Renewable and Sustainable Energy Reviews 79 (2017) 1461–1471

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Developing sustainable supplier selection criteria for solar air-conditioner manufacturer: An integrated approach

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ARTICLE INFO

Keywords:
Sustainable supplier selection
Sustainability
Solar air-conditioner
Criteria interactions
Rough number

ABSTRACT

Due to the increasing awareness of environmental and social issues, many practitioners and researchers have paid much attention to the sustainable supply chain management (SSCM) in recent years. Sustainable supplier selection is one of the most critical activities in the SSCM which can affect supply chain performance. However, the previous literature rarely considers the interrelationships between economic, environmental, and social evaluation criteria in the supplier selection. Moreover, the effect of the criteria importance on the criteria interrelationships is scarcely discussed in previous researches. To deal with these problems, a novel integrated methodology is developed in this paper. The proposed method integrates the merit of pairwise comparison method in determining relative importance, the strength of decision making trial and evaluation laboratory (DEMATEL) in manipulating the complex and intertwined problems with fewer data, and the rough number's advantage in flexibly dealing with vague information. A case study in a solar air-conditioner manufacturer is provided to show the feasibility and effectiveness of the proposed methodology.

1. Introduction

Nowadays, supply chains are increasingly exposed to increased competition, exacerbating scarcity of resources, stricter regulations, and requirements of stakeholders [10,22]. There is also a growing awareness of the requirement for companies to pro-actively build sustainability principles into their supply chain management [34]. Sustainable supply chain management (SSCM) has been considered as an integration and realization of a company's economic, environmental, and social objectives in coordination of critical business processes to improve the company's long-term economic performance [10]. Supplier is one of the most critical factors for the success of sustainable supply chains (SSC). This is because collaboration with economically, environmentally, and socially strong suppliers could improve the supply chain performance [8]. Thus, to maintain a strategically competitive position, it is necessary for operations, purchasing and supply chain managers to select the most suitable supplier [5,6]. Accurate supplier selection helps organizations find the suitable supply chain partners and eventually enhance the organizational performance [11].

Although many studies exist on the topic of supplier selection, the research on the selection of sustainable supplier is fairly rare [19,20,24]. Most of them focus on environmental supplier selection, and they do not consider social aspects. Moreover, it is inappropriate to assume all the supplier selection criteria as independent due to the complexity and uncertainty of the operation environment. There are complex relationships among the supplier selection criteria, e.g. *Eco-design* may have influences on *Reduce, Reuse and Recycle* of the product, and the *Delivery* may influence the *Resource Consumption*. It is necessary for managers to figure out such criteria interrelationships in practice, because the causal-effect relations between selection criteria provide valuable information for companies to discern the potential areas for further sustainability improvement. However, the previous supplier selection approaches scarcely consider the relationships among criteria which may cause underestimation or overestimation of the weights of sustainable supplier selection. Furthermore, the previous approaches often require much additional data. Although some researches try to use decision making trial and evaluation laboratory (DEMATEL) to handle this problem (e.g., [17,11], they often assume that the evaluation criteria are equally important in dealing with the interrelationships of criteria, which does not actually happen in the real supplier selection decision making. In fact, the internal strength of one evaluation criteria may have impact on its influence (intensity of affecting), and eventually affect the supplier

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http://dx.doi.org/10.1016/j.rser.2017.05.081
Received 18 December 2016; Received in revised form 6 May 2017; Accepted 17 May 2017
1364-0321/

Table 1
Sustainable supplier selection criteria in previous literature.

Sustainable supplier selection criteria	Explanation
Economic criteria	
Quality [25,13,9,40]	Product quality and reliability level provided by a supplier.
Delivery [15]	The ability to follow the predefined delivery schedule and the on time delivery reliability.
Cost/price (profitability of suppliers) [16,29]	Purchasing cost, holding cost, ordering cost, and supplier's bidding price of the product.
Environmental criteria	
Environmental management system (EMS) [40,21]	A set of systematic processes and practices that enable a supplier to reduce its environmental impacts, which includes the organizational structure, planning and implementing policy (e.g., ISO 14001 and TQEM) for environmental protection.
Resource consumption [25,5,6,41]	The use of resources, including energy, power and water, are to be reduced by the practices such as modifying production, maintenance and process, conservation, recycling and reusing materials.
Eco-design [24,18]	Designing product with consideration of environmental impacts during the whole product lifecycle including the stages of procurement, manufacture, use, and disposal.
Reduce, Reuse and Recycle (3R) [38,9]	Pollution (e.g., air pollution and water pollution) reduction, greening packaging and waste recycling & reuse.
Social criteria	
Occupational health and safety [19,20,4]	Implementing some regulations (e.g., OHSAS 18001), taking ergonomic and safety measure, and utilizing other instruments that ensure the labor safety and their health (both the physical and mental health).
Employee right and welfare [24,27,5,6]	Suppliers are committed to uphold the rights of employees, to treat them with dignity and respect, and to maintain a culture of security, nondiscrimination and equality. Compensation paid to employee shall comply with all applicable wage laws.
Training and community development [15,27,5,6]	Training employee and managers to implement the policies and processes to meet the sustainability requirements; Creating job opportunities creation and engaging in community development.

selection performance. To fully and accurately reflect the positions of selection criteria, it is also necessary to calculate criteria weights considering their interrelationships. In this way, it helps to avoid potential risk of selecting the wrong suppliers. Besides, it is hard to acquire accurate decision makers' preferences in the supplier selection process, because the decision information in form of linguistic terms is often subjective and vague.

Based on the above discussions, the objective of this research is to develop an integrated approach to determine the final criteria weights of sustainable supplier selection considering the interrelationships among evaluation criteria with different prior importance. The proposed methodology integrates the merit of pairwise comparison method in determining relative importance of sustainability criteria, the strength of the DEMATEL in manipulating the complex and intertwined criteria with fewer data, and the rough number's advantage in flexibly dealing with vague information. The proposed approach helps to elucidate the causal relationships between sustainability criteria by using the framework of DEMATEL. It provides a mechanism of integrating both strength (importance) and influence of the criteria to fully reflect the position of sustainability criteria, which helps to avoid potential risk of selecting the wrong suppliers. The necessary information derived from the proposed method, such as interactions between criteria and the inner importance of criteria, can help companies to identify the potential areas where sustainable suppliers need to improve. With the proposed method, companies can help their suppliers improve sustainability for better management of sustainable supply chain operations. Moreover, the rough number used in the proposed method can flexibly manipulate such vagueness. To the best of our knowledge, no previous studies have investigated the subject of sustainable supplier selection with this kind of integrated method. This research results will improve the managers' view on the nature of interrelationships between the sustainable supplier selection criteria. Besides, the proposed method can be widely used as a structural model for analyzing intertwined factors and causal relationships between them. In particular, the proposed method can be applied to assess alternatives when both strength (importance) and influence of criteria cannot be neglected.

The paper is organized as follows: Section 2 presents a literature review of SSCM and sustainable supplier selection. Section 3 develops an integrated importance-influence analysis method for sustainable supplier selection and characterizes the novel computational procedure. In Section 4, a case study and a comparative analysis are conducted using the supplier selection problem of a solar air-conditioner manufacturer. Conclusions and suggestions for future research are made in Section 5.

2. Literature review

2.1. Sustainable supply chain management

As the introduction of sustainability into the context of supply chain management, many practitioners and researchers have paid much attention to SSCM in recent years. Existing literatures have provided some definitions for SSCM. Seuring and Müller [33] consider that SSCM is the management of cooperation among companies, material, information and capital flows in the supply chain while considering sustainable development from the economic, environmental and social perspectives. Seuring [32] proposes that SSCM is a combination of supply chain management and sustainable development where the social and environmental issues along the supply chain need to be considered, thereby taking precautions against some related sustainable problems.

2.2. Sustainable supplier selection

Suppliers needs to be carefully assessed and selected due to their critical roles in the supply chain management and their influences on the company's sustainability performance [1]. In the past, economic criteria (such as price, quality, and delivery) are usually used solely by purchasing managers to evaluate and select suppliers [15]. The environmental and social criteria for supplier selection are always omitted. After SSCM's starting to attract increasing attention in the field of supply chain management, researchers pointed out the importance of incorporating the social and environmental indicators into the conventional supplier selection process. Hence, the social and environmental criteria need to be included in the supplier selection framework beside economic criteria. Table 1 summarizes the sustainable supplier selection criteria drawing the greatest attention in previous literature.

In the past, many supplier selection methodologies have been proposed in the literature. For example, Yang and Wu [37] use the grey entropy-based method to select green supplier. Lu et al. [26] propose a green supplier evaluation approach based on multi-objective decision making method. A fuzzy goal programming approach is provided in Tsai and Hung [35] to optimize the green supply chain under activity-based costing and evaluate performance with a value-chain structure. Lee et al. [25] introduce a green supplier selection approach with fuzzy extended analytic hierarchy process (AHP) for high-tech industry. Büyüközkan and Çifçi [8] develop a supplier selection method on the basis of fuzzy analytic network process (ANP) within a framework of multi-person decision-making. Azadnia et al. [3] develop a sustainable supplier selection method based on fuzzy AHP rule-based weighted fuzzy approach and multi-objective programming. Amindoust et al. [2] propose a supplier selection approach based on fuzzy inference system, which can handle the subjectivity of assessments. Other familiar supplier selection methods include the case based reasoning-based approach [12], the fuzzy quality function deployment (QFD)-based approach [7], and the cloud model-based method [36].

Although these methods have brought great insights to supplier evaluation literature, most of them focus on environmental supplier selection and neglect social aspects. Furthermore, most of them rarely take into account the interrelationships among evaluation indicators and require extra information. The DEMATEL approach can identify the interrelationships among factors in the supplier selection and it does not require a large amount of data [17]. Therefore, DEMATEL is suitable to solve the supplier selection problem in SSCM practice and with intertwined criteria (economic, environmental and social). However, the traditional DEMATEL cannot handle the subjectivity and the vagueness of decision makers' assessments. Even more important is the fact that the normal DEMATEL often assumes that the evaluation criteria are equally important in dealing with the interrelationships of criteria. For those reasons, there is a clear need for a new formal decision support methodology for the sustainable supplier selection under vague environment, which can simultaneously consider the interrelationships among evaluation criteria and internal strengths of criteria.

3. Methodology

The main objective of this research is to develop an integrated approach to determine the final criteria weights of sustainable supplier selection considering interrelationships among evaluation criteria with different prior importance. Besides, vagueness manipulation is also considered in the proposed approach. A schematic diagram of the proposed method is presented in Fig. 1.

3.1. Determination of the rough relative importance matrix

The significance of sustainable supplier selection criteria depends largely on a combination of "the relative importance" and "the exerting and received influence" of the criteria. Hence, the sustainable supply chain managers need to firstly determine the relative importance of criteria between each pair of them. Pairwise comparison matrix can be used to obtain the relative importance matrix of sustainable supplier selection criteria. In order to manipulate the subjective and vague information in the group pairwise comparison, we utilize the rough number derived from rough set theory to describe decision makers' judgments. The rough number enables decision makers to flexibly express their true perceptions.

Step 1.1. Construct the pairwise comparison matrix and consistency test

Assume that there are k experts involved in the decision making process of pairwise comparison. The decision maker can evaluate the relative importance of sustainable supplier selection criteria using the nine-point scale shown in Table 2.

According to Table 2, the kth decision maker's pair-wise comparison matrix S_k can be obtained as follows:

$$S_k = [s_{ij}^k]_{n\times n}\ ,\ k = 1, 2, \ldots, m \tag{1}$$

where s_{ij}^k is the kth expert's judgment for the ith criterion importance compared with the jth criterion, m is the number of experts, and n is the number of criteria. Note that s_{ij}^k=1, when i=j. This indicates that the ith criterion (C_i) are equally important to itself.

Consistency test of each pair-wise comparison matrix can be implemented by

$$\alpha = \frac{\chi_{\max} - n}{n - 1} \tag{2}$$

$$\beta = (\frac{\alpha}{RI(n)}) \tag{3}$$

where α is the consistency coefficient, $\chi_{\max}$ is the largest eigenvalue of the matrix S_k, β is the consistency ratio, n is the dimension of the matrix S_k, and $RI(n)$ is the random index. The $RI(n)$ depends on the value of n and ranges between 0 and 1.49 for 1- to 10-dimensional matrices [30].

When the consistency ratio $\beta < 0.1$, the matrix S_k is considered to pass the consistency test, i.e., decision makers' evaluations on the criteria importance are consistent. While the consistency ratio $\beta > 0.1$, decision makers must adjust their evaluations again until the matrix S_k pass the consistency test.

After testing consistency of each matrix S_k, decision makers can construct the group pair-wise comparison matrix $\tilde{S}$ as follows:

$$\tilde{S} = [\tilde{s}_{ij}]_{n\times n}\ ;\ s_{ij}^k = 1,\ \text{when } i = j \tag{4}$$

where $\tilde{s}_{ij} = \{s_{ij}^1, s_{ij}^2, \ldots, s_{ij}^k, \ldots, s_{ij}^m\}$.

Step 1.2. Determine the rough pairwise comparison matrix

Assume $J = \{s_{ij}^1, s_{ij}^2, \ldots, s_{ij}^k, \ldots, s_{ij}^m\}$ is a set of judgments with m classes. The judgments in J are ordered in the manner of $s_{ij}^1 < s_{ij}^2 < \cdots < s_{ij}^k < \cdots < s_{ij}^m$. O is the universe including all the objects in J and A is an arbitrary object of O, and the lower approximation and upper approximation of s_{ij}^k can be obtained by

$$\underline{Apr}(s_{ij}^k) = \cup\{A \in O/J(A) \le s_{ij}^k\} \tag{5}$$

$$\overline{Apr}(s_{ij}^k) = \cup\{A \in O/J(A) \ge s_{ij}^k\} \tag{6}$$

where $\underline{Apr}(s_{ij}^k)$ is the lower approximation of s_{ij}^k, and $\overline{Apr}(s_{ij}^k)$ is the upper approximation of s_{ij}^k.

Next, the judgment sequence $\tilde{s}_{ij}$ in matrix $\tilde{S}$ are converted into rough number. A rough number has lower and upper limits that denote boundaries of an interval, and it merely relies on the original data without the need for auxiliary information [23]. Rough number can better reflect the true perceptions of experts and thus enhances the objectivity of the original data. However, it lacks the mechanism to explore the relationships between elements. The DEMATEL framework can effectively identify the casual relationships between elements, but it cannot manipulate the vagueness and inconsistency of judgments. Thus, it is necessary to integrate rough number in the present framework. The judgment, s_{ij}^k, can be converted into a rough number with lower limit and upper limit as follows:

$$\underline{Lim}(s_{ij}^k) = (\prod_{m=1}^{N_{ijL}} x_{ij})^{1/N_{ijL}} \tag{7}$$

$$\overline{Lim}(s_{ij}^k) = (\prod_{m=1}^{N_{ijU}} y_{ij})^{1/N_{ijU}} \tag{8}$$

where $\underline{Lim}(s_{ij}^k)$ is the lower limit and $\overline{Lim}(s_{ij}^k)$ is the upper limit of the rough number, x_{ij} and y_{ij} are the objects in the lower approximation and the upper approximation of s_{ij}^k, N_{ijL} and N_{ijU} are the number of elements in the lower approximation and the upper approximation of s_{ij}^k.

To keep reciprocal property of the pair-wise comparison matrixes

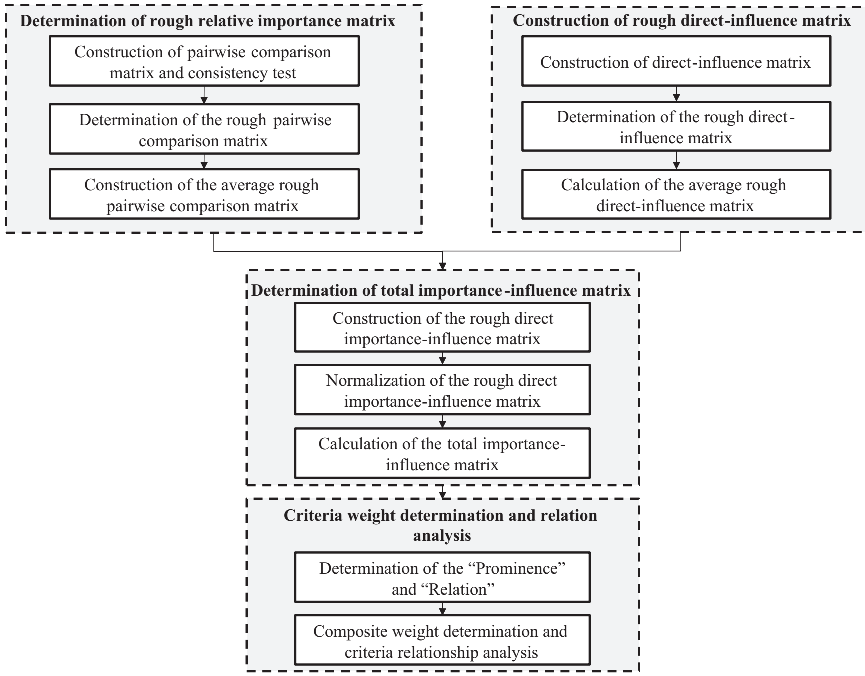

Fig. 1. The proposed integrated importance-influence analysis method.

Table 2
The nine-point scale for importance.

Score	Importance	Score	Importance
1	Equally important		
3	Moderately important	1/3	Moderately unimportant
5	Strongly important	1/5	Strongly unimportant
7	Very strongly important	1/7	Very strongly unimportant
9	Extremely important	1/9	Extremely unimportant
2, 4, 6, 8	The intermediate importance	1/2,1/4,1/6,1/8	The intermediate unimportance

without violation of the Pareto principle, the method of geometric mean is used to synthesize different decision maker's judgments in Eqs. (7)–(8) [31]. The rough number form $RN(s_{ij}^k)$ of $\tilde{s}_{ij}$ can then be obtained using Eq. (9).

$$RN(s_{ij}^k) = [\underline{Lim}(s_{ij}^k), \overline{Lim}(s_{ij}^k)] = [s_{ij}^{kL}, s_{ij}^{kU}] \tag{9}$$

where s_{ij}^{kL} and s_{ij}^{kU} are the lower limit and the upper limit of $RN(r_{ij}^k)$ in the kth matrix.

The boundary interval denoted as $RBnd(s_k)$ is defined as follows:

$$RBnd(s_{ij}^k) = \overline{Lim}(s_{ij}^k) - \underline{Lim}(s_{ij}^k) = s_{ij}^{kU} - s_{ij}^{kL} \tag{10}$$

where $RBnd(s_{ij}^k)$ indicates the consistency between the kth expert's judgment s_{ij}^k and the judgments of the rest of experts. A rough number with a smaller boundary interval can be considered as more precise one. The smaller the $RBnd(s_{ij}^k)$ is, the more consistent the experts' judgments are.

Then, the group judgment of k experts $\tilde{s}_{ij} = \{s_{ij}^1, s_{ij}^2, \ldots, s_{ij}^k, \ldots, s_{ij}^m\}$ can be converted into the rough sequence $RN(\tilde{s}_{ij})$ as follows:

$$RN(\tilde{s}_{ij}) = \{[s_{ij}^{1L}, s_{ij}^{1U}], [s_{ij}^{2L}, s_{ij}^{2U}], \ldots, [s_{ij}^{mL}, s_{ij}^{mU}]\} \tag{11}$$

Suppose $Z_1 = [Z_1{}^l, Z_1{}^u]$ and $Z_2 = [Z_2{}^l, Z_2{}^u]$ are two rough numbers, where $Z_1{}^l$ and $Z_2{}^l$ are their lower limits and $Z_1{}^u$ and $Z_2{}^u$ are their upper limits respectively, then the arithmetic operations of rough numbers are defined as follows [39].

$$Z_1 + Z_2 = [Z_1{}^l + Z_2{}^l, Z_1{}^u + Z_2{}^u] \tag{12}$$

$$Z_1 \times k = [kZ_1{}^l, kZ_1{}^u] \tag{13}$$

where k is a nonzero constant, and

$$Z_1 \times Z_2 = [Z_1{}^l \times Z_2{}^l, Z_1{}^u \times Z_2{}^u] \tag{14}$$

Step 1.3. Construct the average rough pairwise comparison matrix

The average of rough numbers $\overline{RN(\tilde{s}_{ij})}$ can be obtained as:

$$\overline{RN(\tilde{s}_{ij})} = [s_{ij}^L, s_{ij}^U] \tag{15}$$

$$s_{ij}^L = \left(\prod_{k=1}^{m} s_{ij}^{kL}\right)^{1/m} \tag{16}$$

$$s_{ij}^U = \left(\prod_{k=1}^{m} s_{ij}^{kU}\right)^{1/m} \tag{17}$$

where s_{ij}^L and s_{ij}^U are the lower limit and the upper limit of $[s_{ij}^L, s_{ij}^U]$, and m is the number of decision makers.

Then the avergae rough pairwise comparison matrix S can be obtained as follows:

$$S = [[s_{ij}^L, s_{ij}^U]]_{n\times n}; \ [s_{ij}^L, s_{ij}^U] = [1, 1], \text{ when } i = j \tag{18}$$

3.2. Construction of the rough direct-influence matrix

Step 2.1. Construct the direct-influence matrix

In this step, the m experts are invited to evaluate the direct influences between the n sustainable supplier selection criteria C_i (i=1,2,...,n) in terms of the verbal scores in Table 3.

As a result, the kth expert's $n\times n$ direct-influence matrix M_k of the sustainable supplier selection criteria is obtained as follows:

$$M_k = [r_{ij}^k]_{n\times n}; \quad r_{ij}^k = 0, \text{ when } i = j; \ k = 1, 2, \ldots, m \tag{19}$$

where r_{ij}^k represents the kth expert's assessment for the ith criterion (C_i)'s influence on the jth criterion (C_j).

Note that r_{ij}^k=0, when i=j. This indicates that the ith criterion (C_i) cannot exert influence on itself.

Table 3
Linguistic terms for rating direct relations between criteria.

NO.	Linguistic terms	Corresponding scores
1	Very high influence (VHI)	4
2	High influence(HI)	3
3	Medium influence(MI)	2
4	Low influence(LI)	1
5	No influence(NI)	0

Step 2.2. Determine the rough direct-influence matrix

This step is to synthesize the m experts' $n \times n$ direct-influence matrixes $\mathrm{M}_k (k = 1, 2, ..., m)$ to obtain the group direct-influence matrix $\widetilde{\mathrm{M}}$ as follows:

$$\widetilde{\mathrm{M}} = [\tilde{r}_{ij}]_{n \times n}; \ \ \tilde{r}_{ij} = \widetilde{0}, \ \text{when } i = j \tag{20}$$

where $\tilde{r}_{ij} = \{r_{ij}^1, r_{ij}^2, \ldots, r_{ij}^k, \ldots, r_{ij}^m\}_{1 \times m}$ and $\widetilde{0}=\{0,0,...,0\}_{1\times m}$.

By analogy with Eqs. (5)–(8), the kth expert's rough direct-influence matrix $\widetilde{\mathrm{M}}_k$ can be obtained as follows:

$$\widetilde{\mathrm{M}}_k = [[r_{ij}^{kL}, r_{ij}^{kU}]]_{n \times n}; \ \ [r_{ij}^{kL}, r_{ij}^{kU}] = [0, 0], \ \text{when } i = j; \ \ k = 1, 2, \ldots, m \tag{21}$$

where r_{ij}^{kL} and r_{ij}^{kU} are the lower limit and the upper limit of the rough interval form of r_{ij}^k. The rough interval form of the element in $\tilde{r}_{ij}$ which includes 0 is defined as [0,0].

Step 2.3. Calculate the average rough direct-influence matrix

Then the individual rough direct-influence matrix $\widetilde{\mathrm{M}}_k$ are aggregated into an average group rough direct-influence matrix M as

$$M = [[r_{ij}^L, r_{ij}^U]]_{n \times n}; \ \ [r_{ij}^L, r_{ij}^U] = [0, 0], \ \text{when } i = j \tag{22}$$

The average $[r_{ij}^L, r_{ij}^U]$ of rough numbers in the average rough direct-influence matrix M can be obtained by

$$r_{ij}^L = (\prod_{k=1}^{m} r_{ij}^{kL})^{1/m} \tag{23}$$

$$r_{ij}^U = (\prod_{k=1}^{m} r_{ij}^{kU})^{1/m} \tag{24}$$

where r_{ij}^L and r_{ij}^U are the lower limit and the upper limit of $[r_{ij}^L, r_{ij}^U]$.

3.3. Determination of the total importance-influence matrix

Step 3.1. Construct the rough direct importance-influence matrix

The rough direct importance-influence matrix D is obtained by

$$D = S \times M = [d_{ij}]_{n \times n} \tag{25}$$

$$d_{ij} = [d_{ij}^L, d_{ij}^U] = [s_{ij}^L \times r_{ij}^L, s_{ij}^U \times r_{ij}^U] \tag{26}$$

where d_{ij}^L and d_{ij}^U are the lower limit and the upper limit of the rough number d_{ij} in the matrix D;s_{ij}^L and s_{ij}^U are the lower limit and the upper limit of the rough number $[s_{ij}^L, s_{ij}^U]$ in the avergae rough pairwise comparison matrix S; r_{ij}^L and r_{ij}^U are the lower limit and the upper limit of the rough number $[r_{ij}^L, r_{ij}^U]$ in the average rough direct-influence matrix M.

The proposed approach evaluates both the strength of the acting factor and the intensity of its influence, and integrates roles of strength and intensity together to be a new "modified direct influence". This new "modified direct influence" is defined by "aggregating importance and influence as a product", which means that the internal strength (importance) of the criterion modify (weigh) the intensity of direct influence. The "modified direct influence" stresses the crucial role of interrelations between the sustainability criteria considering their initial strengths.

In fact, when decision maker considers the influence between two factor, the common sense suggests that the effect of influence depends not only on "the intensity of affecting" but also on "the strength of factor" that acts. For example, a certain change of price of some products which are supplied by two suppliers may occur. One supplier is larger (higher strength), the other is smaller (lower strength). If the two suppliers react to the price change similarly, the change in a total demand of the larger supplier will be much bigger than that of the smaller one. Thus, the final effect of the interactions between criteria depends on a combination of strength of an acting factor and its influence.

Step 3.2. Normalize the rough direct importance-influence matrix

After obtaining the rough direct-influence matrix D, the linear scale transformation is then used to transform the rough direct importance-influence d_{ij} into comparable scales. The normalized rough direct-influence matrix C is determined by

$$C = [\tilde{u}_{ij}]_{n \times n} \tag{27}$$

$$\tilde{u}_{ij} = \left[\frac{d_{ij}^L}{\gamma}, \frac{d_{ij}^U}{\gamma}\right] = [u_{ij}^L, u_{ij}^U] \tag{28}$$

$$\gamma = \max_{1 \le i \le n}\left(\sum_{j=1}^{n} d_{ij}^U\right) \tag{29}$$

where u_{ij}^L and u_{ij}^U are the lower limit and the upper limit of the rough number $\tilde{u}_{ij}$ respectively.

Step 3.3. Calculate the total importance-influence matrix

Once obtaining the normalized rough group direct importance-influence matrix C, we can separate the rough numbers within this matrix into separate sub-matrices C^L and C^U.

$$C^L = [u_{ij}^L]_{n \times n}, \ \text{and } C^U = [u_{ij}^U]_{n \times n} \tag{30}$$

Theorem 1. The total strength-relation matrix T^s (s= L,U) is given by $T^s = C^s(I - C^s)^{-1}$

Proof. According to the properties of matrix C^s (s= L,U), $\lim_{\alpha \to \infty} (C^s)^\alpha = O$ [14,28].

Then, we have

$$\begin{aligned} T^s &= \lim_{\alpha \to \infty} C^s + (C^s)^2 + ... + (C^s)^\alpha \\ &= \lim_{\alpha \to \infty} C^s[I + C^s + (C^s)^2 + ... + (C^s)^{\alpha-1}][(I - C^s)(I - C^s)^{-1}] \\ &= \lim_{\alpha \to \infty} C^s[I - (C^s)^\alpha](I - C^s)^{-1} \\ &= C^s(I - C^s)^{-1} \end{aligned}$$

∀ s= L, U, where O is the null matrix and I is the identity matrix.

This completes the proof of Theorem 1.

Hence, the total importance-influence matrix T^s (s= L,U) can be acquired according to as blow:

$$T^L = [t_{ij}^L]_{n \times n} = C^L(I - C^L)^{-1},$$

$$T^U = [t_{ij}^U]_{n \times n} = C^U(I - C^U)^{-1} \tag{31}$$

The rough total importance-influence matrix T can be represented as

$$T = [\tilde{t}_{ij}]_{n\times n} \tag{32}$$

where $\tilde{t}_{ij} = [t_{ij}^L, t_{ij}^U]$, t_{ij}^L and t_{ij}^U are the lower limit and the upper limit of the rough interval $\tilde{t}_{ij}$ in the rough total importance-influence matrix T.

Then, we convert the rough numbers in the rough total importance-influence matrix T into definite values using the following equations:

(1) Normalization

$$\tilde{z}_i^L = (z_i^L - \min_i z_i^L)/\Delta_{\min}^{\max} \tag{33}$$

$$\tilde{z}_i^U = (z_i^U - \min_i z_i^L)/\Delta_{\min}^{\max} \tag{34}$$

$$\Delta_{\min}^{\max} = \max_i z_i^U - \min_i z_i^L \tag{35}$$

where z_i^L and z_i^U are the lower limit and the upper limit of the rough number $\tilde{z}_i$ respectively; $\tilde{z}_i^L$ and $\tilde{z}_i^U$ are the normalized form of z_i^L and z_i^U, respectively.

(2) Determine the total normalized definite value by

$$\beta_i = \frac{\tilde{z}_i^L \times (1 - \tilde{z}_i^L) + \tilde{z}_i^U \times \tilde{z}_i^U}{1 - \tilde{z}_i^L + \tilde{z}_i^U} \tag{36}$$

(3) Compute the final definite value form $\tilde{z}_i^{der}$ for $\tilde{z}_i$ by

$$\tilde{z}_i^{der} = \min_i z_i^L + \beta_i \Delta_{\min}^{\max} \tag{37}$$

Therefore, we can obtain the definite value form of the rough total importance-influence matrix T as

$$T^* = [t_{ij}]_{n\times n} \tag{38}$$

where t_{ij} is the definite value form of $\tilde{t}_{ij}$, which is calculated with Eqs. (33)–(37).

3.4. Composite weight determination and relation analysis of criteria

Step 4.1. Determine the "Prominence" and "Relation"

The sum of rows and the sum of columns of the matrix T^*, represented by x_i and y_i, respectively, can be acquired by

$$x_i = \sum_{j=1}^{n} t_{ij}, \; i = 1, 2, \ldots, n, \tag{39}$$

$$y_j = \sum_{i=1}^{n} t_{ij}, \; j = 1, 2, \ldots, n, \tag{40}$$

where x_i shows the total effects, both direct and indirect, given by criterion i to the other criteria, y_j shows the total effects, both direct and indirect, received by criterion j from the other criteria.

The vector P_i named "Prominence" is made by adding the sum of rows x_i to the sum of columns y_i. Similarly, the vector R_i named "Relation" is made by subtracting y_i from x_i.

$$P_i = x_i + y_i, \;\; i = j \tag{41}$$

$$R_i = x_i - y_i, \;\; i = j \tag{42}$$

The vector P_i combines the interrelations of both directions (the horizontally exerted and vertically received influence) of the i^{th} criterion and therefore is considered as an overall influence of that criterion. The larger the value of P_i, the greater the overall prominence (visibility/importance/influence) of the i^{th} criterion in terms of overall relationships with other criteria. The vector R_i reveals the difference between the exerted influence and the received influence of the i^{th} criterion, and it is a basis for classification of the criteria. When the value R_i is positive, the i^{th} criterion is a net cause for other criteria and belongs to the cause group. If the value R_i is negative, the i^{th} criterion is reliant on the change of other criteria and thus belongs to the effect group.

Step 4.2. Composite weight determination and criteria relationship analysis

The composite weight w_i of the ith criterion is comuputed by using

$$w_i = \frac{\sqrt{P_i^2 + R_i^2}}{\sum_{i=1}^{n} \sqrt{P_i^2 + R_i^2}} \tag{43}$$

The composite weight w_i is used to measure the comprehensive influence (the total exerted influence and the total received influence) of a criterion. In addition, based on the "Prominence" P_i and "Relation" R_i, an impact-relation map can be obtained by mapping the dataset of (P_i, R_i). In the impact-relation map, the prominence axis indicates how important a criterion relative to the available set of criteria, while the relation axis divides the criteria into cause and effect groups.

4. Results and discussions

To validate the applicability and effectiveness of the proposed approach, we apply it in a solar air-conditioner manufacturing company. Company G is a multinational corporation that provides various solar air-conditioning systems and solutions throughout the world. It has been under scrutiny to achieve sustainable supply chain by the stakeholders and customers. Although the company has invested resources in sustainable supply chains, there is still lack of consensus among the managers about the importance of the criteria for sustainable supplier selection. Besides, managers of this company expect to explore interrelationships between different criteria to discern the potential areas for further sustainability improvement. In this respect, the developed methodology is applied in this case study to evaluate and analyze sustainable supplier selection criteria as well as extract their interrelationships.

Four managers from different functions in Company G are invited to evaluate the criteria of sustainable supplier selection. All of them have some roles in interacting with suppliers. These experts include a procurement manager, a strategic sourcing manager, a head of suppliers' evaluation committee, and a supplier quality manager. All the members have more than 8 years work experience. This case study is about ranking of criteria based on experts' knowledge and experience. To understand and validate the criteria identified from the literature analysis, a focused group discussion (about 1.5 h) with the managers is held. The group considers that the ten evaluation criteria in Table 1 can be applied to sustainable supplier selection in the company based on their expertise. That is, *Quality, Delivery, Cost/ price, EMS* (Environment management system), *Eco-D* (Eco-design), *3R* (Reduce, Reuse and Recycle), *RC* (Resource consumption), *E R & W* (Employee right and welfare), *O H&S* (Occupational health and safety), and *T & CD* (Training and community development). Therefore, the team decides to provide the necessary inputs to be used in this research based on the evaluation criteria in Table 1.

4.1. Implementation

4.1.1. Determination of the rough relative importance matrix

Step 1.1. Construct the pairwise comparison matrix and consistency test

The four experts evaluate the relative importance of the sustainable supplier selection criteria with the nine-point scale in Table 2. For example, the first expert's pair-wise comparison matrix S_1 is obtained as follows:

$$S_1 = \begin{bmatrix} 1 & 3 & 3 & 3 & 5 & 5 & 3 & 1 & 3 & 5 \\ 1/3 & 1 & 5 & 3 & 5 & 5 & 3 & 1/2 & 3 & 3 \\ 1/3 & 1/5 & 1 & 1/2 & 3 & 3 & 3 & 1/2 & 1 & 5 \\ 1/3 & 1/3 & 2 & 1 & 3 & 3 & 3 & 1 & 3 & 5 \\ 1/5 & 1/5 & 1/3 & 1/3 & 1 & 1/2 & 1/2 & 1/6 & 1/2 & 2 \\ 1/5 & 1/5 & 1/3 & 1/3 & 2 & 1 & 1 & 1/3 & 1 & 5 \\ 1/3 & 1/3 & 1/3 & 1/3 & 2 & 1 & 1 & 1/3 & 1 & 3 \\ 1 & 2 & 2 & 1 & 6 & 3 & 3 & 1 & 3 & 7 \\ 1/3 & 1/3 & 1 & 1/3 & 2 & 1 & 1 & 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1/5 & 1/5 & 1/2 & 1/5 & 1/3 & 1/7 & 1/3 & 1 \end{bmatrix}$$

Only half of the matrix S_1 needs to be filled out as the other half is always the reciprocal. The consistency ratio of the pair-wise comparison matrix S_1 β=0.057 < 0.1. Thus, the pair-wise comparison matrix S_1 passes the consistency test, and the first expert's evaluations on the criteria are in consistency and acceptable. Similarly, other decision makers' pairwise comparison matrixes can also be obtained. Then the group pair-wise comparison matrix $\tilde{S}$ can be built as follows:

$$\begin{bmatrix} 1,1,1,1 & 3,2,4,3 & 3,4,5,4 & 5,5,7,5 \\ 1/3,\ 1/2,\ 1/4,\ 1/3 & 1,1,1,1 & 3,3,5,2 & 3,4,5,3 \\ 1/3,\ 1/3,\ 1/2,\ 1/4 & 1/5,\ 1/3,\ 1/3,\ 1/4 & 1,1,3,1 & 5,4,4,3 \\ 1/3,\ 1/4,\ 1/5,\ 1/3 & 1/3,\ 1/4,\ 1/4,\ 1/2 & 3,2,2,1 & 5,4,3,2 \\ 1/5,\ 1/7,\ 1/6,\ 1/4 & 1/5,\ 1/6,\ 1/7,\ 1/2 & 1/2,1,1/3,1/3 & 2,3,3,2 \\ 1/5,\ 1/3,\ 1/4,\ 1/5 & 1/5,\ 1/4,\ 1/6,\ 1/3 & 1,1/2,1/2,1 & 5,6,4,7 \\ 1/3,\ 1/5,\ 1/4,\ 1/5 & 1/3,\ 1/5,\ 1/5,\ 1/4 & 1,1/2,1/2,1/3 & 3,3,5,3 \\ 1,1/3,1/2,1/3 & 2,3,1,1 & 3,2,5,3 & 7,5,5,5 \\ 1/3,\ 1/4,\ 1/5,\ 1/4 & 1/3,\ 1/3,\ 1/5,\ 1/2 & 1,1,1,1 & 3,5,3,5 \\ 1/5,\ 1/5,\ 1/7,\ 1/5 & 1/3,\ 1/4,\ 1/5,\ 1/3 & 1/3,1/5,1/3,1/5 & 1,1,1,1 \end{bmatrix}$$

Step 1.2. Determine the rough pairwise comparison matrix

According to Eqs. (7)–(9), the judgment sequence in matrix $\tilde{S}$ is converted into the rough number form. For example, the four experts' evaluation on the 1st criterion' importance relative to the 2nd criterion can be denoted as {3,2,4,3}. Using Eqs. (7)–(9), {3,2,4,3} can be converted into rough interval form as below:

$$\underline{Lim}(3) = \sqrt[3]{3 \times 2 \times 3} = 2.621,\ \overline{Lim}(3) = \sqrt[3]{3 \times 4 \times 3} = 3.302;$$

$$\underline{Lim}(2) = 2,\ \overline{Lim}(2) = \sqrt[4]{3 \times 2 \times 4 \times 3} = 2.913.$$

$$\underline{Lim}(4) = \sqrt[4]{3 \times 2 \times 4 \times 3} = 2.913,\ \overline{Lim}(4) = 4.$$

Thus, {3,2,4,3} can be represented with the rough interval set {[2.621,3.302], [2.000,2.913], [2.913,4.000], [2.621,3.302] }.

Similarly, other definite elements in the matrix $\tilde{S}$ can be converted into rough number forms.

Step 1.3. Construct the average rough pairwise comparison matrix

According to Eqs. (15)–(18), the avergae rough pairwise comparison matrix S can be obtained as shown in Table 4.

4.1.2. Construction of the rough direct-influence matrix

Step 2.1. Construct the direct-influence matrix

The four experts are then invited to evaluate the direct influences between the different sustainable supplier selection criteria in terms of the linguistic terms in Table 3. The corresponding scores are provided in Table 5. It should be noted that the influences between sustainability criteria are based on experts' subjective perceptions. For example, the managers provide relatively high influence values of *Quality* on *Delivery*, because unqualified product/part requires the company to remedy defects or to rework, which may affect the on-time delivery.

Steps 2.2 & 2.3. Determine the rough direct-influence matrix and calculate the average rough direct-influence matrix

According to Eqs. (5)–(8), the scores of direct influences can be converted into rough number forms. After that, the individual rough direct-influences are aggregated into an average group rough direct-influence matrix M (see Table 6) by Eqs. (22)–(24).

4.1.3. Determination of the total importance-influence matrix

Steps 3.1 & 3.2. Construct and normalize the rough direct importance-influence matrix

The rough direct importance-influence matrix is calculated via Eqs. (25)–(26). The rough direct importance-influence matrix considers both the relative importance of criteria and the influences among them. Then the rough direct importance-influence matrix is normalized based on Eqs. (27)–(29). The normalized rough direct-influence matrix is provided in Table 7.

Step 3.3. Calculation of the total importance-influence matrix

The rough total importance-influence matrix *T* is calculated with Eqs. (30)–(32), and it is converted into definite value form in Table 8 according to Eqs. (33)–(38).

4.1.4. Composite weight determination and relation analysis of the criteria

Step 4.1. Determine the "Prominence" and the "Relation"

The sum of rows x_i and the sum of columns y_i of the total importance-influence matrix *T* can be obtained in Table 9 using Eqs. (39)–(40). Then, the "Prominence" P_i and the "Relation" R_i are calculated based on Eqs. (41)–(42).

Table 4
The avergae rough pairwise comparison matrix.

	Quality	Delivery	Cost/price	…	E R & W	T & CD
Quality	[1.000,1.000]	[2.515,3.357]	[2.515,3.357]	…	[3.534,,4.372]	[5.106,5.793]
Delivery	[0.298,0.398]	[1.000,1.000	[3.230,4.162]	…	[2.550,3.736]	[3.230,4.162]
Cost/Price	[0.298,0.398]	[0.240,0.310]	[1.000,1.000]	…	[1.071,1.617]	[3.534,4.372]
EMS	[0.240,0.310]	[0.272,0.380]	[1.044,1.354]	…	[1.472,2.326]	[2.615,4.126]
RC	[0.162,0.214]	[0.169,0.307]	[0.228,0.359]	…	[0.379,0.639]	[2.213,2.711]
Eco-D	[0.213,0.273]	[0.194,0.274]	[0.379,0.639]	…	[0.595,0.841]	[4.668,6.173]
3R	[0.213,0.273]	[0.213,0.273]	[0.242,0.382]	…	[0.430,0.680]	[3.097,3.751]
O H & S	[0.379,0.639]	[1.185,2.060]	[1.472,2.326]	…	[2.550,3.736]	[5.106,5.793]
E R & W	[0.229,0.283]	[0.268,0.392]	[0.618,0.934]	…	[1.000,1.000]	[3.409,4.401]
T & CD	[0.173,0.196]	[0.240,0.310]	[0.229,0.283]	…	[0.227,0.293]	[1.000,1.000]

Table 5
Direct influences between the different sustainable supplier selection criteria.

	Quality	Delivery	Cost/price	EMS	RC	…	E R & W	T & CD
Quality	0,0,0,0	3,3,2,4	3,4,4,3	1,1,2,1	2,1,2,2	…	1,1,2,1	2,2,1,1
Delivery	1,2,1,1	0,0,0,0	3,2,1,1	2,1,2,1	3,3,2,2	…	2,1,1,1	1,2,1,1
Cost/price	1,2,2,1	1,1,2,1	0,0,0,0	1,1,1,1	1,0,0,1	…	3,4,3,3	3,3,2,3
EMS	1,2,2,1	1,1,1,1	2,2,1,2	0,0,0,0	3,3,2,2	…	1,1,1,2	2,2,1,1
RC	2,2,3,1	1,2,1,1	3,2,2,1	1,1,1,1	0,0,0,0	…	2,1,1,1	1,1,1,1
Eco-D	4,3,3,3	3,1,2,1	4,4,3,2	3,3,3,2	4,3,4,3	…	2,1,1,1	1,2,2,1
3R	2,3,2,2	2,2,2,2	3,3,3,2	3,3,2,3	3,4,2,3	…	2,2,1,1	1,2,1,1
O H & S	2,2,3,1	2,1,2,2	1,1,2,1	2,2,3,2	1,0,0,1	…	3,3,2,3	2,2,3,1
E R & W	1,1,2,1	1,1,1,2	3,2,1,1	2,1,1,2	1,0,0,1	…	0,0,0,0	1,2,2,1
T & CD	2,2,1,1	2,1,1,2	2,2,1,2	2,2,1,2	1,2,1,2	…	1,1,1,2	0,0,0,0

Table 6
The average rough direct-influence matrix.

	Quality	Delivery	Cost/price	…	E R & W	T & CD
Quality	[0.000,0.000]	[2.515,3.357]	[3.224,3.722]	…	[1.044,1.354]	[1.189,1.682]
Delivery	[1.044,1.354]	[0.000,0.000]	[1.185,2.060]	…	[1.044,1.354]	[1.044,1.354]
Cost/Price	[1.189,1.682]	[1.044,1.354]	[0.000,0.000]	…	[3.054,3.402]	[2.512,2.925]
EMS	[1.1891.682]	[1.000,1.000]	[1.477,1.915]	…	[1.044,1.354]	[1.189,1.682]
RC	[1.472,2.326]	[1.044,1.354]	[1.472,2.326]	…	[1.044,1.354]	[1.000,1.000]
Eco-D	[3.054,3.402]	[1.185,2.060]	[2.632,3.673]	…	[1.044,1.354]	[1.189,1.682]
3R	[2.051,2.388]	[2.000,2.000]	[2.512,2.925]	…	[1.189,1.682]	[1.044,1.354]
O H & S	[1.472,2.326]	[1.477,1.915]	[1.044,1.354]	…	[2.512,2.925]	[1.472,2.326]
E R & W	[1.044,1.354]	[1.044,1.354]	[1.185,2.060]	…	[0.000,0.000]	[1.189,1.682]
T & CD	[1.189,1.682]	[1.189,1.682]	[1.477,1.915]	…	[1.044,1.354]	[0.000,0.000]

Step 4.2. Composite weight determination and criteria relationship analysis

The composite weights of each criterion can be obtained according to Eq. (43), and the results are also provided in Table 9. Table 9 shows that the criterion of Quality has the highest overall prominence (visibility/importance/influence) in terms of the overall relationships with other criteria. Based on the weights w_i listed in Table 9, all the criteria can be prioritized as follows: Quality > T & CD > Delivery > RC > EMS=3R > O H & S > Eco-D > Cost/price > E R & W.

Based on the "Prominence" P_i and the "Relation" R_i obtained in Table 9, the impact-relation map can be drawn in Fig. 2 by mapping the dataset of the (P_i, R_i).

It can be seen from Fig. 2 that six criteria with positive "Relations" belong to the cause group and have net cause for other criteria. These cause criteria are *Quality, Delivery*, *EMS* (Environment management system), *O H & S* (Occupational health and safety), *Eco-D* (Eco-design), and *Cost/price,* respectively. On the contrary, the rest of risk factors with the negative "Relations" belong to the effect group, which are reliant on the change of the cause criteria. These effect criteria are *E R & W* (Employee right and welfare), *3 R* (Reduce, Reuse and Recycle), *RC* (Resource consumption), and *T & CD* (Training and community development). To achieve higher performance in effect group criteria, it will be critical to pay much attention to the cause group criteria in advance because of their influences on the effect group criteria.

To further explore the detailed interactions between the sustainable supplier selection criteria, it is necessary to draw a relationship digraph based on the data in Table 8. Since the numbers of relationships contain different possibilities, we only map those relationships which are over a threshold Δ. The threshold value is calculated by taking the mean and standard deviation of the values from the matrix in Table 8, then adding the one standard deviation 0.060 to the mean 0.047 to obtain the threshold value Δ=0.107. All the relationships that exceed 0.107 are included in the final interaction map in Fig. 3. It can be observed that the criterion of *Quality* obtains six dispatching arrows as the most interactive criterion, which indicates that it has a frequent and influential relation with other criteria. Besides, the *T & CD* (Training and community development) is influenced by five criteria, which makes it to be a net effect criterion. Fig. 3 also shows that *EMS* (Environment management system) has direct influences on both *3R* (Reduce, Reuse and Recycle) and *RC* (Resource consumption).

4.2. Comparisons and discussion

To further validate the effectiveness and strengths of the approach proposed in this paper, a comparative analysis is conducted with the

Table 7
The normalized rough direct-influence matrix.

	Quality	Delivery	Cost/price	…	E R & W	T & CD
Quality	[0.000,0.000]	[0.089,0.158]	[0.114,0.176]	…	[0.052,0.083]	[0.085,0.137]
Delivery	[0.004,0.008]	[0.000,0.000]	[0.054,0.121]	…	[0.037,0.071]	[0.047,0.079]
Cost/Price	[0.005,0.009]	[0.004,0.006]	[0.000,0.000]	…	[0.046,0.077]	[0.125,0.180]
EMS	[0.004,0.007]	[0.004,0.005]	[0.022,0.036]	…	[0.022,0.044]	[0.044,0.098]
RC	[0.003,0.007]	[0.002,0.006]	[0.005,0.012]	…	[0.006,0.012]	[0.031,0.038]
Eco-D	[0.009,0.013]	[0.003,0.008]	[0.014,0.033]	…	[0.009,0.016]	[0.078,0.146]
3R	[0.006,0.009]	[0.006,0.008]	[0.009,0.016]	…	[0.007,0.016]	[0.045,0.071]
O H & S	[0.008,0.021]	[0.025,0.055]	[0.022,0.044]	…	[0.090,0.154]	[0.106,0.189]
E R & W	[0.003,0.005]	[0.004,0.007]	[0.010,0.027]	…	[0.000,0.000]	[0.057,0.104]
T & CD	[0.003,0.005]	[0.004,0.007]	[0.005,0.008]	…	[0.003,0.006]	[0.000,0.000]

Table 8
The total importance-influence matrix in form of definite value.

	Quality	Delivery	Cost/price	EMS	RC	...	E R & W	T & CD
Quality	0.006	0.145	0.191	0.095	0.211	...	0.101	0.217
Delivery	0.011	0.003	0.099	0.097	0.219	...	0.071	0.122
Cost/price	0.009	0.006	0.004	0.016	0.010	...	0.066	0.189
EMS	0.009	0.007	0.032	0.005	0.148	...	0.038	0.105
RC	0.004	0.003	0.006	0.005	0.003	...	0.007	0.037
Eco-D	0.014	0.007	0.023	0.024	0.145	...	0.016	0.140
3R	0.008	0.007	0.012	0.014	0.059	...	0.011	0.064
O H & S	0.019	0.039	0.039	0.075	0.017	...	0.150	0.206
E R & W	0.004	0.005	0.015	0.010	0.005	...	0.002	0.084
T & CD	0.003	0.005	0.006	0.007	0.009	...	0.005	0.004

Table 9
The "Prominence" P_i, "Relation" R_i and weights of the criteria.

	x_i	y_j	P_i	R_i	w_i	Rank
Quality	1.232	0.088	1.320	1.144	0.157	1
Delivery	0.840	0.227	1.068	0.613	0.111	3
Cost/price	0.433	0.426	0.859	0.007	0.077	8
EMS	0.610	0.347	0.957	0.264	0.089	5
RC	0.086	0.827	0.913	−0.741	0.106	4
Eco-D	0.479	0.384	0.864	0.095	0.078	7
3R	0.197	0.674	0.872	−0.477	0.089	5
O H & S	0.635	0.118	0.753	0.516	0.082	6
E R & W	0.156	0.468	0.623	−0.312	0.063	9
T & CD	0.058	1.167	1.225	−1.109	0.148	2

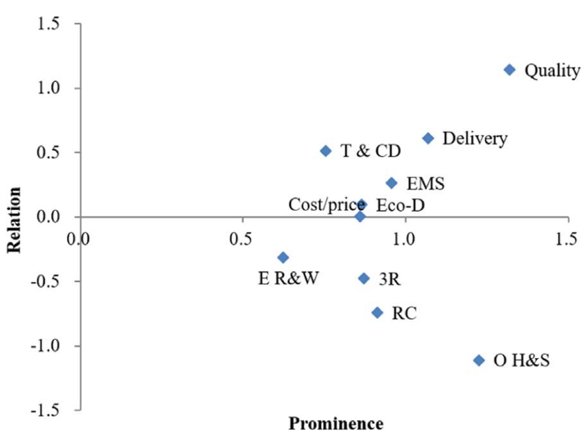

Fig. 2. Impact-relation map of the sustainable supplier selection criteria.

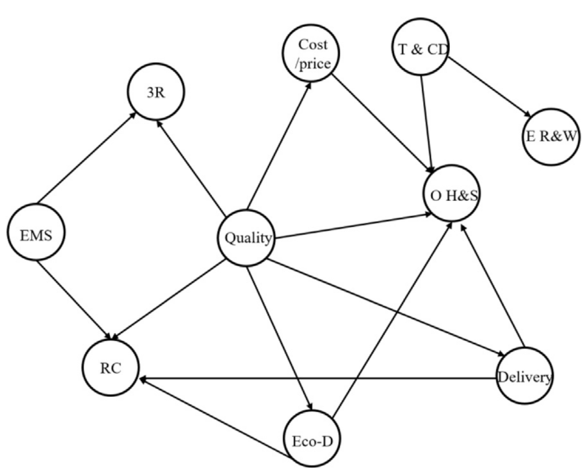

Fig. 3. Interaction map of the sustainable supplier selection criteria.

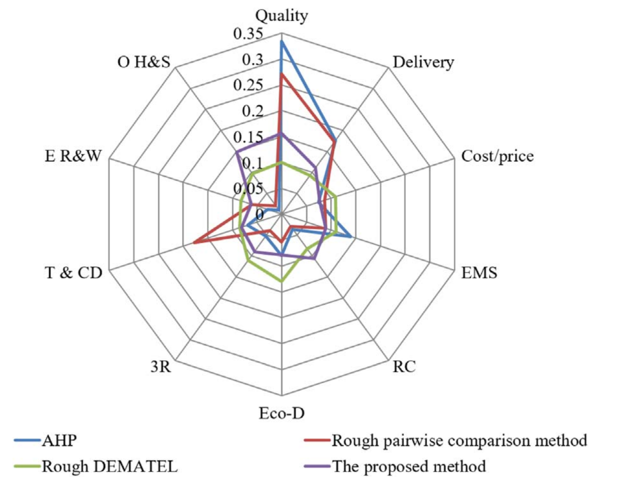

Fig. 4. Sustainable supplier selection criteria weights derived from different methods.

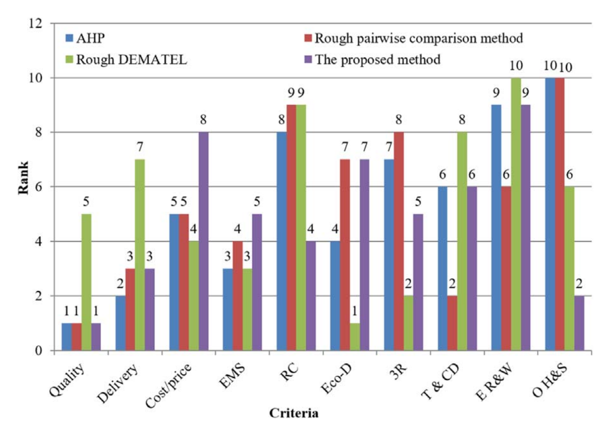

Fig. 5. Ranks of sustainable supplier selection criteria with different methods.

AHP, the rough pairwise comparison method and the rough DEMATEL. The weights and ranking orders of the ten sustainable supplier selection criteria produced by these methods are displayed in Figs. 4–5, respectively.

The first comparison is conducted with the results obtained from the AHP method. Both the AHP method and the proposed method consider *Quality* as the most important criterion (see Fig. 4). Beside, *T & CD* (Training and community development) has the same rank of 6 in the two methods. However, the rest of the criteria have different priorities in the AHP and the proposed method. For example, *Cost/price* is ranked as the 5th in the AHP, but it is ranked as the 8th in the proposed method (see Fig. 5). This difference is mainly caused by the different manipulation mechanisms of criteria relationships. The AHP method considers that the sustainable supplier selection criteria are independent with each other. However, the proposed method considers the criteria interactions as critical inputs of weight determination. Moreover, the proposed method can flexibly manipulate vagueness in the decision making process. The AHP use definite values to represent the decision makers' judgments which do not reflect the vagueness in decision making process.

The second comparison is conducted with the results obtained from the rough pairwise comparison method. As we can see from Fig. 4, the weights from the proposed method are different from those obtained with the rough pairwise comparison method, although both methods consider *Quality* as the most important criterion. Fig. 5 also shows that *T & CD* (Training and community development) is ranked the 2nd in the proposed method. However, the *T & CD* (Training and community development) is ranked the 10th in the rough pairwise comparison method. The reasons for this divergence mainly lie in the deficiencies associated with the pairwise comparison-based method, which only considers criteria importance. The rough pairwise comparison method does not consider interactions between the criteria. On the contrary, the proposed approach not only considers criteria importance, but also considers its interactions with other criteria. In this respect, the proposed approach provides more accurate information than the rough pairwise comparison method. Moreover, unlike the proposed method, the rough pairwise comparison method cannot provided the specific cause and effect analysis of the criteria.

The third comparative method is the rough DEMATEL. According to Figs. 4–5, the ranking results from the rough DEMATEL and the proposed method are different. The *Eco-D* (Eco-design), *3R* (Reduce, Reuse and Recycle), and *EMS* (Environment management system) are ranked as the top three most important criteria in the rough DEMATEL method. However, the *Eco-D* (Eco-design), *3R* (Reduce, Reuse and Recycle), and *EMS* (Environment management system) are ranked as the 7th, the 5th, and the 5th in the proposed method. This is because the proposed approach considers impact of strengths of *Eco-D* (Eco-design), *3R* (Reduce, Reuse and Recycle), and *EMS* (Environment management system) on the criteria relations. In contrast, the strengths of criteria are not included in the rough DEMATEL although it considers the interactions between different criteria.

On balance, the proposed risk evaluation framework has some evident advantages (see Table 10), which are listed below:

(1) The proposed approach simultaneously considers the criteria strength and the influence between different criteria, which does not appear in previous literature. This feature makes the result more comprehensive and reasonable. Furthermore, the cause and effect analysis based on the total importance-relation of sustainable supplier selection criteria provides more specific suggestions for managers.
(2) The proposed approach can effectively manipulate criteria evaluation data provided by multiple experts in vague linguistic context, because it uses the rough interval to capture the vagueness in criteria weighting process. It provides more meaningful information for facilitating criteria development.
(3) Different with the fuzzy method, the proposed approach does not need much prior information (e.g. fuzzy membership function, data distribution) in the decision making process. This feature makes it easy to be adopted by managers in practice.

5. Conclusions

A sustainable supplier selection framework for SSCM has been proposed in this paper. After developing the sustainable supplier selection criteria based on a systematic status review, a novel integrated method based on pairwise comparison method, DEMATEL, and rough set theory has been proposed. Then it is validated in a case study of solar air-conditioner manufacturer. The new method not only reveals the structure of interactions among the supplier selection criteria, but also help to find the critical criteria affecting the performance of sustainable supplier selection.

Based on the weights of sustainability criteria obtained from the proposed method, the managers in company G do not necessarily to take much time and effort to determine the criteria importance and explore the interrelationships between criteria. They can focus more on providing supplier score regarding the various sustainability criteria. With the obtained criteria weights, these individual perceptions can be aggregated to identify proper sustainable suppliers or sustainability deficiencies of certain suppliers. The case study results also show that *Quality, T & CD* (Training and community development) and *Delivery* are the three most important criteria. They have great impact on the sustainable supplier selection in company G. To avoid the potential risk of sustainable supplier selection, managers should not only take into account the significance of evaluation criteria as in former supplier selection approaches, but also consider the causal-effect relationships between supplier selection criteria. Companies selecting their sustainable suppliers should observe which suppliers have features of better quality, sustainable training and community development, and better delivery performance.

In sum, the proposed methodology makes several contributions to the sustainable supplier selection:

1. A novel methodology for sustainable supplier selection considering both importance and interrelationships of criteria has been developed. Even though some methods consider the interactions among criteria, they consider that the indicators are equally important in dealing with the interrelationships of criteria. The proposed methodology integrates the merits of the pairwise comparison method, the DEMATEL and the rough number. To our knowledge, no previous studies have investigated the subject of supplier selection with this kind of integrated method.
2. Decision makers express their evaluations in linguistic term in supplier selection considering the increasing complexity of the environment and time pressure. Thus, the vagueness and subjectivity is kept and well manipulated based on the flexible rough number in the proposed methodology. The proposed methodology can manipulate the vagueness and subjectivity in the supplier selection without any prior information (e.g., pre-set membership function).
3. The proposed model is applied in selecting sustainable suppliers in SSCM. Very few studies take into account the sustainable issues in the supplier selection problem, thus the characteristic of the proposed method is distinct. The necessary information, such as the critical elements affecting sustainable supplier selection and the interactions among the criteria, can help companies and suppliers discern the potential areas for further improvement. Companies can focus on supplier development with the proposed method and help

Table 10
Main differences between the proposed method and the listed methods.

Methods	Consideration of criteria importance	Consideration of criteria interaction	Cause-effect analysis	Manipulation of vagueness
AHP	Yes	No	No	No
Rough pairwise comparison	Yes	No	No	Yes
Rough DEMATEL	No	Yes	Yes	Yes
The proposed method	Yes	Yes	Yes	Yes

their suppliers improve sustainability in supply chain operations.

Even though the proposed methodology has some strengths in developing sustainable supplier selection criteria, there is still space to improve in the future. The outcome of the supplier selection model based on the integrated importance-influence analysis method is determined by managers in a solar air-conditioner manufacturer. It is beneficial to increase the number of involved companies in different industry to build a more generalized sustainable supplier selection model. In addition, application of other decision support methods (e.g., ANP, TOPSIS, and ELECTRE) will facilitate to extend the application with regard to the sustainable supplier selection. The proposed approach might be also applied to other SSCM problems in future research, such as sustainable supplier development and SSCM practice improvement.

Acknowledgments

The work described in this paper was supported by the National Natural Science Foundation of China (Grant No. 71501006). We want to add appreciation here also for the editor and the anonymous reviewers upon acceptance. This research work was supported also in part by the Specific Projects of Innovation Methods, Ministry of Science and Technology of China (Grant No. 2015IM020300) and the National Natural Science Foundation of China (Grant No. 71671125).

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