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An integrated fuzzy AHP- fuzzy MULTIMOORA model for supply chain risk-benefit assessment and supplier selection

Madjid Tavana [a,b], Akram Shaabani [c], Soleyman Mansouri Mohammadabadi[c] and Nilofar Varzgani[d]

[a]Business Systems and Analytics Department, Distinguished Chair of Business Analytics, La Salle University, Philadelphia, USA; [b]Business Information Systems Department, Faculty of Business Administration and Economics, University of Paderborn, Paderborn, Germany; [c]Faculty of Management and Accounting, Department of Industrial Management, Allameh Tabataba'i University, Tehran, Iran; [d]Business Systems and Analytics Department, La Salle University, Philadelphia, USA

ABSTRACT
Supplier selection is a strategic decision for reducing risk, maximising overall value, and establishing strong, mutually beneficial long-term relationships between the members in supply chain management. Identifying and prioritising the risks and benefits from each supplier enables managers to consider these factors and select the most suitable supplier. We propose an integrated approach for supply chain risk-benefit assessment and supplier selection by combining the fuzzy analytic hierarchy process (AHP) with the fuzzy multiplicative multi-objective optimisation based on ratio analysis (MULTIMOORA). The fuzzy AHP is used to measure the importance of the supply chain risks and benefits and the fuzzy MULTIMOORA is used to rank the suppliers. We present a case study to demonstrate the applicability and exhibit the efficacy of the proposed integrated framework. We also study the uncertainty in the output of our proposed framework using sensitivity analysis.

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1. Introduction

Supply chain risks have enormous impact on companies with volatile supply and demand operating in uncertain economic environments (Kilubi, 2016). Supply chain networks are frequently exposed to recurrent risks that may cause unpredictable disruptions (Atwater et al., 2014). Supply chains are now more sensitive due to internal and external forces that create an environment susceptible to failures. External factors (i.e. market globalisation, global network complexity, unpredictable demand, and uncertain supply) and internal factors (i.e. the necessity for agility, decreased product lifecycles, the growing use of outsourcing, and supplier dependence) put huge pressures on the supply side operations (Lavastre et al., 2012; Vanalle et al., 2019). It is no longer just the material and product flow that causes supply chain risks, companies have to consider efficient and timely flow of information from the original supplier to the delivery of the final product to the end- user (Juttner et al., 2003). Supply chains are also more vulnerable because of the increasing interactions among the organisations involved in the supply chain and the dependency on external vendors. These disruptions hinder the efficiency of the supply chain by obstructing the free flow of materials and information among the participating organisations (Atwater et al., 2014; Punniyamoorthy et al., 2013). In todays' business environment, the supply chain is facing ever-increasing risks from manufacturers, customers and especially suppliers. Hence, supply chains must be able to respond quickly to external and internal risks while maintaining efficiency (Aqlan & Lam, 2015). In this globally competitive business market, supplier selection is one of the most challenging tasks in a supply chain (Paul, 2015).

The increasingly critical role of suppliers makes the success of a supply chain highly dependent on the selection of good suppliers (Hsu et al., 2013; Yücenur et al., 2011). Selecting the best supply partner not only reduces cost but also enhances corporate competitiveness (Tavana & Hatami-Marbini, 2011). Therefore, choosing appropriate suppliers is a vital objective for companies wishing to minimise their supply chain risks and maximise their supply chain benefits (Chen & Wu, 2013). The relationship between a company and its supplier is therefore crucial and companies must establish a set of evaluation criteria to streamline the supplier selection process (Azadeh & Alem, 2010).

Understanding all the risk and benefit factors and finding a suitable strategy for considering these supply chain

CONTACT Madjid Tavana tavana@lasalle.edu Business Systems and Analytics Department, Distinguished Chair of Business Analytics, La Salle University, Philadelphia, PA 19141, USA; Business Information Systems Department, Faculty of Business Administration and Economics, University of Paderborn, D-33098 Paderborn, Germany

risks and benefits is vital for decision making and efficient network design. The aim of this study is to develop a managerial framework for selecting the best supplier in the outsourcing section (inbound) for a manufacturer of consumer electronic goods. We propose an integrated approach for supply chain risk-benefit assessment and supplier selection by combining the fuzzy analytic hierarchy process (AHP) with the fuzzy multiplicative multi-objective optimisation based on ratio analysis (MULTIMOORA).

Identifying and prioritising the risks associated with suppliers is key to risk mitigation. The proposed fuzzy AHP- fuzzy MULTIMOORA allows the decision makers to choose an appropriate supplier by considering various risks and benefits and understanding how they affect the supply chain. The supply chain risks and benefits can be categorised into factors (main criteria) and sub-factors (sub-criteria) which can affect the supply chain efficiency and productivity. By displaying the cause and effect between the supply chain risks and benefits, this research aims to select the preferred supplier in the supply chain while minimising risks and maximising benefits. Due to the critical nature of this issue, it is not surprising that a number of studies have analysed the supplier selection problem using different operations research methods such as multi-criteria decision making (MCDM), simulation (e.g. discrete-event and agent-based), optimizations (e.g. linear and non-linear optimizations, parametric and non-parametric methods, and meta-heuristics), and statistical methods (e.g. design of experiments and Taguchi methods).

The main advantage of using the combined fuzzy AHP- fuzzy MULTIMOORA approach over other approaches is the ability to classify and rank the criteria, sub-criteria and alternatives for each risk. Fuzzy AHP expresses the connection between the criteria, sub-criteria, and alternatives and evaluates them by creating a hierarchical structure. This approach uses expert opinions to assign importance weights to each risk and benefit criteria and sub-criteria. Subsequently, fuzzy MULTIMOORA ranks the suppliers and identifies the best supplier in the final step of the fuzzy AHP- fuzzy MULTIMOORA approach. We establish a hierarchy and importance rankings among these risks and benefits (and subsequently suppliers) so that the lower ranked risks and benefits are given less prominence than the higher ranked risks and benefits. We apply our proposed method to a manufacturer of consumer electronic goods and show this approach improves the supplier evaluation and selection process.

The rest of the paper is organised as follows. In Section 2, a review of literature related to supply chain risks and benefits, and supplier selection is provided, with a detailed analysis of classifying supply chain risks and benefits into criteria and sub-criteria. The proposed integrated fuzzy AHP- fuzzy MULTIMOORA framework is introduced in Section 3. In Section 4, we show the results of the proposed solution framework on outsourcing decisions in a manufacturer of consumer electronic goods. Finally, research summary, conclusions, and managerial implications are highlighted in Section 5.

2. Literature review

2.1. Supply chain risks and benefits

The definition of risk is known to be dependent on the field of study (Jemison, 1987). Based on the definition that was first introduced by Lowrance (1980), risk implies the possibility and impact of uncertain factors. Rowe (1980) describes risk as the possibility of realising negative outcomes from uncertainties, by considering risk as a measure of the probability and severity of adverse effects (Ghadge et al., 2017). In the supply chain, the uncertainty in delivering information, material and product to the end user in a timely manner is what is defined as risk (Juttner et al., 2003; Mavi et al., 2016; Venkatesh et al., 2015). Similarly, Wagner and Bode (2006) also defined supply chain risk as 'the negative deviation from the expected value of a certain performance measure, resulting in negative consequences for the focal firm'. Ellis et al. (2010) proposed a definition for the risk in supply chain that is more compatible with this research; 'An individual's perception of the total potential loss associated with the disruption of supply of a particular purchased item from a particular supplier'. Mital et al. (2017) summarises this succinctly that supply-chain risks can create delays which in turn causes unanticipated changes in the flow of information and product.

Risks in supply chains have been classified into many sub-groups based on the context of the research, yet most of these studies only focus on a section or a portion of risks rather than examining all the risks in supply chain. Chang et al. (2015) identified supply chain risks and the implications of performance-related risk management for risk mitigation. Goh et al. (2007) categorised supply chain risks into interior risks that are intrinsic to the business and cover supply, demand and trade credit risks, and exterior risks occurring from the interactions between the supply chain and the environment. Kumar Pradhan and Routroy (2014) classified the risks in supply chain into process capability, delivery performance, demand and supply fluctuation at supplier end, business practices, and rework. Mavi et al. (2016) examined supplier selection in the context of supply chain risk management by considering supply, demand, logistics, manufacturing, information and environmental risks. Tang (2006) categorised the supply chain risks into operational and disruption risks. Chen et al. (2013) examined three types of risks, namely demand, supply and process risk. Chopra and Sodhi (2004) identified nine sources of supply chain risks as delays, forecasts, disruptions, systems, intellectual property, receivables, procurement, inventory, and capacity. Rogers et al. (2016) classified the supply chain risks into cultural, infrastructure, economic, operational, forecasting, and supplier related risks. Christopher and Peck (2004) introduced risks associated with the process, control, demand, supply, and environment.

Tang and Tomlin (2008) examined supply, process, and demand risks, intellectual property risks, behavioural risks, and political/social risks. Sreedevi and Saranga (2017) introduced suitable types of flexibility to alleviate the three major aspects of supply chain risk including delivery, manufacturing process and supply risk. Tummala and Schoenherr (2011) presented a comprehensive and integrated approach to risk management in the supply chain. The structural approach was divided into risk identification, risk measurement, risk assessment, risk reduction, and risk control and monitoring through the data management system. Manuj and Mentzer (2008) presented a theory of global supply chain risk management strategy using grand theory and classified risks of supply chain as supply, operations, demand, and other risks including security and those relevant to currency. Following this research, the authors classified risks of the supply chain as supply, demand, operational, macro policy, security, resource and competitive risks (Manuj & Mentzer, 2008).

While there are many available classifications regarding the risks and benefits in the supply chain, the characteristics and importance of these risks and benefits may differ based on the industry of the supply chain and the geographical location of the chain. Therefore, in this research, in addition to considering previous classifications of the risks and benefits in supply chain, these risks and benefits are determined according to structured interviews with industry experts and academic professionals for a manufacturer of consumer electronic goods. In the first stage of this research, supplier selection criteria according to supply chain risks and benefits are identified and then in the second stage, based on the findings of the first stage, the most suitable supplier is selected. The proposed classification of risks and benefits are categorised into the following four groups: operational, supply, financial, and technological.

2.2. Supplier selection

Supplier evaluation is an essential activity for most companies and producers (Wood, 2016). Due to its direct impact on cash flows and profitability, supplier selection has been recognised as a fundamental strategic decision for maintaining competitive position in organisations (Banaeian et al., 2016). Supplier selection can be considered a MCDM problem with many constraints such as the cost, quality, risk, and sustainability (Zhang et al., 2012). Supplier evaluation and selection requires the use of both qualitative and quantitative factors to analyze the trade-off between attaining the highest quality and maintaining feasible costs.

Rao et al. (2017) reviewed the problem of supplier selection according to supply chain risk management in two stages. In the first stage, a list of qualified suppliers based on four features (i.e. quality, price, flexibility and delivery) is identified and in the second stage, the best supplier is selected according to smaller risks, classified into seven categories. Mavi et al. (2016) considered another set of risks including supply, manufacturing, demand, logistics, information, and environment risks and evaluated suppliers using fuzzy TOPSIS. Chen and Wu (2013) introduced an integrated AHP and FMEA framework for supplier selection considering supply chain risk. The results showed that the proposed framework for supplier selection diminished risks in the supply chain. Micheli et al. (2008) examined the connection between supplier selection and supply risk management of the Italian engineering, procurement, and construction sector. The study findings point out that supply risk can be managed through both supplier selection and supply risk management. Zimmer et al. (2017) used input-output analysis with fuzzy AHP for supplier selection by considering social risks of global supply chains in the automotive industry.

Other studies in the field of supplier selection have used AHP (Chiouy et al., 2011; Sevkli et al., 2008; Yadav & Sharma, 2016); fuzzy AHP (Chamodrakas et al., 2010; Kahraman et al., 2003; Kilincci & Onal, 2011); analytic network process (ANP) (Gencer & Gürpinar, 2007; Hsu & Hu, 2009); fuzzy ANP (FANP) (Vinodh et al., 2011; Wei et al., 2010); VIKOR (Zhi-guang, 2012); fuzzy VIKOR (Sanayei et al., 2010; Shemshadi et al., 2011); fuzzy multi-objective optimisation on the basis of ratio analysis (MOORA) (Matawale et al., 2016); technique for order preference by similarity to ideal solution (TOPSIS) (Avlonitis & Panagopoulos, 2005; Boran et al., 2009; Li et al., 2008); and fuzzy TOPSIS (Fuzzy TOPSIS) (Kannan et al., 2014; Wang et al., 2009), particle swarm optimisation (Kuo et al., 2010); fuzzy goal programming (Ku et al., 2009; Tsai & Hung, 2009), simulation (Zouggari & Benyoucef, 2012); simulation–optimisation (Ding et al., 2003; Ding et al., 2005); Taguchi method (Pi & Low, 2006), data envelopment analysis (DEA) (Toloo & Nalchigar, 2011; Wu, 2009), interpretative structural

Table 1. Risks to the supply chain by the suppliers.

No.	Criteria	Sub-criteria	Description	Source
1	Operational risks C1	Machine, equipment or facility failure C11	Any interruption due to failure of machine, equipment or facility affect SC effectiveness at industrial standpoint	Aqlan and Lam, (2015); Atwater et al. (2014); Chen and Wu (2013); Ho et al., (2010); Mangla et al., (2015); Punniyamoorthy et al. (2013); Xia and Chen (2011); Wang et al. 2012; Ma et al. (2012); Qianlei (2012); Yang and Li (2010); Lockamy (2014); de Oliveira et al. (2017); Truong Quang and Hara (2017); Tang (2006); Lavastre et al. (2014); Kırılmaz and Erol (2017); Samvedi et al. (2013); Juttner et al. (2003).
		Design risks C12	It corresponds to the imprecision or flaws in designing of green process methodologies like mismanaged green material, operations, approaches.	Mangla et al. (2015)
		The scarcity of skilled labour risks C13	The lack of experience and knowledge of the workforce can lower the organisational SC performance	Lockamy (2014); Lockamy and McCormack (2009); Mangla et al. (2015).
2	Supply risk C2	Procurement costs risks C21	Preparation of green and or eco-friendly raw the material can add costs at supplier end, although, their environmental performance may be affected	Chen and Wu (2013); Ho et al. (2010); Mangla et al. (2015); Tang (2006); Wang et al. (2012); Ma et al. (2012); Qianlei (2012); Yang and Li (2010); Ghadge et al. (2013); de Oliveira et al. (2017); Truong Quang and Hara (2017); Mavi et al. (2016); Rogers et al. (2016); Viswanadham and Samvedi (2013); Chatterjee and Kar (2016); Manuj and Mentzer (2008).
		Key supplier failures risks C22	Failure of every principal supplier can stop the functioning of an SC	Samvedi et al. (2013); Manuj and Mentzer (2008); Mangla et al. (2015).
		Supplier quality risks C23	The issues of quality at supplier's finish will affect SC efficiency at industrial prospect	Nyamah et al. (2017); Pournader et al. (2016); Kumar Sharma and Sharma (2015); Chen et al. (2013); Ho et al. (2015); Lavastre et al. (2014); Mavi et al. (2016); Kırılmaz and Erol (2017); Radivojević and Gajović (2014); Samvedi et al. (2013); Tse and Tan (2011); Manuj and Mentzer (2008); Aqlan and Lam (2015); Mangla et al. (2015).
3	Financial risk C3	The Sourcing of funds C31	Any problem related to funding sourcing and its basis would certainly influence the objective of adoption of effective GSC practices in business	Ali et al. (2017); Mital et al. (2017); Ho et al. (2015); Rangel et al. (2015); Atwater et al. (2014); Chen and Wu (2013); Ho et al. (2010); Mangla et al. (2015); Tang (2006); Kumar Sharma and Sharma (2015); Cavinato (2004).
		Inflation and currency exchange rates C32	Inflation and variations in currency exchange rates would affect the financial concerns, and thus GSC effectiveness might be affected	
4	Technology risks C4	Inability to use new technology C41	Inability to use new technology can quickly cause problems such as lack of punctual delivery and staying away from competitors	Chen and Wu (2013); Ho et al. (2010); Kumar Sharma and Sharma (2015); Kırılmaz and Erol (2017); Rajesh et al. (2015); Viswanadham and Samvedi (2013); Viswanadham and Samvedi (2013); Aqlan and Lam (2015).
		Failure in Information technology C42	It affects the SC effectiveness	Ghadge et al. (2013); Lavastre et al. (2014); Kırılmaz and Erol (2017); Radivojević and Gajović (201).

modelling (ISM) (Kumar & Singh, 2012; Thresh Kumar et al., 2014); and DEMATEL (Dey et al., 2012; Hsu et al., 2013).

Based on their findings, there are remarkable differences in the social risks associated with each supplier as well as different risk structures along the n-tier chain. Table 1 presents a general literature review of supply chain risk factors and their associated sub-risks followed by a brief description of each category.

3. Research method

The goal of this study is to select a preferred supplier based upon an assessment of supply chain risks and benefits. Using a thorough review of previous studies and research, first, the supply chain risks and benefits are identified. After identifying and extracting the risk and benefit criteria, according to a structured interview with industry experts and academic scholars, risks and benefits are categorised into four groups: operational, supply, financial, and technological. These four categories have been validated and confirmed by the participants. Furthermore, a questionnaire was designed according to existing research techniques and it was distributed among the managers in the supply chain department of a manufacturer of consumer electronic goods. This manufacturer uses six internal suppliers in their outsourcing department that is introduced here by using the fuzzy AHP-fuzzy MULTIMOORA preferred supplier approach. In this research, the fuzzy AHP approach is used to construct the hierarchical structure of criteria and sub-criteria of risk and benefits, and to rank the importance of the criteria by assigning weights and using the fuzzy MULTIMOORA approach for ranking the suppliers. In the fuzzy AHP technique, triangular fuzzy numbers and linguistic variables are used for ranking the suppliers quantitatively and for reviewing the importance of the weights of the risk and benefit criteria and sub-criteria.

The fuzzy AHP method is used because the elements of each level depend only on the elements of the upper level. In other words, each sub-criterion is only dependent on its own criterion according to a one-way relationship. In the ANP method, there is interdependencies among the elements within levels. For this reason, the hierarchical problem here is not applicable to ANP structure. In addition, scale Likert is used to capture the expert opinion on each criterion and sub-criterion along with scoring alternatives (suppliers). Figure 1 depicts the framework used in this study.

In the following sections, details related to Phases 2 and 3 are further explained. Section 3.1 discusses the steps of the fuzzy AHP method, the underlying formulas, and the use of fuzzy numbers. Section 3.2 explores the use of fuzzy MULTIMOORA for ranking the suppliers using the outcome of the fuzzy AHP method.

3.1. Fuzzy AHP

The analytic hierarchy process (AHP) introduced by Satty (1980) is a well-known MCDM approach used to analyze complicated decision making problems (Tavana et al., 2016). AHP has widely been used as a MCDM or weight estimation tool (Singh & Sharma, 2014). Individual judgment in decision making has been often obscurant and difficult to measure precisely. Fuzzy logic is hence commonly used for handling problems characterised by this vagueness and imprecision. This approach tends to be dependent on the choice of experts who have a strong influence on the results of AHP. Consequently, the ranking of AHP is imprecise in nature. The AHP method can be integrated into fuzzy set theory to overcome the uncertainty, vagueness and imprecision in the subjective judgements of the AHP methodology (Dalvi & Kant, 2017). The purpose of any fuzzy AHP approach is to prioritise the ranking of alternatives. Fuzzy AHP is a decision support system used to help decision-makers make better choices both in relation to explicit and implicit criteria, also known as tangible criteria and intangible criteria (Cheng et al., 2009; Mohamadi et al., 2017).

Chang (1996) proposed a well-known and widely used fuzzy extension of AHP. However, Wang et al. (2008) criticised this approach for calculating the relative weights and demonstrated that this fuzzy extension can lead to an incorrect prioritisation, through assigning ‘zero weights’ to some decision factors, and implying their elimination as unnecessary items. This elimination is contrary to the hierarchical structure and leads to a wrong prioritisation of criteria and alternatives. Therefore, the weights calculated using Chang’s (1996) method should not be considered as the relative importance of criteria and alternatives. We agree with Wang et al.’s (2008) conclusion and to avoid this shortcoming, we adopted the fuzzy AHP approach proposed by Calabrese et al. (2013) and Ulutas et al. (2016) in our proposed framework. Furthermore, we use the consistency test of Kwong and Bai (2003) in our model to avoid the consistency concerns of using the discrete scale of one to nine in the conventional AHP which cannot take into account the uncertainty and ambiguity inherent in subjective judgments in the conventional fuzzy AHP method. The steps of fuzzy AHP, as used in the present study, are enumerated as follows:

Step 1: Identify supplier selection criteria and the hierarchical structure based on the literature review and expert opinions.

Step 2: Use the hierarchical structure and construct a matrix of pairwise comparisons using expert opinions and the linguistic variables represented by the triangular fuzzy numbers in Table 2.

Step 3: Construct the group decisions matrix by considering M experts, each supplying a fuzzy judgment matrix; and constructing the fuzzy pairwise comparison matrix $\tilde{A} = [\tilde{a}_{ij}]$ for $\tilde{A}_1, \dots, \tilde{A}_M$:

$$\tilde{A} = (\tilde{a}_{ij})_{n\times n} = \begin{bmatrix} (1,1,1) & \dots & (l_{12}, m_{12}, u_{12}) & \dots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & \dots & (1,1,1) & \dots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & & \vdots & & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & \dots & (l_{n2}, m_{n2}, u_{n2}) & \dots & (1,1,1) \end{bmatrix} \tag{1}$$

where:

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) = \tilde{a}_{ij}^{-1} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right) \quad i,j = 1,\dots,n; \quad i \neq j \tag{2}$$

represents the linguistic judgment for the items i and j; thus $\tilde{A}$ is a square and symmetrical matrix. Equation (3) is used next to construct the group decision matrix:

$$l_{ij} = \left(\prod_{m=1}^{M} {l_{ij}}^{m}\right)^{1/M}, m_{ij} = \left(\prod_{m=1}^{M} {m_{ij}}^{m}\right)^{1/M}, \quad u_{ij} = \left(\prod_{m=1}^{M} {u_{ij}}^{m}\right)^{1/M} \tag{3}$$

where, M is the number of experts, and (l, m, u) is a triangular fuzzy number (Lin, 2013).

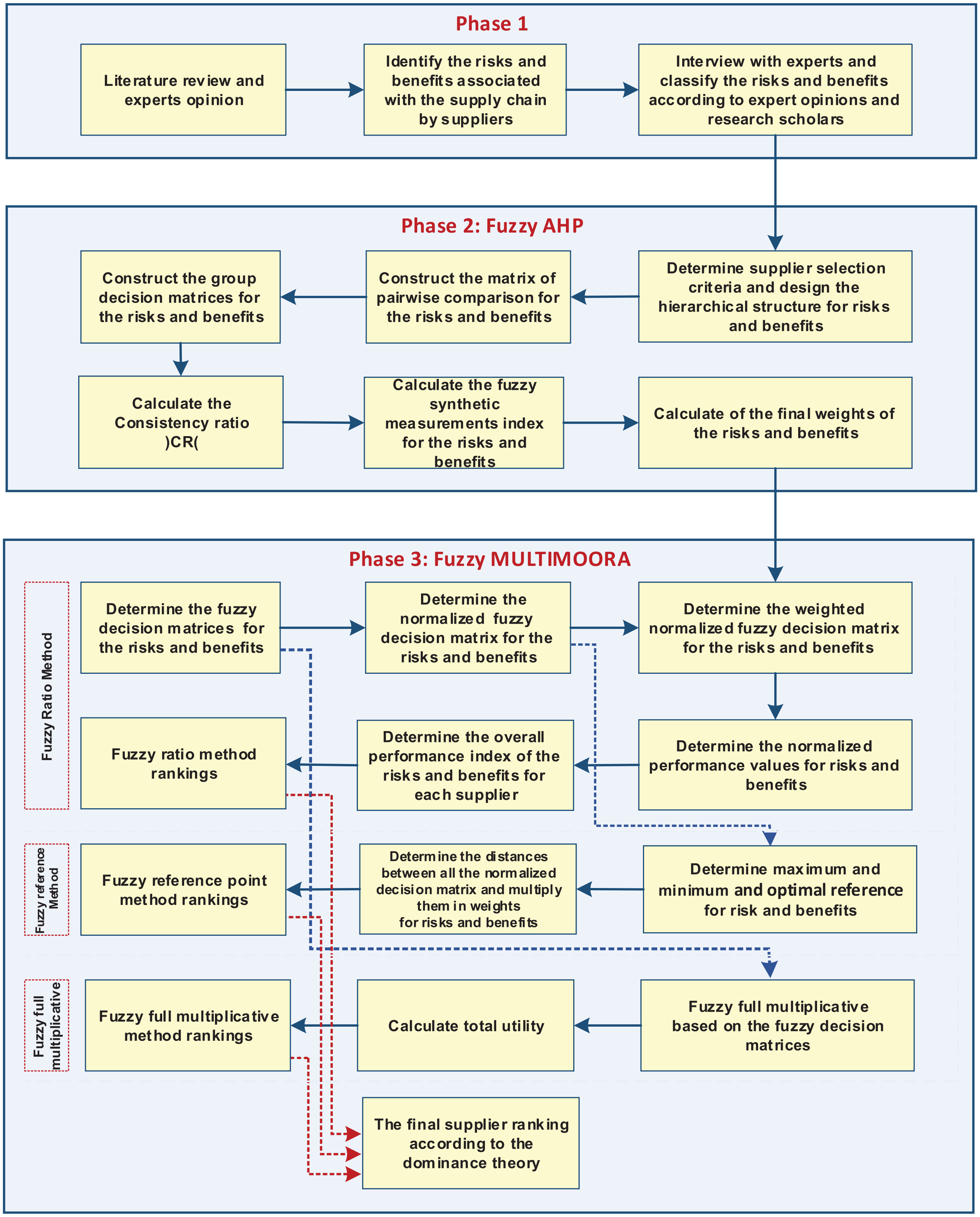


Figure 1. Proposed method.

The fuzzy AHP method requires calculating a consistency ratio (*CR*) to measure how consistent the judgments of the decision makers have been relative to large samples of purely random judgments. If the *CR* exceeds 0.10, the judgment is untrustworthy because it is too close to random judgement, and the pairwise comparison must be repeated. We use the method proposed by Kwong and Bai (2003) and Calabrese et al. (2013) to calculate *CR*.

Table 2. Linguistic variables.

Linguistic variables for fuzzy AHP (Cheng, 1997)			Linguistic variables for fuzzy MOORA (Amiri, 2010)	
Linguistic variables	Fuzzy Scale	Response Scale	Linguistic variables	Fuzzy Scale
Equally Important	(1,1,1)	(1,1,1)	Very low (VL)	(0,0,0.2)
Moderately Important	(2/3,1,3/2)	(2/3,1,3/2)	Low (L)	(0,0.2,0.4)
Important	(3/2,2,5/2)	(2/5,1/2,2/3)	Medium (M)	(0.2,0.4,0.6)
Very Important	(5/2,3,7/2)	(2/7,1/3,2/5)	High (H)	(0.4,0.6,0.8)
Much more Important	(7/2,4,9/2)	(2/9,1/4,2/7)	Very High (VH)	(0.6,0.8,1)

In order to calculate CR, we must calculate the consistency index (CI). We first convert the fuzzy comparison matrix into a crisp comparison matrix by using a centroid defuzzification method called 'center of gravity' (Yager, 1981). We then use the translation formula for triangular fuzzy numbers proposed by Wang and Elhag (2007) in Equation (4) and then calculate CI with Equation (5) by Kwong and Bai (2003) as:

$$a_{ij}(\tilde{a}_{ij}) = \frac{l_{ij} + m_{ij} + u_{ij}}{3}, \quad i, j = 1, 2, \ldots, n \qquad (4)$$

$$CI = \frac{(\lambda_{\max} - n)}{n - 1} \qquad (5)$$

Equation (6) is used next to calculate CR according to the random indices (RIs) given in Table 3 (Golden et al., 1989):

$$CR = \frac{CI}{RI(n)} \qquad (6)$$

where $\lambda_{\max}$ is the largest eigenvalue of the comparison matrix, n is the dimension of the matrix, and $RI(n)$ is a random index.

The matrix is consistent if CR is smaller than 0.10 (Forman, 1990). The threshold of tolerance can be modified according to the scope of the analysis. In case of inconsistency, it is necessary to proceed with a matrix review process and ask decision-makers to provide new comparison judgments. The review process continues until consistency is achieved (Calabrese et al., 2019).

Step 4: Calculate the relative row sum for each row in $\tilde{A}$ as:

$$\tilde{R}S_i = \sum_{j=1}^{n} \tilde{a}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij} \right) \quad i, j = 1, \ldots, n \qquad (7)$$

Table 3. Random indices.

n	3	4	5	6	7	8	9
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Step 5: Normalise the relative row sums $\widetilde{RS}_i$ using the normalisation formula suggested by Wang et al. (2008) and Ulutas et al. (2016):

$$\begin{aligned} \tilde{S}_i &= \frac{\widetilde{RS}_i}{\sum_{j=1}^{n} \widetilde{RS}_j} \\ &= \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{j=1}^{n} l_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1,k=i}^{n} \sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{j=1}^{n} u_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} l_{kj}} \right) \\ &= (l(\tilde{w}_i), m(\tilde{w}_i), u(\tilde{w}_i)) \quad i = 1, \ldots, n \end{aligned} \qquad (8)$$

The normalised row sums, $\tilde{S}_i = (i = 1, \ldots, n)$, are then compared using the degree of possibility (Figure 2):

$$V(\tilde{S}_i \geq \tilde{S}_j) = \begin{cases} 1 & \text{if} \quad m_{i\geq} m_j \\ \dfrac{u_i - l_j}{(u_i - m_i) - (m_j - l_j)} & \text{if} \quad l_j \leq u_i \ i, \\ & \quad j = 1, \ldots, n; j \neq i \\ 0 & .. \quad \text{otherwise} \end{cases} \qquad (9)$$

Finally, the relative crisp weight of each item is calculated by normalising the degree of possibility

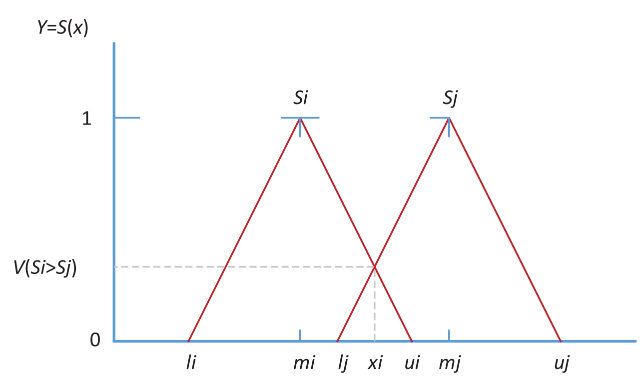


Figure 2. Graphic representation of the pairwise comparison of two fuzzy numbers with triangular membership functions.

values:

$$w_i = \frac{V(\tilde{S}_i \geq \tilde{S}_j | j = 1, \ldots, n; j \neq i)}{\sum_{k=1}^{n} V(\tilde{S}_k \geq \tilde{S}_j | j = 1, \ldots, n; j \neq k)},$$
$$i = 1, \ldots, n \tag{10}$$

where:

$$V(\tilde{S}_i \geq \tilde{S}_j | j = 1, \ldots, n; j \neq i) = \min_{j \in \{1,\ldots,n\},\, j \neq i} V(\tilde{S}_i \geq \tilde{S}_j)$$
$$i = 1, \ldots, n \tag{11}$$

Wang et al. (2008) assert that Equation (10) is only useful for comparing triangular fuzzy numbers because it expresses the highest intersection point of the membership functions related to $\tilde{S}_i$ and $\tilde{S}_j$ (see Figure 2). They conclude that if pairwise comparison matrices (1) are consistent, crisp weights belong to the intervals defined by (8). Following this conclusion, in our model, we convert the triangular fuzzy numbers for weight $\tilde{S}_i$, i.e. $(l(\tilde{w}_i), m(\tilde{w}_i), u(\tilde{w}_i))$ for the i-th criterion, into the crisp weight w_i of the i-th criterion by:

$$w_i = \tilde{S}_i = \frac{\widetilde{RS}_i}{\sum_{j=1}^{n} \widetilde{RS}_j}$$
$$= (l(\tilde{w}_i), m(\tilde{w}_i), u(\tilde{w}_i));\ i = 1, \ldots, n. \tag{12}$$

3.2. Fuzzy MULTIMOORA

The MULTIMOORA method is composed of MOORA and the full multiplicative form of multiple objectives. Brauers and Zavadskas (2011) argue that MULTIMOORA is the most robust system of multiple objective optimisation and show it is the only multicriteria method capable of satisfying all six conditions of robustness with three or more methods. Recent applications of MULTIMOORA include supplier selection (Karaca & Ulutaş, 2017; Liu et al., 2018; Stević et al., 2017), risk evaluation (Fattahi & Khalilzadeh, 2018; Zhao et al., 2017), logistics partner selection (Awasthi & Baležentis, 2017), residential house element and material selection (Zavadskas et al., 2017), project management (Dorfeshan et al., 2018), location planning of electric vehicle charging stations (Liu et al., 2018), robot evaluation and selection (Liu et al., 2018), agricultural machines and equipment selection (Hafezalkotob et al., 2018), mining method selection (Liang et al., 2019), entertainment company/industrial group selection (Wu et al., 2018), house element and material selection (Zavadskas et al., 2017), vehicle selection (Wu et al., 2017), battery recycling mode selection (Ding & Zhong, 2018), product design selection (Souzangarzadeh et al., 2017), augmented reality goggles selection (Aydin, 2018), and enterprise resource planning (Tian et al., 2017). Hafezalkotob et al. (2019) present a comprehensive review of the MULTIMOORA method.

3.2.1. Fuzzy MOORA (fuzzy ratio system method)

Multi-objective optimisation with ratio analysis or MOORA, first introduced by Brauers and Zavadskas (2006), is the process of simultaneously optimising two or more conflicting attributes (objectives) subject to certain constraints. The MOORA is a MCDM method commonly used in the literature (Akkaya et al., 2015) for solving business problems such as product and process design, finance, aircraft design, oil and gas industry, manufacturing sector, automobile design, or elsewhere where optimal decisions must take into consideration the trade-offs between two or more conflicting objectives (Chakraborty, 2011; Gadakh et al., 2013). The MOORA constructs a ranking derived from three calculations: the ratio system, the reference point, and the full multiplicative form of multiple objectives (Ceballos et al., 2016; Hafezalkotob & Hafezalkotob, 2015). Brauers and Zavadskas (2006) introduced fuzzy MOORA as a MCDM method for the first time for a privatisation study in a subsistence economy. There are three different approaches for solving problems with fuzzy MOORA: the fuzzy ratio method, the reference point approach, and the full multiplicative form. In this paper, we use the fuzzy ratio method of Akkaya et al. (2015). The steps of the fuzzy ratio method applied in this study are similar to the methods proposed by Akkaya et al. (2015), Gupta et al. (2017) and Karande and Chakraborty (2012):

Step 1: Form decision matrices using triangular fuzzy numbers.

$$\tilde{X} = \begin{bmatrix} [x_{11}^l, x_{11}^m, x_{11}^u] & [x_{12}^l, x_{12}^m, x_{12}^u] & \cdots & [x_{1n}^l, x_{1n}^m, x_{1n}^u] \\ \vdots & \vdots & \cdots & \vdots \\ [x_{m1}^l, x_{m1}^m, x_{m1}^u] & [x_{m2}^l, x_{m2}^m, x_{m2}^u] & \cdots & [x_{mm}^l, x_{mm}^m, x_{mm}^u] \end{bmatrix} \tag{13}$$

Step 2: Transform the decision matrix into the normalised fuzzy decision matrix using Equations (14), (15), and (16):

$$AS = \tilde{X}_{ij}^{*} = (x_{ij}^{l*}, x_{ij}^{m*}, x_{ij}^{u*},)\text{and} \quad \forall i, j;$$

$$x_{ij}^{l*} = \frac{x_{ij}^{l}}{\sqrt{\sum_{i=1}^{m} [(x_{ij}^{l})^2 + (x_{ij}^{m})^2 + (x_{ij}^{u})^2 +]}} \tag{14}$$

$$x_{ij}^{m*} = \frac{x_{ij}^{m}}{\sqrt{\sum_{i=1}^{m} [(x_{ij}^{l})^2 + (x_{ij}^{m})^2 + (x_{ij}^{u})^2 +]}} \tag{15}$$

$$x_{ij}^{u*} = \frac{x_{ij}^{u}}{\sqrt{\sum_{i=1}^{m} [(x_{ij}^{l})^2 + (x_{ij}^{m})^2 + (x_{ij}^{u})^2 +]}} \tag{16}$$

Step 3: Determine the weighted normalised fuzzy decision matrix by using Equations (17), (19), (19), and (20):

$$\text{As} \quad V_{ij} = (v_{ij}^l, v_{ij}^m, v_{ij}^u);$$

$$v_{ij}^l = w_j \chi_{ij}^{l*} \tag{17}$$

$$v_{ij}^m = w_j \chi_{ij}^{m*} \tag{18}$$

$$v_{ij}^u = w_j \chi_{ij}^{u*} \tag{19}$$

We used the weights obtained from Fuzzy AHP to calculate the weighted normalised fuzzy decision matrix.

Step 4: Calculate the normalised performance values by subtracting the total cost criteria from the total benefit criteria using Equation (20):

$$\text{As} \quad V_{ij} = (v_{ij}^l, v_{ij}^m, v_{ij}^u);$$

$$y_i = \sum_{j=1}^{g} V_{ij} - \sum_{j=g+1}^{n} V_{ij} \tag{20}$$

where $\sum_{j=1}^{g} V_{ij}$ is the benefit criteria (for 1, … ,g), $\sum_{j=g+1}^{n} V_{ij}$ is the risk criteria (for g+1, … ,n), g is the maximum number of criteria, and $(n-g)$ is the minimum number of criteria. For the benefit criteria, we can compute the overall ratings of an alternative for the lower values, middle values and the upper values of the triangular membership function as follows:

$$y_i^{+l} = \sum_{j=1}^{n} v_{ij}^l | j \in J^{\max} \tag{21}$$

$$y_i^{+m} = \sum_{j=1}^{n} v_{ij}^m | j \in J^{\max} \tag{22}$$

$$y_i^{+u} = \sum_{j=1}^{n} v_{ij}^u | j \in J^{\max} \tag{23}$$

Similarly, the overall ratings of an alternative are calculated for the risk criteria as follows:

$$y_i^{-l} = \sum_{j=1}^{n} v_{ij}^l | j \in J^{\max} \tag{24}$$

$$y_i^{-m} = \sum_{j=1}^{n} v_{ij}^m | j \in J^{\max} \tag{25}$$

$$y_i^{-u} = \sum_{j=1}^{n} v_{ij}^u | j \in J^{\max} \tag{26}$$

Step 5: Determine the overall performance index (y) for each alternative by calculating the de-fuzzified values of the overall ratings for the risk and benefit criteria for each alternative using the vertex method as follows:

$$\text{As} \quad y_i = (y_i^l, y_i^m, y_i^u);$$

$$BNP_i(y_i) = \frac{(y_i^u - y_i^l) + (y_i^m - y_i^l)}{3} + y_i^l \tag{27}$$

where BNP_i denotes the overall performance value of the i-th alternative.

Step 6: Using the overall performance index in descending order, next rank the alternatives from the best to the worst. The alternative, which has the highest overall performance index is the most preferred choice.

3.2.2. Fuzzy reference point method

The reference point approach uses the normalised performance of the i-th alternative on the j-th criterion, which is calculated according to Equations (14), (15), and (16). A maximum criterion reference point is determined among the normalised performances which is more realistic and non-subjective as the coordinates (r_j). Adalı and Işık (2017) and Akkaya et al. (2015) show the Tchebycheff min–max metric formulated according to Equation (28) is the most appropriate formulation for the reference point:

$$\begin{cases} \tilde{r}_j^{+} = \left(\max\limits_i \; x_{ij}{}^{l*}, \max\limits_i \; x_{ij}{}^{m*}, \max\limits_i \; x_{ij}{}^{u*} \right), \\ \quad j \le g; \text{ for criteria to be maximized} \\ \tilde{r}_j^{=} = \left(\min\limits_i \; x_{ij}{}^{l*}, \min\limits_i \; x_{ij}{}^{m*}, \min\limits_i \; x_{ij}{}^{u*} \right), \\ \quad j \rangle g; \text{ for criteria to be minimized} \end{cases} \tag{28}$$

If the decision makers want to give more importance to a criterion, Equation (28) is reformulated by considering the weights of the criteria as follows:

$$\min_i \left(\max_j \; W_j \; \times |\tilde{r}_j - \tilde{x}_{ij}^{*}| \right) \tag{29}$$

Finally, the alternatives are ranked according to Equation (27) and the best alternative is chosen with the minimum total deviation from the reference points (Adalı & Işık, 2017).

3.2.3. Fuzzy full multiplicative form

The Full Multiplicative Form is the third step of the MULTIMOORA method. The full multiplicative form of multiple criteria, which consists of both maximisation and minimisation of a purely multiplicative utility function, was first developed by Miller and Starr (1969). The main characteristics of this form is being nonlinear, non-additive, and not using attribute weights (Adalı & Işık, 2017). To obtain the utility of the full multiplicative form, the product of weighted normalised alternatives ratings on benefit criteria are divided by the product of the weighted normalised alternatives ratings on the risk criteria (Hafezalkotob et al., 2019):

$$\tilde{U}'_i = \frac{\tilde{A}_i}{\tilde{B}_i} \tag{30}$$

where $\tilde{A}_i = (A_{i1}, A_{i2}, A_{i3}) = \prod_{j=1}^{g} (x^*{}_{ij})^{w_j}$ symbolises the product of objectives of the i-th alternative to be maximised with $g = 1, 2, \ldots, n$ denoting the number of objectives (structural indicators) to be maximised, and $\tilde{B}_i = (B_{i1}, B_{i2}, B_{i3}) = \prod_{j=g+1}^{m} (x^*{}_{ij})^{w_j}$ symbolises the product of the objectives of the i-th alternative to be minimised with $n - g$ denoting the number of objectives (indicators) to be minimised. In the utility formula of the full multiplicative form, multiplying the normalised ratings with weights leads to the same result as the situation in which no weights are considered. Thus, weights should be considered as exponents of the utility equation in the full multiplicative form (Hafezalkotob et al., 2019). Defuzzification is needed to rank the alternatives according to Equation (27) since the overall utility ($\tilde{U}'_i$) is a fuzzy number. The higher the BNP_i is the higher rank of the i-th alternative (Akkaya et al., 2015).

The best alternative based on the full multiplicative form has the maximum utility ($\tilde{U}'_i$) and the ranking of this technique is generated in descending order as:

$$R_{FMF} = \left\{ A_{i|\max_i u_i} > \ldots > A_{i|\max_i u_i} \right\}. \tag{31}$$

3.2.4. Final ranking (dominance theory)

The three methods of MULTIMOORA are assumed to have equal importance. A number of aggregation methods can be used to integrate the rankings of the three subordinate methods. In this regard, the most common ranking aggregation method in the MULTIMOORA literature is dominance theory (Hafezalkotob et al., 2019), which is also the concept adopted in the original MULTIMOORA suggested by Brauers and Zavadskas (2011). Accordingly, the final ranking of the alternatives is obtained using dominance theory. Absolute dominance, general dominance in two of the three methods, and transitiveness principles are used to obtain the final ranking of the alternatives (Brauers & Zavadskas, 2011).

4. Results

The integrated fuzzy AHP-fuzzy MULTIMOORA model proposed in this study is used to help Technoron Electronics[1], a manufacturer of consumer electronic goods in New Jersey, with supplier evaluation and selection. We designed two questionnaires presented in Appendix A to collect the relevant data used in the fuzzy AHP and fuzzy MULTIMOORA methods. The process begins with fuzzy AHP and design of the hierarchical structure according to the supplier selection and risk-benefit factors identified through literature review and expert opinions. Figure 3 presents the hierarchical structure of the risks and benefits used at Technoron.

Fuzz AHP is used to assign priorities to each criterion in the hierarchical structure presented in Figure 3. The pairwise comparison matrices for the evaluation criteria are constructed using a team of experts. We used the group decisions matrix and Equation (3) to determine the criteria weights. Equations (4), (5), and (6) were used to calculate the CR of the pairwise comparison matrices. The result presented in Table 4 indicate the final CRs are less than 0.10 for the risk and benefit factors.

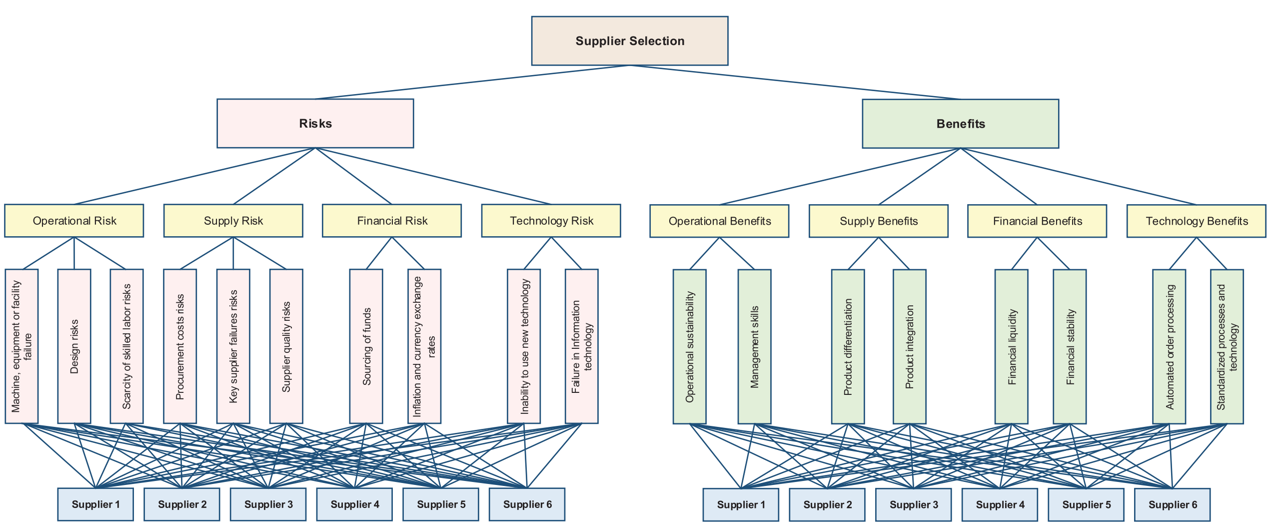


Figure 3. Hierarchical structure.

Table 4. Fuzzy group decision matrix of criteria.

(a) Risk criteria

Risk	C1			C2			C3			C4		
C1	1	1	1	0/654	0/816	1	1	1/414	1/936	0/338	0/408	0/516
C2	1	1/224	1/527	1	1	1	1	1/414	1/936	0/285	0/333	0/4
C3	0/516	0/707	1	0/516	0/707	1	1	1	1	0/285	0/333	0/4
C4	1/936	2/449	2/958	2/5	3	3/5	2/5	3	3/5	1	1	1

$$CI = \frac{(\lambda_{\max} - n)}{n-1} = \frac{(4.085-4)}{3-1} = 0.0284$$

$$CR = \frac{CI}{RI(n)} = \frac{0.0284}{0.9} = 0.0315$$

$$\widetilde{RS}_1 = (1,1,1) \oplus (0.654, 0.816, 1) \oplus (1, 1.414, 1.936) \oplus (0.338, 0.408, 0.516) = (3.33, 4.04, 4.96)$$

$$\tilde{S}_1 = \frac{\widetilde{RS}_1}{\sum_{j=1}^{n} \widetilde{RS}_j} = \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{j=1}^{n} l_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1,k=i}^{n} \sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{j=1}^{n} u_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} l_{kj}} \right)$$

$$= \left(\frac{3.33}{24.35}, \frac{4.04}{21.88}, \frac{4.96}{20.08} \right) = (0.136, 0.184, 0.247)$$

Then,
WC1 = (0.136,0.184,0.247)
WC2 = (0.146,0.196,0.261)
WC3 = (0.105,0.140,0.193)
WC4 = (0.389,0.477,0.557)

(b) Benefit criteria

Benefits	B1			B2			B3			B4		
B1	1	1	1	1/5	2	2/5	1/5	2	2/5	1/5	2	2/5
B2	0/4	0/5	0/666	1	1	1	0/666	1	1/5	1/5	2	2/5
B3	0/4	0/5	0/666	1/5	1	0/666	1	1	1	2/5	3	3/5
B4	0/4	0/5	0/666	0/4	0/5	0/666	0/285	0/333	0/4	1	1	1

$$CI = \frac{(\lambda_{\max} - n)}{n-1} = \frac{(4.21-4)}{3-1} = 0.0703$$

$$CR = \frac{CI}{RI(n)} = \frac{0.0703}{0.9} = 0.0781$$

$$\widetilde{RS}_1 = (1,1,1) \oplus (1.5, 2, 2.5) \oplus (1.5, 2, 2.5) \oplus (1.5, 2, 2.5) = (7, 9, 11)$$

$$\tilde{S}_1 = \frac{\widetilde{RS}_1}{\sum_{j=1}^{n} \widetilde{RS}_j} = \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{j=1}^{n} l_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1,k=i}^{n} \sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{j=1}^{n} u_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} l_{kj}} \right)$$

$$= \left(\frac{7}{28.23}, \frac{9}{27.33}, \frac{11}{27.05} \right) = (0.247, 0.329, 0.406)$$

Then,
WB1 = (0.247,0.329,0.406).
WB2 = (0.173,0.237,0.312).
WB3 = (0.256,0.310,0.381).
WB4 = (0.0976,0.121,0.157).

Table 5. Fuzzy group decision matrix of operational risks.

Operational risk	C11			C12			C13		
C11	1	1	1	2.291	2.828	3.354	1.936	2.449	2.958
C12	0.745	0.353	0.436	1	1	1	2.5	3	3.5
C13	0.845	0.408	0.516	0.285	0.333	0.4	1	1	1

Wc11 = (0.432,0.507,0.462)
Wc12 = (0.315,0.351,0.401)
Wc13 = (0.148,0.140,0.168)

Table 6. Fuzzy group decision matrix of supply risks.

Supply risk		C21			C22			C23	
C21	1	1	1	2.291	2.828	3.354	1	1.414	1.936
C22	0.745	0.353	0.436	1	1	1	1	1.414	1.936
C23	1.936	0.707	0.666	1.290	0.707	1	1	1	1

Wc21 = (0.226,0.502,0.474)
Wc22 = (0.234,0.265,0.283)
Wc23 = (0.304,0.231,0.274)

Table 7. Fuzzy group decision matrix of financial risks.

Financial risk		C31			C32	
C31	1	1	1	1	1.414	1.936
C32	1.936	0.707	0.666	1	1	1

Wc31 = (0.545,0.585,0.5)
Wc32 = (0.5,0.414,0.454)

Table 8. Fuzzy group decision matrix of technology risks.

Technology risk		C41			C42	
C41	1	1	1	2.958	1.414	1.732
C42	0.577	0.707	0.845	1	1	1

Wc41 = (0.682,0.585,0.633)
Wc42 = (0.366,0.414,0.317)

Equations (7) and (8) are used to calculate the fuzzy synthetic measurement index. Equations (12) are then employed to construct the comparison matrices and the global priority weights of the evaluation criteria. The results are presented in Tables 4–8.

After determining the synthetic measurements index, we calculate the ratio and final weights shown in Table 9. The zero weights for some sub-criteria implies that those sub-criteria have no effect on supplier selection.

Next, we use the fuzzy MULTIMOORA method to evaluate the alternatives. Six alternative suppliers (S1, S2, S3, S4, S5 and S6) were evaluated. The fuzzy decision matrix presented in Table 10(a) and (b) shows the values used for the risk and benefit criteria, respectively.

We then use Equations (14), (15), and (16) to normalise the fuzzy decision matrix. The normalised fuzzy decision matrices for the risks and benefits are shown in Table 11(a) and (b), respectively.

Next, we use Equations (17), (18) and (19) to construct the weighted normalised fuzzy decision matrices for the risks and benefits. The overall ratings of the criteria for each alternative is calculated using Equation (20). For the benefit criteria, we use Equations (21), (22), and (23) and compute the overall ratings of an alternative for the lower values, middle values and the upper values of the triangular membership function, respectively. Similarly, for the risk criteria, we use Equations (24), (25), and (26) and compute the overall ratings of an alternative for the lower values, middle values and the upper values of the triangular membership function, respectively. The weighted normalised fuzzy decision matrices for the risks and benefits are presented in Table 12(a) and (b). We then use Equation (27) to de-fuzzify the overall rating of the criteria. The ranking result of the suppliers according to the fuzzy ratio system method (S6 > S5 > S4 > S3 > S1 > S2) is presented in Table 13. According to the fuzzy ratio method. Supplier 6 is the best alternative supplier.

Table 9. The final criteria weights of risks.

(a) Risk criteria

Criterion	Risks criteria	Risk weight		Risk sub-criteria weight	Final weight
C1	Operational risk	(0.136,0.184,0.247)	C11	(0.432,0.507,0.462)	(0.059,0.093,0.114)
			C12	(0.315,0.351,0.401)	(0.043,0.065,0.099)
			C13	(0.148,0.140,0.168)	(0.02,0.026,0.041)
C2	Supply risk	(0.146,0.196,0.261)	C21	(0.226,0.502,0.474)	(0.033,0.098,0.123)
			C22	(0.234,0.265,0.283)	(0.034,0.052,0.074)
			C23	(0.304,0.231,0.274)	(0.044,0.045,0.071)
C3	Financial risk	(0.105,0.170,0.193)	C31	(0.545,0.585,0.5)	(0.057,0.082,0.096)
			C32	(0.5,0.414,0.454)	(0.052,0.058,0.087)
C4	Technology risk	(0.389,0.477,0.557)	C41	(0.682,0.585,0.633)	(0.265,0.279,0.353)
			C42	(0.366,0.414,0.317)	(0.142,0.197,0.177)

(b) Benefit criteria

Criterion	Risks criteria	Risk weight		Risk sub-criteria weight	Final weight
B1	Operational benefit	(0.247,0.329,0.406)	B11	(0.6,0.66,0.714)	(0.148,0.219,0.290)
			B12	(0.285,0.333,0.4)	(0.0708,0.109,0.162)
B2	Supply benefit	(0.173,0.237,0.312)	B21	(0.714,0.75,0.777)	(0.124,0.178,0.242)
			B22	(0.222,0.25,0.285)	(0.038,0.059,0.089)
B3	Financial benefit	(0.256,0.310,0.381)	B31	(0.777,0.8,0.818)	(0.199,0.248,0.311)
			B32	(0.181,0.2,0.222)	(0.046,0.062,0.084)
B4	Technology benefit	(0.0976,0.121,0.157)	B41	(0.714,0.75,0.777)	(0.069,0.091,0.122)
			B42	(0.222,0.25,0.285)	(0.021,0.030,0.045)

Table 10. Fuzzy decision matrix.

(a) Risks

Supplier	C11	C12	C13	C21	C22	C23	C31	C32	C41	C42
S1	(0,0,0.2)	(0,0,0.2)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.6,0.8,1)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.6,0.8,1)	(0.2,0.4,0.6)	(0.4,0.6,0.8)
S2	(0.4,0.6,0.8)	(0,0,0.2)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.6,0.8,1)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.6,0.8,1)	(0.4,0.6,0.8)	(0.4,0.6,0.8)
S3	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.6,0.8,1)	(0,0.2,0.4)	(0.6,0.8,1)	(0.4,0.6,0.8)
S4	(0,0.2,0.4)	(0,0,0.2)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.6,0.8,1)	(0,0.2,0.4)	(0,0.2,0.4)
S5	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0,0.2,0.4)	(0.4,0.6,0.8)	(0,0.2,0.4)	(0,0.2,0.4)	(0,0.2,0.4)	(0.6,0.8,1)	(0,0.2,0.4)	(0.4,0.6,0.8)
S6	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0,0.2,0.4)	(0.4,0.6,0.8)	(0,0.2,0.4)	(0.2,0.4,0.6)	(0,0.2,0.4)	(0.6,0.8,1)	(0,0.2,0.4)	(0,0.2,0.4)

(b) Benefits

Supplier	B11	B12	B21	B22	B31	B32	B41	B42
S1	(0,0.2,0.4)	(0,0.2,0.4)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.4,0.6,0.8)
S2	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0,0.2,0.4)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.4,0.6,0.8)
S3	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.2,0.4,0.6)
S4	(0.2,0.4,0.6)	(0,0.2,0.4)	(0.2,0.4,0.6)	(0,0.2,0.4)	(0.2,0.4,0.6)	(0,0.2,0.4)	(0.2,0.4,0.6)	(0,0.2,0.4)
S5	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.4,0.6,0.8)	(0.2,0.4,0.6)	(0.6,0.8,1)	(0.2,0.4,0.6)	(0.4,0.6,0.8)
S6	(0.6,0.8,1)	(0.6,0.8,1)	(0.4,0.6,0.8)	(0.6,0.8,1)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.6,0.8,1)

Table 11. Normalised fuzzy decision matrix.

(a) Risks

Supplier	C11	C12	C13	C21	C22	C23	C31	C32	C41	C42
S1	0	0	0.267	0.371	0.424	0.371	0.267	0.424	0.267	0.371
	0.447	0.447	0.534	0.557	0.565	0.557	0.534	0.565	0.534	0.557
	0.894	0.894	0.801	0.742	0.707	0.742	0.801	0.707	0.801	0.742
S2	0.371	0	0.267	0.371	0.424	0.371	0.371	0.424	0.371	0.371
	0.557	0.447	0.534	0.557	0.565	0.557	0.557	0.565	0.557	0.557
	0.742	0.894	0.801	0.742	0.707	0.742	0.742	0.707	0.742	0.742
S3	0.371	0.267	0.371	0.371	0.371	0.371	0.424	0	0.424	0.371
	0.557	0.534	0.557	0.557	0.557	0.557	0.565	0.447	0.565	0.557
	0.742	0.801	0.742	0.742	0.742	0.742	0.707	0.894	0.707	0.742
S4	0	0	0.262	0.371	0.371	0.267	0.267	0.424	0	0
	0.447	0.447	0.534	0.557	0.557	0.534	0.535	0.565	0.447	0.447
	0.894	0.894	0.801	0.742	0.742	0.801	0.801	0.707	0.894	0.894
S5	0.267	0.267	0	0.371	0	0	0	0.424	0	0.371
	0.534	0.534	0.447	0.557	0.447	0.447	0.447	0.565	0.447	0.557
	0.801	0.801	0.894	0.742	0.894	0.894	0.894	0.707	0.894	0.742
S6	0.371	0.267	0	0.371	0	0.267	0	0.424	0	0
	0.557	0.534	0.447	0.557	0.447	0.534	0.447	0.565	0.447	0.447
	0.742	0.801	0.894	0.742	0.894	0.801	0.894	0.707	0.894	0.894

(b) Benefits

Supplier	B11	B12	B21	B22	B31	B32	B41	B42
S1	0	0	0.267	0.371	0.267	0.267	0.267	0.371
	0.447	0.447	0.534	0.557	0.534	0.534	0.534	0.557
	0.894	0.894	0.801	0.742	0.801	0.801	0.801	0.742
S2	0.267	0.371	0	0.371	0.267	0.371	0.371	0.371
	0.534	0.557	0.447	0.557	0.534	0.557	0.557	0.557
	0.801	0.742	0.894	0.742	0.801	0.742	0.742	0.742
S3	0.371	0.267	0.267	0.267	0.371	0.267	0.371	0.267
	0.557	0.534	0.534	0.534	0.557	0.534	0.557	0.534
	0.742	0.801	0.801	0.801	0.742	0.801	0.742	0.801
S4	0.267	0	0.267	0	0.267	0	0.267	0
	0.534	0.447	0.534	0.447	0.534	0.447	0.534	0.447
	0.801	0.894	0.801	0.894	0.801	0.894	0.801	0.894
S5	0.267	0.371	0.267	0.371	0.267	0.424	0.267	0.371
	0.534	0.557	0.534	0.557	0.534	0.565	0.534	0.557
	0.801	0.742	0.801	0.742	0.801	0.707	0.801	0.742
S6	0.424	0.424	0.371	0.424	0.371	0.371	0.371	0.424
	0.565	0.565	0.557	0.565	0.557	0.557	0.557	0.565
	0.707	0.707	0.742	0.707	0.742	0.742	0.742	0.707

Next, we use Equations (28) and (29) to calculate the overall performance value of the alternatives presented in Tables 14 and 15 using the fuzzy reference point method (Adalı & Işık, 2017; Akkaya et al., 2015). Table 14(a) and (b) present the reference point vector for the risks and benefits, respectively. Table 15(a) and (b) present the

Table 12. Weighted normalised fuzzy decision matrix.

(a). Risks

Supplier	C11	C12	C13	C21	C22	C23	C31	C32	C41	C42
S1	0	0	0.005	0.012	0.014	0.016	0.015	0.022	0.0709	0.052
	0.0419	0.029	0.013	0.055	0.029	0.025	0.044	0.032	0.149	0.11
	0.102	0.088	0.033	0.092	0.052	0.053	0.077	0.062	0.283	0.131
S2	0.021	0	0.005	0.012	0.014	0.016	0.021	0.022	0.098	0.052
	0.052	0.029	0.013	0.055	0.029	0.025	0.045	0.032	0.155	0.11
	0.085	0.088	0.033	0.092	0.052	0.053	0.071	0.062	0.262	0.131
S3	0.021	0.011	0.007	0.012	0.012	0.016	0.024	0	0.112	0.052
	0.052	0.034	0.014	0.055	0.029	0.025	0.046	0.026	0.158	0.11
	0.085	0.079	0.030	0.092	0.055	0.053	0.068	0.078	0.249	0.131
S4	0	0	0.005	0.012	0.012	0.016	0.015	0.022	0	0
	0.041	0.029	0.013	0.055	0.029	0.025	0.044	0.032	0.125	0.088
	0.151	0.088	0.033	0.092	0.055	0.053	0.077	0.062	0.315	0.158
S5	0	0.011	0	0.012	0.092	0.016	0	0.022	0	0.052
	0.0419	0.034	0.011	0.055	0.012	0.025	0.036	0.032	0.125	0.11
	0.102	0.079	0.037	0.092	0.029	0.053	0.086	0.062	0.315	0.131
S6	0.012	0.011	0	0.012	0.092	0.0	0	0.022	0	0
	0.0501	0.034	0.011	0.055	0.012	0.0203	0.036	0.032	0.125	0.088
	0.0918	0.079	0.039	0.092	0.029	0.064	0.086	0.062	0.315	0.158

(b) Benefits

Supplier	B11	B12	B21	B22	B31	B32	B41	B42
S1	0	0	0.0332	0.014	0.053	0.012	0.018	0.008
	0.095	0.049	0.0953	0.033	0.132	0.033	0.048	0.016
	0.259	0.145	0.194	0.066	0.25	0.067	0.098	0.033
S2	0.039	0.026	0	0.014	0.053	0.017	0.025	0.008
	0.117	0.061	0.079	0.033	0.132	0.034	0.05	0.016
	0.232	0.12	0.217	0.066	0.25	0.062	0.091	0.033
S3	0.055	0.018	0.033	0.010	0.071	0.012	0.025	0.0058
	0.122	0.058	0.095	0.031	0.138	0.033	0.05	0.016
	0.215	0.13	0.194	0.071	0.231	0.067	0.091	0.036
S4	0.039	0	0.033	0	0.053	0	0.018	0
	0.117	0.049	0.095	0.026	0.132	0.027	0.048	0.013
	0.232	0.145	0.194	0.079	0.25	0.075	0.098	0.04
S5	.0.039	0.026	0.033	0.014	0.053	0.019	0.018	0.008
	0.117	0.061	0.095	0.033	0.132	0.035	0.048	0.016
	0.232	0.120	0.194	0.066	0.25	0.059	0.098	0.033
S6	0.063	0.030	0.046	0.016	0.071	0.017	0.025	0.009
	0.124	0.062	0.099	0.033	0.138	0.034	0.05	0.017
	0.205	0.115	0.18	0.063	0.231	0.062	0.091	0.031

Table 13. Alternative rankings using fuzzy ratio method.

$$y_i = \sum_{j=1}^{g} \tilde{v}_{ij} - \sum_{j=g+1}^{n} \tilde{v}_{ij}$$

	Benefits			Risks				
Supplier	l	m	u	l	m	u	BNP_i	Fuzzy ratio method rankings
S1	0.1400	0.5078	1.115	0.2104	0.5318	0.944	0.0148	5
S2	0.1850	0.5269	1.074	0.2659	0.5503	0.9331	0.0123	6
S3	0.235	0.5471	1.039	0.2725	0.5523	0.9245	0.0242	4
S4	0.1449	0.5116	1.117	0.0801	0.4841	1.0435	0.0553	3
S5	0.2134	0.5409	1.056	0.1148	0.5006	1.0275	0.0558	2
S6	0.2822	0.5606	0.981	0.0800	0.4849	1.041	0.0727	1

weighted distance between the normalised matrix entries and the reference points for the risks and benefits, respectively. We then use Equation (27) to calculate the fuzzy reference points rankings (S6 > S4 > S5 > S1 > S2 > S3) presented in Table 16. According to the fuzzy reference points method, Supplier 6 is the best supplier alternative.

We then use Equation (30) for the full multiplicative form of multi-criteria, which consists of both

Table 14. Reference point vector (r).

(a) Risks

	C11	C12	C13	C21	C22	C23	C31	C32	C41	C42
r	0	0	0	0.371	0	0	0	0	0	0
	0.447	0.447	0.447	0.557	0.447	0.447	0.447	0.447	0.447	0.447
	0.894	0.894	0.894	0.742	0.894	0.894	0.894	0.894	0.894	0.894

(b) Benefits

	B11	B12	B21	B22	B31	B32	B41	B42
r	0.424	0.424	0.371	0.424	0.371	0.424	0.371	0.424
	0.565	0.565	0.557	0.565	0.557	0.565	0.557	0.565
	0.707	0.707	0.742	0.707	0.742	0.707	0.742	0.707

Table 15. Weighted distance between the normalised matrix entries and the reference points.

(a) Risks

Supplier	C11	C12	C13	C21	C22	C23	C31	C32	C41	C42
S1	0	0	0.005	0	0.014	0.016	0.015	0.022	0.0709	0.052
	0	0	0.0022	0	0.006	0.005	0.007	0.006	0.024	0.021
	0	0	0.0038	0	0.013	0.010	0.008	0.016	0.032	0.026
S2	0.021	0	0.005	0	0.014	0.016	0.021	0.022	0.098	0.052
	0.0103	0	0.0022	0	0.006	0.005	0.009	0.006	0.03	0.021
	0.017	0	0.0038	0	0.013	0.010	0.014	0.016	0.053	0.026
S3	0.021	0.011	0.007	0	0.012	0.016	0.024	0	0.112	0.052
	0.0103	0.005	0.002	0	0.005	0.005	0.009	0	0.033	0.021
	0.017	0.009	0.006	0	0.011	0.010	0.018	0	0.066	0.026
S4	0	0	0.005	0	0.012	0.011	0.015	0.022	0	0
	0	0	0.0022	0	0.005	0.003	0.007	0.006	0	0
	0	0	0.0038	0	0.011	0.006	0.008	0.016	0	0
S5	0.015	0.011	0	0	0	0	0	0.022	0	0.052
	0.008	0.005	0	0	0	0	0	0.006	0	0.021
	0.0106	0.009	0	0	0	0	0	0.016	0	0.026
S6	0.021	0.011	0	0	0	0.011	0	0.022	0	0
	0.0103	0.005	0	0	0	0.003	0	0.006	0	0
	0.017	0.009	0	0	0	0.006	0	0.016	0	0

(b) Benefits

Supplier	B11	B12	B21	B22	B31	B32	B41	B42
S1	0.063	0.03	0.012	0.002	0.02	0.007	0.007	0.0011
	0.026	0.013	0.004	0.0005	0.005	0.0019	0.002	0.00002
	0.054	0.03	0.014	0.003	0.018	0.008	0.007	0.0016
S2	0.023	0.003	0.046	0.002	0.02	0.0024	0	0.0011
	0.006	0.0009	0.019	0.0005	0.005	0.0005	0	0.00002
	0.027	0.005	0.014	0.003	0.018	0.003	0	0.0016
S3	0.007	0.011	0.012	0.006	0	0.007	0	0.003
	0.001	0.003	0.004	0.001	0	0.0019	0	0.0009
	0.010	0.015	0.014	0.008	0	0.008	0	0.004
S4	0.0233	0.03	0.012	0.016	0.02	0.019	0.007	0.009
	0.006	0.013	0.004	0.007	0.005	0.007	0.002	0.003
	0.027	0.03	0.014	0.016	0.018	0.015	0.007	0.008
S5	0.0233	0.003	0.012	0.002	0.02	0	0.007	0.001
	0.006	0.0009	0.004	0.0005	0.005	0	0.002	0.0002
	0.027	0.005	0.014	0.003	0.018	0	0.007	0.0016
S6	0	0	0	0	0	0.0024	0	0
	0	0	0	0	0	0.0005	0	0
	0	0	0	0	0	0.003	0	0

maximisation and minimisation of a purely multiplicative utility function. This form is non-linear, non-additive, and does not use the criteria weights. The overall utility of each alternative using the full multiplicative form ($\tilde{U}_i'$) is presented in Table 17. Defuzzification is needed to calculate BNP_i according to Equation (27) since the overall utility ($\tilde{U}_i'$) is a fuzzy number. The overall ranking of the suppliers according to the

Table 16. Alternative rankings using the fuzzy reference point approach.

Supplier	$\left(\max_j W_j \times \left\lvert \tilde{r}_j - \tilde{x}^*_{ij} \right\rvert\right)$			BNP_i	Fuzzy reference point method rankings
S1	0.0709	0.024	0.032	0.0426	4
S2	0.098	0.03	0.053	0.060	5
S3	0.112	0.033	0.066	0.0706	6
S4	0.03	0.013	0.03	0.0245	2
S5	0.052	0.021	0.026	0.0338	3
S6	0.022	0.006	0.016	0.0152	1

Table 18. Alternative rankings (aggregation and comparison).

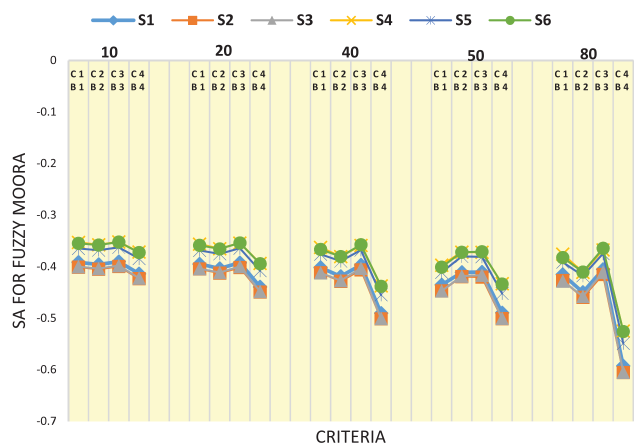
Supplier	Fuzzy ratio method rankings (Table 13)	Fuzzy reference point method rankings (Table 16)	Fuzzy full multiplicative method rankings (Table 17)	Fuzzy MULTIMOORA method rankings
S1	5	4	5	5
S2	6	5	6	6
S3	4	6	4	4
S4	3	2	3	3
S5	2	3	2	2
S6	1	1	1	1

full multiplicative form (S6 > S5 > S4 > S3 > S1 > S2) is given in Table 17. According to the full multiplicative form method, Supplier 6 is the best alternative supplier.

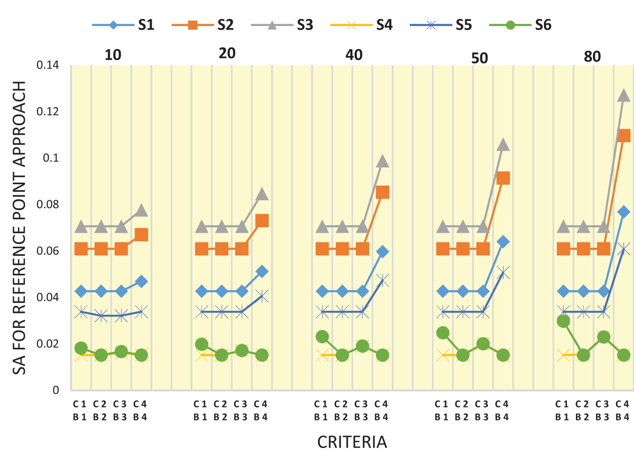
Finally, the fuzzy MULTIMOORA is used to determine the final ranking of the suppliers presented in Table 18 using dominance theory. According to dominance theory, the MULTIMOORA ranking of the supplier is S6 > S5 > S4 > S3 > S1 > S2.

As shown in Table 18, Supplier 6 is the most preferred supplier because all three methods pick Supplier 6 as the best alternative supplier (absolute dominance). Supplier 5 is ranked second because of partial dominance since two of the three methods (fuzzy ratio method and fuzzy full multiplicative method) pick Supplier 5 as the second best method (partial dominance).

Next, the consistency of the final ranking is analysed for various values of the determinant weights since the preference of the model is dependent on the subjective judgments of the decision makers. Akkaya et al. (2015) and Büyüközkan and Çifçi (2012) recommend a careful review of the weights when the ranking is very sensitive to small changes in the criteria weights. To test the sensitivity, we conducted a sensitivity analysis by increasing the weight of each criterion individually based on the results obtained from the fuzzy AHP steps. The fuzzy MULTIMOORA steps were then repeated for each scenario and the resulting changes in the alternative raking were observed. To perform the sensitivity analysis, the weight of each criterion is increased by 10% -80% while the weight of other criteria is kept constant. As shown in Figure 4, the ranking remained unchanged, showing the robustness and stability of the model proposed in this study.



(a). Fuzzy MOORA



(b). Reference points approach

Figure 4. Sensitivity analysis results.

Table 17. Alternative rankings using fuzzy full multiplicative form approach.

Supplier	$\tilde{A}_i$			$\tilde{B}_i$			$\tilde{U}'_i = \frac{\tilde{A}_i}{\tilde{B}_i}$			BNP_i	Fuzzy full multiplicative method rankings
S1	0	0.33	0.43	0	0.44	0.58	0	0.74	0.73	0.493	5
S2	0	0.4	0.52	0	0.57	0.72	0	0.41	0.72	0.480	6
S3	0.41	0.5	0.61	0	0.6	0.76	0	0.82	0.8	0.543	4
S4	0	0.33	0.43	0	0.28	0.43	0	1.171	0.98	0.720	3
S5	0.36	0.45	0.57	0	0.33	0.46	0	1.35	1.22	0.857	2
S6	0.57	0.67	0.84	0	0.28	0.43	0	2.33	1.91	1.419	1

5. Conclusions and managerial implications

Supplier risks and benefits in supply chains may have different drivers that impact the operations and efficiencies associated with the success of supply chains. We conducted an extensive literature review and used expert opinions to define four sets of risks and benefits in supply chains. These four sets of risks and benefits are grouped into *operational*, *supply*, *finance*, and *technology* factors. Each risk and benefit set include elements, which contribute to the supplier selection decisions. The supply chain risks considered in this study included machine, equipment or facility failure; design risks; scarcity of skilled labour risks; procurement costs risks; key supplier failures risks; supplier quality risks; sourcing of funds, inflation and currency exchange rates; inability to use new technology; and failure of information technology; and also the supply chain benefits considered in this study included operational sustainability, management skills; product differentiation, product integration; financial liquidity, financial stability; automated order processing, standardised processes and technology. The MULTIMOORA framework used in this study ranks the suppliers using risks and benefits simultaneously. We proposed an integrated framework to combine the fuzzy AHP method with the fuzzy MULTIMOORA method for a manufacturer of consumer electronic goods in Jersey City. The fuzzy AHP is used to measure the importance of the supply chain risk and benefit factors and the fuzzy MULTIMOORA is used to rank the suppliers. The ranking result from the fuzzy AHP indicate 'technology risk' is the most important risky set of factors followed by 'supply risk', 'operational risk', and 'financial risk'. As for the benefits, 'operational benefit' is considered the most important beneficial set of factors followed by 'financial benefit', 'supply benefit', and 'technology benefit'. The ranking result from the fuzzy AHP-fuzzy MULTIMOORA method indicated that Supplier 6 is the most preferred supplier with superior risk and benefit performance over the other suppliers. We also studied the uncertainty in the output of our proposed integrated framework using sensitivity analysis. We performed a sensitivity analysis for the fuzzy MOORA method and the fuzzy reference point method with a 10% – 80% change and the ranking remained unchanged. The results show robust rankings and the stability of the model proposed in this study.

In this study, we proposed an integrated supplier selection framework, which considers both supplier risks and benefits simultaneously. The proposed framework uses fuzzy logic, AHP, and MULTIMOORA to reduce the complexities inherent in supplier selection problems by decomposing the evaluation process into manageable steps. This decomposition is achieved without simplifying the problem. The proposed method is analytical, comprehensive, flexible, structured, and robust.

We first used the fuzzy AHP method to measure the importance of the supply chain risk and benefit factors. Many real-world problems involve uncertain, inadequate, imprecise, vague, and ambiguous information. We used fuzzy logic to model uncertainties and ambiguities in real-world problems because fuzzy logic is much closer in spirit to human thinking and natural language. Experts and practicing managers often lack confidence in data and judgements. Fuzzy Logic can translate managers' knowledge and experience into a set of basic rules in linguistic terms, which are intuitive and easy to understand. We used Fuzzy AHP because it adopts a hierarchical structure for modelling the suppliers' risk and benefit factors, allows for using verbal judgements that are easy to comprehend, and provides a mechanism to verify the consistency of expert judgments. While intuition is still favoured by some practicing managers, it is dangerously unreliable when used to solve complex problems. Fuzzy logic and AHP used here provide a systematic and scientific approach to capture and synthesise managerial intuition and judgement.

We then use MULTIMOORA to rank the alternative suppliers. MULTIMOORA combines three subordinate rankings obtained by the fully compensatory, non-compensatory, and incompletely compensatory models of the fuzzy ratio method, the fuzzy reference point method, and the fuzzy full multiplicative method. The results of the three ranking methods are then integrated into a final ranking using dominance theory. The integrated framework proposed in this study provides an efficient and effective procedure for selecting the most preferred supplier. It is reasonable to assume that this approach can be used in many other real-world problems and if utilised properly, can assist practicing managers in a wide range of problems from operational to strategic decision problems.

The main limitation of this study is the lack of experts who are well versed in risk-benefit analysis and quantitative decision-making. It would be interesting to collect data related to the supplier selection problem from numerous respondents with different levels of experience, qualification, and positions to investigate how expert selection would affect the supplier evaluation and selection process. Secondly, it would be interesting to explore how the interdependencies and correlations between selection criteria impact the supplier evaluation and selection process. Finally, the proposed model can be implemented in a decision support system for assisting manufacturers in performance assessment and supplier selection.

Note

1. Some of the names and data presented in this study are changed to protect the anonymity of the company.

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Disclosure statement

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Notes on contributors

Madjid Tavana is Professor and Distinguished Chair of Business Analytics at La Salle University, where he serves as Chairman of the Business Systems and Analytics Department. He also holds an Honorary Professorship in Business Information Systems at the University of Paderborn in Germany. Dr Tavana is Distinguished Research Fellow at the Kennedy Space Center, the Johnson Space Center, the Naval Research Laboratory at Stennis Space Center, and the Air Force Research Laboratory. He was recently honoured with the prestigious Space Act Award by NASA. He holds an MBA, PMIS and Ph.D. in Management Information Systems and received his Post-Doctoral Diploma in Strategic Information Systems from the Wharton School at the University of Pennsylvania. He has published 17 books and over 270 research papers in international scholarly academic journals. He is the Editor-in-Chief of the *International Journal of Applied Decision Sciences*, *International Journal of Management and Decision Making*, *International Journal of Communication Networks and Distributed Systems*, *International Journal of Knowledge Engineering and Data Mining*, *International Journal of Strategic Decision Sciences and International Journal of Enterprise Information Systems*.

Akram Shaabani is a doctoral candidate in the Department of Industrial Management at the Allameh Tabataba'i University in Tehran, Iran. Her research interest is in multi-criteria decision making. She has published several papers in international journals and presented her research and several international and domestic conferences.

Soleyman Mansouri Mohammadabadi is a doctoral candidate in the Department of Industrial Management at the Allameh Tabataba'i University. His research interest is in decision support systems. He has published several papers in international journals and presented his research in several international and domestic conferences.

Nilofar Varzgani is an Assistant Professor in the Department of Business Systems & Analytics at La Salle University in Pennsylvania. She received her BBA from the Institute of Business Administration, Karachi, Pakistan and her Ph.D. from Rutgers University in New Jersey. Her research interest focuses on Supply Chain Management, Financial Analytics, Deterministic and Stochastic environments.

ORCID

Madjid Tavana http://orcid.org/0000-0003-2017-1723
Akram Shaabani http://orcid.org/0000-0001-8802-0038

References

Adalı, E. A., & Işık, A. T. (2017). The multi-objective decision making methods based on MULTIMOORA and MOOSRA for the laptop selection problem. *Journal of Industrial Engineering International*, *13*(2), 229–237. https://doi.org/10.1007/s40092-016-0175-5

Akkaya, G., Turanoğlu, B., & Öztaş, S. (2015). An integrated fuzzy AHP and fuzzy MOORA approach to the problem of industrial engineering sector choosing. *Expert Systems with Applications*, *42*(24), 9565–9573. https://doi.org/10.1016/j.eswa.2015.07.061

Ali, I., Nagalingam, S., & Gurd, B. (2017). Building resilience in SMEs of perishable product supply chains: Enablers, barriers and risks. *Production Planning & Control*, 7287(August), 1–15. https://doi.org/10.1080/09537287.2017.1362487

Amiri, M. P. (2010). Project selection for oil-fields development by using the AHP and fuzzy TOPSIS methods. *Expert Systems with Applications*, *37*(9), 6218–6224. https://doi.org/10.1016/j.eswa.2010.02.103

Aqlan, F., & Lam, S. S. (2015). A fuzzy-based integrated framework for supply chain risk assessment. *International Journal of Production Economics*, *161*, 54–63. https://doi.org/10.1016/j.ijpe.2014.11.013

Atwater, C., Gopalan, R., Lancioni, R., & Hunt, J. (2014). Measuring supply chain risk: Predicting motor carriers' ability to withstand disruptive environmental change using conjoint analysis. *Transportation Research Part C: Emerging Technologies*, *48*, 360–378. https://doi.org/10.1016/j.trc.2014.09.009

Avlonitis, G. J., & Panagopoulos, N. G. (2005). Antecedents and consequences of CRM technology acceptance in the sales force. *Industrial Marketing Management*, *34*(4), 355–368. https://doi.org/10.1016/j.indmarman.2004.09.021

Awasthi, A., & Baležentis, T. (2017). A hybrid approach based on BOCR and fuzzy MULTIMOORA for logistics service provider selection. *International Journal of Logistics Systems and Management*, *27*(3), 261–282. https://doi.org/10.1504/IJLSM.2017.084466

Aydin, S. (2018). Augmented reality goggles selection by using neutrosophic MULTIMOORA method. *Journal of Enterprise Information Management*, *31*(4), 565–576. https://doi.org/10.1108/JEIM-01-2018-0023

Azadeh, A., & Alem, S. M. (2010). A flexible deterministic, stochastic and fuzzy data envelopment analysis approach for supply chain risk and vendor selection problem: Simulation analysis. *Expert Systems with Applications*, *37*(12), 7438–7448. https://doi.org/10.1016/j.eswa.2010.04.022

Banaeian, N., Mobli, H., Fahimnia, B., Nielsen, I. E., & Omid, M. (2016). Green supplier selection using fuzzy group decision making methods: A case study from the agri-food industry. *Computers and Operations Research*, *89*, 337–347. https://doi.org/10.1016/j.cor.2016.02.015

Boran, F. E., Gencc, S., Kurt, M., & Akay, D. (2009). A multicriteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method. *Expert Systems with Applications*, *36*(8), 11363–11368. https://doi.org/10.1016/j.eswa.2009.03.039

Brauers, W., & Zavadskas, E. K. (2011). MULTIMOORA optimization used to decide on a bank loan to buy property. *Technological and Economic Development of Economy*, *17*(1), 174–188. https://doi.org/10.3846/13928619.2011.560632

Brauers, W. K., & Zavadskas, E. K. (2006). The MOORA method and its application to privatization in a transition economy. *Control and Cybernetics*, *35*(2), 445–469.

Büyüközkan, G., & Çifçi, G. (2012). A combined fuzzy AHP and fuzzy TOPSIS based strategic analysis of electronic service quality in healthcare industry. *Expert Systems with Applications*, *39*(3), 2341–2354. https://doi.org/10.1016/j.eswa.2011.08.061

Calabrese, A., Costa, R., Levialdi, N., & Menichini, T. (2019). Integrating sustainability into strategic decision-making: A fuzzy AHP method for the selection of relevant sustainability issues. *Technological Forecasting and Social Change*, *139*, 155–168. https://doi.org/10.1016/j.techfore.2018.11.005

Calabrese, A., Costa, R., & Menichini, T. (2013). Using fuzzy AHP to manage intellectual Capital assets: An application to the ICT service industry. *Expert Systems with Applications*, *40*(9), 3747–3755. https://doi.org/10.1016/j.eswa.2012.12.081

Cavinato, J. L. (2004). Supply chain logistics risks. *International Journal of Physical Distribution & Logistics Management*, *34*(5), 383–387. https://doi.org/10.1108/09600030410545427

Ceballos, B., Lamata, M. T., & Pelta, D. A. (2016). A comparative analysis of multi-criteria decision-making methods. *Progress in Artificial Intelligence*, *5*(4), 315–322. https://doi.org/10.1007/s13748-016-0093-1

Chakraborty, S. (2011). Applications of the MOORA method for decision making in manufacturing environment. *International Journal of Advanced Manufacturing Technology*, *54*(9–12), 1155–1166. https://doi.org/10.1007/s00170-010-2972-0

Chamodrakas, I., Batis, D., & Martakos, D. (2010). Supplier selection in electronic marketplaces using satisficing and fuzzy AHP. *Expert Systems with Applications*, *37*(1), 490–498. https://doi.org/10.1016/j.eswa.2009.05.043

Chang, D.-Y. (1996). Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research*, *95*(3), 649–655. https://doi.org/10.1016/0377-2217(95)00300-2

Chang, W., Ellinger, A. E., & Blackhurst, J. (2015). A contextual approach to supply chain risk mitigation. *The International Journal of Logistics Management*, *26*(3), 642–656. https://doi.org/10.1108/IJLM-02-2014-0026

Chatterjee, K., & Kar, S. (2016). *Multi-criteria analysis of supply chain risk management using interval valued fuzzy TOPSIS*. (Mcdm). https://doi.org/10.1007/s12597-015-0241-6

Chen, J., Sohal, A. S., & Prajogo, D. I. (2013). Supply chain operational risk mitigation: A collaborative approach. *International Journal of Production Research*, *51*(7), 2186–2199. https://doi.org/10.1080/00207543.2012.727490

Chen, P.-S., & Wu, M.-T. (2013). A modified failure mode and effects analysis method for supplier selection problems in the supply chain risk environment: A case study. *Computers and Industrial Engineering*, *66*(4), 634–642. https://doi.org/10.1016/j.cie.2013.09.018

Cheng, C.-H. (1997). Evaluating naval tactical missile systems by fuzzy AHP based on the grade value of membership function. *European Journal of Operational Research*, *96*(2), 343–350. https://doi.org/10.1016/S0377-2217(96)00026-4

Cheng, J. H., Lee, C. M., & Tang, C. H. (2009). An application of fuzzy delphi and fuzzy AHP on evaluating wafer supplier in semiconductor industry. *WSEAS Transactions on Information Science and Applications*, *6*(5), 756–767.

Chiouy, C.-Y., Chou, S.-H., & Yeh, C.-Y. (2011). Using fuzzy AHP in selecting and prioritizing sustainable supplier on CSR for Taiwan's electronics industry. *Journal of Information and Optimization Sciences*, *32*(5), 1135–1153. https://doi.org/10.1080/02522667.2011.10700110

Chopra, S., & Sodhi, M. S. (2004). Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review*, *46*, 53–61. https://doi.org/10.1108/IJOPM-10-2012-0449

Christopher, M., & Peck, H. (2004). Building the resilience supply chain. *International Journal of Logistics Management*, *15*(2), 1–14. https://doi.org/10.1080/13675560600717763

Dalvi, M. V., & Kant, R. (2017). Ranking the barriers of supplier development using fuzzy AHP approach. *International Journal of Procurement Management*, *10*(1), 106. https://doi.org/10.1504/IJPM.2017.080919

de Oliveira, U. R., Marins, F. A. S., Rocha, H. M., & Salomon, V. A. P. (2017). The ISO 31000 standard in supply chain risk management. *Journal of Cleaner Production*, *151*, 616–633. https://doi.org/10.1016/j.jclepro.2017.03.054

Dey, S., Kumar, A., Ray, A., & Pradhan, B. B. (2012). Supplier selection: Integrated theory using dematel and quality functions deployment methodology. *Procedia Engineering*, *38*, 3560–3565. https://doi.org/10.1016/j.proeng.2012.06.411

Ding, H., Benyoucef, L., & Xie, X. (2003). A simulation-optimization approach using genetic search for supplier selection. *Proceedings of the 2003 Winter Simulation Conference*, 2, 1260–1267. https://doi.org/10.1109/WSC.2003.1261559

Ding, H., Benyoucef, L., & Xie, X. (2005). A simulation optimization methodology for supplier selection problem. *International Journal of Computer Integrated Manufacturing*, *18*(2–3), 210–224. https://doi.org/10.1080/0951192052000288161

Ding, X., & Zhong, J. (2018). Power battery recycling mode selection using an Extended MULTIMOORA method. *Scientific Programming*, *2018*, 1–14. https://doi.org/10.1155/2018/7675094

Dorfeshan, Y., Mousavi, S. M., Mohagheghi, V., & Vahdani, B. (2018). Selecting project-critical path by a new interval type-2 fuzzy decision methodology based on MULTIMOORA, MOOSRA and TPOP methods. *Computers & Industrial Engineering*, *120*, 160–178. https://doi.org/10.1016/j.cie.2018.04.015

Ellis, S. C., Henry, R. M., & Shockley, J. (2010). Buyer perceptions of supply disruption risk: A behavioral view and empirical assessment. *Journal of Operations Management*, *28*(1), 34–46. https://doi.org/10.1016/j.jom.2009.07.002

Fattahi, R., & Khalilzadeh, M. (2018). Risk evaluation using a novel hybrid method based on FMEA, extended MULTIMOORA, and AHP methods under fuzzy environment. *Safety Science*, *102*, 290–300. https://doi.org/10.1016/j.ssci.2017.10.018

Forman, E. H. (1990). Random indices for incomplete pairwise comparison matrices. *European Journal of Operational Research*, *48*(1), 153–155. https://doi.org/10.1016/0377-2217(90)90072-J

Gadakh, V. S., Shinde, V. B., & Khemnar, N. S. (2013). Optimization of welding process parameters using MOORA method. *International Journal of Advanced Manufacturing Technology*, *69*(9–12), 2031–2039. https://doi.org/10.1007/s00170-013-5188-2

Gencer, C., & Gürpinar, D. (2007). Analytic network process in supplier selection: A case study in an electronic firm. *Applied Mathematical Modelling*, *31*(11), 2475–2486. https://doi.org/10.1016/j.apm.2006.10.002

Ghadge, A., Dani, S., Chester, M., & Kalawsky, R. (2013). A systems approach for modelling supply chain risks. *Supply Chain Management: An International Journal*, *18*(5), 523–538. https://doi.org/10.1108/SCM-11-2012-0366

Ghadge, A., Dani, S., Ojha, R., & Caldwell, N. (2017). Using risk sharing contracts for supply chain risk mitigation: A buyer-supplier power and dependence perspective. *Computers and Industrial Engineering*, *103*, 262–270. https://doi.org/10.1016/j.cie.2016.11.034

Goh, M., Lim, J. Y. S., & Meng, F. (2007). A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research*, *182*(1), 164–173. https://doi.org/10.1016/j.ejor.2006.08.028

Golden, B. L., Wasil, E. A., & Harker, P. T. (1989). *The analytic hierarchy process*. Applications and Studies.

Gupta, V., Kapur, P. K., & Kumar, D. (2017). Measuring and evaluating data distribution strategies using an integrated approach of fuzzy based MOORA and AHP. *Life Cycle Reliability and Safety Engineering*, *6*(1), 37–45. https://doi.org/10.1007/s41872-017-0004-x

Hafezalkotob, A., & Hafezalkotob, A. (2015). Extended MULTIMOORA method based on Shannon entropy weight for materials selection. *Journal of Industrial Engineering International*, *12*(1), 1–13. https://doi.org/10.1007/s40092-015-0123-9

Hafezalkotob, A., Hafezalkotob, A., Liao, H., & Herrera, F. (2019). An overview of MULTIMOORA for multi-criteria decision-making: Theory, developments, applications, and challenges. *Information Fusion*, *51*(December 2018), 145–177. https://doi.org/10.1016/j.inffus.2018.12.002

Hafezalkotob, A., Hami-Dindar, A., Rabie, N., & Hafezalkotob, A. (2018). A decision support system for agricultural machines and equipment selection: A case study on olive harvester machines. *Computers and Electronics in Agriculture*, *148*, 207–216. https://doi.org/10.1016/j.compag.2018.03.012

Ho, W., Xu, X., & Dey, P. K. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *European Journal of Operational Research*, *202*(1), 16–24. https://doi.org/10.1016/j.ejor.2009.05.009

Ho, W., Zheng, T., Yildiz, H., & Talluri, S. (2015). Supply chain risk management: A literature review. *International Journal of Production Research*, *53*(16), 5031–5069. https://doi.org/10.1080/00207543.2015.1030467

Hsu, C.-W., & Hu, A. H. (2009). Applying hazardous substance management to supplier selection using analytic network process. *Journal of Cleaner Production*, *17*(2), 255–264. https://doi.org/10.1016/j.jclepro.2008.05.004

Hsu, C.-W., Kuo, T.-C., Chen, S.-H., & Hu, A. H. (2013). Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production*, *56*, 164–172. https://doi.org/10.1016/j.jclepro.2011.09.012

Jemison, D. B. (1987). Risk adn the relationship among strategy, organizational processes, and performance. *Management Science*, *33*(9), 1087–1101. https://doi.org/10.1287/mnsc.33.9.1087

Juttner, U., Peck, H., & Christopher, M. (2003). Supply chain risk management: Outlining an agenda for future research. *International Journal of Logistics Research and Applications*, *6*(4), 197–210. https://doi.org/10.1080/13675560310001627016

Kahraman, C., Cebeci, U., & Ulukan, Z. (2003). Multi-criteria supplier selection using fuzzy AHP. *Logistics Information Management*, *16*(6), 382–394. https://doi.org/10.1108/09576050310503367

Kannan, D., De Sousa Jabbour, A. B. L., & Jabbour, C. J. C. (2014). Selecting green suppliers based on GSCM practices: Using fuzzy TOPSIS applied to a Brazilian electronics company. *European Journal of Operational Research*, *233*(2), 432–447. https://doi.org/10.1016/j.ejor.2013.07.023

Karaca, C., & Ulutaş, A. (2017). Supplier performance evaluation by using SWARA and MULTIMOORA. In edited by A. M. Çilingirtürk, A. Albrychiewicz-Słocińska, B. B. Bali (Ed.), *Economics management & econometrics* (pp. 137–151). IJOPEC.

Karande, P., & Chakraborty, S. (2012). A fuzzy-MOORA approach for ERP system selection. *Decision Science Letters*, *1*(1), 11–21. https://doi.org/10.5267/j.dsl.2012.07.001

Kilincci, O., & Onal, S. (2011). Fuzzy AHP approach for supplier selection in a washing machine company. *Expert Systems with Applications*, *38*(8), 9656–9664. http://www.sciencedirect.com/science/article/pii/S0957417411001928 https://doi.org/10.1016/j.eswa.2011.01.159

Kilubi, I. (2016). Investigating current paradigms in supply chain risk management – a bibliometric study. *Business Process Management Journal*, *22*(4), 662–692. https://doi.org/10.1108/BPMJ-05-2015-0060

Kırılmaz, O., & Erol, S. (2017). A proactive approach to supply chain risk management: Shifting orders among suppliers to mitigate the supply side risks. *Journal of Purchasing and Supply Management*, *23*(1), 54–65. https://doi.org/10.1016/j.pursup.2016.04.002

Ku, C.-Y., Chang, C.-T., & Ho, H.-P. (2009). Global supplier selection using fuzzy analytic hierarchy process and fuzzy goal programming. *Quality & Quantity*, *44*(4), 623–640. https://doi.org/10.1007/s11135-009-9223-1

Kumar, P., & Singh, R. K. (2012). A fuzzy AHP and TOPSIS methodology to evaluate 3PL in a supply chain. *Journal of Modelling in Management*, *7*(3), 287–303. https://doi.org/10.1108/17465661211283287

Kumar Pradhan, S., & Routroy, S. (2014). Analyzing the supply chain risk issues for an Indian manufacturing company. *Journal of Advances in Management Research*, *11*(2), 144–162. https://doi.org/10.1108/JAMR-11-2012-0047

Kumar Sharma, S., & Sharma, S. (2015). Developing a Bayesian network model for supply chain risk assessment. *Supply Chain Forum: An International Journal*, *16*(4), 50–72. https://doi.org/10.1080/16258312.2015.11728693

Kuo, R. J., Hong, S. Y., & Huang, Y. C. (2010). Integration of particle swarm optimization-based fuzzy neural network and artificial neural network for supplier selection. *Applied Mathematical Modelling*, *34*(12), 3976–3990. https://doi.org/10.1016/j.apm.2010.03.033

Kwong, C. K., & Bai, H. (2003). Determining the importance weights for the customer requirements in QFD using a fuzzy AHF with an extent analysis approach. *IIE Transactions (Institute of Industrial Engineers)*, *35*(7), 619–626. https://doi.org/10.1080/07408170304355

Lavastre, O., Gunasekaran, A., & Spalanzani, A. (2012). Supply chain risk management in French companies. *Decision Support Systems*, *52*(4), 828–838. https://doi.org/10.1016/j.dss.2011.11.017

Lavastre, O., Gunasekaran, A., & Spalanzani, A. (2014). Effect of firm characteristics, supplier relationships and techniques used on supply chain risk management (SCRM): an empirical investigation on French industrial firms. *International Journal of Production Research*, *52*(11), 3381–3403. https://doi.org/10.1080/00207543.2013.878057

Li, W., Chen, Y., & Fu, Y. (2008). Combination of TOPSIS and 0-1 programming for supplier selection in supply chain management. *Proceedings of 2008 IEEE International Conference on Networking, Sensing and Control, ICNSC*, 1531–1535. https://doi.org/10.1109/ICNSC.2008.4525464

Liang, W., Zhao, G., & Hong, C. (2019). Selecting the optimal mining method with extended multi-objective optimization by ratio analysis plus the full multiplicative form (MULTIMOORA) approach. *Neural Computing and Applications*, *31*(10), 5871–5886. https://doi.org/10.1007/s00521-018-3405-5

Lin, C. (2013). Application of fuzzy Delphi method (FDM) and fuzzy analytic hierarchy process (FAHP) to criteria weights for fashion design scheme evaluation. *International Journal of Clothing Science and Technology*, *25*(3), 171–183. https://doi.org/10.1108/09556221311300192

Liu, A., Xiao, Y., Ji, X., Wang, K., Tsai, S.-B., Lu, H., Cheng, J., Lai, X., Wang, J. (2018). A novel two-stage integrated model for supplier selection of green fresh product. *Sustainability*, *10*(7), 2371. https://doi.org/10.3390/su10072371

Liu, H.-C., Yang, M., Zhou, M., & Tian, G. (2018). An integrated multi-criteria decision making approach to location planning of electric vehicle charging stations. *IEEE Transactions on Intelligent Transportation Systems*, *20*(1), 362–373. https://doi.org/10.1109/TITS.2018.2815680

Liu, H. C., Zhao, H., You, X. Y., & Zhou, W. Y. (2019). Robot evaluation and selection using the hesitant fuzzy linguistic MULTIMOORA method. *Journal of Testing and Evaluation*, *47*(2), 1405–1426. https://doi.org/10.1520/JTE20170094

Lockamy III, A. (2014). Assessing disaster risks in supply chains. *Industrial Management & Data Systems*, *114*(5), 755–777. https://doi.org/10.1108/IMDS-11-2013-0477

Lockamy III, A., & McCormack, K. (2009). Examining operational risks in supply chains. *Supply Chain Forum: An International Journal*, *10*(1), 2–14. https://doi.org/10.1080/16258312.2009.11517204

Lowrance, W. W. (1980). The nature of risk. In *Societal risk assessment.general Motors research Laboratories* (pp. 5–17, Vol. 31). https://doi.org/10.1007/978-1-4899-0445-4_1

Ma, R., Yao, L., & Huang, R. (2012). *The Green Supply Chain Management Risk Analysis*. *574*, 734–739. https://doi.org/10.4028/www.scientific.net/AMR.573-574.734

Mangla, S. K., Kumar, P., & Barua, M. K. (2015). Risk analysis in green supply chain using fuzzy AHP approach: A case study. *Resources, Conservation & Recycling*, 1–16. https://doi.org/10.1016/j.resconrec.2015.01.001

Manuj, I., & Mentzer, J. T. (2008). Global supply chain risk management strategies. *International Journal of Physical Distribution & Logistics Management*, *38*(3), 192–223. https://doi.org/10.1108/09600030810866986

Matawale, C. R., Matawale, C. R., Datta, S., Datta, S., Mahapatra, S. S., & Mahapatra, S. S. (2016). Supplier selection in agile supply chain: Application potential of FMLMCDM approach in comparison with fuzzy-TOPSIS and fuzzy-MOORA. *Benchmarking: An International Journal*, *23*(7), 2027–2060. https://doi.org/10.1108/BIJ-07-2015-0067

Mavi, R. K., Goh, M., & Mavi, N. K. (2016). Supplier selection with Shannon Entropy and fuzzy TOPSIS in the context of supply chain risk management. *Procedia - Social and Behavioral Sciences*, *235*(October), 216–225. https://doi.org/10.1016/j.sbspro.2016.11.017

Micheli, G. J. L., Cagno, E., & Zorzini, M. (2008). Supply risk management vs supplier selection to manage the supply risk in the EPC supply chain. *Management Research News*, 31(11), 846–866. https://doi.org/10.1108/01409170810913042

Miller, D. W., & Starr, S. M. (1969). *Decisions and operations and research* (2nd ed.). Prentice- Hall Inc.

Mital, M., Del Guidice, M., & Papa, A. (2017). Comparing supply chain risks for multiple product categories with cognitive mapping and analytic hierarchy process. *Technological Forecasting and Social Change*, (February), 0–1. https://doi.org/10.1016/j.techfore.2017.05.036

Mohamadi, S., Ebrahimi, A., & Alimohammadlou, M. (2017). An application of fuzzy screening, fuzzy AHP and fuzzy Shannon's entropy on identification and prioritisation of effective factors in assessment of contractors in Fars electric Power Distribution company, Iran. *International Journal of Procurement Management*, *10*(2), 194. https://doi.org/10.1504/IJPM.2017.082787

Nyamah, E. Y., Jiang, Y., Feng, Y., & Enchill, E. (2017). *Agri-food supply chain performance: an empirical impact of risk*. https://doi.org/10.1108/MD-01-2016-0049

Paul, S. K. (2015). Supplier selection for managing supply risks in supply chain: A fuzzy approach. *International Journal of Advanced Manufacturing Technology*, *79*(1–4), 657–664. https://doi.org/10.1007/s00170-015-6867-y

Pi, W. N., & Low, C. (2006). Supplier evaluation and selection via Taguchi loss functions and an AHP. *International Journal of Advanced Manufacturing Technology*, *27*(5–6), 625–630. https://doi.org/10.1007/s00170-004-2227-z

Pournader, M., Pournader, M., Rotaru, K., Rotaru, K., Kach, A. P., Kach, A. P., . . . Razavi Hajiagha, S. H. (2016). An analytical model for system-wide and tier-specific assessment of resilience to supply chain risks. *Supply Chain Management: An International Journal*, *21*(5), 589–609. https://doi.org/10.1108/SCM-11-2015-0430

Punniyamoorthy, M., Thamaraiselvan, N., & Manikandan, L. (2013). Assessment of supply chain risk: Scale development and validation. *Benchmarking: An International Journal*, *20*(1), 79–105. https://doi.org/10.1108/14635771311299506

Qianlei, L. (2012). The study on the risk management of agricultural products green supply chain based on systematic analysis. *Business Computing and Global Informatization (BCGIN), IEEE 2nd International Conference*, 1, 250–253. https://doi.org/10.1109/BCGIN.2012.71

Radivojević, G., & Gajović, V. (2014). Supply chain risk modeling by AHP and fuzzy AHP methods. *Journal of Risk Research*, *17*(3), 337–352. https://doi.org/10.1080/13669877.2013.808689

Rajesh, R., Ravi, V., & Venkata Rao, R. (2015). Selection of risk mitigation strategy in electronic supply chains using grey theory and digraph-matrix approaches. *International Journal of Production Research*, *53*(1), 238–257. https://doi.org/10.1080/00207543.2014.948579

Rangel, D. A., de Oliveira, T. K., & Leite, M. S. A. (2015). Supply chain risk classification: Discussion and proposal. *International Journal of Production Research*, *53*(22), 6868–6887. https://doi.org/10.1080/00207543.2014.910620

Rao, C., Xiao, X., Goh, M., Zheng, J., & Wen, J. (2017). Compound mechanism design of supplier selection based on multi-attribute auction and risk management of supply chain. *Computers & Industrial Engineering*, *105*, 63–75. https://doi.org/10.1016/j.cie.2016.12.042

Rogers, H., Srivastava, M., Pawar, K. S., & Shah, J. (2016). Supply chain risk management in India – practical insights. *International Journal of Logistics Research and Applications*, *19*(4), 278–299. https://doi.org/10.1080/13675567.2015.1075476

Rowe, W. D. (1980). *Risk assessment approaches and methods*. Society, technology and risk assessment. London: Academic Press, 343.

Samvedi, A., Jain, V., & Chan, F. T. S. (2013). Quantifying risks in a supply chain through integration of fuzzy AHP and fuzzy TOPSIS. *International Journal of Production Research*, *51*(8), 2433–2442. https://doi.org/10.1080/00207543.2012.741330

Sanayei, A., Farid Mousavi, S., & Yazdankhah, A. (2010). Group decision making process for supplier selection with VIKOR under fuzzy environment. *Expert Systems with Applications*, *37*(1), 24–30. https://doi.org/10.1016/j.eswa.2009.04.063

Satty, T. L. (1980). *The analytic process*. HcGraw-Hill.

Sevkli, M., Koh, S. C. L., Zaim, S., Demirbag, M., & Tatoglu, E. (2008). Hybrid analytical hierarchy process model for supplier selection. *Industrial Management and Data*, *108*(1), 122–142. https://doi.org/10.1108/02635570810844124

Shemshadi, A., Shirazi, H., Toreihi, M., & Tarokh, M. J. (2011). A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting. *Expert Systems with Applications*, *38*(10), 12160–12167. https://doi.org/10.1016/j.eswa.2011.03.027

Singh, R. K., & Sharma, M. K. (2014). Selecting competitive supply chain using fuzzy AHP and extent analysis. *Journal of Industrial and Production Engineering*, *31*(8), 524–538. https://doi.org/10.1080/21681015.2014.999723

Souzangarzadeh, H., Rezvani, M. J., & Jahan, A. (2017). Selection of optimum design for conical segmented aluminum tubes as energy absorbers: Application of MULTIMOORA method. *Applied Mathematical Modelling*, *51*, 546–560. https://doi.org/10.1016/j.apm.2017.07.005

Sreedevi, R., & Saranga, H. (2017). Uncertainty and supply chain risk: The moderating role of supply chain flexibility in risk mitigation. *International Journal of Production Economics*, *193*, 332–342. https://doi.org/10.1016/j.ijpe.2017.07.024

Stević, Ž., Pamučar, D., Vasiljević, M., Stojić, G., & Korica, S. (2017). Novel integrated multi-criteria model for supplier selection: Case study construction company. *Symmetry*, *9*(11), 279. https://doi.org/10.3390/sym9110279

Tang, C., & Tomlin, B. (2008). The power of flexibility for mitigating supply chain risks. *International Journal of Production Economics*, *116*(1), 12–27. https://doi.org/10.1016/j.ijpe.2008.07.008

Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics*, *103*(2), 451–488. https://doi.org/10.1016/j.ijpe.2005.12.006

Tavana, M., & Hatami-Marbini, A. (2011). A group AHP-TOPSIS framework for human spaceflight mission planning at NASA. *Expert Systems with Applications*, *38*(11), 13588–13603. https://doi.org/10.1016/j.eswa.2011.04.108

Tavana, M., Zareinejad, M., Di Caprio, D., & Kaviani, M. A. (2016). An integrated intuitionistic fuzzy AHP and SWOT method for outsourcing reverse logistics. *Applied Soft Computing Journal*, *40*, 544–557. https://doi.org/10.1016/j.asoc.2015.12.005

Thresh Kumar, D., Palaniappan, M., Kannan, D., & Shankar, K. M. (2014). Analyzing the CSR issues behind the supplier selection process using ISM approach. *Resources, Conservation and Recycling*, *92*, 268–278. https://doi.org/10.1016/j.resconrec.2014.02.005

Tian, Z., Wang, J., Wang, J., & Zhang, H. (2017). An improved MULTIMOORA approach for multi-criteria decision-making based on interdependent inputs of simplified neutrosophic linguistic information. *Neural Computing and Applications*, *28*(S1), 585–597. https://doi.org/10.1007/s00521-016-2378-5

Toloo, M., & Nalchigar, S. (2011). A new DEA method for supplier selection in presence of both cardinal and ordinal data. *Expert Systems with Applications*, *38*(12), 14726–14731. https://doi.org/10.1016/j.eswa.2011.05.008

Truong Quang, H., & Hara, Y. (2017). Risks and performance in supply chain: The push effect. *International Journal of Production Research*, 7543(August), 1–20. https://doi.org/10.1080/00207543.2017.1363429

Tsai, W.-H., & Hung, S.-J. (2009). A fuzzy goal programming approach for green supply chain optimisation under activity-based costing and performance evaluation with a value-chain structure. *International Journal of Production Research*, *47*(18), 4991–5017. https://doi.org/10.1080/00207540801932498

Tse, Y. K., & Tan, K. H. (2011). Managing product quality risk in a multi-tier global supply chain. *International Journal of Production Research*, *49*(1), 139–158. https://doi.org/10.1080/00207543.2010.508942

Tummala, R., & Schoenherr, T. (2011). Assessing and managing risks using the supply chain risk management process (SCRMP). *Supply Chain Management: An International Journal*, *16*(6), 474–483. https://doi.org/10.1108/13598541111171165

Ulutas, A., Shukla, N., Kiridena, S., & Gibson, P. (2016). A utility-driven approach to supplier evaluation and selection: Empirical validation of an integrated solution framework. *International Journal of Production Research*, *54*(5), 1554–1567. https://doi.org/10.1080/00207543.2015.1098787

Vanalle, R. M., Lucato, W. C., Ganga, G. M. D., & Alves Filho, A. G. (2019). Risk management in the automotive supply chain: An exploratory study in Brazil. *International Journal of Production Research*, *0*(0), 1–17. https://doi.org/10.1080/00207543.2019.1600762

Venkatesh, V. G., Rathi, S., & Patwa, S. (2015). Analysis on supply chain risks in Indian apparel retail chains and proposal of risk prioritization model using Interpretive structural modeling. *Journal of Retailing and Consumer Services*, *26*, 153–167. https://doi.org/10.1016/j.jretconser.2015.06.001

Vinodh, S., Anesh Ramiya, R., & Gautham, S. G. (2011). Application of fuzzy analytic network process for supplier selection in a manufacturing organisation. *Expert Systems with Applications*, *38*(1), 272–280. https://doi.org/10.1016/j.eswa.2010.06.057

Viswanadham, N., & Samvedi, A. (2013). Supplier selection based on supply chain ecosystem, performance and risk criteria. *International Journal of Production Research*, *51*(21), 6484–6498. https://doi.org/10.1080/00207543.2013.825056

Wagner, S. M., & Bode, C. (2006). An empirical investigation into supply chain vulnerability. *Journal of Purchasing and Supply Management*, *12*(6 SPEC. ISS.), 301–312. https://doi.org/10.1016/j.pursup.2007.01.004

Wang, J. W., Cheng, C. H., & Huang, K. C. (2009). Fuzzy hierarchical TOPSIS for supplier selection. *Applied Soft Computing Journal*, *9*(1), 377–386. https://doi.org/10.1016/j.asoc.2008.04.014

Wang, X., Kai, H., Yee, R. W. Y., & Diaz-rainey, I. (2012). A two-stage fuzzy-AHP model for risk assessment of implementing green initiatives in the fashion supply chain. *Intern. Journal of Production Economics*, *135*(2), 595–606. https://doi.org/10.1016/j.ijpe.2011.03.021

Wang, Y.-M., & Elhag, T. M. S. (2007). A fuzzy group decision making approach for bridge risk assessment. *Computers & Industrial Engineering*, *53*(1), 137–148. https://doi.org/10.1016/j.cie.2007.04.009

Wang, Y.-M., Luo, Y., & Hua, Z. (2008). On the extent analysis method for fuzzy AHP and its applications. *European Journal of Operational Research*, *186*(2), 735–747. https://doi.org/10.1016/j.ejor.2007.01.050

Wei, J. Y., Sun, A. F., & Wang, C. H. (2010). The application of fuzzy-ANP in the selection of supplier in supply chain management. *2010 International Conference on Logistics Systems and Intelligent Management, ICLSIM 2010*, *3*, 1357–1360. https://doi.org/10.1109/ICLSIM.2010.5461187

Wood, D. A. (2016). Supplier selection for development of petroleum industry facilities, applying multi-criteria decision making techniques including fuzzy and intuitionistic fuzzy TOPSIS with flexible entropy weighting. *Journal of Natural Gas Science and Engineering*, *28*, 594–612. https://doi.org/10.1016/j.jngse.2015.12.021

Wu, D. (2009). Supplier selection: A hybrid model using DEA, decision tree and neural network. *Expert Systems with Applications*, *36*(5), 9105–9112. https://doi.org/10.1016/j.eswa.2008.12.039

Wu, S., You, X., Liu, H., & Wang, L. (2017). Improving quality function deployment analysis with the cloud MULTIMOORA method. *International Transactions in Operational Research*. https://doi.org/10.1111/itor.12484

Wu, X., Liao, H., Xu, Z., Hafezalkotob, A., & Herrera, F. (2018). Probabilistic linguistic MULTIMOORA: A multicriteria decision making method based on the probabilistic linguistic expectation function and the improved Borda rule. *IEEE Transactions on Fuzzy Systems*, *26*(6), 3688–3702. https://doi.org/10.1109/TFUZZ.2018.2843330

Xia, D., & Chen, B. (2011). A comprehensive decision-making model for risk management of supply chain. *Expert Systems with Applications*, *38*(5), 4957–4966. https://doi.org/10.1016/j.eswa.2010.09.156

Yadav, V., & Sharma, M. K. (2016). Multi-criteria supplier selection model using the analytic hierarchy process approach. *Journal of Modelling in Management*, *11*(1), 326–354. https://doi.org/10.1108/JM2-06-2014-0052

Yager, R. R. (1981). A procedure for ordering fuzzy subsets of the unit interval. *Information Sciences*, *24*(2), 143–161. https://doi.org/10.1016/0020-0255(81)90017-7

Yang, Z., & Li, J. (2010). *Assessment of Green Supply Chain Risk Based on Circular Economy*. 1276–1280.

Yücenur, G. N., Vayvay, Ö., & Demirel, N. Ç. (2011). Supplier selection problem in global supply chains by AHP and ANP approaches under fuzzy environment. *International Journal of Advanced Manufacturing Technology*, *56*(5–8), 823–833. https://doi.org/10.1007/s00170-011-3220-y

Zavadskas, E. K., Bausys, R., Juodagalviene, B., & Garnyte-Sapranaviciene, I. (2017). Model for residential house element and material selection by neutrosophic MULTIMOORA method. *Engineering Applications of Artificial Intelligence*, *64*, 315–324. https://doi.org/10.1016/j.engappai.2017.06.020

Zhang, D. Y., Cao, X., Wang, L., & Zeng, Y. (2012). Mitigating the risk of information leakage in a two-level supply chain through optimal supplier selection. *Journal of Intelligent Manufacturing*, *23*(4), 1351–1364. https://doi.org/10.1007/s10845-011-0527-3

Zhao, H., You, J.-X., & Liu, H.-C. (2017). Failure mode and effect analysis using MULTIMOORA method with continuous weighted entropy under interval-valued intuitionistic fuzzy environment. *Soft Computing*, *21*(18), 5355–5367. https://doi.org/10.1007/s00500-016-2118-x

Zhi-guang, Z. H. A. N. G. (2012). A VIKOR method for supplier selection. *Journal of Gansu Lianhe University (Natural Science Edition)*, (5), 7.

Zimmer, K., Fröhling, M., Breun, P., & Schultmann, F. (2017). Assessing social risks of global supply chains: A quantitative analytical approach and its application to supplier selection in the German automotive industry. *Journal of Cleaner Production*, *149*, 96–109. https://doi.org/10.1016/j.jclepro.2017.02.041

Zouggari, A., & Benyoucef, L. (2012). Simulation based fuzzy TOPSIS approach for group multi-criteria supplier selection problem. *Engineering Applications of Artificial Intelligence*, *25*(3), 507–519. https://doi.org/10.1016/j.engappai.2011.10.012

Appendix A

Questionnaire 1 (Fuzzy AHP): used for capturing the importance of criteria and sub-criteria

Please indicate the importance of each criteria compared to other criteria with regard the following scales: Equally Important (1), Moderately Important (2), Important (3), Very Important (4), or Significantly More Important (5).	
Q1	How important is Operational risks (C1) compared to Supply risk (C2)?
Q2	How important is Operational risks (C1) compared to Financial risk (C3)?
Q3	How important is Operational risks (C1) compared to Technology risks (C4)?
Q4	How important is Supply risk (C2) compared to Financial risk (C3)?
Q5	How important is Supply risk (C2) compared to Technology risks (C4)?
Q6	How important is Financial risk (C3) compared to Technology risks (C4)?
Operational risks (C1)	
Q7	How important is Machine, equipment or facility failure (C11) compared to Design risks (C12)?
Q8	How important is Machine, equipment or facility failure (C11) compared to the scarcity of skilled labour risks (C13)?
Q9	How important is Design risks (C12) compared to the scarcity of skilled labour risks (C13)?
Supply risk (C2)	
Q10	How important is Procurement costs risks (C21) compared to Key supplier failures risks (C22)?
Q11	How important is Procurement costs risks (C21) compared to Supplier quality risks (C23)?
Q12	How important is Key supplier failures risks (C22) compared to Supplier quality risks (C23)?
Financial risk (C3)	
Q13	How important is The Sourcing of funds (C31) compared to Inflation and currency exchange rates (C32)?
Technology risks (C4)	
Q14	How important is Inability to use new technology (C41) compared to Failure in Information technology (C42)?

Questionnaire 2 (Fuzzy MULTIMOORA): used for capturing the importance of the alternatives with respect to sub-criteria

Please indicate the importance of each supplier with respect to the sub-criteria using the following scales: Very low (VL)(1), Low (L)(2), Medium (M)(3), High (H)(4), or Very High (VH)(5).

Supplier	C11	C12	C13	C21	C22	C23	C31	C32	C41	C42
S1										
S2										
S3										
S4										
S5										
S6										