A Combined Fuzzy Decision Making Approach to Supply Chain Risk Assessment

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Abstract—Many firms implemented various initiatives such as outsourced manufacturing which could make a supply chain (SC) more vulnerable to various types of disruptions. So managing risk has become a critical component of SC management. Different types of SC vulnerability management methodologies have been proposed for managing SC risk, most offer only point-based solutions that deal with a limited set of risks. This research aims to reinforce SC risk management by proposing an integrated approach. SC risks are identified and a risk index classification structure is created. Then we develop a SC risk assessment approach based on the analytic network process (ANP) and the VIKOR methods under the fuzzy environment where the vagueness and subjectivity are handled with linguistic terms parameterized by triangular fuzzy numbers. By using FANP, risks weights are calculated and then inserted to the FVIKOR to rank the SC members and find the most risky partner.

I. INTRODUCTION

MANAGING risk in supply chains has emerged as an important topic in supply chain management. The topic derives its importance due to several industry trends currently in place: increase in strategic outsourcing by firms, globalizations of markets, increasing reliance on suppliers for specialized capabilities and innovation, reliance on supply networks for competitive advantage, and emergence of information technologies that make it possible to control and coordinate extended supply chains. These trends have manifested themselves in an increase in outsourcing and off-shoring of manufacturing and R&D activities, low cost country (LCC) sourcing, and collaboration with international supplier partners [20]-[32]. While these increase the strategic options for firms, they also increase the probability of experiencing adverse events in supply chains that significantly threaten normal business operations of firms in the supply chains. Along with the increase in these initiatives, there has been an increase in the potential and magnitude of supply chain risks [4]. Recent events involving food supply chains (for example, Melamine in infant formula and powdered milk

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sourced from China) underscore risks of extended supply chains. Supply chain disruptions can also adversely affect the financial performance of firms.

The study by Hendricks and Singhal [21] showed how media announcements of supply chain disruptions can affect stock price and shareholder value. Supply chain risks, their impact and management are receiving much attention among practitioners and academicians alike. So supply chain risk management has become as an important area of investigation in operations and supply chain management.

Supply chain risk management (SCRM) can be viewed as a strategic management activity in firms given that it can affect operational, market and financial performance of firms. Organizational efficiency and performance are enhanced when strategy to reduce uncertainty takes into account ''context'' and ''environmental realities'' [18]. In the case of SCRM, context can be interpreted to refer to sources of risk, magnitude of risk and its relationship to business objectives, and threat of disruption in supply chains. Environmental realities can be interpreted to mean the degree of exposure to adverse events, scope of extended supply chains, supplier management practices, etc. Therefore, the essence of SCRM is to make decisions that optimally align organizational processes and decisions to exploit opportunities while simultaneously minimizing risk [37]-[61]. Supply chain disruptions can ''materialize'' either inside or outside a supply chain. As Wagner and Bode [62] point out, ''the financial default of a supplier and an earthquake that destroys production capacity are situations with completely different attributes and therefore have different effects on the supply chain''. This observation points to the need for effective methodology for anticipating, identifying, classifying and assessing risks in supply chains.

Since Bellman and Zadeh [3] developed the theory of decision behavior in a fuzzy environment, various relevant models were developed, and have been applied to different fields such as control engineering, artificial intelligence, management science, and Multiple Criteria Decision Making (MCDM) among others. The concept of combining the fuzzy theory and MCDM is referred to as fuzzy MCDM (FMCDM). Several practicable applications of utilizing FMCDM in criteria evaluation and alternatives selection are demonstrated in previous studies [2]-[6]-[10]-[11]-[24]-[31]-[44]-[63]-[66]. Primarily, the MCDM problems are first classified into distinct aspects and different alternatives/strategies and the criteria are defined based on various points of view from

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stakeholders. Then, a finite set of alternatives/strategies can be evaluated in terms of multi-criteria. Choosing a suitable method to measure the criteria can help the evaluators and analysts to process the cases to be evaluated and determine the best alternative. Like most cases of evaluation, a number of criteria have to be considered for performance appraisal [65]. Consequently, supply chain risk assessment can be regarded as a MCDM problem. In this research, a FMCDM approach was proposed to establish a risk evaluation model for supply chains.

The aims of this research are as follows: (1) enumerate risk factors through a review of the literature and industry interviews; (2) build the risk evaluation indexes system for supply chain; (3) use FANP (Fuzzy Analytic Network Process) to find the fuzzy weights of the indexes by subjective perception; (4) apply FVIKOR (Fuzzy VIšekriterijumsko KOmpromisno Rangiranje) to rank supply chain members; and (5) provide suggestions based on the research results for supply chain risk assessment and serve as a reference for future research in this field.

The rest of this paper is organized as follows. In section II, some of the prior literature related to Supply chain risk management is reviewed. In section III, the proposed method is developed. In section IV, an empirical study is illustrated. Finally, according to the findings of this research, conclusions and suggestions are presented.

II. SUPPLY CHAIN RISK MANAGEMENT

Since the mid-eighties the supply chain management concept has been discussed intensively in practice and within the scientific community.

However, besides enjoying successes, the supply chain management approach also faces new challenges [1]-[28]. The occurrence of new risks such as uncertain demand, the increasing vulnerability of supply chains due to trends such as globalization, saturation of markets or terrorist attacks have forced companies to establish new concepts for risk assessment. It is therefore necessary to define a "manageable" security/risk level which is ultimately a socalled trade-off between supply chain costs, security and performance (e.g. taking on responsibility in the case of disruptions in supply chains). Thus the supply chain management concept has to be enhanced by methods of complexity and risk management. Fig. 1 illustrates the trade-off between supply chain costs and supply chain security.
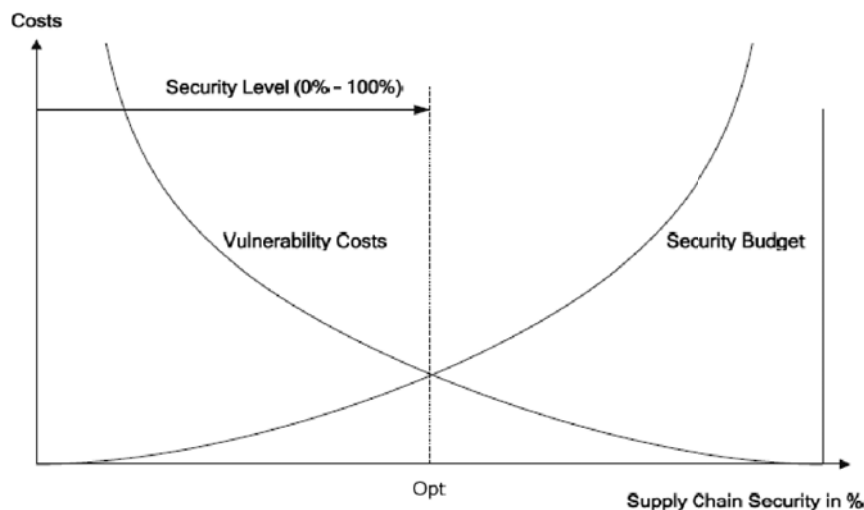

Fig. 1 The trade-off between supply chain security, vulnerability and costs [55]

In recent years, the notion of the term "risk" has been given greater attention in research on supply chain management both by academics and practitioners. It is worth mentioning that 100% security or a 0% probability of risk occurrence is not possible in real-life supply chain scenarios. The goal is to determine a "manageable" security/risk level (denoted point *Opt* in Fig. 1).

The definition of the term "risk" strongly depends on the context and field of research involved [54]. An operational definition in the context of supply chain risk management is as follows: *"Risk is the product of the probability of occurrence of a (negative) event and the resulting amount of damage"*. [30]-[35].

Risks within supply chains can be categorized into supply, process, demand, control and environmental risks in accordance with the SCOR (= Supply Chain Operation Reference) model processes *plan, source, make* and *deliver* developed by the non-profit organization SCC (Supply Chain Council) (cf. Fig. 2).

The above-mentioned types of risks, risk drivers and their impacts are categorized in Table I [12]-[26]-[60].

Kersten et al. [30] define supply chain risk management as *"a concept of Supply Chain Management, which contains all strategies and measures, all knowledge, all institutions, all processes and all technologies, which can be used on the*

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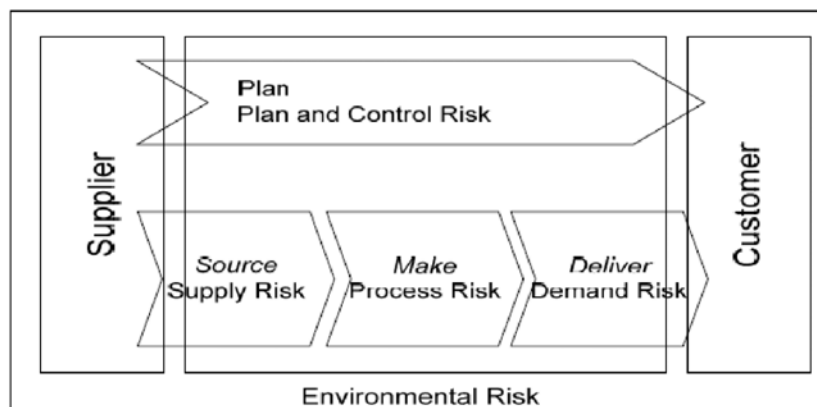*technical, personal and organizational level to reduce supply chain risk"* [30].

Fig. 2 Categories of risks in supply chains [30]

TABLE I
CATEGORIES OF SUPPLY CHAIN RISKS FROM THE LITERATURE

Risk category	Risk driver	Risk impact
Plan and control risk	- Applied methods, concepts and tools - IT systems (breakdown, introduction or change of IT systems, virus damage, change of interfaces, data loss)	- Opportunity costs - Cost of capital - Logistics costs
Supply risk	- Quality of material - Suppliers (failure, single sourcing, adherence to delivery dates) - Supplier dependence - Global sourcing - Supplier concentration - Supply market - Damage to cargo - Monopoly situations (single sourcing) - New strategic alignment of suppliers - Illiquidity and insolvency of suppliers	- Production stop - Replacement purchase costs - Supply interruptions
Process risk	- Lead times - Capacity bottleneck - Output - Quality - Machine damage - Human error - Faulty planning - Trouble with third-party logistics provider - Major technological change	- Supply difficulties - Repair costs
Demand risk	- Demand fluctuations - Changes in preferences - Cancellations - Planning and communication flaws in sales department - Inflexibility	- Supply difficulties - Safety stock (Bullwhip effect)
Environmental risk	- Natural disasters (fire, earthquake, flood, rock fall, landslide, avalanche, etc.) - Weather (iciness, storm, heat) - Political instability (strike, taxes, war, terrorist attacks, embargo, political labor conflicts, industrial disputes) - Import or export controls - Social and cultural grievances - Crime - Price and currency risks/inflation	- Opportunity costs - Replacement costs

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As illustrated in Fig. 3, rigorous supply chain risk management is a cyclic process encompassing the following six phases [19]-[22]-[26]-[27]-[29]-[46]:

1) **Formulation/Revision of Risk Strategy**: In this phase a risk strategy is defined that needs to be aligned with companies' corporate strategy. The risk strategy determines the risk management processes as well as the organizational structure and technological infrastructure. The risk strategy profile is based on past experiences and the estimation of future risks that may occur.

2) **Risk Identification & Monitoring:** This phase includes the identification of stakeholders and objectives to create initial awareness of potential supply chain risks as well as the continuous monitoring of supply chain processes to anticipate disruptions before they occur [52].

3) **Risk Analysis, Prioritization and Assessment:** This phase requires the assessment, prioritization and monetization of risks in order to make them more operational for basing decisions on. Risk analysis and prioritization by risk impact, probability, risk level and other criteria, help us focus on the most critical supply chain risks.

4) **Risk Response and Action Planning & Scheduling**: This phase includes risk action planning and scheduling in order to react adequately to disruptions. The risks to be monitored will be assigned with the appropriate handling options (e.g. avoidance, transfer, prevention, acceptance or mitigation) [39].

5) **Risk Controlling:** This phase includes status reporting on the execution of risk action plans as well as risk tracking and tracing in terms of probability, impact and other risk metrics. The progress of the risk situation in their respective risk action plans is analyzed.

6) **Comparison of Risk Situation and Risk Strategy**: Learning from previous disruptions plays an important role in this phase. The knowledge gained in previous phases is used to draw up risk reports and compare the current risk situation with the risk strategy in order to adopt it. In future, certain risks may be managed in a more appropriate manner.

It is worth mentioning that the above-described phases do not necessarily have to be conducted in a sequential order; phases are often performed iteratively or even simultaneously.
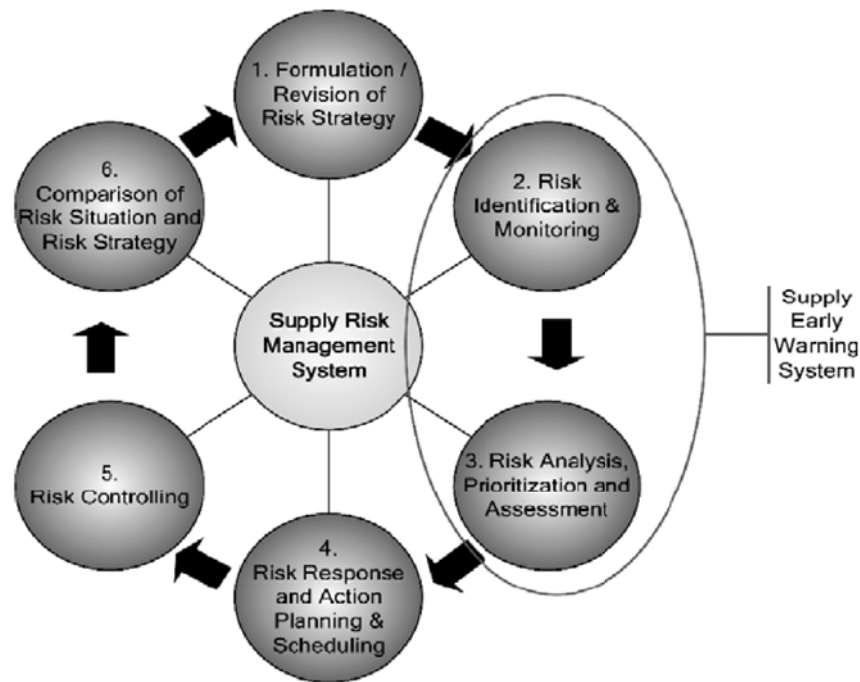

Fig. 3 Supply Chain Risk Management System [22]-[26]-[27]

In Fig. 3 the position of the subsystem "supply early warning system" is highlighted. This subsystem in the overall supply risk management system includes all methods and techniques that are applied to identify, analyze, control and assess supply chain risks [26]-[56].

III. PROPOSED METHODOLOGY

supply chain risk assessment consists of two parts: risk identification and risk measurement and evaluation. Risk identification is the basis of risk evaluation for supply chains, the purpose of which is to recognize the risk factors from the supply chain. Risk measurement and evaluation is to estimate the risk magnitude of supply chain by using some qualitative or quantitative approaches and technologies. As the vague and imprecise attitudes of human judgment for the risk factors evaluation, fuzzy synthetically evaluation methods were applied to evaluate risk [16]-[25]-[33]-[53]. However, these methods assumed that the relations among all the risk factors are simply hierarchical or linear, and ignored the interaction of the risk factors, and this limitation would reduce the accuracy

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of measurement and evaluation. Analytic network process (ANP) is a multi-attribute synthetic evaluation method, which is capable of handling interdependence and feedback among the evaluation criteria. Feedback can better capture the complex effects of interplay in human society. In addition, to deal with imprecise and uncertain human comparisons judgements [36], a fuzzy analytic network process (F-ANP) with use of triangular numbers is proposed in this paper to evaluate the risk in supply chain [14].

The MCDM technique is a powerful tool widely used for evaluating and ranking problems containing multiple, usually conflicting criteria. Over the years different behavioral scientists, operational researchers and decision theorists have proposed a variety of methods describing how a DM might arrive at a preference judgment while choosing among the multiple attribute alternatives. Recently, the VIKOR method has been introduced as an applicable technique to implement within MCDM [41]. The VIKOR method provides a maximum group utility for the majority and a minimum of an individual regret for the opponent. It introduces the multi-criteria ranking index based on the particular measure of closeness to the ideal solution [41]. The details of this method, which are described in section D, can also be found in [41]-[43]-[59]. In its actual setting, via this method, we can reach the exact values for the assessment of the alternatives and these values can be quite restrictive with unquantifiable criteria. This will come true especially, when the evaluation is made by using the linguistic terms. To model such information, the VIKOR method can be extended based on fuzzy logic [69] to process such data and to provide a more comprehensive evaluation. Opricovic and Tzeng [42] have also suggested using fuzzy logic for the VIKOR method. However, they simply used fuzzy values to define the attributes' ratings and their importance at the first phases of their study, and then, by applying some defuzzification techniques, they put forward the VIKOR method into practice. What we basically suggest in this study is to extend the method such that all subsequent phases make use of fuzzy logic in order not to lose important information with the mapping process at beginning [5].

The analytical structure of this research is illustrated in Fig. 4. A risk analysis is conducted based on the selected risks. First the FANP approach is employed to calculate the relative weights of the risk evaluation indexes. Then, according to these weights the MCDM analytical tool of VIKOR is used to rank the supply chain members and determine the most risky partner of the supply chain. The concepts of the fuzzy set theory and details of the analytical method are explained in the following subsections.

A. Fuzzy set theory

Expressions such as ''not very clear'', ''probably so'', and ''very likely'', are used often in daily life, and more or less represent some degree of uncertainty of human thought. The fuzzy set theory proposed by Zadeh [69], an important concept applied in the scientific environment, has been available to other fields as well. Consequently, the fuzzy theory has become a useful tool for automating human activities with uncertainty-based information. Therefore, this research incorporates the fuzzy theory into the risk assessment by objectifying the evaluators' subjective judgments.
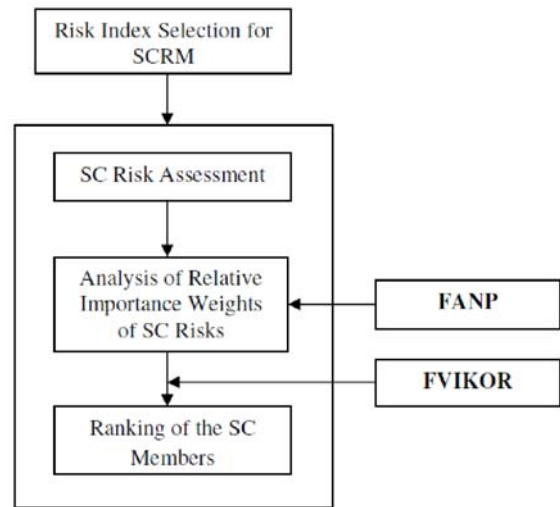
Fig. 4 Risk evaluation framework of the research

Fuzzy number: In the classical set theory, the truth value of a statement can be given by the membership function as $\mu_A(x)$

$$\mu_A(x) = \begin{cases} 1 & \text{if } x \in A, \\ 0 & \text{if } x \notin A. \end{cases} \tag{1}$$

Fuzzy numbers are a fuzzy subset of real numbers, and they represent the expansion of the idea of a confidence interval. According to the definition by Dubois and Prade [17], the fuzzy number $\tilde{A}$ is of a fuzzy set, and its membership function is $\mu_{\tilde{A}}(x) : R \rightarrow [0,1] (0 \leq \mu_{\tilde{A}}(x) \leq 1, x \in X)$, where x represents the criterion and is described by the following characteristics: (1) $\mu_{\tilde{A}}(x)$ is a continuous mapping from R (real line) to the closed interval [0, 1]; (2) $\mu_{\tilde{A}}(x)$ is of a convex fuzzy subset; (3) $\mu_{\tilde{A}}(x)$ is the normalization of a fuzzy subset, which means that there exists a number x_0 such that $\mu_{\tilde{A}}(x0) = 1$. For instance, the triangular fuzzy number (TFN), $\tilde{A} = (l, m, u)$, can be defined as (2) and the TFN membership function is shown in Fig. 5:

$$\mu_{\tilde{A}}(x) = \begin{cases} (x-l)/(m-l) & \text{if } l \leq x \leq m, \\ (u-x)/(u-m) & \text{if } m \leq x \leq u, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

Fig. 5 Membership function of the triangular fuzzy number

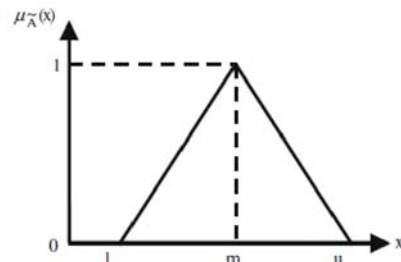World Academy of Science, Engineering and Technology
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Based on the characteristics of TFN and the extension definitions proposed by Zadeh [70], given any two positive triangular fuzzy numbers, $\tilde{A}_1 = (l_1, m_1, u_1)$ and $\tilde{A}_2 = (l_2, m_2, u_2)$, and a positive real number r, some algebraic operations of the triangular fuzzy numbers $\tilde{A}_1$ and $\tilde{A}_2$ can be expressed as follows:

Addition of two TFNs $\oplus$:

$$\tilde{A}_1 \oplus \tilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2). \quad (3)$$

Multiplication of two TFNs $\otimes$:

$$\tilde{A}_1 \otimes \tilde{A}_2 = (l_1 l_2, m_1 m_2, u_1 u_2). \quad (4)$$

Multiplication of any real number r and a TFN $\otimes$:

$$r \otimes \tilde{A}_1 = (rl_1, rm_1, ru_1) \quad \text{for } r > 0$$

And $l_i > 0, \ m_i > 0, \ u_i > 0 \quad (5)$

Subtraction of two TFNs $\ominus$:

$$\tilde{A}_1 \ominus \tilde{A}_2 = (l_1 - u_2, m_1 - m_2, u_1 - l_2)$$

For $l_i > 0, \ m_i > 0, \ u_i > 0. \quad (6)$

Division of two TFNs $\oslash$:

$$A_1 \oslash A_2 = (l_1/u_2, m_1/m_2, u_1/l_2). \quad (7)$$

Reciprocal of a TFN:

$$\tilde{A}_1^{-1} = (1/u_1, 1/m_1, 1/l_1) \quad (8)$$

For $l_i > 0, \ m_i > 0, \ u_i > 0.$

Linguistic variable: Linguistic variables are variables whose values are words or sentences in a natural or artificial language. In other words, they are variables with lingual expression as their values [24]-[70]. The possible values for these variables could be: ''very dissatisfied'', ''not satisfied'', ''fair'', ''satisfied'', and ''very satisfied''. The evaluators are asked to conduct their judgments, and each linguistic variable can be indicated by a triangular fuzzy number (TFN) within the scale range of 0–100. An example of membership functions of five levels of linguistic variables is shown in Fig. 6. For instance, the linguistic variable ''Satisfied'' can be represented as (60, 80, 100). Besides, each evaluator can personally define his/her subjective range of linguistic variables. The use of linguistic variables is applied widely. In this paper, linguistic variables expressed by TFN are adopted to stand for evaluators' subjective measures to determine the degrees of importance among risks and also assess the supply chain members [65].
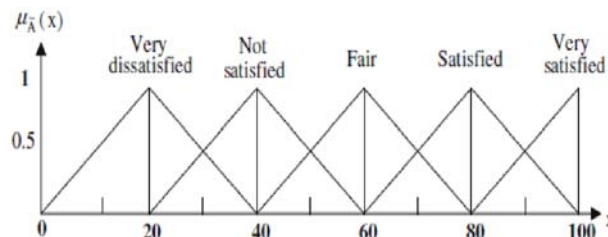

Fig. 6 Membership functions of the five levels of linguistic variables

B. The ANP

The ANP is the most comprehensive framework for the analysis of corporate decisions. It allows both interaction and feedback within clusters of elements (inner dependence) and between clusters (outer dependence). Such feedback best captures the complex effects of interplay in human society, especially when risk and uncertainty are involved. The elements in a cluster may influence other elements in the same cluster and those in other clusters with respect to each of several properties. The main object is to determine the overall influence of all the elements. In that case, first of all properties or criteria must be organized and they must be prioritized in the framework of a control hierarchy. Then the comparisons must be performed and synthesized to obtain the priorities of these properties. Additionally, the influence of elements in the feedback system with respect to each of these properties must be derived. Finally, the resulting influences must be weighted by the importance of the properties and added to obtain the overall influence of each element [47]-[48].

The modeling process can be divided into three steps for the ease of understanding which are described as follows:

Step 1: the pairwise comparisons and relative weight estimation

Before performing the pairwise comparisons, all criteria and clusters compared are linked to each other. There are three types of connections, namely one-way, two-way and loop. If there is only one-way connection between two clusters, only one-way dependencies exist and such a situation is represented with directed rows. If there is a two-way dependence between two clusters, bidirected arrows are used. Loop connections indicate the comparisons in a cluster and inner dependence. The pairwise comparisons are made depending on the 1–9 scale recommended by Thomas L. Saaty, where 1, 3, 5, 7 and 9 indicate equal importance, moderate importance, strong importance, very strong importance and extreme importance, respectively, and 2, 4, 6 and 8 are used for compromise between the above values. The score of a_{ij} in the pairwise comparison matrix represents the relative importance of the component on row (i) over the component on column (j), i.e., $a_{ij} = w_i/w_j$. The reciprocal value of the expression $(1/a_{ij})$ is used when the component j is more important than the component i. If there are n components to be compared, the matrix A is defined as

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$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \vdots & \vdots & & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{bmatrix} =$$

$$\begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \quad (9)$$

Once the pairwise comparisons are completed, like the AHP, a local priority vector (eigenvector) w is computed as an estimate of the relative importance accompanied by the elements being compared by solving the following equation:

$$Aw = \lambda_{max} w \quad (10)$$

Where λ_{max} is the largest eigenvalue of matrix A.

Step 2: formation of the initial supermatrix

All obtained priority vectors are then normalized to represent the local priority vector. To obtain global priorities, the local priority vectors are entered in the appropriate columns of a matrix of influence among the elements, known as a supermatrix [49]. The supermatrix representation of a hierarchy with three levels is given as follows (Fig. 7a):

$$W = \begin{matrix} Goal(G) \\ Criteria(C) \\ Alternatives(A) \end{matrix} \begin{matrix} G & C & A \\ \begin{pmatrix} 0 & 0 & 0 \\ W_{21} & 0 & 0 \\ 0 & W_{32} & I \end{pmatrix} \end{matrix} \quad (11)$$

where W_{21} is a vector that represents the impact of the goal on the criteria, W_{32} is a vector that represents the impact of the criteria on each of the alternatives, and I is the identity matrix. W is referred to as a supermatrix because its entries are matrices. For example, if the criteria are dependent among themselves, then the (2,2) entry of W given by W_{22} would be nonzero. The interdependence is exhibited by the presence of the matrix element W_{22} of the supermatrix W (Fig. 7b).

$$W = \begin{pmatrix} 0 & 0 & 0 \\ W_{21} & W_{22} & 0 \\ 0 & W_{32} & I \end{pmatrix} \quad (12)$$

The influence of a set of elements belonging to a cluster, on any element from another component, can be represented as a priority vector by applying pairwise comparisons [13]. Note that any zero value in the supermatrix can be replaced by a matrix if there is an interrelationship of the elements within a

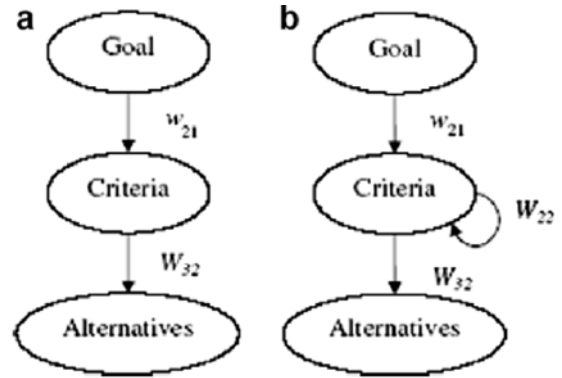cluster or between two clusters. Fig. 7a and b shows hierarchy and network.

Fig. 7 Hierarchy and network: (a) hierarchy; (b) network [67]

Step 3: formation of the weighted supermatrix

An eigenvector is obtained from the pairwise comparison matrix of the row clusters with respect to the column cluster, which in turn yields an eigenvector for each column cluster. The first entry of the respective eigenvector for each column cluster, is multiplied by all the elements in the first cluster of that column, the second by all the elements in the second cluster of that column and so on. In this way, the cluster in each column of the supermatrix is weighted, and the result, known as the weighted supermatrix, is stochastic. Raising a matrix to exponential powers gives the long term relative influences of the elements on each other [40]-[67].

C. Fuzzy ANP

In the proposed methodology, the fuzzy ANP (FANP) has been used to solve the problem of risk evaluation. It is very useful in situations where there is a high degree of interdependence between various attributes of the alternatives. In this approach, pair-wise comparison matrices are formed between various attributes of each level with the help of triangular fuzzy numbers. The FANP can easily accommodate the interrelationships existing among the functional activities [38]. The concept of supermatrices is employed to obtain the composite weights that overcome the existing interrelationships. The values of parameters such are transformed into triangular fuzzy numbers and are used to calculate fuzzy values.

In the pairwise comparison of attributes, DM can use triangular fuzzy numbers to state their preferences. Saaty's scale of 1–9 mentioned in Section B is precise and explicit. Even though the discrete scale of 1–9 has the advantages of simplicity and easiness for use, it does not consider the uncertainty associated with the mapping of one's perception or judgment to a number. On the other hand, DM perception about the supply chain risks, like quality, can be vague and ambiguous, hence cannot be expressed in definite numbers. For these reasons a scale of $\tilde{1}$-$\tilde{9}$ can be defined for triangular fuzzy numbers instead of the scale of 1–9. When comparing risk i with risk j, $\tilde{1}$, $\tilde{3}$, $\tilde{5}$, $\tilde{7}$ and $\tilde{9}$ indicate equal importance

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among the compared risks, moderate importance of i over j, strong importance of i over j, very strong importance of i over j and extreme importance of i over j, respectively, where i = 1, 2, . . ., m, and j = 1, 2, . . ., n (see Table II).

TABLE II
COMPARISON SCALE

(1,1,1)	Equal importance
(2,3,4)	Weak importance
(4,5,6)	Strong importance
(6,7,8)	Demonstrated importance
(8,9,10)	Absolute importance

To evaluate the DM preferences, pairwise comparison matrices are structured by using triangular fuzzy numbers (l, m, u). The m × n triangular fuzzy matrix can be given as follows [46]:   (13)

$$\tilde{A} = \begin{pmatrix} (a_{11}^l, a_{11}^m, a_{11}^u) & (a_{12}^l, a_{12}^m, a_{12}^u) & \cdots & (a_{1n}^l, a_{1n}^m, a_{1n}^u) \\ (a_{21}^l, a_{21}^m, a_{21}^u) & (a_{22}^l, a_{22}^m, a_{22}^u) & \cdots & (a_{2n}^l, a_{2n}^m, a_{2n}^u) \\ \vdots & \vdots & \vdots & \vdots \\ (a_{m1}^l, a_{m1}^m, a_{m1}^u) & (a_{m2}^l, a_{m2}^m, a_{m2}^u) & \cdots & (a_{mn}^l, a_{mn}^m, a_{mn}^u) \end{pmatrix}$$

The element a_{mn} represents the comparison of component m (row element) with component n (column element). If $\tilde{A}$ is a pairwise comparison matrix, it is assumed that it is reciprocal, and the reciprocal value, i.e., $1/a_{mn}$, is assigned to the element $\tilde{a}_{mn}$.   (14)

$$\tilde{A} = \begin{pmatrix} (1,1,1) & (a_{11}^l, a_{11}^m, a_{11}^u) & \cdots & (a_{1n}^l, a_{1n}^m, a_{1n}^u) \\ \left(\frac{1}{a_{11}^u}, \frac{1}{a_{11}^m}, \frac{1}{a_{11}^l}\right) & (1,1,1) & \cdots & (a_{2n}^l, a_{2n}^m, a_{2n}^u) \\ \vdots & \vdots & \vdots & \vdots \\ \left(\frac{1}{a_{1n}^u}, \frac{1}{a_{1n}^m}, \frac{1}{a_{1n}^l}\right) & \left(\frac{1}{a_{2n}^u}, \frac{1}{a_{2n}^m}, \frac{1}{a_{2n}^l}\right) & \cdots & (1,1,1) \end{pmatrix}$$

$\tilde{A}$ is also a triangular fuzzy pairwise comparison matrix. There are several methods for getting estimates for fuzzy priorities $\tilde{w}_i$, where $\bar{w}_i = (w_i^l, w_i^m, w_i^u)$, i= 1, 2, . . ., m, from the judgment matrix $\tilde{A}$ which approximate the fuzzy ratios $\tilde{a}_{ij}$ so that $\tilde{a}_{ij} \approx \tilde{w}_i / \tilde{w}_j$. One of these methods, logarithmic least squares method [7], is reasonable and effective, and it is used in this study. Hence the triangular fuzzy weights for the relative importance of the risks, the feedback of the risks and the alternatives according to the individual risks can be calculated [45]. In our proposed model, the triangular fuzzy weights will be used to support the fuzzy VIKOR for selecting the most risky member.

The logarithmic least squares method for calculating triangular fuzzy weights can be given as follows [40]-[45]:

$$\bar{w}_k = (w_k^l, w_k^m, w_k^u) \quad k = 1, 2, 3, \ldots, n, \quad (15)$$

Where

$$w_k^s = \frac{\left(\prod_{j=1}^n a_{kj}^s\right)^{1/n}}{\sum_{i=1}^n \left(\prod_{j=1}^n a_{ij}^m\right)^{1/n}}, \quad s \in \{l, m, u\}. \quad (16)$$

D. Fuzzy VIKOR

The VIKOR method was introduced as an applicable technique to implement within MCDM [41]-[43]-[59]. It focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria. Practical problems are often characterized by several noncommensurable and conflicting (competing) criteria, and there may have no solution satisfying all the criteria simultaneously. A compromise solution for a problem with some conflicting criteria can help DMs to reach a final decision. The compromise solution, whose foundation was established by Yu [68] and Zeleny [71], is a feasible solution, which is the closest to the ideal, and here "compromise" means an agreement established by mutual concessions. The VIKOR method determines the compromise ranking-list and the compromise solution by introducing the multi-criteria ranking index based on the particular measure of "closeness" to the "ideal" solution [41]. The multi-criteria measure for compromise ranking is developed from the *Lp-metric* used as an aggregating function in a compromise programming method [59].

Although the VIKOR method has numerous advantages, the performance ratings and criteria's weights are quantified as crisp values. However, under many circumstances, crisp data are inadequate to model real-life situations. Since human judgments including preferences are often vague, it is difficult to rate them as exact numerical values. In addition, in case of conflicting situations or criteria, a DM must also consider imprecise or ambiguous data, which is very usual in this type of decision problems. A more realistic approach may be to use linguistic assessments instead of crisp values, that is, to suppose that the ratings and weights of the criteria in the problem are assessed by means of linguistic variables.

Group decision-making is another important concern in this study. Multiple DMs are often preferred rather than a single DM [9]-[23] to avoid the bias and to minimize the partiality in the decision process [33]. The presence of multiple criteria and the involvement of multiple DMs will expand the decision space from one to many dimensions, thus the complexity of the decision process will increase [5].

Based on the concept of fuzzy logic and the VIKOR method, the proposed fuzzy VIKOR method has been developed to provide a rational, systematic process by which to discover a best solution and a compromise solution that can be used to resolve a fuzzy multi-person multi-criteria decision-making problem. The proposed fuzzy VIKOR allows

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decision-makers to specify the preferred solutions for a given decision problem in real organizational settings. The procedure of fuzzy VIKOR consists of the following steps:

Step1: Generate feasible alternatives, determine the evaluation criteria, and form a group of decision makers. Assume that there are m alternatives, k evaluation criteria, and n decision makers.

Step2: Define linguistic variables and their corresponding triangular fuzzy numbers. Linguistic variables were used to evaluate the importance of the criteria and the ratings of alternatives with respect to various criteria.

The linguistic scales and corresponding triangular fuzzy numbers for the evaluation of supply chain members with respect to various risks are as given in Tables III.

TABLE III
LINGUISTIC VARIABLES FOR A RATING OF MEMBERS

linguistic variable	Fuzzy scale
Very Low (VL)	(0,0,0.25)
Low (L)	(0,0.25,0.5)
Medium (M)	(0.25,0.5,0.75)
High (H)	(0.5,0.75,1)
Very High (VH)	(0.75,1,1)

Step 3: Integrate decision-makers' preferences and opinions. The decision is derived by aggregating the fuzzy weight of criteria and fuzzy rating of alternatives from n decision-makers calculated

$$\tilde{w}_j = \frac{1}{n}\left[\sum_{e=1}^{n}\tilde{w}_j^e\right], \quad j = 1, 2, \ldots, k \tag{17}$$

In addition, the preferences and opinions of n decision-makers with respect to j criterion for the important weight of each criterion and the rating of each alternative in the ith alternative can be calculated by

$$\tilde{x}_{ij} = \frac{1}{n}\left[\sum_{e=1}^{n}\tilde{x}_{ij}^e\right], \quad i = 1, 2, \ldots, m \tag{18}$$

Step 4: Calculate fuzzy weighted average and construct the (normalized) fuzzy decision matrix

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_k], \quad j = 1, 2, \ldots, k \tag{19}$$

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{cccc} C_1 & C_2 & \cdots & C_k \\ \left[\begin{array}{cccc} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mk} \end{array}\right] \end{array}$$

$$i = 1, 2, \ldots, m; j = 1, 2, \ldots, k \tag{20}$$

where $\tilde{x}_{ij}$ is the rating of alternative A_i with respect to criterion C_j, and $\tilde{w}_j$ is the important weight of the jth criterion. This study, therefore, denoted linguistic variables $\tilde{x}_{ij}$ and $\tilde{w}_j$ as triangular fuzzy numbers.

Step 5: Determine the fuzzy best value (FBV) and fuzzy worst value (FWV):

$$\tilde{f}_j^* = \max_i \tilde{x}_{ij}, \quad \tilde{f}_j^- = \min_i \tilde{x}_{ij} \tag{21}$$

Step 6: Calculate the values $\tilde{S}_i$, $\tilde{R}_i$:

$$\tilde{S}_i = \sum_{j=1}^{k}\tilde{w}_j(\tilde{f}_j^* - \tilde{x}_{ij})/(\tilde{f}_j^* - \tilde{f}_j^-) \tag{22}$$

$$\tilde{R}_i = \max_j[\tilde{w}_j(\tilde{f}_j^* - \tilde{x}_{ij})/(\tilde{f}_j^* - \tilde{f}_j^-)] \tag{23}$$

where $\tilde{S}_i$ is A_i with respect to all criteria calculated by the sum of the distance for the FBV, and $\tilde{R}_i$ is A_i with respect to the jth criterion, calculated by the maximum distance of FBV

Step 7: Calculate the values $\tilde{S}^*$, $\tilde{S}^-$, $\tilde{R}^*$, $\tilde{R}^-$, $\tilde{Q}_i$:

$$\tilde{S}^* = \min_i \tilde{S}_i, \quad \tilde{S}^- = \max_i \tilde{S}_i$$

$$\tilde{R}^* = \min_i \tilde{R}_i, \quad \tilde{R}^- = \max_i \tilde{R}_i \tag{24}$$

$$\tilde{Q}_i = v(\tilde{S}_i - \tilde{S}^*)/(\tilde{S}^- - \tilde{S}^*) + (1 - v)(\tilde{R}_i - \tilde{R}^*)/(\tilde{R}^- - \tilde{R}^*) \tag{25}$$

Here, $\tilde{S}^*$ is the minimum value of $\tilde{S}_i$, which is the maximum majority rule or maximum group utility, and $\tilde{R}^*$ is the minimum value of $\tilde{R}_i$, which is the minimum individual regret of the opponent. Thus, the index $\tilde{Q}_i$ is obtained and is based on the consideration of both the group utility and individual regret of the opponent. In addition, v here means the weight of the strategy of the maximum group utility. When v>0.5, the decision tends toward the maximum majority rule; and if v = 0.5, the decision tends toward the individual regret of the opponent.

Step 8: Defuzzify triangular fuzzy number $\tilde{Q}_i$ and rank the alternatives, sorting by the value Q_i. The procedure of defuzzification [24]-[42] locates the Best Nonfuzzy Performance value (BNP). Methods used in such defuzzified fuzzy ranking generally include the mean of maximal (MOM), center of area (COA), and α-cut. Utilizing the COA method to find out the BNP is a simple and practical without the need to bring in the preferences of any evaluators. Therefore it is used in this study. The BNP value of the fuzzy number $\tilde{A}_i$ can be found by

$$BNP_i = [(U - L) + (M - L)]/3 + L \quad \forall_i. \tag{26}$$

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Here, the index Q_i (in which $U_T(\tilde{Q}_i)$ is precise in value) can be obtained after defuzzifying $\tilde{Q}_i$, and Q_i can then be used to rank alternatives. Consequently, the smaller the value Q_i, the better the alternative.

Step 9: Determine a compromise solution. Assume that the two conditions given below are acceptable. Then, by using the index Q_i, determine a compromise solution ($\acute{a}$) as a single optimal solution.

[C1] Acceptable advantage:

$$Q(a'') - Q(a') \geqslant DQ$$

$$DQ = \frac{1}{m-1}(DQ = 0.25 \text{ if } m \leqslant 4) \tag{27}$$

[C2] Acceptable stability in decision making: under this condition, $Q(\acute{a})$ must be $S(\acute{a})$ or/and $R(\acute{a})$.

If **[C1]** is not accepted and $Q(a^{(m)}) - Q(a') < DQ$, then $a^{(m)}$ and $\acute{a}$ are the same compromise solution. However, $\acute{a}$ does not have a comparative advantage, so the compromise solutions $\acute{a}, a'', \ldots, a^{(m)}$ are the same. If **[C2]** is not accepted, the stability in decision-making is deficient, although $\acute{a}$ has a comparative advantage. Hence, compromise solutions of $\acute{a}$ and a'' are the same.

Step 10: Select the best alternative. Choose $Q(\acute{a})$ as the best solution with the minimum of Q_i [8].

IV. CASE STUDY

MAPNA GROUP is a conglomeration of parent enterprise and its 29 subsidiaries engaged in development and implementation of power, oil & gas, railway transportation and other industrial projects under EPC & IP schemes as well as manufacturing relative equipment. MAPNA's subsidiaries manufacture gas and steam turbines and their ancillary equipment, turbo-compressors, turbine blades and vanes, power generators, heat recovery steam generators (HRSGs) and conventional boilers, power plant electrical and control systems, cargo and passenger locomotives, etc. MAPNA Combined Cycle Power Plants Construction & Development Co. (MD-2) plays a vital role among MAPNA GROUP subsidiaries in terms of Management Contract (MC) services for implementation of Combined Cycle Power Plants. In this paper we purpose to use our proposed method to assess MD-2's supply chain risks and rank its supply chain members and determine the most risky partner of the supply chain.

The proposed model selects the most risky supply chain member considering the effects of risks on the different members (as explained below) and relations among the risk factors and subfactors. The process of applying the FANP comprises the following main steps.

The first step is to define the main goal for evaluation of the supply chain risks. The main risk factors and subfactors are also identified in this step by the decision makers. Twenty-nine risks have been determined to select the most risky supply chain member under the five risk categories. The risk categories are Plan and Control risk (C), Supply risk (S), Process risk (P), Demand risk (D) and Environmental risk (E).

After the main risk factors and subfactors are defined, the interactions between and within clusters, main risk factors, subfactors and elements can be determined. The network structure including all components of the model is shown in Fig. 8. It is important to emphasize that the relations among all the risk factors are not simply hierarchical and we should consider the interaction of the risk factors. For example, while determining the weight of "lead times" risk, it should be borne in mind that this risk is affected by issues of environmental risk such as natural disasters or import or export controls. Such examples can be further enumerated as demand risk are associated with supply risk and are affected by plan and control risk, just as the process risk are affected by environmental risk. To ensure that these associations are recognized, ANP, specifically the FANP technique, should be used.

Triangular fuzzy numbers are used to investigate the ambiguities involved in the linguistic-data assessment process. Because there are many main risk factors and subfactors for the issue involving supply chain risks evaluation and because most of these are qualitative, it is difficult to assess these criteria quantitatively. Fuzzy numbers reflect the relative strength of each pair of network elements. After comparing the importance score, the fuzzy pair-wise comparison matrices with fuzzy-ratio judgments are constructed according to the network given in Fig. 8. Triangular fuzzy weights are derived from fuzzy pair-wise comparison matrices. While assessing the relative importance of the risks and risks feedback are converted to the triangular fuzzy-importance weights from each matrix. The logarithmic least-squares method is used to calculate the triangular fuzzy weights in this study [7]-[57].

A. Data gathering for the model

The current survey was conducted through the distribution of a comprehensive questionnaire to experts, who work in different sectors of MD-2 company. The questionnaire dealing with data regarding the qualitative and quantitative risks was furnished for the supply chain risks assessment. Many face-to-face interviews were held with various experts in the chosen company to elicit solid information on the selected risks. The final sheet in the questionnaire contained the number of risks and the relations between them. Finally, a decision-making group was brought together to evaluate the questionnaire. The questionnaire form was distributed to each member of the decision group, but they did not carry out any evaluation by themselves before the meeting. They used a brainstorming method, which was conducive to a group decision-making process. Data gathering and processing by the decision-making group was long and tedious. However, some examples of the comparison matrices, evaluated by the expert group, such as weighing the risks clusters with respect to goal (W_{21}) and weighing the risks with respect to other risks (W_{22}) are given in separate appendices. After the comparisons

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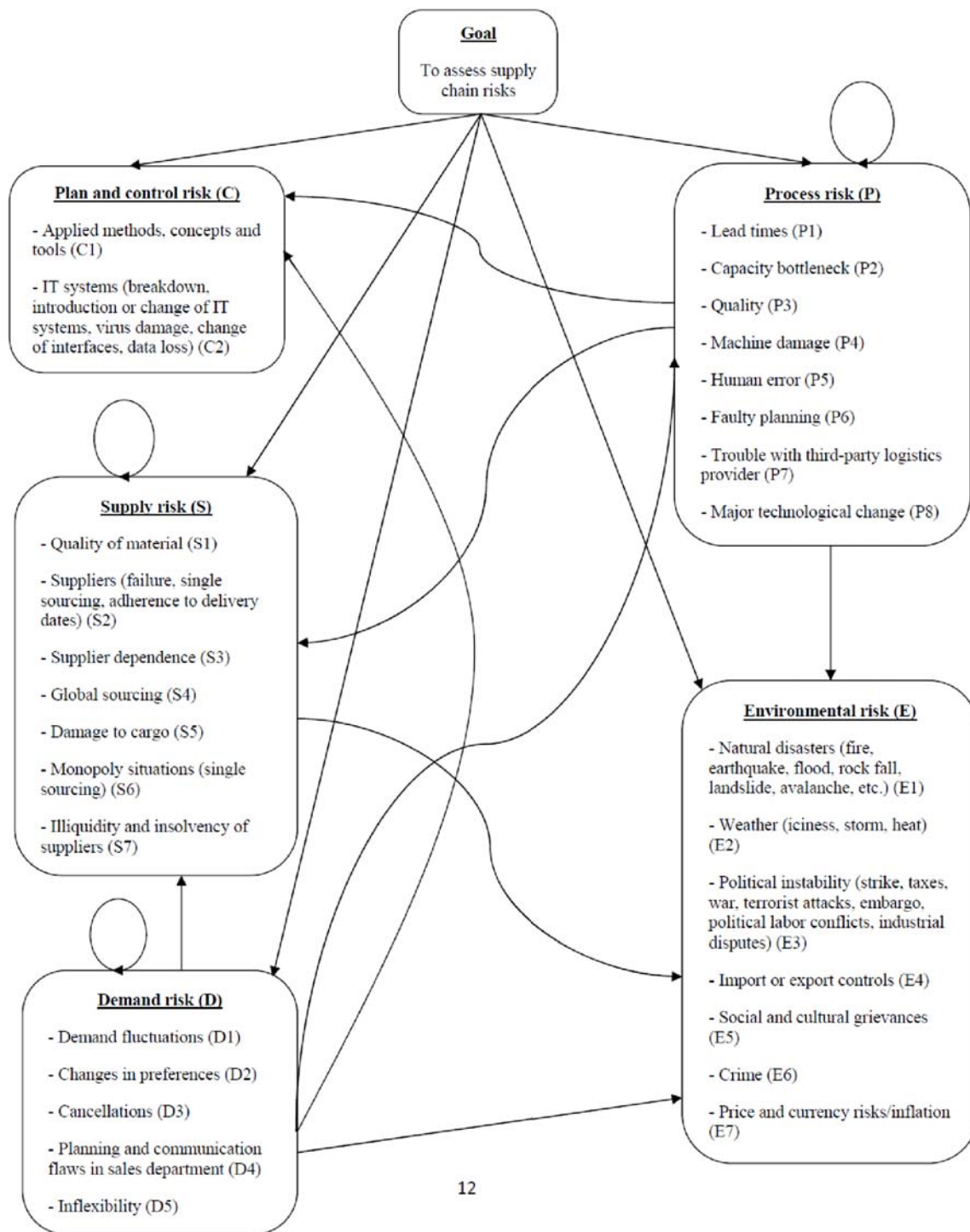
Fig. 8 Network structure of the supply chain risk assessment

were carried out by the decision-making group, the consistency ratios of all the pair-wise comparison matrices were calculated. If the inconsistency ratios of all the pair-wise comparison matrices were less than 0.1, all comparison matrices were deemed to be consistent and the judgments were considered reliable [50]-[57]. In this study, the inconsistency ratios for all the comparison matrices were calculated for the mean values of the fuzzy numbers. Because the lower and upper values provide flexibility for human judgments, they are not expected to have rigid consistency. The inconsistency ratios of the mean values of the comparison matrices were less than 0.1 in the herein-presented experiments, and all the judgments were hence considered reliable.

All pairwise comparisons in the questionnaire were carried out using the triangular fuzzy numbers to tackle the

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ambiguities involved in the linguistic-data assessment process. This fuzzified structure also provided flexibility to the experts and thereby represented the probable changes in the nature of each comparison. The pairwise comparisons are done by using Table II.

B. Comparisons of the risk categories according to the goal (W_{21} vector)

This part of the comparisons is associated with the topmost constituents of the hierarchy in the network. There is no feed-back or inner loop in these comparisons. As shown in Fig. 8, all the risks belong to a category. Therefore, the risk categories are compared by decision-making groups and the weights of the categories are obtained as shown in Table IV (for the questionnaire, see Appendix I). The risks in each category are compared with each other and with respect to the goal for determining their own weights.

Weights of the risks are then multiplied by the category weights to get a column-stochastic vector. The vector obtained is given in Table V, which is constituted by triangular fuzzy numbers.

TABLE IV
FUZZY WEIGHTS OF THE RISK CATEGORIES ACCORDING TO THE GOAL

Risk Category	Weights
Plan and control risk (C)	(0.064,0.070,0.078)
Demand risk (D)	(0.140,0.159,0.181)
Environmental risk (E)	(0.370,0.411,0.446)
Process risk (P)	(0.099,0.113,0.133)
Supply risk (S)	(0.209,0.244,0.281)

TABLE V
FUZZY WEIGHT MATRIX OF THE RISKS ACCORDING TO THE GOAL

C1	(0.017,0.018,0.023)	E1	(0.044,0.053,0.077)	P1	(0.027,0.028,0.051)	S1	(0.032,0.043,0.048)
C2	(0.021,0.023,0.029)	E2	(0.060,0.070,0.101)	P2	(0.018,0.018,0.034)	S2	(0.053,0.075,0.08)
D1	(0.020,0.038,0.059)	E3	(0.044,0.053,0.077)	P3	(0.022,0.023,0.043)	S3	(0.053,0.075,0.08)
D2	(0.023,0.045,0.068)	E4	(0.075,0.089,0.127)	P4	(0.036,0.038,0.068)	S4	(0.061,0.089,0.097)
D3	(0.020,0.038,0.059)	E5	(0.040,0.059,0.104)	P5	(0.016,0.036,0.063)	S5	(0.040,0.059,0.104)
D4	(0.020,0.038,0.059)	E6	(0.060,0.091,0.157)	P6	(0.014,0.028,0.053)	S6	(0.060,0.091,0.157)
D5	(0.046,0.052,0.067)	E7	(0.048,0.076,0.129)	P7	(0.008,0.018,0.032)	S7	(0.048,0.076,0.129)
				P8	(0.010,0.023,0.042)		

C. Evaluation of the fuzzy feedbacks between the risks (matrix W_{22})

Most of the evaluation time has been spent on this phase. The evaluation is completed when a relationship is defined between two risks which belong to the same cluster (inner loop) or to different clusters. risks that do not have any relationship with the other risks are not studied, therefore 34 pair-wise comparison matrices have been evaluated by the decision-making group. An example of the W_{22} comparison matrix can be seen in the Appendix II.

Hence the fuzzy weights of the risks are determined (i.e., $w_i = w_{risks} = W_{22} x W_{21}$) and shown in table VI.

TABLE VI
VALUES OF W_i

C1	(0.005,0.011,0.019)	E1	(0.023,0.031,0.044)	P1	(0.039,0.061,0.083)	S1	(0.023,0.055,0.079)
C2	(0.021,0.029,0.037)	E2	(0.015,0.023,0.03)	P2	(0.004,0.011,0.022)	S2	(0.018,0.027,0.036)
D1	(0.006,0.015,0.027)	E3	(0.031,0.043,0.057)	P3	(0.002,0.014,0.025)	S3	(0.032,0.056,0.074)
D2	(0.023,0.044,0.061)	E4	(0.008,0.016,0.024)	P4	(0.012,0.040,0.072)	S4	(0.009,0.019,0.028)
D3	(0.008,0.024,0.041)	E5	(0.021,0.057,0.084)	P5	(0.04,0.051,0.062)	S5	(0.014,0.023,0.036)
D4	(0.022,0.031,0.043)	E6	(0.013,0.020,0.032)	P6	(0.005,0.012,0.021)	S6	(0.008,0.027,0.049)
D5	(0.016,0.032,0.047)	E7	(0.059,0.074,0.089)	P7	(0.007,0.016,0.025)	S7	(0.063,0.071,0.081)
				P8	(0.039,0.063,0.081)		

After evaluating the fuzzy weights of the MD-2's supply chain risks, in this part we choose four MD-2's supply chain members (MAPNA Generator Engineering & Manufacturing Co. (PARS)(M_1), MAPNA Turbine Engineering & Manufacturing Co. (TUGA)(M_2), MAPNA I & C Engineering & Manufacturing Co. (MECO)(M_3) and MAPNA Boiler Engineering & Manufacturing Co. (M_4)) and use the fuzzy VIKOR methodology to rank this partners with respect to evaluated risks. Finally we determine the most risky partner of its supply chain. The data used for assessment in this study are given, and the evaluation procedure of the proposed fuzzy VIKOR is expressed and summarized as follows:

A committee of three decision makers, D1; D2 and D3, has been formed to select the most risky partner.

The decision makers use the linguistic rating variables shown in Table III to evaluate the ratings of members with respect to

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each risk. The ratings of the four members by the decision makers under the various risks are shown in Table VII.

TABLE VII
RATINGS OF THE FOUR MEMBERS BY THE DECISION MAKERS UNDER THE VARIOUS RISKS

	C_1	C_2	D_1	D_2	D_3	D_4	D_5	E_1	E_2	E_3	E_4	E_5	E_6	E_7	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	S_1	S_2	S_3	S_4	S_5	S_6	S_7
D_1																													
M_1	VH	H	L	H	M	VH	H	H	M	M	L	M	H	M	VL	M	M	VH	H	VH	VH	L	H	M	L	L	M	VH	M
M_2	H	VH	VH	H	H	L	M	VH	VH	H	L	L	VH	H	L	L	M	VH	H	VH	VL	VH	VH	VH	H	L	VH	H	M
M_3	L	H	VH	H	M	M	L	M	L	H	VH	VH	VH	H	L	L	M	M	H	VH	H	VH	M	VH	L	L	VL	H	L
M_4	M	VH	H	L	L	M	VH	VH	VL	H	H	H	VH	L	L	M	H	VH	H	L	H	L	L	H	M	H	VH	H	VH
D_2																													
M_1	H	H	M	VH	H	VH	H	H	M	VH	M	VH	L	L	M	VH	VH	M	H	M	L	VH	H	L	VH	H	M	M	L
M_2	M	VH	L	VH	H	H	H	M	VL	H	L	M	H	VH	H	VH	M	L	L	M	L	H	H	VH	VH	H	M	VH	M
M_3	H	VH	VH	H	H	VH	H	VH	M	L	VH	H	VH	H	L	M	M	H	VH	L	VL	M	H	L	M	VH	M	H	H
M_4	VH	H	VH	H	L	H	H	VH	L	L	M	H	VH	H	L	M	VH	VH	H	L	VH	VH	VH	M	L	H	VH	M	VH
D_3																													
M_1	H	H	L	VH	VH	VH	VH	H	M	VH	H	H	M	VH	VH	L	L	M	VL	L	H	M	M	VH	L	L	M	VH
M_2	VH	VH	VL	H	H	H	VH	M	VL	M	VH	H	VH	H	VH	M	L	H	VH	VH	H	L	VH	M	L	L	H	H	VH
M_3	H	H	VH	M	H	H	VL	L	H	H	VH	VH	VL	H	VH	VH	VH	L	H	VH	VH	VH	L	H	VH	VH	VH	L	VH
M_4	M	VH	L	H	H	VL	M	M	H	H	VH	VH	M	VH	M	L	L	H	VH	VH	H	H	L	H	M	VH	VH	H	L

The linguistic evaluations shown in Table VII are converted into triangular fuzzy numbers. Then the aggregated fuzzy rating of members is calculated to construct the fuzzy decision matrix, as in Table VIII.

The crisp values for decision matrix and weight of each risk are computed as shown in Table IX.

TABLE VIII
AGGREGATED FUZZY RATING OF MEMBERS

	C_1	C_2	D_1	D_2	D_3	D_4	D_5
M_1	(0.58,0.83,1)	(0.5,0.75,1)	(0.08,0.33,0.58)	(0.67,0.92,1)	(0.5,0.75,0.92)	(0.75,1,1)	(0.58,0.83,1)
M_2	(0.5,0.75,0.92)	(0.75,1,1)	(0.25,0.42,0.58)	(0.58,0.83,1)	(0.5,0.75,1)	(0.33,0.58,0.83)	(0.5,0.75,0.92)
M_3	(0.33,0.58,0.83)	(0.58,0.83,1)	(0.75,1,1)	(0.42,0.67,0.92)	(0.42,0.67,0.92)	(0.5,0.75,0.92)	(0.17,0.33,0.58)
M_4	(0.42,0.67,0.83)	(0.67,0.92,1)	(0.42,0.67,0.83)	(0.33,0.58,0.83)	(0.17,0.42,0.67)	(0.25,0.42,0.67)	(0.5,0.75,0.92)

	E_1	E_2	E_3	E_4	E_5	E_6	E_7
M_1	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.58,0.83,0.92)	(0.25,0.5,0.75)	(0.5,0.75,0.92)	(0.25,0.5,0.75)	(0.33,0.58,0.75)
M_2	(0.42,0.67,0.83)	(0.25,0.33,0.5)	(0.42,0.67,0.92)	(0.25,0.5,0.67)	(0.25,0.5,0.75)	(0.67,0.92,1)	(0.58,0.83,1)
M_3	(0.33,0.58,0.75)	(0.25,0.5,0.75)	(0.33,0.58,0.83)	(0.75,1,1)	(0.67,0.92,1)	(0.5,0.67,0.75)	(0.5,0.75,1)
M_4	(0.58,0.83,0.92)	(0.17,0.33,0.58)	(0.33,0.58,0.83)	(0.5,0.75,0.92)	(0.58,0.83,1)	(0.58,0.83,0.92)	(0.42,0.67,0.83)

	P_1	P_2	P_3	P_4	P_5	P_6	P_7
M_1	(0.33,0.5,0.67)	(0.33,0.58,0.75)	(0.33,0.58,0.75)	(0.42,0.67,0.83)	(0.33,0.5,0.75)	(0.33,0.58,0.75)	(0.42,0.67,0.83)
M_2	(0.42,0.67,0.83)	(0.33,0.58,0.75)	(0.17,0.42,0.67)	(0.42,0.67,0.83)	(0.42,0.67,0.83)	(0.58,0.83,0.92)	(0.17,0.33,0.58)
M_3	(0.25,0.5,0.67)	(0.33,0.58,0.75)	(0.42,0.67,0.83)	(0.25,0.5,0.75)	(0.58,0.83,1)	(0.5,0.75,0.83)	(0.42,0.58,0.75)
M_4	(0.08,0.33,0.58)	(0.17,0.42,0.67)	(0.42,0.67,0.83)	(0.67,0.92,1)	(0.58,0.83,1)	(0.25,0.5,0.67)	(0.58,0.83,1)

	P_8	S_1	S_2	S_3	S_4	S_5	S_6
M_1	(0.42,0.67,0.83)	(0.42,0.67,0.92)	(0.17,0.42,0.67)	(0.5,0.75,0.83)	(0.17,0.42,0.67)	(0.17,0.42,0.67)	(0.42,0.67,0.83)
M_2	(0.42,0.67,0.83)	(0.67,0.92,1)	(0.58,0.83,0.92)	(0.42,0.67,0.83)	(0.17,0.42,0.67)	(0.5,0.75,0.92)	(0.58,0.83,1)
M_3	(0.58,0.83,0.92)	(0.25,0.5,0.75)	(0.42,0.67,0.83)	(0.33,0.58,0.75)	(0.5,0.75,0.83)	(0.33,0.5,0.67)	(0.33,0.58,0.83)
M_4	(0.42,0.67,0.83)	(0.25,0.5,0.67)	(0.42,0.67,0.92)	(0.17,0.42,0.67)	(0.58,0.83,1)	(0.75,1,1)	(0.42,0.67,0.92)

	S_7
M_1	(0.33,0.58,0.75)
M_2	(0.42,0.67,0.83)
M_3	(0.42,0.67,0.83)
M_4	(0.5,0.75,0.83)

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TABLE IX
CRISP VALUES FOR DECISION MATRIX AND WEIGHT OF EACH RISK

	C_1	C_2	D_1	D_2	D_3	D_4	D_5	E_1	E_2	E_3	E_4	E_5	E_6	E_7	P_1	P_2
W	0.012	0.029	0.016	0.043	0.024	0.032	0.032	0.033	0.023	0.044	0.016	0.054	0.022	0.074	0.061	0.012
M_1	0.803	0.75	0.33	0.863	0.723	0.917	0.803	0.75	0.5	0.777	0.5	0.723	0.5	0.553	0.5	0.553
M_2	0.723	0.917	0.417	0.803	0.75	0.58	0.723	0.64	0.36	0.67	0.473	0.5	0.863	0.803	0.64	0.553
M_3	0.58	0.803	0.917	0.67	0.67	0.723	0.36	0.553	0.5	0.58	0.917	0.863	0.64	0.75	0.473	0.553
M_4	0.64	0.863	0.64	0.58	0.42	0.447	0.723	0.777	0.36	0.58	0.723	0.803	0.777	0.64	0.33	0.42

	P_3	P_4	P_5	P_6	P_7	P_8	S_1	S_2	S_3	S_4	S_5	S_6	S_7
W	0.014	0.041	0.051	0.013	0.016	0.061	0.052	0.027	0.054	0.019	0.024	0.028	0.072
M_1	0.553	0.64	0.527	0.553	0.64	0.64	0.67	0.42	0.693	0.42	0.42	0.64	0.553
M_2	0.42	0.64	0.64	0.777	0.36	0.64	0.863	0.777	0.64	0.42	0.723	0.803	0.64
M_3	0.64	0.5	0.803	0.693	0.583	0.777	0.5	0.64	0.553	0.693	0.5	0.58	0.64
M_4	0.64	0.863	0.803	0.473	0.803	0.64	0.473	0.67	0.42	0.803	0.917	0.67	0.693

The best and the worst values of all risk ratings are determined as follows:

	C_1	C_2	D_1	D_2	D_3	D_4	D_5	E_1	E_2	E_3	E_4	E_5	E_6	E_7	P_1	P_2
f_j^*	0.58	0.75	0.33	0.58	0.42	0.447	0.36	0.553	0.36	0.58	0.473	0.5	0.5	0.553	0.33	0.42
f_j^-	0.803	0.917	0.917	0.863	0.75	0.917	0.803	0.777	0.5	0.777	0.917	0.863	0.863	0.803	0.64	0.553

	P_3	P_4	P_5	P_6	P_7	P_8	S_1	S_2	S_3	S_4	S_5	S_6	S_7
f_j^*	0.42	0.5	0.527	0.473	0.36	0.64	0.473	0.42	0.42	0.42	0.42	0.58	0.553
f_j^-	0.64	0.863	0.803	0.777	0.803	0.777	0.863	0.777	0.693	0.803	0.917	0.803	0.693

The values of S, R and Q are calculated for all members as table X.

TABLE X
THE VALUES OF S, R AND Q FOR ALL MEMBERS

	S	R	Q (v=0)	Q (v=0.5)	Q (v=1)
M_1	0.44	0.054	0	0	0
M_2	0.59	0.074	1	1	1
M_3	0.53	0.061	0.35	0.46	0.57
M_4	0.45	0.072	0.9	0.49	0.08

The ranking of the members by S, R and Q in decreasing order is shown in Table XI.

TABLE XI
THE RANKING OF THE MEMBERS BY S, R AND Q IN DECREASING ORDER

	S	R	Q (v=0)	Q (v=0.5)	Q (v=1)
M_1	1	1	1	1	1
M_2	4	4	4	4	4
M_3	3	2	2	2	3
M_4	2	3	3	3	2

Finally, we determine a compromise solution as follows: for v = 0 and 0.5 [C1] acceptable advantage-by using (27), we can obtain Q(a") - Q(a') ≥ 0.25 (C1 Accept) and [C2] acceptable stability in decision making. The results are shown in Table XI (C2 Accept). Both C1 and C2 are acceptable. Therefore, we use Q_i to identify the most risky member M_1 as a single result. From the result, the best solution is Q(a'),

which is the member M_1. Therefore, the result suggests that M_1 would be the most risky member of the MD-2's supply chain. But for v = 1 [C1] is not accepted and Q(a") - Q(a') < 0.25, then a" and a' are the same compromise solution. However, a' does not have a comparative advantage, so the compromise solutions a' and a" are the same. Therefore, the result suggests that M_1 and M_4 would be the most risky member of the MD-2's supply chain.

The compromise solution obtained by VIKOR can be accepted by the decision makers because it provides a maximum ''group utility'' of the ''majority'' (with measure S, representing ''concordance''), and a minimum individual regret of an ''opponent'' (with measure R, representing ''discordance''). The compromise solutions can be the basis for negotiations, by involving the criteria weights of the decision makers' preference [51].

V. CONCLUSIONS

The shock of 9/11 is a wake-up call to the uncertainty of a global environment. Except for the terrorism, the growing trend towards outsourcing activities outside core competencies increases the risks of supply chain, and many risk factors have developed from a pressure to enhance productivity, eliminate waste, remove supply chain duplication, and drive for cost improvement.

Risk management of supply chain has similar process as normal risk management, but for those special characteristics of supply chain risk, it still has some aspects needed to be paid attention to, such as complex interactions within numerous

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business partners, which is the main reason why supply chain risks are more difficult to identify and manage [15].

There are many types of risks faced by the supply chain, so it is hard to see which one is bigger. In order to deal with supply chain risks, supply chain risk evaluation should be done to avoid the higher risks. And how to evaluate them correctly so as to deal with them is becoming mere and more important. In this paper using the method of fuzzy ANP to evaluate the risks through ranking risks, and the supply chain enterprise can see which risks are bigger through the result and adopt the positive and pointed measures [58]-[64].

The fuzzy ANP approach proposed in this paper not only can offer a more precise analysis by integrating interdependency relationships, but also can revise the vague and imprecise judgment of human with use of triangular numbers. The case study has demonstrated the fuzzy ANP approach is an efficient tool for risk evaluation of supply chain. However, there is still limitation of this approach, that is, triangular fuzzy numbers may not be the most appropriate for fuzzy ANP, therefore, applying other types of fuzzy numbers with use of the interval of confidence and optimism attitude would be the further research for this paper.

Finally this study proposed a fuzzy MCDM framework to effectively rank supply chain partners considering various risks under a fuzzy environment. The approach basically use the VIKOR method that helps DMs to achieve an acceptable compromise of the maximum "group utility" of the "majority"

and the minimum of the individual regret of the "opponent". In the approach, the importance weights of risks which are determined by ANP method and the ratings of supply chain members are assessed in linguistic terms by triangular fuzzy numbers. By using the suggested approach, the ambiguities involved in the assessment data could be effectively represented and processed to assure a more convincing and effective evaluation process.

In conclusion, the findings of this study can be summarized as follows: 1. Integrating all the relevant experts' opinions, 29 risk factors are selected as being suitable for supply chain risk evaluation; 2. By applying the FANP, the order of relative importance of the five supply chain risk categories is "Plan and control risk (C)", "Process risk (P)", "Demand risk (D)", "Supply risk (S)" and "Environmental risk (E)". The top five priorities of the risks are "Applied methods, concepts and tools (C1)", "Capacity bottleneck (P2)", "Faulty planning (P6)", "Quality (P3)" and "Trouble with third-party logistics provider (P7)", respectively; and 3. Using the fuzzy weights of the risks calculated by FANP, the ranking of the four MD-2's supply chain members by employing the fuzzy VIKOR method is M_1, M_3, M_4 and M_2, respectively. Future research may utilize several other techniques to investigate the casual relationships among risk indexes of the supply chain. Finally, exploring more cases and conducting more empirical studies are recommended to further validate the usefulness of the proposed supply chain risk assessment model.

APPENDIX

APPENDIX I
FUZZY-COMPARISON MATRIX OF THE RISK CATEGORY WITH RESPECT TO THE GOAL, CONTRIBUTED BY THE DECISION MAKERS

Goal	Plan and control risk	Demand risk	Environmental risk	Process risk	Supply risk
Plan and control risk	(1,1,1)	(0.16,0.2,0.25)	(0.1,0.11,0.12)	(0.25,0.33,0.5)	(0.12,0.14,0.16)
Demand risk	(4,5,6)	(1,1,1)	(0.12,0.14,0.16)	(2,3,4)	(0.25,0.33,0.5)
Environmental risk	(8,9,10)	(6,7,8)	(1,1,1)	(6,7,8)	(2,3,4)
Process risk	(2,3,4)	(0.25,0.33,0.5)	(0.12,0.14,0.16)	(1,1,1)	(0.25,0.33,0.5)
Supply risk	(6,7,8)	(2,3,4)	(0.25,0.33,0.5)	(2,3,4)	(1,1,1)

APPENDIX II
FUZZY-COMPARISON MATRIX OF THE ENVIRONMENTAL RISKS WITH RESPECT TO THE GLOBAL SOURCING RISK, CONTRIBUTED BY THE DECISION MAKERS

Global sourcing	Natural disasters	Weather	Political instability	I or E controls	S&C grievances	Crime	P&C risks
Natural disasters	(1,1,1)	(2,3,4)	(0.1,0.11,0.13)	(0.1,0.11,0.13)	(4,5,6)	(6,7,8)	(0.1,0.11,0.13)
Weather	(0.25,0.33,0.5)	(1,1,1)	(0.1,0.11,0.13)	(0.1,0.11,0.13)	(4,5,6)	(6,7,8)	(0.1,0.11,0.13)
Political instability	(8,9,10)	(8,9,10)	(1,1,1)	(2,3,4)	(8,9,10)	(8,9,10)	(2,3,4)
Import or export controls	(8,9,10)	(8,9,10)	(0.25,0.33,0.5)	(1,1,1)	(8,9,10)	(8,9,10)	(2,3,4)
Social&cultural grievances	(0.17,0.2,.25)	(0.17,0.2,.25)	(0.1,0.11,0.13)	(0.1,0.11,0.13)	(1,1,1)	(0.25,0.33,0.5)	(0.1,0.11,0.13)
Crime	(0.13,0.14,0.17)	(0.13,0.14,0.17)	(0.1,0.11,0.13)	(0.1,0.11,0.13)	(2,3,4)	(1,1,1)	(0.1,0.11,0.13)
Price&currency risks	(8,9,10)	(8,9,10)	(0.25,0.33,0.5)	(0.25,0.33,0.5)	(8,9,10)	(8,9,10)	(1,1,1)

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