0.40	0.00	0.00
C2	0.09	0.23	0.00	0.18	0.00	0.39	0.31	0.00	0.00	0.00	0.25	0.25	0.00	0.00
C3	0.11	0.20	0.26	0.00	0.00	0.00	0.00	1.00	1.00	0.82	0.00	0.20	0.69	0.65
C4	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35
C5	0.13	0.29	0.24	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C6	0.03	0.08	0.08	0.07	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C7	0.10	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C8	0.14	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C9	0.03	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00
C10	0.08	0.14	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00
C11	0.06	0.06	0.04	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00
C12	0.08	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
C13	0.02	0.00	0.00	0.03	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

the supermatrix can be calculated. Table 5 presents the weighted supermatrix for this study. The cumulative influence of each criterion on every other criterion will finally be obtained by raising the weighted supermatrix to limiting power. The final weights that obtained from the limited supermatrix are shown in Table 6. These weights would later be used in the fuzzy TOPSIS method.

According to Table 6, it can be observed that the top three most important criteria in the experts' opinions are "carbon governance" (22.9 %), "carbon policy" (18.8 %) and "carbon reduction targets" (17.4 %). These three criteria are in the "organizational management" dimension and occupy 59.1 % importance of all criteria selected. The last three criteria are "GHG verification (ISO 14064)" (0.3 %), "inventory of carbon footprint of product" (0.9 %) and "energy efficiency" (1.4 %).

Evaluate the alternatives by using fuzzy TOPSIS

In this step, five managers of case company were asked to evaluate seven suppliers they are actually cooperating with. By using five levels of linguistic terms "very low," "low," "medium," "high" and "very high" to express their satisfaction judgment toward the suppliers. Table 7 demonstrates the fuzzy decision matrix for low carbon supplier selection in GSCM established by this study, where *S* represents the suppliers.

The fuzzy positive ideal reference point and the negative ideal reference point are then calculated and shown in Table 8. The next step is to calculate the distance of each supplier from fuzzy positive ideal reference point and the negative ideal reference point. The results are illustrated in Table 9.

Table 6 Weights of criteria

Dimensions	Criteria	Normalized by cluster	Limiting	Rank
Organizational management	Carbon governance	0.289	0.229	1
	Carbon policy	0.237	0.188	2
	Carbon reduction targets	0.219	0.174	3
	GHG verification (ISO 14064)	0.004	0.003	13
	Risk assessment for low carbon requirement	0.158	0.125	4
	Training-related carbon management	0.092	0.073	7
Process management	Availability and use of low carbon technologies	0.327	0.015	10
	Energy efficiency	0.294	0.014	11
	Measures of carbon reduction	0.379	0.018	9
Procurement management	Availability of a carbon supplier selection system	0.570	0.070	6
	Requirement of low carbon purchasing	0.430	0.052	5
R&D management	Capability of low carbon design of product	0.763	0.029	8
	Inventory of carbon footprint of product	0.237	0.009	12

Table 7 Fuzzy decision matrix of supplier selection in carbon management

	S1	S2	S3	S4	S5	S6	S7
C1	(6.35, 7.36, 8.36)	(4.98, 6.01, 7.03)	(4.70, 5.80, 6.87)	(6.20, 7.23, 8.25)	(3.56, 4.66, 5.72)	(4.09, 5.16, 6.20)	(4.33, 5.34, 6.35)
C2	(6.73, 7.74, 8.74)	(5.72, 6.76, 7.79)	(5.10, 6.11, 7.13)	(5.86, 6.88, 7.89)	(3.56, 4.66, 5.72)	(3.77, 4.82, 5.86)	(4.44, 5.52, 6.57)
C3	(5.10, 6.21, 7.28)	(4.70, 5.80, 6.87)	(4.98, 6.01, 7.03)	(5.86, 6.88, 7.89)	(3.56, 4.66, 5.72)	(3.77, 4.82, 5.86)	(5.72, 6.76, 7.79)
C4	(6.20, 7.23, 8.25)	(6.20, 7.23, 8.25)	(5.86, 6.88, 7.89)	(6.73, 7.74, 8.74)	(4.98, 6.01, 7.03)	(4.70, 5.72, 6.73)	(5.27, 6.32, 7.36)
C5	(6.00, 7.00, 8.00)	(4.33, 5.34, 6.35)	(4.09, 5.16, 6.20)	(5.10, 6.11, 7.13)	(3.28, 3.87, 4.44)	(2.63, 3.68, 4.70)	(3.77, 4.82, 5.86)
C6	(4.09, 5.16, 6.20)	(4.33, 5.43, 6.49)	(3.28, 4.35, 5.40)	(4.70, 5.80, 6.87)	(3.28, 4.35, 5.40)	(2.49, 3.55, 4.59)	(3.10, 4.21, 5.27)
C7	(6.00, 7.00, 8.00)	(5.40, 6.43, 7.45)	(4.44, 5.52, 6.57)	(5.53, 6.54, 7.55)	(3.56, 4.66, 5.72)	(4.09, 5.16, 6.20)	(4.70, 5.72, 6.73)
C8	(6.20, 7.23, 8.25)	(4.70, 5.72, 6.73)	(6.00, 7.00, 8.00)	(5.40, 6.43, 7.45)	(3.28, 4.35, 5.40)	(3.28, 3.87, 4.44)	(4.33, 5.43, 6.49)
C9	(6.20, 7.23, 8.25)	(5.10, 6.11, 7.13)	(5.53, 6.54, 7.55)	(5.86, 6.88, 7.89)	(4.33, 5.34, 6.35)	(4.09, 5.16, 6.20)	(5.53, 6.54, 7.55)
C10	(4.09, 5.16, 6.20)	(3.48, 4.51, 5.53)	(3.10, 4.21, 5.27)	(3.56, 4.66, 5.72)	(2.00, 2.66, 3.28)	(2.29, 2.95, 3.56)	(2.63, 3.68, 4.70)
C11	(4.33, 5.34, 6.35)	(4.98, 6.01, 7.03)	(3.48, 4.51, 5.53)	(4.70, 5.72, 6.73)	(3.03, 4.07, 5.10)	(3.48, 4.51, 5.53)	(4.00, 5.00, 6.00)
C12	(5.10, 6.11, 7.13)	(4.70, 5.80, 6.87)	(5.53, 6.54, 7.55)	(5.86, 6.88, 7.89)	(3.56, 4.66, 5.72)	(3.03, 4.07, 5.10)	(5.53, 6.54, 7.55)
C13	(6.57, 7.60, 8.63)	(4.98, 6.10, 7.18)	(5.53, 6.54, 7.55)	(6.35, 7.36, 8.36)	(3.56, 4.66, 5.72)	(4.09, 5.16, 6.20)	(5.10, 6.11, 7.13)

Table 8 Fuzzy positive ideal reference point and the fuzzy negative ideal reference point

	Fuzzy positive ideal reference point	Fuzzy negative ideal reference point
C1	(0.174, 0.201, 0.229)	(0.097, 0.127, 0.156)
C2	(0.144, 0.166, 0.188)	(0.076, 0.100, 0.123)
C3	(0.129, 0.151, 0.173)	(0.078, 0.102, 0.126)
C4	(0.002, 0.002, 0.003)	(0.001, 0.002, 0.002)
C5	(0.093, 0.109, 0.125)	(0.041, 0.057, 0.069)
C6	(0.050, 0.061, 0.073)	(0.026, 0.037, 0.048)
C7	(0.011, 0.013, 0.015)	(0.006, 0.008, 0.010)
C8	(0.010, 0.012, 0.013)	(0.005, 0.006, 0.007)
C9	(0.013, 0.015, 0.017)	(0.008, 0.011, 0.013)
C10	(0.045, 0.057, 0.069)	(0.022, 0.029, 0.036)
C11	(0.037, 0.044, 0.052)	(0.022, 0.030, 0.038)
C12	(0.021, 0.025, 0.029)	(0.011, 0.015, 0.018)
C13	(0.006, 0.007, 0.009)	(0.003, 0.004, 0.005)

Table 9 Distance between suppliers and ideal reference points

	Positive							Negative						
	S1	S2	S3	S4	S5	S6	S7	S1	S2	S3	S4	S5	S6	S7
d1	0.0000	0.0370	0.0429	0.0035	0.0743	0.0604	0.0552	0.2313	0.2044	0.2010	0.2289	0.1812	0.1892	0.1919
d2	0.0000	0.0210	0.0349	0.0185	0.0664	0.0627	0.0479	0.1878	0.1719	0.1617	0.1737	0.1421	0.1438	0.1534
d3	0.0151	0.0239	0.0191	0.0000	0.0491	0.0453	0.0026	0.1677	0.1616	0.1642	0.1779	0.1456	0.1474	0.1762
d4	0.0002	0.0002	0.0003	0.0000	0.0006	0.0007	0.0005	0.0032	0.0032	0.0031	0.0033	0.0029	0.0028	0.0030
d5	0.0000	0.0258	0.0288	0.0138	0.0493	0.0520	0.0341	0.1202	0.0998	0.0980	0.1091	0.0804	0.0826	0.0942
d6	0.0068	0.0040	0.0154	0.0000	0.0154	0.0240	0.0170	0.0680	0.0701	0.0619	0.0732	0.0619	0.0566	0.0610
d7	0.0000	0.0011	0.0028	0.0009	0.0045	0.0035	0.0024	0.0156	0.0148	0.0136	0.0150	0.0126	0.0132	0.0139
d8	0.0000	0.0025	0.0004	0.0013	0.0048	0.0056	0.0030	0.0129	0.0110	0.0126	0.0119	0.0095	0.0085	0.0107
d9	0.0000	0.0024	0.0015	0.0008	0.0040	0.0045	0.0015	0.0183	0.0166	0.0172	0.0177	0.0156	0.0154	0.0172
d10	0.0000	0.0073	0.0108	0.0057	0.0284	0.0252	0.0166	0.0650	0.0592	0.0568	0.0607	0.0426	0.0445	0.0524
d11	0.0050	0.0000	0.0112	0.0022	0.0145	0.0112	0.0075	0.0499	0.0536	0.0458	0.0519	0.0439	0.0458	0.0481
d12	0.0028	0.0040	0.0012	0.0000	0.0082	0.0104	0.0012	0.0268	0.0260	0.0280	0.0290	0.0231	0.0217	0.0280
d13	0.0000	0.0016	0.0011	0.0003	0.0031	0.0026	0.0016	0.0090	0.0079	0.0082	0.0088	0.0069	0.0072	0.0079
dt	0.0298	0.1308	0.1705	0.0469	0.3227	0.3082	0.1912	0.9757	0.9001	0.8723	0.9610	0.7684	0.7788	0.8577

In line with the final performance indices, the total distance between positive/negative ideal reference points, the suppliers now can be ranked by calculating the relative closeness RC_i^*. The relative closeness values for S1, S2, S3, S4, S5, S6 and S7 are 0.9703, 0.8731, 0.8365, 0.9535, 0.7043, 0.7165 and 0.8177, respectively. The final ranking of green supplier selection in carbon management by using this hybrid method is S1 > S4 > S2 > S3 > S7 > S6 > S5. After checking with the case company's manager, he agrees with the ranking result provided by the hybrid method.

Conclusion

This study has proposed a hybrid method of fuzzy ANP and fuzzy TOPSIS for carbon management of a green supplier selection system. Previously, there are only a few studies focusing on solving the supplier selection problem in carbon management. By utilizing the proposed model, 13 criteria are identified. Three of the most important criteria are "carbon governance," "carbon policy" and "carbon reduction targets." This priority ranking is actually in accordance with the real situation in the industry. If a supplier has a group whose objective is for carbon management in the organization, it will be interpreted as the supplier which is willing to handle this issue correctly. As for the carbon policy and carbon reduction targets, if a supplier sets these rules or goals, this supplier will also consider all other criteria as well. Therefore, they are much more important than others. However, regarding the last criterion "GHG verification (ISO 14064)," it is very expensive to do it annually and extremely complicated to verify when it comes to products. This is the reason that it is the less important.

Vagueness and imprecision can be effectively addressed by the proposed fuzzy model. The weight range can show decision makers' preferences. The dependency between criteria in ANP makes the calculated weights have a better power of discrimination (Büyüközkan and Çifçi 2012a, b). The proposed hybrid method allows us to find the best supplier in carbon management. Fuzzy TOPSIS is easy to apply yet has the powerful efficiency of ranking alternatives (Önüt and Soner 2008).

In the future study, other methods can be combined with the current method including DEA and artificial neural networks. Besides, in the current study, we only consider carbon management-related criteria. It is worthy if it can be combined with other regular criteria, such as cost or quality.

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