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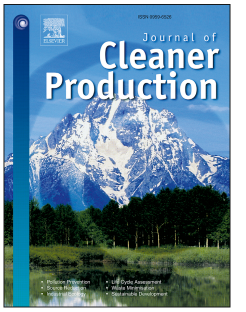

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Abstract

Sustainable supply chain management (SSCM) is gradually becoming a strategic imperative for companies. Different sources of risk factors may appear in SSCM due to its complex nature. Most of the previous studies consider less about the effect of strength of each risk factor on the interdependencies. To solve the problem, a rough weighted decision-making and trial evaluation laboratory (DEMATEL) is proposed. Both internal strength and external influence of risk factors are simultaneously considered to fully reflect the priority of risk factors. The novel approach also has merit in flexibly manipulating the vagueness and ambiguity involved in risk analysis. The applicability and effectiveness of the proposed method are validated by applying it to a company providing telecommunications products. The results show that failure to select the right suppliers is the most prominent risk factor for SSCM, because supplier selection plays an important role in achieving the social, environmental, and economic benefits of SSCM. The proposed method can be used as an effective tool to identify critical SSCM risk issues and interrelationships between different risk factors.

Keywords: Sustainable supply chain management; Risk identification; Sustainability; Strength-relation analysis; Rough numbers.

1. Introduction

Global supply chains today are increasingly exposed to stricter regulations, audits and certifications of sustainability. There is also a growing awareness of the requirement for companies to proactively build the sustainability principles into their supply chains (Su et al., 2015). Sustainable supply chain management (SSCM) has been defined as a strategic, transparent integration and achievement of social, environmental, and economic goals (Svensson and Wagner, 2015) in the systemic coordination of key business processes for improving the long-term economic performance of the individual company and its supply chains (Carter and Easton, 2011). Due to uncertainty of the global economy, increased outsourcing/offshoring activities and information technology advances, the SSCM are probably more vulnerable and exposing companies to higher level of risk (Trkman and McCormack, 2009).

Risk factor is considered as the uncertainty and unexpectedness associated with the occurrence of any event (Gurnani et al., 2012). There are different categories of risk factors faced by SSCM, such as economic risk factors, environmental risk factors, and social risk factors. The key minority of risk factors may have significant effect on the performance of SSCM. It is necessary for managers to identify the critical risk factors especially when the risk management resources are limited.

Risk checklist and risk taxonomy are two qualitative tools used in risk factor identification (Chapman, 2011). The risk checklist is a list of risk factors which are identified based on previous projects and experience of manager. The risk taxonomy provides a structure to organize the checklist of risk factors into general classes. But the two methods consider less about the interconnections of risk factors. The analytic hierarchy process (AHP)-based approaches are usually applied into the risk factor prioritization of supply chain management (Schoenherr et al., 2008). To manipulate the vague information in decision making, fuzzy AHP is utilized in risk factor ranking. Mangla et al. (2015) use fuzzy AHP to rank the risk factors associated with green supply chain practices; Viswanadham and Samvedi (2013) apply fuzzy AHP to identify performances and risk-based decision criteria of supplier selection. These AHP-based methods suffer from the same shortcomings of checklists and taxonomies, and consider less about the interconnections among supply chain risk factors.

Most of the SSCM risk factors are often correlated in practice. Environmental issues such as pollution or product waste problems can damage the company reputation, which in return will most likely decrease sales and profit, damage brand strength and cash flows. Such interrelations between SSCM risk factors may affect their priority decision making. The “hidden influences” of a certain risk factors in connection with other risk factors may cause substantial damages (Chopra and Sodhi, 2004), and the direct and indirect interrelations of risk variables may also influence all supply chain partners (Elmsalmi and Hachicha, 2013). Some researchers use the decision-making and trial evaluation laboratory (DEMATEL) method to explore the interconnections among risk factors. The DEMATEL is a practical tool to visualize the structure of complicated causal relations with direct-relation matrices or digraphs (e.g., cause and effect diagram, interaction map) which portrays a contextual relation between system elements (Fontela and Gabus, 1976). Srivastava et al. (2015) use the DEMATEL to analyze interrelationship between risk factors and performance measures for fresh food retail firms; Wu and Chang (2015) use DEMATEL to analyze critical factors in green supply chain management. These DEMATEL-based methods do not take into account the effect of each factor strength on the influences among the factors. The decision-making process of risk factor involves large amount of information and expert knowledge that are usually imprecise, subjective or even inconsistent, because decision makers use the vague verbal judgments to evaluate the internal strength of SSCM risk factors. Precise decision-making processes are not suitable to manipulate such information. To manipulate the subjective assessments of different experts, fuzzy DEMATEL method is applied to identify the interactions between supply chain risk criteria (Samvedi and Jain, 2013). The fuzzy DEMATEL is also used in other fields, e.g., municipal solid waste management (Tseng and Lin, 2009) and hotel service quality (Tseng, 2009). The fuzzy methods need priori information (e.g., pre-set fuzzy membership function). Most of the previous studies on supply chain risk management has rarely analyzed sustainability issues in supply chains (Hofmann et al., 2014), and has seldom integrated sustainability issues into the existing supply chain risk literature (Borghesi and Gaudenzi, 2012).

Although the previous work provides valuable insights into the risk factors of conventional supply chain management, Schoenherr et al. (2008) consider less on analyzing the risks in the context of SSCM. Wu and Chang (2015) explore the relations between supply chain risks, but very few studies take into account the importance of each factor which may affect the priority among the factors. The previous approaches also lack a flexible mechanism to deal with the subjective evaluations of experts and need much priori information (e.g., pre-set fuzzy membership function in fuzzy methods).

The objective of this study is to find the critical SSCM risk factors and interrelationships with a novel method of rough weighted DEMATEL. Rough number derived from the basic notion of approximations in rough set theory (Zhai et al., 2009) is also introduced to deal with the imprecise information. Internal strength of each risk factor is determined at first with the rough aggregation method to include the uncertain information in the decision making process. To represent external influences between risk factors, a direct-relation matrix in rough number form is constructed at the same time. A total strength-relation matrix that simultaneously considers the internal strength and external influence of risk factors is then developed to fully reflect the overall influence of SSCM risk factors. SSCM risk factors are finally prioritized based on the overall influence of each risk factor to obtain the critical ones. The contribution of this study includes (1) considering the strength and the influence of risk factors simultaneously in the DEMATEL to fully reflect the accurate position of risk factors, which does not appear in the previous literature; (2) using flexible rough numbers to manipulate the vagueness and subjectivity without requiring much prior information (e.g., fuzzy membership function in fuzzy methods, data distribution); and (3) understanding the relationship between SSCM risk factors to generate useful insights and actionable points, and help supply chain managers to focus on the key emerging issues of concern that may affect SSCM performance.

2. Method

Twenty SSCM risk factors are obtained in Table 1 with a systematic and extensive literature survey of supply chain risk, risk management and sustainable operations. One goal of this research is to explore the interrelationships between SSCM risk factors from the economic, social and environment perspectives (Tseng et al., 2015). The twenty SSCM risk factors are grouped into four main dimensions, namely, operational risk factors (Chopra and Sodhi, 2004), economic risk factors (Hofmann, 2011), environmental risk factors (Giannakis and Papadopoulos, 2016), and social risk factors (Giannakis and Papadopoulos, 2016). This research also expect to explore the relationships between the sustainability-related risk factors and the operational risk factors. The four types of SSCM risk factors are incorporated in the analytical framework. The details of the recognized SSCM risk factors with their sources are summarized in the Table 1. After obtaining the risk factors, an integrated approach of critical risk factor identification for SSCM is developed in the following text. A schematic diagram of the proposed method is presented in Fig. 1.

Table 1
Risk factors of SSCM.

Risk factors	Description
Operational risk factors (Chopra and Sodhi, 2004)	
RF1: Demand and supply uncertainty (Tang and Musa, 2011)	Unanticipated or inaccurate demand forecasts; uncertainty due to huge competition in the market; Underutilization and overutilization of capacities or capacity inflexibilities.
RF2: Failure to select the right suppliers (Jharkharia and Shankar, 2007)	Failure to select the suppliers with better sustainability performance on social, environmental, and economic goals.
RF3: Lower responsiveness performance (Simchi-Levi, 2010)	Failure to respond to changes in demand (volume, mix, location) quickly and at reasonable cost.
RF4: Inflexibility of supply source (Sharma and Bhat, 2014)	Inflexibility of supplier (e.g., inflexible capacity) to adapt to environment changes (e.g., demand changes) which may cause delays.
RF5: Poor quality or process yield at supply source (Tummala and Schoenherr, 2011)	Failure to identify, monitor and reduce supply chain disruptions or errors in production or delivery.
RF6: Coordination complexity/effort (Kanda and Deshmukh , 2008)	Extra coordination burden due to information distortion, different goals of SSC members, or disputes between the partners.
RF7: IT and information sharing risks (Dubey et al., 2017)	Lack of necessary IT infrastructure and mechanism to capture and disseminate timely information among chain members.
RF8: Lack of sustainable knowledge/technology (Tang and Tomlin, 2008)	Lack of sound knowledge and understanding about sustainable technology, operations and method among partners.
Economic risk factors (Hofmann, 2011)	
RF9: Volatility of price and cost (Tang and Musa, 2011)	Volatile price and cost (e.g., eco-friendly raw material price, design cost, purchase cost, source cost, and make cost), which cannot ensure timely and reliable delivery and maintain quality.
RF10: Inflation and currency exchange rates (Tummala and Schoenherr, 2011)	Inflation and variations in currency exchange rates would affect the financial concerns, and SSC effectiveness might be affected.
RF11: Market share reduction (Afgan and Carvalho, 2004)	Decrease in market share due to external or internal reasons (e.g., competition and poor quality).
RF12: Reputation loss or brand damage (Sodhi et al., 2012)	Reputation and credibility hurt of the firm, causing customers not to consider the firm as a possible source for meeting their needs.
Environmental risk factors (Giannakis and Papadopoulos, 2016)	
RF13: Natural disasters (Waters, 2011)	Rare but severe disruptions caused by natural disasters (hurricanes, flood, storms, earthquakes).
RF14: Inefficient use of resources (Diesendorf, 2007)	Inefficient resource (e.g., energy, recyclable wastes) use for the production and delivery of goods and services.
RF15: Environmental pollution (Blackburn, 2007)	Air, water, soil or other contamination due to facility operations or products.
RF16: Hazardous waste generation (Dües et al., 2013)	Unusable or unwanted substance or material produced during, or as a result of a process, such as

	manufacturing or transportation.
Social risk factors (Giannakis and Papadopoulos, 2016)	
RF17: Unhealthy/dangerous working environment (Halldórsson et al., 2009)	Working conditions under unhealthy operations in untrusting workplace/use of hazardous materials that threaten health and safety of employee.
RF18: Violation of human rights (Clift, 2003)	Behavior violating dignity of an individual or creating a degrading, e.g., hiring child and forced labor, discrimination, excessive working time beyond legal requirements.
RF19: Failure to fulfill social commitment (Maloni and Brown , 2006)	Failure to involve in local community, education, culture and technological development, job creation, healthcare, societal investment.
RF20: Violation of business ethics (Roberts, 2003)	Behavior violating business ethics, e.g., corruption, unfair-trading, and privacy invasion, etc.

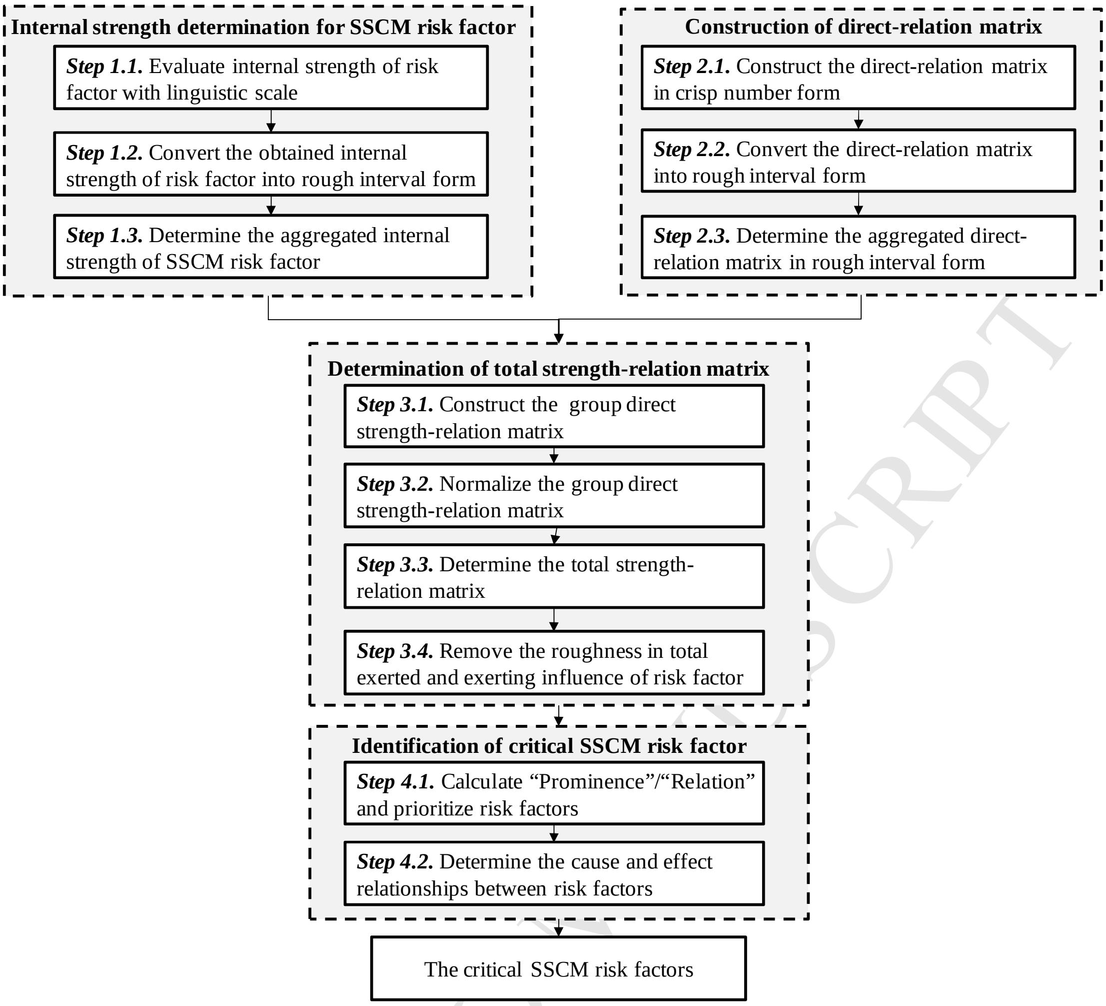


Fig. 1. The proposed critical risk factor identification approach.

2.1. Internal strength determination for SSCM risk factors

Step 1.1. Evaluate internal strength of SSCM risk factors with linguistic scale

When considering the interactions between two SSCM risk factors, the interaction not only depends on the intensity of influencing but also on the strength of the SSCM risk factors that exerts. A certain change of cost of some products which are supplied by two different suppliers may occur. One supplier is larger (higher strength), the other is smaller (lower strength). If the two suppliers react to the cost change similarly, the change in a total supply cost of the larger supplier will be much bigger than that of the smaller one. The final effect of the interactions between SSCM risk factors depends on a combination of strength of an acting factor and influence of an action.

Team members bring different perspectives to identify SSCM risk factors. Team composition becomes an important determinant of the quality of risk identification. Procurement experts, production experts, R&D experts, customer service experts, and marketing experts should be involved in the decision making process of risk identification. The decision maker can evaluate the internal strength of all the SSCM risk factors using the 5-point verbal scale in Table 2. If a decision maker considers that the internal strength between two SSCM risk factors is negligible, or the decision maker cannot assign any other linguistic term to the SSCM risk factors, the internal strength of the risk factors can be set as “No strength”.

Table 2
Linguistic terms for rating internal strength of SSCM risk factors.

No.	Linguistic terms	Corresponding scores
1	Very high strength (VHS)	4
2	High strength (HS)	3
3	Medium strength (MS)	2
4	Low strength(LS)	1
5	No strength(NS)	0

Step 1.2. Convert the internal strength of risk factors into rough interval form

After obtaining the internal strength of risk factors in linguistic form, it is represented with the crisp scores in Table 2. The crisp group judgment of *k* experts can be denoted as $S_i = \{s_i^1, s_i^2, \cdots, s_i^k, \cdots, s_i^m\}$, i=1,2,...,n, where s_i^k is the *k*th expert's assessment on the internal strength of the *i*th SSCM risk factor (RF$_i$), *m* is the number of experts, and *n* is the number of risk factors.

Assume there is a set of *m* classes of expert judgments in *J*, and the elements e_i (k=1,2,…,m) in *J* are ordered in the manner of $e_1 < e_2 < \ldots < e_k < \ldots < e_m$. *U* is the universe including all the objects and *A* is an arbitrary object of *U*, and then the lower approximation $\underline{Apr}(e_k)$ and the upper approximation $\overline{Apr}(e_k)$ can be defined (Zhai et al., 2009) as:

$$\text{Lower approximation: } \underline{Apr}(e_k) = \bigcup\{A \in U / J(A) \le e_k\}$$

$$\text{Upper approximation: } \overline{Apr}(e_k) = \bigcup\{A \in U / J(A) \ge e_k\} \tag{1}$$

The judgment e_k can be represented by a rough number defined by its lower limit $\underline{Lim}(e_k)$ and upper limit $\overline{Lim}(e_k)$ as follows (Zhai et al., 2009):

$$\underline{Lim}(e_k) = \frac{\sum_{i=1}^{N_L} x_i}{N_L}, \quad \overline{Lim}(e_k) = \frac{\sum_{i=1}^{N_U} y_i}{N_U}, \tag{2}$$

where x_i and y_i denote the elements in lower and upper approximation of e_k, respectively. N_L and N_U are the number of objects included in the lower approximation and upper approximation of e_k.

With Eqs. (1)-(2), all the elements e_i (k=1,2,…,m) in *J* can be converted into rough numbers $RN(e_k)$ as

$$RN(e_k) = [\underline{Lim}(e_k), \overline{Lim}(e_k)] = [e_k^L, e_k^U], \tag{3}$$

where e_k^L and e_k^U represent the lower limit and upper limit of rough number $RN(e_k)$, respectively. A rough number with a smaller boundary interval is interpreted as more precise one.

According to Eqs. (1)-(3), the rough number form of the *k*th expert' assessment on the *i*th SSCM risk factor (RF$_i$) strength $\tilde{s}_i^k$ can be obtained as

$$\tilde{s}_i^k = [\tilde{s}_i^{kL}, \tilde{s}_i^{kU}] \tag{4}$$

where $\tilde{s}_i^{kL}$ and $\tilde{s}_i^{kU}$ represent the lower limit and upper limit of rough number $\tilde{s}_i^k$, respectively.

The crisp group judgments of k experts $S_i = \{s_i^1, s_i^2, \cdots, s_i^k, \cdots, s_i^m\}$ (i=1,2,...,n, k=1,2,...,m) can be converted into rough number form as

$$\begin{aligned}\tilde{S}_i &= \{\tilde{s}_i^1, \tilde{s}_i^2, \cdots, \tilde{s}_i^k, \cdots, \tilde{s}_i^m\} \\ &= \{[\tilde{s}_i^{1L}, \tilde{s}_i^{1U}], [\tilde{s}_i^{2L}, \tilde{s}_i^{2U}], \cdots, [\tilde{s}_i^{kL}, \tilde{s}_i^{kU}], \cdots, [\tilde{s}_i^{mL}, \tilde{s}_i^{mU}]\}\end{aligned} \quad (5)$$

Step 1.3. Determine the aggregated internal strength of SSCM risk factors

Different decision makers in the decision team are assigned different weights in terms of their knowledge and expertise. The weights of decision makers w_k (k=1,2,...,m) can be acquired by the method of pair-wise comparison (Hafeez et al., 2002).

According to the arithmetic operations of rough numbers in Appendix A1, the rough aggregated internal strength of SSCM risk factors can be obtained as

$$\overline{S}_i = \sum_{k=1}^{m} w_k \tilde{s}_i^k = [\sum_{k=1}^{m} w_k \tilde{s}_i^{kL}, \sum_{k=1}^{m} w_k \tilde{s}_i^{kU}] \quad (6)$$

where $\sum_{k=1}^{m} w_k \tilde{s}_i^{kL}$ and $\sum_{k=1}^{m} w_k \tilde{s}_i^{kU}$ represent the lower limit and upper limit of the rough aggregated internal strength $\overline{S}_i$, respectively.

2.2. Construction of the direct-relation matrix

Step 2.1. Evaluate influence between risk factors to construct the direct-relation matrix

The m supply chain risk experts assess the direct influences between the n SSCM risk factors RF_i (i=1,2,…,n) in terms of verbal scores in Table 3. The verbal score for an influence assessment is converted into the non-negative integer from 0 to 4, according to the mapping in Table 3.

Table 3

Linguistic terms for rating direct relations between SSCM risk factors.

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

The $n \times n$ direct-relation matrix M_k of the kth expert is obtained as follows:

$$M_k = \begin{bmatrix} 0 & r_{12}^k & \cdots & r_{1n}^k \\ r_{21}^k & 0 & \cdots & r_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1}^k & r_{n2}^k & \cdots & 0 \end{bmatrix}, \quad k=1,2,\ldots,m \quad (7)$$

where r_{ij}^k represents the kth expert' assessment for the influence of the ith SSCM risk factor (RF_i) on the jth SSCM risk factor (RF_j), m is the number of experts, and n is the number of SSCM risk factors.

Note that r_{ij}^k=0, when i=j. This indicates that the ith SSCM risk factor (RF_i) cannot exert influence on its own.

Step 2.2. Convert the direct-relation matrix into rough interval form

From Step 2.1, k direct-relation matrices of SSCM risk factors are obtained. The element $\tilde{r}_{ij}$ in the group direct-relation matrix $\tilde{R}$ can then be obtained by synthesizing the element r_{ij}^k in the k direct-relation matrices sequentially. The group direct-relation matrix $\tilde{R}$ can be acquired as follows:

$$\tilde{R}=\begin{bmatrix} \tilde{0} & \tilde{r}_{12} & \dots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{0} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots & \tilde{0} \end{bmatrix} \tag{8}$$

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

Direct-relation assessment of SSCM risk factors is a complex pair-comparison decision-making process involving large amount of information and expert knowledge that are usually incomplete, imprecise, subjective or even inconsistent. The decision makers often use vague linguistic terms which are frequently expressed using such statements as “Very high influence”, “High influence”, “Low influence”, “Very low influence” and “No influence” to evaluate the interactions between different SSCM risk factors. The rough number is used here to manipulate the imprecise information.

According to Eqs. (1)-(3), the kth rough direct-relation matrix $\tilde{M}_k$ can be obtained as follows:

$$\tilde{M}_k=\begin{bmatrix} [0,0] & [r_{12}^{kL}, r_{12}^{kU}] & \dots & [r_{1n}^{kL}, r_{1n}^{kU}] \\ [r_{21}^{kL}, r_{21}^{kU}] & [0,0] & \cdots & [r_{2n}^{kL}, r_{2n}^{kU}] \\ \vdots & \vdots & \ddots & \vdots \\ [r_{n1}^{kL}, r_{n1}^{kU}] & [r_{n2}^{kL}, r_{n2}^{kU}] & \cdots & [0,0] \end{bmatrix}, \quad k=1,2,\dots,m \tag{9}$$

where r_{ij}^{kL} and r_{ij}^{kU} are the lower limit and upper limit of the rough interval form of r_{ij}^k, respectively.

Step 2.3. Determine the aggregated rough direct-relation matrix

Based on the weights of decision makers w_k (k=1,2,…,m) obtained in Step 1.3 and the arithmetic operations of rough numbers, the individual rough direct-relation matrixes $\tilde{M}_k$ are aggregated into the group rough direct-relation matrix $\tilde{M}$ as

$$\tilde{M}=\sum_{k=1}^{m}(w_k \times \tilde{M}_k)=\begin{bmatrix} [0,0] & [r_{12}^{L}, r_{12}^{U}] & \dots & [r_{1n}^{L}, r_{1n}^{U}] \\ [r_{21}^{L}, r_{21}^{U}] & [0,0] & \cdots & [r_{2n}^{L}, r_{2n}^{U}] \\ \vdots & \vdots & \ddots & \vdots \\ [r_{n1}^{L}, r_{n1}^{U}] & [r_{n2}^{L}, r_{n2}^{U}] & \cdots & [0,0] \end{bmatrix} \tag{10}$$

The aggregate rough interval $[r_{ij}^L, r_{ij}^U]$ in the group rough direct-relation matrix $\tilde{M}$ can be obtained as follows:

$$r_{ij}^L = \sum_{k=1}^{m} w_k r_{ij}^{kL}, \quad r_{ij}^U = \sum_{k=1}^{m} w_k r_{ij}^{kU} \tag{11}$$

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

2.3. Determination of the total strength-relation matrix

Step 3.1. Construct the group direct strength-relation matrix

The rough numbers representing the strength of SSCM risk factors (obtained in Step 1.3) are inserted into the principal diagonal of the group direct-relation matrix $\tilde{M}$ (obtained in Step 2.3), i.e., d_{ii} = internal strength of the risk factor RF_i. For $i \neq j$, d_{ij} = influence of the risk factor RF_i on the risk factor RF_j.

The group direct strength-relation matrix D is obtained as

$$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \tag{12}$$

where

$$d_{ij} = [d_{ij}^L, d_{ij}^U] = \begin{cases} [\sum_{k=1}^{m} w_k \tilde{s}_i^{kL}, \sum_{k=1}^{m} w_k \tilde{s}_i^{kU}], i = j, \\ [\sum_{k=1}^{m} w_k r_{ij}^{kL}, \sum_{k=1}^{m} w_k r_{ij}^{kU}], i \neq j. \end{cases}$$

Step 3.2. Normalize the group direct strength-relation matrix

After obtaining the group direct-relation matrix D, the linear scale transformation is used as a normalization formula to transform the interaction scales of SSCM risk factors into comparable scales. To ensure the existence of the total strength-relation matrix T if there are at least two positive elements in the matrix D and both are not in the same row, the normalized group direct-relation matrix C is obtained as follows:

$$C = [\tilde{u}_{ij}]_{n\times n} = \begin{bmatrix} \tilde{u}_{11} & \tilde{u}_{12} & \dots & \tilde{u}_{1n} \\ \tilde{u}_{21} & \tilde{u}_{22} & \cdots & \tilde{u}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{u}_{n1} & \tilde{u}_{n2} & \cdots & \tilde{u}_{nn} \end{bmatrix} \tag{13}$$

where $\tilde{u}_{ij} = [\frac{d_{ij}^L}{\gamma}, \frac{d_{ij}^U}{\gamma}] = [u_{ij}^L, u_{ij}^U]$, $\gamma = \max_{1\le i\le n}(\sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}^L, \sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}^U)$, u_{ij}^L and u_{ij}^U are the lower limit and upper limit of the rough number $\tilde{u}_{ij}$, respectively.

Step 3.3. Determine the total strength-relation matrix

Once obtaining the normalized group direct strength-relation matrix C, the rough numbers within this matrix can be separated into separate sub-matrices, i.e., C^L and C^U.

$$C^L = \begin{bmatrix} u_{11}^L & u_{12}^L & \dots & u_{1n}^L \\ u_{21}^L & u_{22}^L & \cdots & u_{2n}^L \\ \vdots & \vdots & \ddots & \vdots \\ u_{n1}^L & u_{n2}^L & \cdots & u_{nn}^L \end{bmatrix} \text{ and } C^U = \begin{bmatrix} u_{11}^U & u_{12}^U & \dots & u_{1n}^U \\ u_{21}^U & u_{22}^U & \cdots & u_{2n}^U \\ \vdots & \vdots & \ddots & \vdots \\ u_{n1}^U & u_{n2}^U & \cdots & u_{nn}^U \end{bmatrix}. \tag{14}$$

The total strength-relation matrix T^s (s= L, U) can be acquired according to the Theorem 1 in Appendix A2.

$$T^L = [t_{ij}^L]_{n\times n} = C^L(I - C^L)^{-1},$$
$$T^U = [t_{ij}^U]_{n\times n} = C^U(I - C^U)^{-1}. \tag{15}$$

The total strength-influence matrix T^s (s= L, U) exists, because the series in Eq. (15) converge, if at least one row sum of the matrix C elements is less than 1. This is ensured by the normalization defined in Step 3.2 (Grinstead and Snell, 2006).

The total strength-relation matrix T can be represented as

$$T = [\tilde{t}_{ij}]_{n\times n} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \tag{16}$$

where $\tilde{t}_{ij} = [t_{ij}^L, t_{ij}^U]$ is the overall influence rating for the risk factor RF$_i$ against the risk factor RF$_j$ considering the internal strength of risk factors. t_{ij}^L and t_{ij}^U are the lower limit and the upper limit of the rough interval t_{ij} in the rough total strength-relation matrix T, respectively.

Step 3.4. Remove the roughness in total exerted and exerting influence of risk factors

The sum of rows and the sum of columns of the sub-matrices T^L, T^U, denoted by the rough numbers $\tilde{x}_i$ and $\tilde{y}_i$, can be obtained as follows:

$$\tilde{x}_i = \sum_{j=1}^{n} \tilde{t}_{ij}, \quad \tilde{y}_j = \sum_{i=1}^{n} \tilde{t}_{ij}, \; i=1,2,...,n; \; j=1,2,...,n. \tag{17}$$

The sum of all elements $\tilde{x}_i$ of the ith row of the matrix T is interpreted as the total influence exerted by the risk factor RF$_i$ on all other risk factors in the system considering internal strengths. The sum of all risk factors $\tilde{y}_i$ of the jth column of the matrix T is interpreted as the total influence exerted by all other risk factors on the the risk factor RF$_j$ considering internal strengths.

To effectively determine the “Prominence” and the “Relation”, the sum of rows $\tilde{x}_i$ to the sum of columns $\tilde{y}_i$ in the total strength-relation matrix T need to be converted into the crisp forms $\tilde{x}_i^{der}$ and $\tilde{y}_i^{der}$ as follows:

(1) Normalization

$$\tilde{x}_i^L = (x_i^L - \min_i x_i^L) / \Delta_{\min}^{\max}, \quad \tilde{x}_i^U = (x_i^U - \min_i x_i^L) / \Delta_{\min}^{\max} \tag{18}$$

where $\Delta_{\min}^{\max} = \max_i x_i^U - \min_i x_i^L$, x_i^L and x_i^U are the lower limit and the upper limit of the rough number $\tilde{x}_i$, respectively; $\tilde{x}_i^L$ and $\tilde{x}_i^U$ are the normalized forms of x_i^L and x_i^U.

(2) Determination of a total normalized crisp value

$$\alpha_i = \frac{\tilde{x}_i^L \times (1 - \tilde{x}_i^L) + \tilde{x}_i^U \times \tilde{x}_i^U}{1 - \tilde{x}_i^L + \tilde{x}_i^U} \tag{19}$$

(3) Computation of the final crisp form $\tilde{x}_i^{der}$ for $\tilde{x}_i$

$$\tilde{x}_i^{der} = \min_i x_i^L + \alpha_i \Delta_{\min}^{\max} \tag{20}$$

The final crisp form $\tilde{y}_i^{der}$ for $\tilde{y}_i$ can be obtained similarly.

2.4. Identification of critical SSCM risk factors

Step 4.1. Calculate "Prominence"/"Relation" and prioritize risk factors

The vector P_i named "Prominence" is made by adding $\tilde{x}_i^{der}$ to $\tilde{y}_i^{der}$. The vector R named "Relation" is made by subtracting $\tilde{x}_i^{der}$ to $\tilde{y}_i^{der}$.

$$P_i = \tilde{x}_i^{der} + \tilde{y}_i^{der}, \quad R_i = \tilde{x}_i^{der} - \tilde{y}_i^{der}, \text{ when } i = j \tag{21}$$

The vector P_i combines the interrelations of both directions (the horizontally exerted and the vertically received influence) of the risk factor RF_i and therefore is interpreted as an overall influence intensity of that risk factor. It reveals how much importance the SSCM risk factor has. The larger the value of P_i the greater the overall prominence (visibility/importance/influence) of RF_i in terms of overall relationships with other SSCM risk factors. All the SSCM risk factors can then be prioritized based on the "Prominence".

The vector R_i shows the difference between the exerted and received influence, and it is a basis for classification of the SSCM risk factors. When the value R_i is positive, the risk factor RF_i belongs to the cause group. The risk factor RF_i is a net cause for other SSCM risk factors. If the value R_i is negative, the risk factor RF_i belongs to the effect group.

Step 4.2. Determine the cause and effect relationships between SSCM risk factors

Based on the "Prominence" P_i and the "Relation" R_i obtained in Step 4.1, the impact-relation map can be acquired by mapping the dataset of the (P_i, R_i), providing valuable insights for critical risk factor identification. In the impact-relation map, the prominence axis shows how important a criterion relative to the available set of SSCM risk factors, whereas the relation axis will divide the SSCM risk factors into cause and effect groups.

To graphically describe the interrelationships between SSCM risk factors, it is necessary to draw a relationship digraph to identify most influential relationships of risk factors based on the data in the rough total strength-relation matrix T. The rough numbers in the matrix T should be converted into crisp numbers. Eqs. (18)-(20) can be used similarly to remove the roughness of the matrix T. The crisp total strength-relation matrix T^* can then be obtained as

$$T^* = [t_{ij}]_{n\times n} = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & \cdots & t_{nn} \end{bmatrix} \tag{22}$$

where t_{ij} is the crisp form of $\tilde{t}_{ij}$.

Since the number of relationships can include all the possibilities, only those relationships that are over a threshold Δ are mapped in the interaction map. If the threshold value is too low, the map will be too complex to show the necessary information for decision-making. If the threshold value is too high, many factors will be presented as independent factors without relations to another factors. The threshold value can be calculated by Eq. (23) taking the mean $\bar{t}_{ij}$ and the standard deviation σ of the matrix T^* (Fu et al., 2012). All the relationships that exceed the threshold Δ are bolded in the matrix T^* and included in the final impact-relation map.

$$\Delta = \overline{t_{ij}} + \sigma \tag{23}$$

3. Results and discussion

3.1. Case background

To demonstrate the feasibility and effectiveness of the proposed risk factor identification method for SSCM, the method is applied into Company H providing telecommunications equipment in China. Company H is a major multinational company that manufactures and sells various telecommunications products and solutions throughout world. Due to the increased competition, exacerbating scarcity of resources, stricter regulations, and requirements of stakeholders, Company H has decided to invest resources in sustainable supply chains. The uncertainty of global economy, increased outsourcing/offshoring activities bring potential risks to SSCM of Company H. There is still lack of consensus among the managers about the importance of the risk factors. Some managers also do not know the interrelationships and the mutual influences between the risk factors, which will influence the risk mitigation priority. The proposed methodology is applied in this case study to evaluate and analyze SSCM risk factors as well as extract their interrelationships. Five managers having experience in interacting with suppliers from different functions in Company H are invited. These experts include procurement manager, production manager, R&D manager, customer service manager, and marketing manager. All the experts have more than 8 years work experience. This group of managers provides a broad supply chain (both customers and suppliers) focus with significant work experience.

In the data collection stage, the risk factors are extracted from the operational process in company and literature review. The research team then organized a focused group discussion lasting an hour to understand and validate the risk factors identified from the literature. The group experts consider that all the twenty risk factors in Table 1 are relevant for their work, and thus decide to provide the necessary inputs to be used in this research based on the twenty risk factors in Table 1.

3.2. Implementation

3.2.1. Internal strength determination for SSCM risk factors

Step 1.1. Internal strength of each SSCM risk factor is evaluated with linguistic scale

In this step, the five decision makers are invited to evaluate the internal strength of different SSCM risk factors according to Table 2. All the internal strength of risk factors are provided in form of verbal scales in Table 4.

Table 4
The internal strength of SSCM risk factors evaluated by decision makers.

	DM1	DM2	DM3	DM4	DM5
RF1	HS	MS	MS	MS	MS
RF2	HS	MS	MS	HS	MS
RF3	VHS	VHS	VHS	VHS	HS
RF4	VHS	HS	HS	MS	HS
RF5	VHS	VHS	VHS	VHS	VHS
RF6	MS	MS	MS	LS	MS
RF7	MS	MS	LS	LS	MS
RF8	HS	MS	MS	LS	LS
RF9	HS	LS	MS	HS	MS
RF10	MS	MS	LS	LS	LS
RF11	HS	VHS	HS	HS	MS
RF12	VHS	MS	MS	HS	HS
RF13	MS	MS	LS	MS	MS
RF14	VHS	VHS	VHS	VHS	HS
RF15	VHS	VHS	VHS	VHS	VHS
RF16	HS	MS	MS	LS	MS
RF17	VHS	VHS	MS	HS	HS
RF18	VHS	MS	HS	HS	HS
RF19	MS	MS	MS	MS	LS
RF20	VHS	MS	MS	MS	HS

Note: Very high strength (VHS), High strength (HS), Medium strength (MS), Low strength (LS), No strength (NS).

Step 1.2. Convert internal strength of risk factors into rough interval form

According to Table 2, all the linguistic judgments in Table 4 can be represented by the crisp scores 0-4. The evaluation set of the first risk factor RF1 can be denoted as S_1={HS,MS,MS,MS,MS}={3,2,2,2,2}. In order to manipulate the imprecise, subjective and vague linguistic decision making information in the internal strength of the risk factor, S_1 is converted into the rough interval form according to Eqs. (1)-(5) as follows:

$$\underline{Lim}(3)=\frac{2+2+2+2+3}{5}=2.2\,,\quad \overline{Lim}(3)=3\,;$$

$$\underline{Lim}(2)=\frac{2+2+2+2}{4}=2\quad,\quad \overline{Lim}(2)=\frac{2+2+2+2+3}{5}=2.2\,.$$

S_1 can then be converted into rough interval set as $\tilde{S}_1=\{[2.2,3],[2,2.2],\cdots,[2,2.2],\cdots,[2,2.2]\}$. The other rough internal strength of risk factors can be obtained similarly.

Step 1.3. Determine the aggregated internal strength of SSCM risk factor

Considering different background of the experts, the method of pair-wise comparison (Hafeez et al. 2002) is conducted to obtain their weights as w_1=0.394,w_2=0.124,w_3=0.216,w_4=0.164 and w_5=0.102. According to Eq. (6), the rough aggregated internal strength of SSCM risk factors can be obtained in Table 5.

Table 5
The rough internal strength of SSCM risk factors.

Risk factors	Internal strength of risk factor	Risk factors	Internal strength of risk factor
RF1	[2.079,2.515]	RF11	[2.705,3.318]
RF2	[2.223,2.735]	RF12	[2.448,3.415]
RF3	[3.718,3.980]	RF13	[1.627,1.957]
RF4	[2.726,3.505]	RF14	[3.718,3.980]
RF5	[4.000,4.000]	RF15	[4.000,4.000]
RF6	[1.669,1.967]	RF16	[1.726,2.505]
RF7	[1.372,1.848]	RF17	[2.799,3.694]
RF8	[1.485,2.454]	RF18	[2.755,3.515]
RF9	[1.881,2.742]	RF19	[1.718,1.980]
RF10	[1.207,1.711]	RF20	[2.262,3.244]

3.2.2. Construction of the direct-relation matrix

Step 2.1. Evaluate influence between risk factors to construct direct-relation matrix

The five supply chain risk experts assess the direct influences between the twenty SSCM risk factors (see Table 6) in the light of the verbal scores in Table 3.

Based on Table 3, the verbal scores for influence assessments in Table 6 can be converted into non-negative integers from 0 to 4. Different direct-relation matrixes M_k (k=1,2,3,4,5) of SSCM risk factors can be obtained according to Eq. (7). The direct-relation matrix provided by the first decision maker M_1 is shown in Table 7.

Table 6
The verbal scores of direct-relations between SSCM risk factors.

	RF1	RF2	...	RF19	RF20
RF1	NI,NI,NI,NI,NI	HI,VHI,HI,MI,VHI	...	MI,HI,LI,LI,NI	NI,LI,LI,NI,MI
RF2	HI,HI,MI,LI,VHI	NI,NI,NI,NI,NI	...	MI,MI,LI,MI,MI	MI,MI,LI,HI,LI
RF3	LI,NI,NI,LI,LI	NI,NI,NI,NI,NI	...	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI
RF4	LI,LI,NI,NI,NI	NI,NI,NI,NI,NI	...	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI
RF5	HI,VHI,VHI,HI,MI	NI,NI,NI,NI,NI	...	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI
RF6	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI	...	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI
RF7	MI,MI,LI,NI,NI	NI,NI,NI,NI,NI	...	NI,NI,NI,NI,NI	HI,LI,LI,LI,NI
RF8	NI,NI,NI,NI,NI	HI,MI,MI,LI,HI	...	HI,NI,LI,HI,MI	MI,LI,MI,NI,MI
...	...	...	...	...	...
RF16	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI	...	NI,NI,MI,HI,MI	MI,MI,HI,MI,LI
RF17	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI	...	MI,NI,NI,MI,LI	NI,NI,NI,NI,NI
RF18	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI	...	HI,MI,LI,MI,LI	HI,MI,MI,LI,NI
RF19	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI	...	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI
RF20	NI,NI,NI,NI,NI	MI,MI,HI,VHI,NI	...	NI,NI,NI,NI,NI	NI,NI,NI,NI,NI

Note: Very high influence (VHI), High influence (HI), Medium influence (MI), Low influence (LI), No influence (NI). Only part of direct-relations of risk factors are provided due to space limitation. The full data are provided in the supplementary materials.

Step 2.2.The direct-relation matrixes in crisp number form are converted into rough interval forms

The individual direct-relation matrixes are then synthesized sequentially to obtain a group one. Considering the uncertain information involved in the pair-comparison decision-making process of the direct-relation matrixes, the rough numbers are also used to manipulate the imprecise information. According to Eqs. (8)-(9), the rough direct-relation matrix $\tilde{M}_k$ of different expert can be obtained.

Step 2.3. According to Eqs. (10)-(11), the aggregated rough direct-relation matrix is determined based on the weights of decision makers. The group rough direct-relation matrix is provided in Table 8.

Table 7

The direct-relation matrix M_1.

	RF1	RF2	RF3	RF4	RF5	RF6	RF7	RF8	RF9	...	RF19	RF20
RF1	0	3	2	2	0	3	0	0	3	...	2	0
RF2	3	0	3	4	3	3	2	3	2	...	2	2
RF3	1	0	0	4	0	0	0	0	0	...	0	0
RF4	1	0	3	0	4	3	0	0	0	...	0	0
RF5	3	0	0	3	0	2	1	0	3	...	0	0
RF6	0	0	4	3	3	0	2	0	0	...	0	0
RF7	2	0	4	4	3	4	0	0	0	...	0	3
RF8	0	3	2	3	3	4	0	0	3	...	3	2
RF9	4	2	1	4	3	3	0	0	0	...	3	0
RF10	3	4	0	2	0	0	0	0	4	...	3	0
RF11	1	2	0	3	0	0	0	0	4	...	3	0
RF12	4	0	0	0	0	0	0	0	0	...	0	0
RF13	3	0	4	4	3	2	3	0	3	...	0	0
RF14	0	0	0	0	3	0	0	0	2	...	0	0
RF15	0	0	0	0	0	0	0	0	0	...	2	0
RF16	0	0	0	0	0	0	0	0	0	...	0	2
RF17	0	0	0	0	0	0	0	0	0	...	2	0
RF18	0	0	0	0	0	0	0	0	0	...	3	3
RF19	0	0	0	0	0	0	0	0	0	...	0	0
RF20	0	2	0	0	0	0	0	0	0	...	0	0

Note: Only part of data are provided due to space limitation. The full data are provided in the supplementary materials.

3.2.3. Determination of total strength-relation matrix

Step 3.1. Construct the group direct strength-relation matrix in rough interval form

The rough number representing the strength of SSCM risk factors in Table 5 are inserted into the principal diagonal of the group direct-relation matrix in Table 8. The group direct strength-relation matrix *D* is obtained in Table 9 according to Eq. (12).

Step 3.2. Normalize the group direct strength-relation matrix

To transform the interaction scales of SSCM risk factors into comparable scales and ensure the existence of the total strength-relation matrix *T*, the group direct-relation matrix *C* is normalized according to Eq. (13).

Step 3.3.Determine the total strength-relation matrix.

According to Eqs. (14)-(16), the total strength-relation matrix T can be obtained in Table 10. The elements in Table 10 indicate the overall influence ratings of decision makers for the risk factor RF_i against the risk factor RF_j considering their internal strengths.

Step 3.4. Remove the roughness in total exerted and exerting influence of risk factors

The sum of rows $\tilde{x}_i$ and the sum of columns $\tilde{y}_i$ of the rough total strength-relation matrix, are calculated with Eq. (17) (see Table 11). Following Eqs. (18)-(20), the roughness in $\tilde{x}_i$ and $\tilde{y}_i$ can be removed to obtain the final crisp form $\tilde{x}_i^{der}$ and $\tilde{y}_i^{der}$, which are also provided in Table 11.

Table 8
The group direct-relation matrix in the rough interval form.

	RF1	RF2	RF3	RF4	...	RF20
RF1	[0.000,0.000]	[2.678,3.564]	[0.428,1.394]	[1.884,3.236]	...	[0.252,1.104]
RF2	[1.919,3.209]	[0.000,0.000]	[2.614,3.273]	[3.198,3.698]	...	[1.390,2.273]
RF3	[0.396,0.864]	[0.000,0.000]	[0.000,0.000]	[2.896,3.748]	...	[0.000,0.000]
RF4	[0.207,0.711]	[0.000,0.000]	[2.780,3.639]	[0.000,0.000]	...	[0.000,0.000]
RF5	[2.780,3.639]	[0.000,0.000]	[0.000,0.000]	[1.262,2.244]	...	[0.000,0.000]
RF6	[0.000,0.000]	[0.000,0.000]	[2.875,3.729]	[2.412,3.366]	...	[0.000,0.000]
RF7	[0.590,1.662]	[0.000,0.000]	[2.772,3.520]	[2.543,3.708]	...	[0.851,2.061]
RF8	[0.000,0.000]	[1.822,2.699]	[1.421,2.628]	[1.657,3.291]	...	[1.059,1.871]
RF9	[2.590,3.662]	[1.812,3.107]	[0.799,2.404]	[2.448,3.415]	...	[0.102,0.890]
RF10	[2.361,3.220]	[3.409,3.873]	[0.000,0.000]	[0.772,1.520]	...	[0.000,0.000]
RF11	[1.252,2.104]	[1.063,1.885]	[0.000,0.000]	[1.881,2.787]	...	[0.000,0.000]
RF12	[2.485,3.454]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF13	[2.511,3.643]	[0.000,0.000]	[3.627,3.957]	[3.396,3.864]	...	[0.000,0.000]
RF14	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF15	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF16	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[1.728,2.387]
RF17	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF18	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[1.138,2.467]
RF19	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF20	[0.000,0.000]	[1.429,3.061]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]

Note: Only part of rough direct-relations of risk factors are provided due to space limitation. The full data are provided in the supplementary materials.

Table 9
The group direct strength-relation matrix.

	RF1	RF2	RF3	RF4	...	RF20
RF1	[2.079,2.515]	[2.678,3.564]	[0.428,1.394]	[1.884,3.236]	...	[0.252,1.104]
RF2	[1.919,3.209]	[2.223,2.735]	[2.614,3.273]	[3.198,3.698]	...	[1.390,2.273]
RF3	[0.396,0.864]	[0.000,0.000]	[3.718,3.980]	[2.896,3.748]	...	[0.000,0.000]
RF4	[0.207,0.711]	[0.000,0.000]	[2.780,3.639]	[2.726,3.505]	...	[0.000,0.000]
RF5	[2.780,3.639]	[0.000,0.000]	[0.000,0.000]	[1.262,2.244]	...	[0.000,0.000]
RF6	[0.000,0.000]	[0.000,0.000]	[2.875,3.729]	[2.412,3.366]	...	[0.000,0.000]
RF7	[0.590,1.662]	[0.000,0.000]	[2.772,3.520]	[2.543,3.708]	...	[0.851,2.061]
RF8	[0.000,0.000]	[1.822,2.699]	[1.421,2.628]	[1.657,3.291]	...	[1.059,1.871]
RF9	[2.590,3.662]	[1.812,3.107]	[0.799,2.404]	[2.448,3.415]	...	[0.102,0.890]
RF10	[2.361,3.220]	[3.409,3.873]	[0.000,0.000]	[0.772,1.520]	...	[0.000,0.000]
RF11	[1.252,2.104]	[1.063,1.885]	[0.000,0.000]	[1.881,2.787]	...	[0.000,0.000]
RF12	[2.485,3.454]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF13	[2.511,3.643]	[0.000,0.000]	[3.627,3.957]	[3.396,3.864]	...	[0.000,0.000]
RF14	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF15	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF16	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[1.728,2.387]
RF17	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF18	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[1.138,2.467]
RF19	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	[0.000,0.000]	...	[0.000,0.000]
RF20	[0.000,0.000]	[1.429,3.061]	[0.000,0.000]	[0.000,0.000]	...	[2.262,3.244]

Note: Only part of data are provided due to space limitation. The full data are provided in the supplementary materials.

Table 10
The total strength-relation matrix.

	RF1	RF2	RF3	RF4	...	RF20
RF1	[0.004, 0.005]	[0.006, 0.008]	[0.001, 0.003]	[0.004, 0.007]	...	[0.001, 0.002]
RF2	[0.004, 0.007]	[0.005, 0.006]	[0.006, 0.007]	[0.007, 0.008]	...	[0.003, 0.005]
RF3	[0.001, 0.002]	[0.000, 0.000]	[0.008, 0.008]	[0.006, 0.008]	...	[0.000, 0.000]
RF4	[0.001, 0.002]	[0.000, 0.000]	[0.006, 0.008]	[0.006, 0.008]	...	[0.000, 0.000]
RF5	[0.006, 0.008]	[0.000, 0.000]	[0.000, 0.000]	[0.003, 0.005]	...	[0.000, 0.000]
RF6	[0.000, 0.000]	[0.000, 0.000]	[0.006, 0.008]	[0.005, 0.007]	...	[0.000, 0.000]
RF7	[0.001, 0.004]	[0.000, 0.000]	[0.006, 0.008]	[0.005, 0.008]	...	[0.002, 0.004]
RF8	[0.000, 0.000]	[0.004, 0.006]	[0.003, 0.006]	[0.004, 0.007]	...	[0.002, 0.004]
RF9	[0.006, 0.008]	[0.004, 0.007]	[0.002, 0.005]	[0.005, 0.008]	...	[0.000, 0.002]
RF10	[0.005, 0.007]	[0.007, 0.008]	[0.000, 0.000]	[0.002, 0.003]	...	[0.000, 0.000]
RF11	[0.003, 0.005]	[0.002, 0.004]	[0.000, 0.000]	[0.004, 0.006]	...	[0.000, 0.000]
RF12	[0.005, 0.007]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.000, 0.000]
RF13	[0.005, 0.008]	[0.000, 0.000]	[0.008, 0.009]	[0.007, 0.009]	...	[0.000, 0.000]
RF14	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.000, 0.000]
RF15	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.000, 0.000]
RF16	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.004, 0.005]
RF17	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.000, 0.000]
RF18	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.002, 0.005]
RF19	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	[0.000, 0.000]	...	[0.000, 0.000]
RF20	[0.000, 0.000]	[0.003, 0.007]	[0.000, 0.000]	[0.000, 0.000]	...	[0.005, 0.007]

Note: Only part of data are provided due to space limitation. The full data are provided in the supplementary materials.

Table 11
The sum of rows, sum of columns, "Prominence" and "Relation".

Risk factors	$\tilde{x}_i$	$\tilde{x}_i^{der}$	$\tilde{y}_i$	$\tilde{y}_i^{der}$	P_i	R_i	Ranking
RF1	[0.036, 0.063]	0.046	[0.042, 0.064]	0.052	0.098	-0.006	7
RF2	[0.087, 0.122]	0.114	[0.031, 0.046]	0.036	0.150	0.078	1
RF3	[0.026, 0.036]	0.028	[0.046, 0.063]	0.054	0.082	-0.026	10
RF4	[0.036, 0.052]	0.041	[0.059, 0.085]	0.075	0.117	-0.034	3
RF5	[0.050, 0.071]	0.060	[0.045, 0.062]	0.053	0.113	0.006	5
RF6	[0.026, 0.038]	0.029	[0.039, 0.054]	0.045	0.074	-0.016	14
RF7	[0.034, 0.049]	0.038	[0.014, 0.026]	0.016	0.055	0.022	17
RF8	[0.073, 0.112]	0.099	[0.008, 0.011]	0.008	0.107	0.091	6
RF9	[0.046, 0.082]	0.063	[0.047, 0.067]	0.057	0.121	0.006	2
RF10	[0.029, 0.043]	0.033	[0.009, 0.011]	0.009	0.042	0.024	20
RF11	[0.021, 0.035]	0.023	[0.051, 0.082]	0.069	0.092	-0.046	9
RF12	[0.017, 0.023]	0.017	[0.072, 0.103]	0.096	0.113	-0.078	4
RF13	[0.055, 0.077]	0.066	[0.012, 0.017]	0.012	0.079	0.054	11
RF14	[0.036, 0.054]	0.042	[0.042, 0.066]	0.054	0.095	-0.012	8
RF15	[0.026, 0.034]	0.027	[0.041, 0.056]	0.048	0.075	-0.021	13
RF16	[0.028, 0.042]	0.032	[0.022, 0.035]	0.025	0.057	0.007	16
RF17	[0.020, 0.031]	0.022	[0.043, 0.064]	0.054	0.076	-0.032	12
RF18	[0.019, 0.031]	0.021	[0.031, 0.048]	0.037	0.058	-0.016	15
RF19	[0.011, 0.019]	0.012	[0.026, 0.053]	0.036	0.048	-0.025	18
RF20	[0.021, 0.034]	0.023	[0.019, 0.036]	0.023	0.046	0.000	19

3.2.4. Identification of critical SSCM risk factor

Step 4.1. Calculate the “Prominence”/“Relation” and prioritize the risk factors

To prioritize the SSCM risk factors and analyze the cause-effect relations between them, Eq. (21) is used to calculate the “Prominence”(P_i) and the “Relation” (R_i). Both P_i and R_i are provided in Table 11. Based on the value of “Prominence” and “Relation”, the impact-relation map of SSCM risk factors can be acquired by mapping the dataset of (P_i, R_i) in Fig. 2. In the impact-relation map, the prominence axis shows how important a risk factor relative to the available set of SSCM risk factors, whereas the relation axis will divide the SSCM risk factors into cause and effect groups.

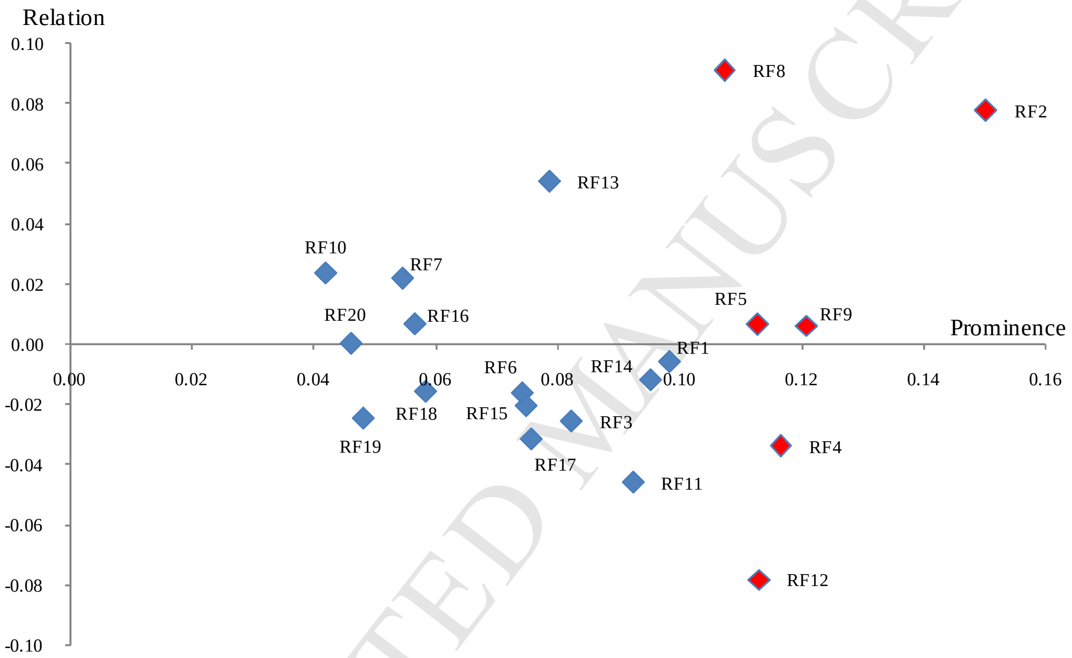


Fig. 2. The impact-relation map of SSCM risk factors.

Based on the “Prominence” P_i calculated with Eq. (21), the RF2 (Failure to select the right suppliers) has the highest prominence (visibility/importance/influence) in terms of overall relationships with other SSCM risk factors, because P_2 (0.150) is the largest one among all the P_i in Table 11. All the SSCM risk factors can be prioritized as follows：RF2＞RF9＞RF4＞RF12＞RF5＞RF8＞RF1＞RF14＞RF11＞RF3＞RF1 ＞RF17＞RF15＞RF6＞RF18＞RF16＞RF7＞RF19＞RF20＞RF10. The six most important risk factors from the above priority are RF2 (Failure to select the right suppliers), RF9 (Volatility of price and cost), RF4 (Inflexibility of supply source), RF12 (Reputation loss or brand damage), RF5 (Poor quality or process yield at supply source) and RF8 (Lack of sustainable knowledge/technology), which are shown with red diamonds in Fig. 2.

Based on the “Relation” calculated with Eq. (21), all the SSCM risk factors can be classified into cause group and effect group, as shown in Fig. 2. It can be seen from the Fig. 2 that “Relations” of eight risk factors are positive. These SSCM risk factors are RF2 (Failure to select the right suppliers), RF5 (Poor quality or process yield at supply source), RF7 (IT and information sharing risks), RF8 (Lack of sustainable knowledge/technology), RF9 (Volatility of price and cost), RF10 (Inflation and currency exchange rates), RF13 (Natural disasters), and RF16 (Hazardous waste generation). They belong to the cause group and have net cause for other SSCM risk factors. The "Relations" of the rest of risk factors are negative, and they belong to the effect group which are reliant on the change of cause SSCM risk factors.

Step 4.2. Determine the cause and effect relationships between SSCM risk factors

To further explore the detailed interactions between SSCM risk factors, it is necessary to draw a relationship digraph to identify most influential relationships of risk factors based on the data in the total strength-relation matrix. The rough numbers in the total strength-relation T are firstly converted into crisp numbers (Table 12) using Eq. (22).

Table 12

The crisp total strength-relation matrix of SSCM risk factors.

	RF1	RF2	RF3	RF4	RF5	RF6	RF7	RF8	RF9	RF10	RF11	RF12	RF13	RF14	RF15	RF16	RF17	RF18	RF19	RF20
RF1	0.0051	**0.0072**	0.0016	**0.0060**	0.0001	**0.0053**	0.0000	0.0000	**0.0065**	0.0000	**0.0057**	0.0001	0.0000	0.0039	0.0000	0.0000	0.0001	0.0044	0.0034	0.0011
RF2	**0.0061**	**0.0055**	**0.0068**	**0.0081**	**0.0069**	**0.0065**	**0.0053**	**0.0056**	**0.0061**	0.0000	0.0014	**0.0071**	**0.0062**	0.0045	**0.0054**	**0.0054**	**0.0079**	**0.0078**	0.0041	0.0041
RF3	0.0011	0.0000	**0.0085**	**0.0076**	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0066**	**0.0069**	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RF4	0.0007	0.0000	**0.0074**	**0.0072**	**0.0069**	**0.0070**	0.0000	0.0000	0.0001	0.0000	**0.0054**	**0.0070**	0.0000	0.0043	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RF5	**0.0075**	0.0001	0.0000	0.0038	**0.0086**	0.0020	0.0007	0.0000	**0.0056**	0.0000	**0.0071**	**0.0073**	0.0000	**0.0058**	0.0018	0.0048	**0.0068**	0.0001	0.0000	0.0000
RF6	0.0000	0.0000	**0.0076**	**0.0066**	**0.0054**	0.0039	0.0036	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	**0.0062**	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
RF7	0.0021	0.0000	**0.0072**	**0.0073**	0.0047	**0.0074**	0.0035	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	**0.0069**	0.0000	0.0000	0.0001	0.0000	0.0000	0.0030
RF8	0.0001	0.0050	0.0046	**0.0059**	**0.0063**	**0.0073**	0.0026	0.0045	**0.0060**	0.0000	0.0045	**0.0074**	0.0051	**0.0073**	**0.0069**	**0.0064**	**0.0054**	0.0039	0.0047	0.0031
RF9	**0.0074**	**0.0056**	0.0033	**0.0069**	**0.0070**	**0.0055**	0.0000	0.0000	0.0052	0.0000	0.0049	0.0042	0.0000	0.0041	0.0007	0.0025	0.0001	0.0041	0.0026	0.0006
RF10	**0.0064**	**0.0082**	0.0001	0.0023	0.0001	0.0001	0.0000	0.0000	**0.0080**	0.0030	0.0034	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0001	0.0049	0.0000
RF11	0.0036	0.0030	0.0000	0.0052	0.0001	0.0001	0.0000	0.0000	**0.0060**	0.0000	**0.0068**	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0030	0.0000
RF12	0.0068	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	**0.0076**	**0.0067**	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RF13	**0.0073**	0.0001	**0.0085**	**0.0084**	0.0038	0.0026	**0.0053**	0.0000	**0.0068**	**0.0073**	0.0040	0.0002	0.0038	0.0001	**0.0062**	0.0000	0.0041	0.0000	0.0001	0.0000
RF14	0.0000	0.0000	0.0000	0.0000	0.0032	0.0000	0.0000	0.0000	**0.0053**	0.0000	0.0001	0.0040	0.0000	**0.0085**	0.0051	**0.0056**	**0.0076**	**0.0068**	0.0000	0.0000
RF15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0051	**0.0073**	0.0000	0.0000	**0.0085**	0.0000	0.0048	0.0000	0.0051	0.0000
RF16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	**0.0075**	0.0000	0.0037	**0.0082**	0.0047	0.0050	0.0000	0.0026	0.0045
RF17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	**0.0073**	0.0000	0.0000	**0.0064**	0.0000	**0.0075**	0.0035	0.0023	0.0000
RF18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0068**	0.0000	0.0000	0.0000	0.0000	0.0042	0.0071	0.0045	0.0039
RF19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0069**	0.0000	0.0000	0.0000	0.0000	0.0019	0.0022	0.0040	0.0000
RF20	0.0001	0.0050	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0038	0.0000	**0.0061**	**0.0068**	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0064**

Notes: the bold numbers indicates the relationships that exceed the threshold 0.0052.

According to Eq. (23), the threshold value of the total strength-relation is calculated as Δ=0.0052by taking the mean 0.0023 and standard deviation 0.0029 from the matrix *T* in Table 12. All the relationships that exceed the threshold 0.0052 (see the bold numbers in Table 12) are included in the final interaction map in Fig. 3. The top five critical relations between risk factors are RF13 (Natural disasters)→RF3 (Lower responsiveness performance), RF13 (Natural disasters)→RF4 (Inflexibility of supply source), RF10 (Inflation and currency exchange rates)→RF2 (Failure to select the right suppliers), RF16 (Hazardous waste generation) → RF15(Environmental pollution), RF2 (Failure to select the right suppliers)→RF4 (Inflexibility of supply source).

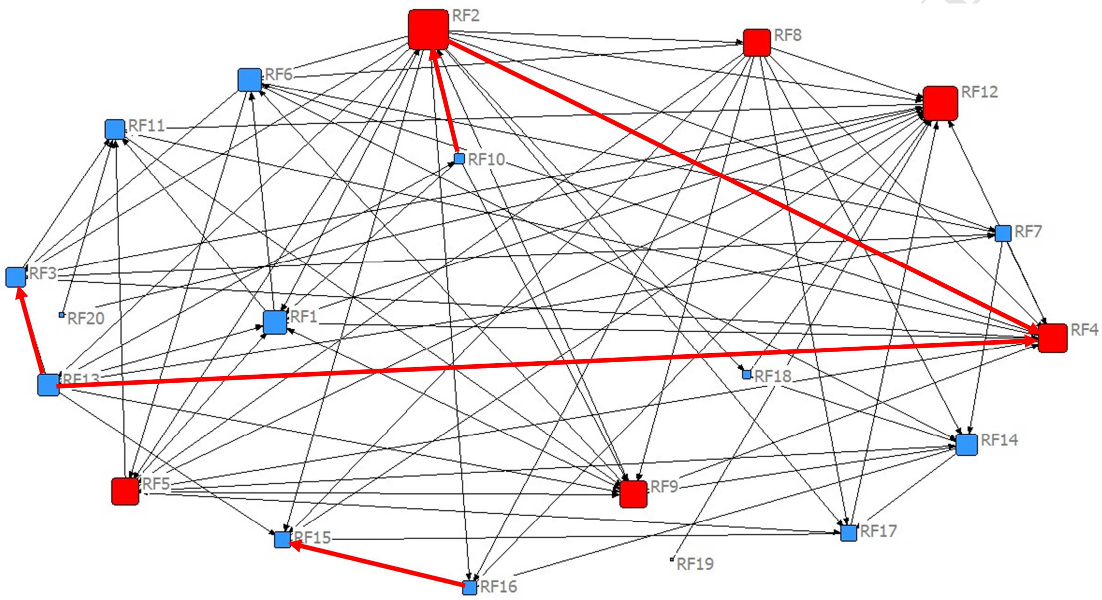


Fig. 3. The interaction map of SSCM risk factors.
Note: Red squares in Fig. 3 represent the top six important risk factor; Red bold arrows represent the top five critical relations between risk factors; the size of square denotes the relation intensity of the risk factor with others.

3.3. Comparisons and discussion

To validate the effectiveness and strengths of the approach proposed in this paper, a comparative analysis is conducted to solve the same problem. The comparative methods include the AHP-based method (Schoenherr et al., 2008), the DEMATEL-based method (Wu and Chang, 2015), and the fuzzy DEMATEL-based method (Samvedi and Jain, 2013). The ranking orders of the twenty risk factors produced by these methods are shown in Table 13. Fig. 4 is a pictorial representation and comparison of the ranking of different methods, and Fig. 5 provides comparisons of the top ten critical relations in different methods. There are some differences between the ranking orders derived from the four methods.

Table 13
Comparison analysis of the ranking results of risk factors.

Risk factors	AHP		DEMATEL		Fuzzy DEMATEL		The proposed method	
	Importance	Ranking	P_i	Ranking	P_i	Ranking	P_i	Ranking
RF1	0.040	11	1.460	4	0.534	7	0.098	7
RF2	0.098	2	1.989	1	0.860	1	0.150	1
RF3	0.053	10	1.001	12	0.370	12	0.082	10
RF4	0.039	12	1.480	3	0.590	5	0.117	3
RF5	0.099	1	1.416	6	0.535	6	0.113	5
RF6	0.017	17	1.068	11	0.381	11	0.074	14
RF7	0.015	18	0.772	15	0.251	16	0.055	17
RF8	0.071	4	1.396	7	0.595	4	0.107	6
RF9	0.070	5	1.659	2	0.654	2	0.121	2
RF10	0.015	19	0.671	18	0.213	19	0.042	20
RF11	0.035	13	1.299	8	0.478	8	0.092	9
RF12	0.057	9	1.429	5	0.611	3	0.113	4
RF13	0.065	6	1.077	10	0.407	10	0.079	11
RF14	0.033	14	1.174	9	0.434	9	0.095	8
RF15	0.065	7	0.823	14	0.301	14	0.075	13
RF16	0.033	15	0.753	16	0.255	15	0.057	16
RF17	0.057	8	0.911	13	0.345	13	0.076	12
RF18	0.098	3	0.717	17	0.237	17	0.058	15
RF19	0.014	20	0.646	20	0.217	18	0.048	18
RF20	0.026	16	0.659	19	0.193	20	0.046	19

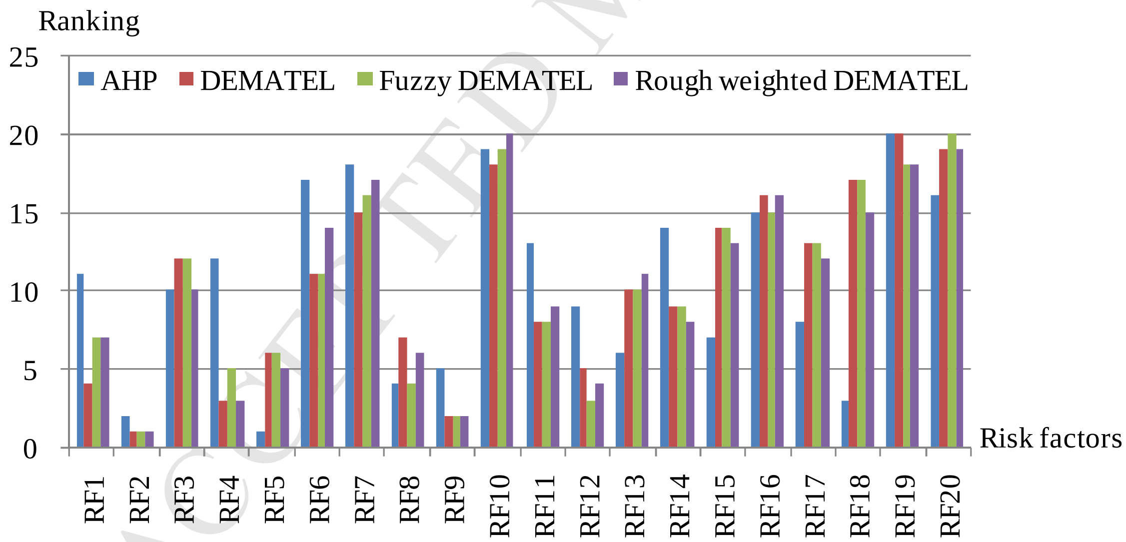
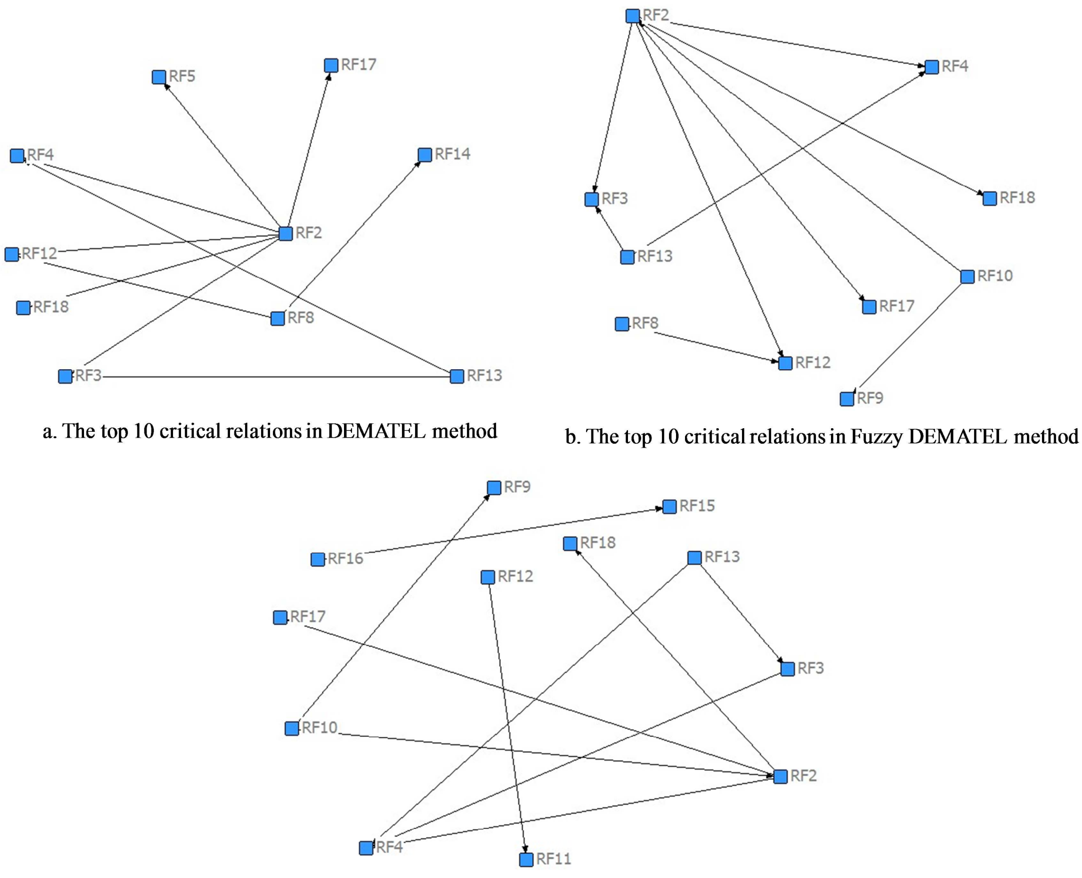


Fig. 4. Comparative ranking of the critical factor identification methods.



a. The top 10 critical relations in DEMATEL method

b. The top 10 critical relations in Fuzzy DEMATEL method

c. The top 10 critical relations in the method of rough weighted DEMATEL

Fig. 5. Comparative ranking of the top ten critical relations in different methods.

The first comparison is conducted with the result obtained from the AHP-based method. As can be seen from Table 13, except for RF3 (Lower responsiveness performance), the ranking orders of other risk factors determined by the rough weighted DEMATEL are different from those obtained with the AHP method. The reasons for this divergence mainly lie in the deficiencies associated with the AHP method, which only considers the risk factor strength in the risk identification process. The AHP method does not integrate the influence into its analysis framework. RF18 (Violation of human rights) ranks the third in the AHP method, because most of the decision makers only consider that this risk factor will cause serious consequence. The proposed rough weighted DEMATEL not only considers the strength of RF18, but also considers its interactions with other risk factors. The total influence of RF18 (excreted and received influence) is 0.067 which is lower than most of the risk factors. The proposed method provides a relative lower rank order of 15 for the RF18. Unlike the rough weighted DEMATEL, the AHP method cannot provided specific cause and effect analysis of SSCM risk factors.

The second comparative method is the crisp DEMATEL method. According to Table 13 and Fig. 4, the ranking results from the DEMATEL and the proposed method are different except for RF2, RF4, RF9, and RF20. The critical relations of risk factors in DEMATEL and the proposed method are also different. The influence of RF10 on

RF2 (RF10→RF2) is considered as one of the most critical relations in the rough weighted DEMATEL (Fig. 5c). This relation does not appear in the crisp DEMATEL method as one of the most critical relations (Fig. 5a). This is because the proposed method considers impact of strengths of the risk factors RF10 and RF2 ([1.207, 1.711] and [2.223, 2.735]) on the relation RF10→RF2. The strength of RF10 and RF2 are not included in the DEMATEL although it considers the interactions between risk factors. The proposed method also has mechanism of manipulating uncertainty in the risk decision making process. The risk factor decision making information is converted into rough number which considers the uncertainty in the verbal judgments of experts. The five experts provide their judgments on the relation between RF2 and RF1 as {HI,HI,MI,LI,VHI}. The rough weighted DEMATEL then converts such verbal scores into [2.250,3.333], [2.250,3.333], [1.500,3.000], [1.000,2.600] and [2.600,4.000], which considers the vagueness of decision making information. The DEMATEL only represents the verbal judgments {HI,HI,MI,LI,VHI} into crisp scores 3,3,2,1, and 4. Thus, in risk identification decision-making, the rough weighted DEMATEL can provide more valuable information than the crisp DEMATEL method.

The third comparison is conducted with the result obtained from the fuzzy DEMATEL method. Using the fuzzy DEMATEL method, the obtained ranking results are presented in Table 13 and Fig. 4. There are some degree of similarity between the ranking result of the proposed method and the ranking result produced by the fuzzy DEMATEL. Some risk factors even have the same ranking orders, e.g., RF2, RF9, and RF19. This is because both the rough weighted DEMATEL and the fuzzy DEMATEL have mechanisms of manipulating uncertainty in decision making. The proposed method uses the rough numbers, while the fuzzy DEMATEL uses the fuzzy numbers based on the fuzzy set theory. The rough weighted DEMATEL is more flexible in dealing with the uncertain decision making information. When evaluating influence of risk factors, five decision makers provide their judgments as {3,3,2,2,1}. The proposed method converts this judgment set into {[2.200,3.000], [2.200,3.000], [1.667,2.500], [1.667,2.500], [1.000,2.200]},and aggregates the rough intervals into [1.875,2.729]. While the fuzzy DEMATEL converts this judgment set into {[2,4], [2,4], [1,3], [1,3], [0,2]}, and aggregates the interval numbers into [1.2,3.2] with fixed interval of 2. When the original scores {3,3,2,2,1}change into {2,2,2,1,1}, the rough approach converts this judgment set into {[1.600,2.000], [1.600,2.000], [1.600,2.000], [1.000,1.600], [1.000,1.600]},and aggregates the rough intervals into [1.441,1.894]. The fuzzy DEMATEL converts new judgment set into {[1,3], [1,3], [1,3], [0,2], [0,2]}, and aggregates the rough numbers into [0.6,2.6] with fixed interval of 2 which does not reflect judgments changes in uncertainty. This is caused by the pre-set fuzzy membership function in fuzzy DEMATEL. The rough weighted DEMATEL is more flexible and reasonable than the fuzzy DEMATEL. The fuzzy DEMATEL does not consider the strength of the risk factor in the total relation decision making process. This causes some differences of the critical relations identified in the two methods. The relation “RF16→RF15” and “RF12→RF11” are considered as critical risk factor relations (shown in Fig. 5c), while they are not identified as the critical ones in the fuzzy DEMATEL (shown in Fig. 5b).

A qualitative comparison between the proposed rough weighted DEMATEL and the previous methods is summarized in Table 14.

Table 14
Main differences between the rough weighted DEMATEL and the listed methods.

Methods	Consideration of risk factor strength	Consideration of risk factor influence	Cause and effect analysis	Manipulation of uncertainty	Reliance on much prior information	Flexibility
AHP	Yes	No	No	No	No	Low
DEMATEL	No	Yes	Yes	No	No	Low
Fuzzy DEMATEL	No	Yes	Yes	Partial	Yes	Low
The rough weighted DEMATEL	Yes	Yes	Yes	Yes	No	High

4. Theoretical and practical implications

The results of risk factor identification provide significant insights into the theory and practice, thereby contributing to the risk management in the field of SSCM. Based on such insights, supply chain managers can take specific measures to assess, control and mitigate the identified SSCM risk factors.

From the theoretical perspective, this study develops a SSCM risk factor identification method simultaneously considering the strength and influence of risk factors. This research fills the gap of identifying sustainability risk factors (Borghesi and Gaudenzi, 2012) and SSCM risk factor interrelationships (Elmsalmi and Hachicha, 2013). In the reality, many managers consider less about the interrelationships of SSCM risk factors. The proposed method may help to understand the mechanism of interactions between risk factors. With such a decision-making tool, a SSCM can become truly “pro-active” (Pagell and Wu, 2009), because it can support planning the direction of risk management in advance by determining how SSCM risk factors influence each other. The proposed rough weighted DEMATEL can also describe the interdependencies between SSCM risk factors comprehensively, because it considers the effect of risk factor strength on the interdependencies, which does not appear in the previous literature. The proposed approach can help supply chain managers to make environmentally and financially reasonable decisions. This study provides a methodological contribution to the SSCM literature. The proposed method can also facilitate to create awareness of SSCM risk. The involvement of managers from different functions is essential in establishing a thorough consideration of critical risk issues and interrelationships when determining a complete risk analysis and priority (Lin and Tseng, 2016).

Several practical implications can also be derived as follows. Firstly, the most critical risk factor is “Failure to select the right suppliers” (RF2) in SSCM, i.e., failing to select suppliers with stronger sustainability performance on social, environmental, and economic goals. “Failure to select the right suppliers” can affect the environmental concerns and social aspects of SSCM, because supplier selection plays an important role in achieving the "triple bottom line" of social, environmental, and economic benefits (Govindan et al., 2013). The managers should stress requirements of supplier assessment to achieve higher quality of supplier selection in order to control SSCM risks. It is also necessary to strengthen supervision and training of suppliers. The major objective in such cases is selecting the right supplier and ensure the sustainable process and results of the whole chain. Secondly, managers should pay attention to the risk factor of "Inflexibility of supply source" (RF4), because it can lead to changes of other risk factors even though it is a net receivers. The inflexibility of supply source can generate risks especially to the individual production company and the sustainability of the whole sustainable supply chain (Mulhall and Bryson, 2014). It is necessary for the company to manipulate inflexibility of supply source by collaborating with multiple suppliers and adopting flexible supply contracts. Finally, if company wants to acquire high performance of risk management for the "effect risk factors", it would control the "cause risk factors" beforehand. If the company expect to control the risk factor of "Inflexibility of supply source" (RF4), it would be necessary to pay attention to the risk factor of "Failure to select the right suppliers" (RF2). This is because the "Failure to select the right suppliers" is the influenced risk factor and can be improved, while the "Inflexibility of supply source" is the influencing risk factor and can dispatch influences. Supply chain managers must be aware of such relationships to control and mitigate the risk factors for the success of SSCM. The risk factor of "Environmental pollution" (RF15) can also be improved by controlling the risk factor of "Hazardous waste generation" (RF16), because the former belong to the "effect risk factor" and the latter is the "cause risk factor". Supply chain managers must assess the practice of monitoring of the hazardous waste generation in environmental performance evaluation of suppliers. The company should also avoid or reduce using hazardous substances in products and/or production, and collaborate with suppliers for cleaner production or lean production (Vanalle and Santos, 2014).

5. Conclusions and suggestions

To identify the critical risk factors of SSCM, an approach based on rough logic and the DEMATEL method was developed in this paper. The scientific and practical value of this study are as follows: The proposed rough weighted DEMATEL can simultaneously consider the internal strength and external influences of SSCM risk factors. This feature provides more detailed information for risk decision making and makes the ranking results more accurate. The proposed method can also effectively manipulate the vague and subjective information with the flexible rough intervals which indicates the uncertainty in judgments. Different from the fuzzy methods, the rough weighted DEMATEL does not need much prior information (e.g., fuzzy membership function, data distribution) in decision making process, which makes it easy to be adopted by managers in practice. For practitioners, the proposed rough weighted DEMATEL can help to understand the relationships between SSCM risk factors to generate useful insights and actionable measures. It also helps supply chain managers to focus on the key emerging risk issues that may affect SSCM performance.

Even with research and managerial insights provided by the rough weighted DEMATEL, there are still some limitations. One limitation is that the evaluations of the internal strength of the risk factors are based on the overall judgments of experts, which may increase the difficulty of decision making. In future research, the internal strength can be specifically determined by considering the probabilities of occurrences of the risk factors and their impacts on SSCM performance. The relations between risk factors in the proposed methodology are not differentiated into positive influences and negative influences. Different kinds of influences will be integrated in the methodology proposed in this paper to make it more accurate in risk factor analysis. Finally, further applications in various companies and industry sectors would be also helpful to compare different cases and findings.

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Appendix 1. If $RN_1 = \lceil L_1, \ U_1 \rfloor$ and $RN_2 = \lceil L_2, \ U_2 \rfloor$ are two rough numbers, where L_1 and L_2 are their lower limits, and U_1 and U_2 are their upper limits, then the arithmetic operations of rough number are as follows (Zhai et al., 2009).

$RN_1+RN_2=\lceil L_1, U_1\rfloor+\lceil L_2, U_2\rfloor=\lceil L_1+L_2, U_1+U_2\rfloor$

$RN1\times k=\lceil L_1, U_1\rfloor\times k=\lceil kL_1, kU_1\rfloor$, $RN_2\times k=\lceil L_2, U_2\rfloor\times k=\lceil kL_2, kU_2\rfloor$,

where k is a nonzero constant, and

$RN_1\times RN_2=\lceil L_1, U_1\rfloor\times\lceil L_2, U_2\rfloor=\lceil L_1\times L_2, U_1\times U_2\rfloor$.

Appendix 2. 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 ($s= L, U$),

$\lim_{\alpha\to\infty}(C^s)^\alpha = O$ (Papoulis and Pillai, 2002). Then,

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

$\forall$ $s= L, U$, where O is the null matrix and I is the identity matrix. □

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Highlights

- ✧ A listing of risk factors for sustainable supply chain management (SSCM) is described.
- ✧ A new method to identify interdependencies of SSCM risk factors is developed.
- ✧ The method simultaneously considers the internal strength and external influence of risk factor.
- ✧ The proposed method is applied to a telecommunications provider in China.
- ✧ The application results show critical risk factors and key relations between them.