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ORIGINAL PAPER

A multi-criteria decision-making approach for evaluating carbon performance of suppliers in the electronics industry

C. W. Hsu · R. J. Kuo · C. Y. Chiou

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Abstract Although interest in addressing environmental perspectives in supplier management is rising, incorporating the issue of carbon management into supplier selection in green supply chain is still considerably scarce. This study presents a model for evaluating carbon performance of suppliers by utilizing multiple-criteria decision-making. Through literature reviews and expert opinions, 13 criteria within carbon performance are identified for evaluating suppliers. Subsequently, the analytic network process is utilized to determine the relative weights of each criterion. Finally, the VlseKriterijumska Optimizacija I Kompromisno Resenje technique is employed to evaluate carbon performance of suppliers and compromise solution under each of the evaluation criteria. An illustrative example in an electronics company is presented to demonstrate how to select the most appropriate supplier in accordance with carbon management. To be effective in mitigating carbon risk across the supply chain, the proposed hybrid model can help firms evaluate carbon performance of suppliers for facilitating low carbon supply chain.

C. W. Hsu (✉)
Department of Ecotourism, Tungnan University,
New Taipei City, Taiwan
e-mail: jcwhsu@mail.tnu.edu.tw

R. J. Kuo
Department of Industrial Management, National Taiwan University of Science and Technology, No. 43,
Section 4, Kee-Lung Road, Taipei, Taiwan

C. Y. Chiou
Department of International Trade and Logistics,
Overseas Chinese University,
100, Chiao Kwang Road, Taichung 407, Taiwan

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Introduction

With increased awareness of climate change in the supply chain, supplier selection and evaluation with carbon performance are becoming recognized as significant in making purchasing decision (Dou and Sarkis 2010; Hsu et al. 2012a, b; Le and Lee 2011; Schoenherr et al. 2012). The World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) (2009) reported that at least 80 % of carbon emissions are produced in the total supply chain. The challenge for global supply chain network is selection of raw material and component suppliers in order to meet the quantity of emitted carbon dioxide (Le and Lee 2011). According to the 2010 supply chain report from the carbon disclosure project (CDP), more than half of its members surveyed said that in the future, they would cease doing business with suppliers that do not manage their carbon emissions. Some CDP members have attempted to develop a way to address the impact of the supply chain on climate change in recent times. By controlling the carbon footprint across a supply chain, Wittneben and Kiyar (2009) emphasize that greenhouse gas (GHG) emissions from suppliers require consideration to adequately assess the contributions of any business to climate change. Companies in different industry sectors are beginning to recognize the carbon issue as one of the critical factors in green supply chain management (GSCM) (Lee 2011). In the case of electronics industry, Nokia Corporation (2009) has started collaborative work with its suppliers of components and contract manufacturers in the area of carbon dioxide emission at the end of 2007. Later, Dell (2009) and HP Corporation (2009) published aggregated supply chain GHG emissions through supplier engagement to report GHG emissions and establish reduction targets. If suppliers fail to meet these requirements with Dell, suppliers can be impacted on the ranking and may be diminished potentially on ability to compete for Dell's business (Dell 2009). Therefore, more effective evaluation of suppliers can lead to markedly improved carbon management along the supply chain (CDP 2011). As noted previously, companies are increasingly requiring their suppliers to manage their carbon emissions as a condition for doing business with them.

Supplier selection and evaluation is a multi-criteria decision-making (MCDM) problem (Huang and Keskar 2007; Liaoa and Rittscherb 2007; Tuzkaya et al. 2009), which provides an effective framework for supplier comparison based on the evaluation of multiple conflict criteria (Shyur and Shih 2006). Literature related to MCDM has proposed several supplier selection and evaluation methodologies, some familiar examples of systematic analysis include analytic hierarchy process (AHP) (Tam and Tummala 2001), fuzzy QFD (Bevilacqua et al. 2006), analytic network process (ANP) (Shyur and Shih 2006; Gencer and Gürpinar 2007; Hsu and Hu 2009; Zhu et al. 2010; Kuo and Lin 2011), case-based reasoning (CBR) systems (Choy et al. 2003), and multiple objective programming (Zhu 2004). However, the application of the mathematical programming model to supplier selection may have problems in including qualitative criteria, particularly for supplier partnership policies (Ghodsypour and O'Brien 2001). Furthermore, the computational complexities inherent in multiple objective programming frequently prohibit consideration of many crucial attributes for supplier selection (Chan and Kumar 2007). To overcome this problem, either the weighting model of the AHP or the ANP can be used since it is more useful for treating qualitative factors than other models such as mathematical programming models. The ANP technique is now widely embraced in supplier selection to provide good insights in terms of feedback systematic and interdependencies property (Bayazit 2006; Gencer and Gürpinar 2007; Hsu and Hu 2009; Zhu et al. 2010; Pang and Bai 2011). Moreover, ANP is not practically usable if the number of alternatives is huge, so that this may cause fatigue in decision-making (Briand 1998). Another favorable technique for solving MCDM problem in supplier selection is the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Chen and Wang 2009; Liou and Chuang 2010; Hsu et al. 2012a, b), which focuses on ranking and selecting from a set of alternatives, and determines compromise solutions for a problem with conflicting criteria, and helps the decision-makers to reach a final decision (Opricovic and Tzeng 2007).

Although there are a number of researches in the field of supplier selection and evaluation using a hybrid MCDM model, supplier evaluation specifically considering carbon performance using ANP and VIKOR method has rarely been found. According to the characteristics of problem and the advantage of aforementioned two techniques, this study proposes a hybrid MCDM model based on the ANP that is utilized to determine relative weight. And then, the VIKOR with ANP weights is proposed for evaluating carbon performance of supplier to discover the performance scores and gaps. An illustrated example of electronics manufacturer in Taiwan has been demonstrated the proposed framework for facilitating appropriate supplier selection in terms of carbon management. Given the fact that the proposed model indeed paves a new way for managers to manage and evaluate suppliers who are capable of having competence in carbon management. This study was conducted in Tungnan University in New Taipei City, Taiwan, from January to June 2012.

Materials and methods

Analytic network process

The ANP is the general form of the AHP, which has been used in MCDM to release restrictions associated with hierarchical structures (Huang et al. 2005). AHP can integrate qualitative information and quantitative values (Meade and Sarkis 1998) and can handle MCDM problems (Saaty 1980). Nevertheless, AHP has disadvantages. It does not sufficiently consider interdependencies (Chung et al. 2005), and it does not allow for the integrated dynamic modeling of environments (Meade and Sarkis 1998). As a result, Saaty (1980) introduced a super-matrix approach in dealing with the interdependencies among clusters. Currently, this approach is called the ANP method. The advantages of the ANP include the abilities to incorporate dependencies and feedback using a hierarchical decision network, to represent and analyze interactions, and to synthesize their mutual effects through a single logical procedure (Sarkis and Sundarraj 2002). Additionally, ANP can be used as a decision analysis tool to solve multi-criteria supplier selection problems that contain interdependencies (Bayazit 2006) and provide systematic feedback (Gencer and Gürpinar 2007). ANP modeling thus better fits the problem examined in this study, and offers the advantage of providing a systematic approach to supplier evaluation as well as previous studies (Bayazit 2006; Shyur and Shih 2006; Gencer and Gürpinar 2007; Hsu and Hu 2009; Zhu et al. 2010).

In this study, the matrix manipulation relies on the concept of Saaty and Takizawa (1986), as well as the study conducted by Shyur and Shih (2006), instead of Saaty's original super matrix for ease of understanding. The detailed description of the matrix deployment process of the ANP method can be found in the work of Saaty and Takizawa (1986) and Shyur and Shih (2006). Some essential steps are as follows.

Step 1: determining the weights of criteria within independence

Without assuming the interdependence between criteria, the decision-maker is asked to respond to the relative weighting of each criterion via a paired comparison matrix. A scale of 1–9 is used to compare the two components. A score of 1 indicates that the two components have equal importance, whereas a score of 9 indicates the overwhelming dominance of the considered component (row component) over the comparison component (column component). If the impact of one component is weaker than that of its comparison component, it will be scored from 1 to 1/9, with 1 indicating indifference and 1/9 indicating the overwhelming dominance of the column component over the row component. Once the pair-wise comparisons are completed, the local vector w_1 is computed as the unique solution of

$$Aw_1 = \lambda_{\max} w_1 \tag{1}$$

where $\lambda_{\max}$ is the largest eigenvalue of pair-wise comparison matrix A. All acquired vectors are normalized to get the e-vectors w_2 of these relative importance weights.

Step 2: determining the weights of criteria within interdependence

Considering the interdependence among criteria, the decision-maker is asked to answer the question for evaluating the interdependencies related to "which criterion will influence criterion a more: b or c", and "what is the relative impact of criterion a compared to criterion b or c". Various pair-wise comparison matrices are constructed for each criterion. The e-vector from these matrices is thus used to form interdependence weight matrix M, where zeros are assigned to the eigenvector weights of the criteria with independent relationship.

Step 3: synthesizing the weights

By synthesizing the results of step 1 and 2, the relative weights of criteria considering interdependence can be acquired as follows:

$$w_c = Mw_2 \tag{2}$$

VIKOR

The compromise ranking method (known as VIKOR) has been introduced as one applicable technique to implement within MCDM (Opricovic 1998), which is based on the basic concept of the positive-ideal solution and negative-ideal solution to evaluate the standard of different project in the competition from MCDM model (Opricovic and Tzeng 2004). The positive-ideal solution indicates the alternative with the highest value, while the negative-ideal solution indicates the alternative with the lowest value. VIKOR focuses on ranking and selecting from a set of alternatives, and determines compromise solutions for a problem with conflicting criteria, and helps the decision-makers to reach a final decision (Opricovic and Tzeng 2007). Various studies regarded VIKOR as a suitable technique to evaluate each alternative for each criterion function (Opricovic and Tzeng 2004; Liou and Chuang 2010). The compromise ranking algorithm VIKOR has the following steps (Tzeng et al. 2002; Opricovic and Tzeng 2007; Liou and Chuang 2010).

Step 1: determine the best and the worst values

The best value is f_j^* and the worst value is f_j^- in evaluation criteria. Those values can be computed by Eqs. (3) and (4).

$$f_j^* = \max_i f_{ij}, \quad i = 1, 2, \ldots, m \tag{3}$$

$$f_j^- = \min_i f_{ij}, \quad i = 1, 2, \ldots, m \tag{4}$$

where, f_j^* is the positive-ideal solution for the jth criterion, and f_j^- is the negative-ideal solution for the jth criterion.

Step 2: calculate the distance

This step is to compute the distance from each alternative to the positive-ideal solution. The value can be computed by Eqs. (5) and (6).

$$S_i = \sum_{j=1}^{n} w_j \left(\left|f_j^* - f_{ij}\right|\right) / \left(\left|f_j^* - f_j^-\right|\right) \tag{5}$$

$$Q_i = \max_i \left\{ w_j \left(\left|f_j^* - f_{ij}\right|\right) / \left(\left|f_j^* - f_j^-\right|\right) \quad j = 1, 2, \ldots, n \right\} \tag{6}$$

where, w_j represents the weights of the criteria from ANP, S_i shows the mean of group utility and represents the distance of the ith alternative achievement to the positive-ideal solution, and Q_i represents the maximal regret of each alternative.

Step 3: calculate the index value

There index values are defined as:

$$R_i = v\left[\frac{S_i - S^*}{S^- - S^*}\right] + (1 - v)\left[\frac{Q_i - Q^*}{Q^- - Q^*}\right] \quad (7)$$

where, $S^* = \min_i S_i$ (or setting the best $S^* = 0$), $S^- = \max_i S_i$ (or setting the worst $S^- = 1$), $Q^* = \min_i Q_i$ (or setting the best $Q^* = 0$), and $Q^- = \max_i Q_i$ (or setting the worst $Q^- = 1$). Equation (7) can be re-written as $R_i = vS_i + (1 - v)\,Q_i$, when $S^* = 0$ and $Q^* = 0$ (i.e., all criteria have been achieve to the aspire level) and $S^- = 1$ and $Q^- = 1$ (i.e., the worst situation), where v is introduced as a weight for the strategy of maximum group utility, whereas $1 - v$ is the weight of the individual regret. In Eq. (7), when $v = 1$, it represents decision-making process that could use the strategy of maximum group utility. On the other hand, when $v = 0$, it represents decision-making process that could use the strategy of minimum individual regret. In general, $v = 0.5$ would be used if the decision process is concerned about both maximum group utility and individual regret (Tzeng et al. 2002; Liou and Chuang 2010). The compromise solution is determined by VIKOR, and it can be accepted by the decision-makers based on a maximum group utility of the majority and a minimum of the individual regret of the opponent.

Results and discussion

An illustrated case of electronics manufacturer

Since suppliers of brand name companies, such as Nokia, Dell and HP are mainly from Taiwan, one of the most industrialized countries in the Asia–Pacific region and home to a large number of electrical and electronics manufacturers involved in original equipment manufacturing (OEM) and original design manufacturing (ODM) (Chien and Shih 2007; Hsu and Hu 2008), these electronics companies are subject to customer requests for carbon management either at organization or product level. Hence, the main risks and pressures OEMs and ODMs faced with their suppliers include carbon management in the green supply chain. Therefore, both types of manufacturers must select suppliers capable of delivering both high-quality products and competent carbon management. To solve this question, a comprehensive model of carbon management for supplier selection is necessary for managers to determining appropriate suppliers as a long-term collaborative partnership in the green supply chain.

As pointed out by Shah and Siddiqui (2006), the case study is an appropriate methodology for addressing the phenomena in which the research has lesser or no control. The case company in this study has embraced and is interested in incorporating carbon management into supplier evaluation and selection because it suffers pressure from buyers, and it has become a CDP member of carbon management in the supply chain. The case company would like to implement a systematic method of evaluating suppliers based on competency of carbon management because of worldwide trend for increasing environmental regulations on climate change initiatives.

Step 1: identifying evaluation criteria

The first step in hybrid decision model is to construct the decision structure of supplier selection problem and to identify the relevant criteria related to carbon performance and alternatives developed. Through interviews with three senior supply chain and environmental management representatives from the case company, a framework of 13 criteria for carbon performance were recognized in literature (Cogan et al. 2008; CDP 2010; Hsu et al. 2012a, b) for evaluating suppliers, which is acceptance by senior managers of criteria and their clusters which are presented in Table 1. This model has three levels (see Fig. 1). The second level consists of 13 criteria of carbon performance. The third level is the alternative in the illustrated case.

Step 2: determining the interrelationship among criteria

After 13 criteria of carbon performance for supplier evaluation were recognized from literature, a simple correlation matrix questionnaire with three experts was applied to determine the interrelationship among the criteria. A questionnaire was prepared to inquire about the relationship of one criterion to another and to synergize the interrelationship among the criteria. As illustrated in Table 2, C_5 was affected by C_1 and C_9 based on expert opinion.

Step 3: calculating the weights by ANP

By considering the interdependent relationships exist in the real supplier selection and evaluation environment, ANP method in this study is utilized to solve the dependence and feedback problem of each criterion. To determine the relative importance of criteria for the objective of selecting the best supplier, the decision-maker is asked to respond to the weights of all criteria without assuming the interdependence between criteria. After the pair-wise comparison matrices are developed, a vector of priorities (i.e., eigenvector or eigenvector) in each matrix is calculated and subsequently normalized to sum to 1.0 or 100 %. This study utilized a two-stage algorithm to calculate the

Table 1 Criteria for supplier selection in carbon performance

Criteria	Description
Carbon governance (C_1)	Carbon management for firms has been incorporated into their board and executive structures to ensure that the strategy is effectively turned into action
Carbon policy (C_2)	By integrating carbon policies into their procurement departments, company can facilitate low carbon management practices across the organization
Carbon reduction targets (C_3)	Setting targets to reduce carbon emissions has become as critical strategy for firm to facilitating low carbon management
Carbon risk assessment (C_4)	Carbon risk assessment can greatly enhance the awareness and understanding of firm on how to carry out the strategies of climate change mitigation
Training-related carbon management (C_5)	To be effective in carbon management implementation, relevant education and training for employees need to be launched to promote environmental consciousness
Life cycle cost management (C_6)	While incorporating life cycle cost management into carbon emissions mitigation, companies can get an insightful analysis of carbon management from a cost-effective perspective
Measures of carbon management (C_7)	Companies can take internal and external measures to mitigate carbon emissions
Involvement in initiatives for carbon management (C_8)	Working together with NGOs, governments, or other companies on carbon initiatives, firms are encouraged to measures, manage, disclose, and reduce their carbon emissions in mitigating carbon risks
Management systems of carbon information (C_9)	Management systems of carbon information for firms can effectively collect carbon emissions data and manage business risks related to carbon issues
Supplier collaboration (C_{10})	Carbon emissions are mainly produced in the total supply chain, collaborative initiatives with suppliers on carbon management practices and technology can effectively facilitate low carbon supply chain and operation
Carbon accounting and inventory (C_{11})	Carbon accounting and inventory is essentially an initial step in developing strategies and evaluating progress for controlling carbon emissions in the operations of a company, product, and supply chain
Carbon verification (C_{12})	External verification of carbon inventories with third party is becoming increasingly important in order to demonstrate organization's positive approach to climate change publicly
Carbon disclosure and report (C_{13})	For effective communication with stakeholders, reporting and disclosure of carbon emissions is an important first step toward a successful climate change strategy and green image promotion

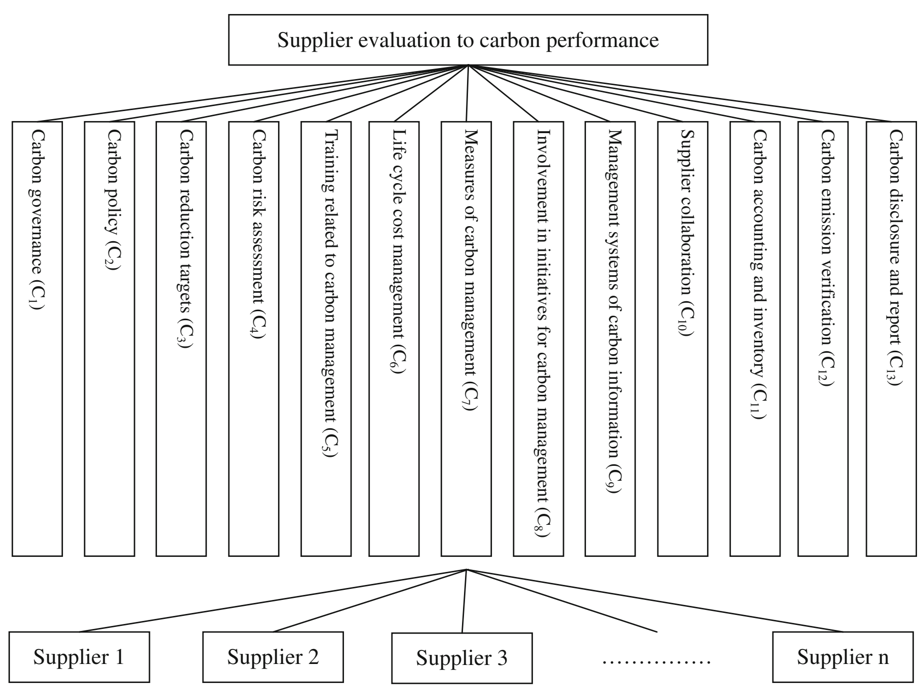

Fig. 1 The framework of supplier evaluation

e-vector, which first adds the value in each column of the matrix and then separates each entry in each column by the total of that column; the normalized matrix is acquired through meaningful comparison among components. The evaluation results are presented in Table 3; the normalized eigenvector can be generated as $w_2 = (C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10}, C_{11}, C_{12}, C_{13}) = (0.080, 0.076, 0.065, 0.073, 0.059, 0.128, 0.049, 0.091, 0.061, 0.062, 0.080, 0.064, 0.113)$.

The interdependence between criteria is now considered based on Table 2, and weight matrix of criteria is defined as w_2. In total, 13 pair-wise comparison matrices are generated and the decision-makers examine the relative for each criterion. The normalized eigenvector for these matrices is calculated, as shown in Table 4.

By obtaining the synthesis of the results, the relative importance of the evaluation criteria considering interdependence can be obtained as follows:

Table 2 The correlation between criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
C_1		⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
C_2	⊙		⊙	⊙		⊙	⊙	⊙	⊙	⊙		⊙	⊙
C_3													
C_4													
C_5	⊙	⊙	⊙	⊙		⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
C_6	⊙	⊙	⊙							⊙			
C_7	⊙	⊙	⊙	⊙		⊙				⊙			
C_8	⊙	⊙	⊙							⊙			
C_9	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙		⊙	⊙	⊙	⊙
C_{10}	⊙	⊙	⊙	⊙		⊙	⊙						
C_{11}	⊙	⊙	⊙	⊙		⊙	⊙			⊙		⊙	
C_{12}	⊙	⊙	⊙			⊙	⊙			⊙			
C_{13}	⊙	⊙								⊙			

$$W_c = w_2 \times w_1 = \begin{bmatrix} 0.060 & 0.087 & 0.112 & 0.137 & 0.211 & 0.131 & 0.092 & 0.223 & 0.262 & 0.107 & 0.402 & 0.255 & 0.236 \\ 0.085 & 0.095 & 0.109 & 0.136 & 0 & 0.075 & 0.150 & 0.173 & 0.314 & 0.068 & 0 & 0.255 & 0.195 \\ 0 & 0 & 0.053 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.136 & 0.239 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.076 & 0.081 & 0.053 & 0.088 & 1.000 & 0.087 & 0.092 & 0.226 & 0.284 & 0.074 & 0.309 & 0.188 & 0.193 \\ 0.145 & 0.135 & 0.160 & 0 & 0 & 0.176 & 0 & 0 & 0 & 0.135 & 0 & 0 & 0 \\ 0.104 & 0.095 & 0.085 & 0.129 & 0 & 0.143 & 0.094 & 0 & 0 & 0.100 & 0 & 0 & 0 \\ 0.106 & 0.113 & 0.091 & 0 & 0 & 0 & 0 & 0.076 & 0 & 0.067 & 0 & 0 & 0 \\ 0.092 & 0.103 & 0.088 & 0.149 & 0.550 & 0.073 & 0.165 & 0.303 & 0.140 & 0.080 & 0.158 & 0.128 & 0.172 \\ 0.109 & 0.077 & 0.102 & 0.133 & 0 & 0.091 & 0.162 & 0 & 0 & 0.061 & 0 & 0 & 0 \\ 0.087 & 0.072 & 0.056 & 0.092 & 0 & 0.108 & 0.131 & 0 & 0 & 0.095 & 0.131 & 0 & 0.095 \\ 0.050 & 0.043 & 0.045 & 0 & 0 & 0.116 & 0.113 & 0 & 0 & 0.085 & 0 & 0.079 & 0 \\ 0.086 & 0.099 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.127 & 0 & 0 & 0.205 \end{bmatrix} \times \begin{bmatrix} 0.080 \\ 0.076 \\ 0.065 \\ 0.073 \\ 0.059 \\ 0.128 \\ 0.049 \\ 0.091 \\ 0.061 \\ 0.062 \\ 0.080 \\ 0.064 \\ 0.113 \end{bmatrix} = \begin{bmatrix} 0.170 \\ 0.118 \\ 0.003 \\ 0.023 \\ 0.189 \\ 0.060 \\ 0.056 \\ 0.032 \\ 0.154 \\ 0.051 \\ 0.062 \\ 0.039 \\ 0.043 \end{bmatrix}.$$

As for the relative weights of criteria for evaluating carbon performance of supplier, "training related to carbon management (C_5)" (0.189), "carbon governance (C_1)" (0.170), "management systems of carbon information (C_9)" (0.154), and "carbon policy (C_2)" (0.118) are the top four significant evaluation criteria, which comprised more than 60 % of the overall weighting.

Step 4: compromise ranking by VIKOR

After the weights of criteria are determined by ANP, the VIKOR method is employed to evaluate carbon performance of supplier selection (Table 5). There are three managers in case company conducting the assessment who are responsible in the field of supplier management. By considering the easy-to-use proposed model in case company, in this research, v value of VIKOR is set to 0.5 based on both maximum group utility and individual regret within experts' opinion. Since R_i represents the gap between the alternative and ideal solution, it is observed that S_1 contains the smallest gap in terms of the value of VIKOR. Summing these values for each of the alternatives provides in Table 6, S_1 thus was the best supplier.

Table 3 Comparison matrix for the evaluation criteria

w_1	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	e-Vector
C_1	1.000	1.442	1.000	0.843	0.843	1.000	1.186	1.289	1.326	1.710	1.326	0.920	0.693	0.080
C_2	0.693	1.000	1.913	1.000	1.186	0.843	1.186	1.710	1.326	1.216	0.843	0.843	0.405	0.076
C_3	1.000	0.523	1.000	0.843	0.843	0.754	1.186	1.442	1.119	1.000	1.000	1.000	0.405	0.065
C_4	1.186	1.000	1.186	1.000	1.000	0.693	1.710	0.822	0.693	0.693	1.442	1.442	0.843	0.073
C_5	1.186	0.843	1.186	1.000	1.000	0.405	0.693	0.585	1.000	1.442	0.693	0.693	0.481	0.059
C_6	1.000	1.186	1.326	1.442	2.466	1.000	4.217	1.913	2.466	1.442	2.466	3.557	1.000	0.128
C_7	0.843	0.843	0.843	0.585	1.442	0.237	1.000	0.585	1.000	0.693	0.481	0.481	0.405	0.049
C_8	0.776	0.585	0.693	1.216	1.710	0.523	1.710	1.000	1.442	1.710	2.466	2.466	1.186	0.091
C_9	0.754	0.754	1.289	1.442	1.000	0.405	1.000	0.693	1.000	1.216	0.693	0.693	0.585	0.061
C_{10}	0.585	0.822	1.442	1.442	0.693	0.693	1.442	0.585	0.822	1.000	0.585	0.585	0.776	0.062
C_{11}	0.754	1.186	1.000	0.693	1.442	0.405	2.080	0.405	1.442	1.710	1.000	2.924	1.000	0.080
C_{12}	1.087	1.186	1.000	0.693	1.442	0.281	2.080	0.405	1.442	1.710	0.342	1.000	0.342	0.064
C_{13}	1.442	2.466	2.466	1.186	2.080	1.000	2.466	0.843	1.710	1.289	1.000	2.924	1.000	0.113

Table 4 Degree of relative impact for evaluation criteria

w_2	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
C_1	0.060	0.087	0.112	0.137	0.211	0.131	0.092	0.223	0.262	0.107	0.402	0.255	0.236
C_2	0.085	0.095	0.109	0.136		0.075	0.150	0.173	0.314	0.068		0.255	0.195
C_3			0.053										
C_4				0.136	0.239								
C_5	0.076	0.081	0.100	0.088	1.000	0.087	0.092	0.226	0.284	0.074	0.309	0.188	0.193
C_6	0.145	0.135	0.160			0.176				0.135			
C_7	0.104	0.095	0.085	0.129		0.143	0.094			0.100			
C_8	0.106	0.113	0.091					0.076		0.067			
C_9	0.092	0.103	0.088	0.149	0.550	0.073	0.165	0.303	0.140	0.080	0.158	0.128	0.172
C_{10}	0.109	0.077	0.102	0.133		0.091	0.162			0.061			
C_{11}	0.087	0.072	0.056	0.092		0.108	0.131			0.095	0.131	0.095	
C_{12}	0.050	0.043	0.045			0.116	0.113			0.085		0.079	
C_{13}	0.086	0.099								0.127			0.205

A hybrid MCDM model of supplier selection is proposed in this study, it provides a systematically analytic approach to evaluate supplier performance of carbon management. With respect to the importance and priority of criteria from ANP, moreover, it is observed that training-related carbon management (C_5) is the most significant criterion in evaluating carbon performance followed by carbon governance (C_1) and management systems of carbon information (C_9). It implies that these three criteria play a crucial role in influencing the decision of supplier selection. Such information can be extremely helpful for managers to recognize areas where suppliers ought to improve. Then, it is easy for a company to engage in supplier development and help the suppliers improve on their efforts to better carbon performance. Obviously this hybrid model is capable of having competence in handing the interrelationship among criteria and determining the priority criteria for facilitating supplier management in terms of carbon performance.

Additionally, supplier selection associated with carbon management performance is based on the gap from the ideal solution that differs from the conventional aggregated method, i.e., the simple additive weighting (SAW) method. The advantage of VIKOR for proposed model is to use an aggregating function to determine a solution with the shortest distance from the ideal solution and farthest distance from the negative-ideal solution. Results of the study reveal that $S_1 > S_3 > S_2 > S_4 > S_5$ in terms of overall score of carbon management, where S_1 is considered as most appropriate supplier. Company can use the concept of maximum group utility and minimum individual regret to select the real "closest to the ideal" solution as well as supplier selection and evaluation with carbon management. In this study, the $v = 0.5$ is adopted

Table 5 Performance matrix of suppliers on each criterion

Criteria	Weights	S_1	S_2	S_3	S_4	S_5
Carbon governance (C_1)	0.170	0.0000	0.0800	0.0400	0.1000	0.0600
Carbon policy (C_2)	0.118	0.0278	0.0417	0.0000	0.0556	0.0556
Carbon reduction targets (C_3)	0.003	0.0000	0.0010	0.0007	0.0023	0.0017
Carbon risk assessment (C_4)	0.023	0.0107	0.0133	0.0080	0.0187	0.0187
Training-related carbon management (C_5)	0.189	0.0316	0.0316	0.0789	0.0789	0.0631
Life cycle cost management (C_6)	0.060	0.0210	0.0490	0.0350	0.0490	0.0420
Measures of carbon management (C_7)	0.056	0.0067	0.0333	0.0200	0.0200	0.0200
Involvement in initiatives for carbon management (C_8)	0.032	0.0151	0.0189	0.0151	0.0151	0.0189
Management systems of carbon information (C_9)	0.154	0.0906	0.1087	0.0543	0.0543	0.1087
Supplier collaboration (C_{10})	0.051	0.0060	0.0180	0.0120	0.0240	0.0240
Carbon accounting and inventory (C_{11})	0.062	0.0144	0.0217	0.0072	0.0289	0.0361
Carbon verification (C_{12})	0.039	0.0091	0.0182	0.0091	0.0228	0.0273
Carbon disclosure and report (C_{13})	0.043	0.0100	0.0250	0.0100	0.0350	0.0350

Table 6 Result of the VIKOR analysis

Supplier	S_i	Q_i	VIKOR (R_i)
S_1	0.2429	0.5556	0.3942 (1)
S_2	0.4603	0.6667	0.6066 (3)
S_3	0.2903	0.5556	0.4179 (2)
S_4	0.5046	0.7778	0.6237 (4)
S_5	0.5110	0.7778	0.6269 (5)

as basic to trade-off between maximum group utility and minimum individual regret for evaluating supplier. While company emphasize on the maximum group utility, then $v = 1$ would be used; on the contrary, $v = 0$ would be used if the company is concerned about minimum individual regret. It implies that VIKOR method is useful and feasible for the manager to select the suitable weights (v) in the decision-making process of supplier selection with various requirements.

After discussing the findings with three experts of the case company, carbon performance for supplier selection and evaluation has been regarded as an emerging parameter for maintaining the long-term collaborative relationship. Based on opinions of experts, accordingly, the carbon management scorecard (CMS) should be launched and further integrated into the quarterly business review (QBR) in terms of 13 criteria within the proposed MCDM model in this study. By incorporating the carbon issue into procurement policies, suppliers will be required to perform a preliminary self-assessment or to be audited throughout the CMS questionnaire. After that, the company can obtain a draft understanding on the capability of carbon management for its suppliers that help them identify and prioritize specific carbon risks. Based on the CMS model, suppliers can engage their own first tier suppliers in the same way to help understand, prioritize, and address specific carbon risks. Also, this hybrid model can enable the road map of supplier management to effectively mitigate and manage carbon risk derived from supply chain.

Conclusion

The supply chain-based conceptual framework and operational model to incorporate carbon management into supplier selection have been presented. By identifying the related criteria of carbon management activities for the proposed framework, a hybrid model of integration of ANP and VIKOR methods was applied to an electronics company for facilitating supplier management in the emerging field of carbon management. Without appropriate consideration of suppliers' ability to accomplish with climate change, company may be risky and lead to supply chain disrupted. Studies have shown that companies suffering supply chain disruptions experienced 33–40 % lower stock returns relative to their industry benchmarks (Hendricks and Singhal 2005). By offering a comprehensive model in this study, not only can firms evaluate suppliers, but can also engage in collaboration with suppliers on capability building to improve their efforts of carbon management.

Compared with the previous investigations, the proposed method may have the following contributions to supplier selection and evaluation. First, a new hybrid MCDM model for evaluating suppliers with emphasis on carbon performance has been developed. Such a framework has never being found in the previous literature. And from the illustrated example this model shows its potential advantage in selecting suitable suppliers in terms of carbon management. Second, a hybrid model of integration of

ANP and VIKOR methods was applied in supplier evaluation and it is rarely found from the previous studies. After identification of problem structure and interrelationships between criteria, the key criteria influencing supplier selection have been recognized. ANP can capture both quantitative and qualitative criteria and reflect more realistic results among decision attributes and alternatives owing to the existence of interdependent relationships in the real supplier selection and evaluation environment. Therefore, ANP modeling can serve as a new method and offer insights to managers in selecting suppliers systematically. Also, the hybrid model considers both maximum group utility and individual regret to measure the gaps between alterative and ideal solutions, which can strengthen the ability to conduct carbon performance assessment of suppliers under lack of quantitative information. Third, a company which wants to incorporate carbon issue into supplier management can adopt the presented model or road map of suppliers' carbon management to its needs.

Although the results obtained from this research are satisfactory, there still a room for improvement. The outcome of the carbon performance model with the MCDM method conducted in this study is exclusively determined by three managers of the case company; it is worthwhile to increase the number of participating firms for construing a more generalized model of suppliers' carbon management for mastering carbon risk. In responding to the preference of decision-makers in assigning precise numerical values, the fuzzy ANP and fuzzy VIKOR can be utilized in future research. Furthermore, the proposed method can be extended and developed into intelligent software to illustrate the practical application.

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