A novel hesitant-fuzzy-based group decision approach for outsourcing risk

[1*]Morteza Yazdani, [2]Ahmed Mohammed, [3]Chunguang Bai and [4]Ashraf Labib

[1]ESIC Busienss & Marketing school, Madrid, Spain

morteza.yazdani@esic.edu

(**corresponding author*)

[2]Faculty of Transport & Logistics

Muscat University

Building 142, Al Ghubra North, Muscat, Sultanate of Oman

E-mail: amm.alhamdany@gmail.com

[3]University of Electronic Science and Technology of China

No.2006, Xiyuan Ave, West Hi-Tech Zone, 611731, Chengdu, P.R.China

E-mail: cbai@uestc.edu.cn

[4]Faculty of Business and Law

University of Portsmouth

Portsmouth, United Kingdom

E-mail: ashraf.labib@port.ac.uk

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Abstract

Outsourcing is recognized as a strategic instrument for companies to move towards diversified operation advantages and efficient global market. However, outsourcing agreements may fail due to insufficient risk consideration and evaluation. This requires an effective risk evaluation approach that necessitates an entire comprehension of the system, its requirements and dimensions. This paper proposes a novel fuzzy group multiple-criteria decision-making approach through integrating triangular fuzzy hesitant sets (TFHS), Failure Mode and Effect Analysis (FMEA) and combined compromise solution (CoCoSo) algorithm. This approach (F-FMEA-CoCoSo, henceforth) analyzes and evaluates the possible risks level of alternative outsourcing providers. It hereby provides measurable information for managers according to the linguistic opinions of industrial experts. Utilization of hesitant fuzzy variables allows decision making participants to state their opinion more precisely. A case study of an Iranian chemical company is used to exemplify the applicability and suitability of the proposed F-FMEA-CoCoSo approach. The model reflects an analytical approach while experts are experiencing considerable uncertainty in risky conditions of outsourcing operations. CoCoSo contains an integrated approach of compromise solutions and its utilization enables investigators to assure results reliability which is proven via the sensitivity analysis. Through this study, we found that risk evaluation of outsourcing providers must consider four key-factors: multi-experts, multi-criteria, multi-uncertainties and measurability.

Keywords: Risk management; Outsourcing; Fuzzy; Hesitant set theory; CoCoSo; FMEA.

1. Introduction

Organizations need effective and reactive supply chain coordination to cope with the increasing complexity and uncertainty in today's business environment (Bai and Sarkis, 2019; Mohammed et al., 2021 and 2021a). However, complex supply chain approaches mean that more interfaces exist, so it may increase uncertainty and complexity and has higher vulnerability of disruptions (Kurniawan et al., 2017; Bai et al., 2016). Griffith (2001) defined Outsourcing as "*the strategic use of outside resources or suppliers to perform activities traditionally handled by internal staff and resources*". For example, in 2006, AMR conducted an industry-based study in which 42% of companies need to coordinate more than four supply chains to maintain the supply of multiple products to different markets (AMR, 2006). Amongst various supply chain approaches adopted towards cost-effective business, outsourcing was identified as a major source of a possible disruption (Cezar et al., 2017). For example, at the end of 2001, Land Rover's Discovery car was shut down due to the bankruptcy of UPF Thompson, the sole outsourcing provider of Discovery chassis (Sheffi and rice, 2005). For another example, on July 5, 2010, Toyota began to recall more than 90000 luxury Lexus and Crown cars in Japan, as part of the global recall of defective engines, which once again frustrated the car manufacturer suffering from quality problems (Labib, 2014). This is mainly due to the quality problems of their outsourcing providers. Similar situations emerge one after another (Scheibe and Blackhurst, 2018).

Although outsourcing has many advantages, organizations realize the necessity for incorporating risk measures into them outsourcing decision-making (Hessami et al., 2019; and Luqman et al., 2021). In existing literatures, the decision-making problems of supply chain outsourcing mainly include outsourcing decision-making, outsourcing risks evaluation, outsourcing activity control, outsourcing outcome analysis, and decision related to make-or-buy (Pamucar et al., 2021; Zarbakhshnia et al., 2020; Lee et al., 2012). This paper emphasis on outsourcing risks evaluation of outsourcing providers. As far as we know, there are few literatures on the quantitative evaluation of risk of outsourcing providers in supply chain context. In other words, there is still limited understanding of evaluating and quantifying the risks of outsourcing providers in making outsourcing decisions as revealed from the literature (da Silva et al., 2020). However, the following aspects of outsourcing provider risk evaluation make it very difficult. First, there is a lack of systematic criteria to effectively evaluate their risk level. Second, the uncertainty of risk will be increased by the complexity of risk, the difficulty to quantify the risk level and the limitation cognition of experts (Kafetzopoulos et al., 2019). Third, risk evaluation of outsourcing providers also requires systematic evaluation from different perspectives, such as occurrence of risk, severity of risk, and detection of risk, and considers the different opinions of multiple experts at the same time. Within these boundaries associated with outsourcing risks, this paper aims to address the following research questions (RQs):

RQ1: What are the numerous risks that may rise in outsourcing?

RQ2: How to effectively evaluate risks of outsourcing providers through the subjective judgment of group experts?

RQ3: How to build a decision-making approach that not only handle the conflict among multiple-criteria and multiple-experts, but also effectively address measurability and uncertainty of those risks.

To answer these RQs, this paper proposes a novel F-FMEA- CoCoSo (Yazdani et al. 2019a) approach to evaluate risks of outsourcing providers. This research makes three major contributions. First, we develop a practical risk criteria framework in chemical industry based on the literature review and discussion with chemical industry experts. Therefore, these risk criteria are different from other criteria proposed in the literature from a purely academic point and are closely related to the real industry. Second, this paper proposed a novel fuzzy group multiple-criteria decision-making approach through integrating triangular fuzzy hesitant sets (TFHS), Failure Mode and Effect Analysis (FMEA) and combined compromise solution (CoCoSo) algorithm. TFHS is used to describe the subjective judgment of experts and solve the uncertainty of each expert evaluation and the different cognition among experts. FMEA is used to evaluate the risk level of outsourcing providers in multiple dimensions in uncertain environment. CoCoSo algorithm is used to evaluate and select outsourcing providers based on their profile vis-a-vis a set of criteria. CoCoSo is a multi-criteria decision making (MCDM) based on compromise solution (Yazdani et al. 2019b; Torkayesh et al. 2021) Third, the F-FMEA-CoCoSo approach and risk criteria are applied on a practical case to provide insights to managers and researchers to comprehensively evaluating outsourcing risks.

Therefore, this work contributes to this body of knowledge as follows:

- It presents a holistic framework that poses the key-outsourcing risks from academic and industrial perspectives. This helps outsourcing decision-makers in recognizing outsourcing's risks criteria. Also, it supports the claimed complexity of analyzing and evaluating outsourcing risks;

- It proposes an evaluation and analysis approach that handles uncertain multiple experts' opinions for the outsourcing decision-making process;
- It presents measurable scores for both risks criteria and outsourcing providers, and thus reflect managerial insights that support managers' outsourcing decisions;
- It applies the proposed outsourcing decision-making approach on a real case study in the chemical sector. This poses practical insights and implications towards the re-application of this approach on other case studies; and
- It performs a sensitivity analysis to prove the reliability of the proposed quantitative evaluation process.

This paper proceeds as follows: Section 2 presents literature on outsourcing risks and applied mathematical approaches. In Section 3, the TFHS, and F-FMEA-CoCoSo approach are introduced. Section 4 presents proposed approach implementation, sensitivity analysis and outcome discussion with a case study. Then, Section 5 includes the managerial implications of this study. Section 6 presents conclusions, research limitations and potential directions for further research on outsourcing risks evaluation.

2. Literature review

2.1 Supply chain outsourcing

Outsourcing has gained an increasingly focus by practitioners and scholars due to its strategic correlation with companies' competitiveness (Davis-Sramek et al., 2019). It refers to usage of external resources, in which organizations employ external companies to implement or complete their non-core processes. Outsourcing transfers traditionally internal activities to external suppliers. Three global reasons to increasing interest in outsourcing: (1) increased technological expertise, (2) more reliable and cheaper transportation, and (3) the rapid development and application of telecommunications and computer technology. This is not a new concept, but it does add complexity and risk to the supply chain.

Supply chain outsourcing has received a considerable interest in different industries. Mason et al. (2002) found out that outsourcing activities in electronics manufacturing sector increase the company agility, enhance communication and information sharing between buyer and supply partners and a strong alliance is very vital for company survival. Islam and Sobhani (2010) investigated the most essential factors that affect outsourcing decisions in the manufacturing sector in Bangladesh through statistical analysis. Peng (2012) utilized logistics cost, the operation efficiency, quality of service suppliers and the technology level to select logistic outsourcing suppliers in a frozen food industry. Tavana et al. (2016) presented a research to assess on third-party reverse logistic providers for a manufacturer of composite pipes in USA. In a textile supply chain, Sardar et al (2016) suggested a sustainable outsourcing strategy for their international markets with the goal of cost savings and delivery to the domestic market. In another study, group of authors discussed the strategic determinant of logistic outsourcing in air freight system. They realized that improving more flexible services is the most effective element (Rahman et al. 2017). There were rarely few studies dedicated to evaluate outsourcing providers in the chemical industry.

Literature presents the supply chain outsourcing topic from different perspectives such as the management of outsourcing risks including supply disruption risk, foreign exchange risk and quality risk (Dong and Cooper, 2016; Sandhu et al., 2018), evaluating the alignment between outsourcing and companies strategy (Kaipia and Turkulainen, 2017), and evaluating outsourcing providers (Ishizaka and López, 2019; Govindan et al., 2019; Pournader et al., 2019). However, it can be inferred that the integration of supply risks and evaluation of outsourcing providers - the scope of this research - is still scare and there is a room for further development (Davis-Sramek et al., 2019; Perlekar and Thakkar, 2019).

2.2 Risks in outsourcing

Organizations recognize outsourcing decisions as a competitive weapon that helps to achieve diversified operational advantages and efficient global market (Chatterjee and Kar, 2016), but outsourcing is also risky, and about half of the outsourcing agreements fail due to inadequate planning and analysis. Thus, outsourcing faces various risks.

Several risks related to outsourcing are proposed in the literature. These risks could be increased logistic and inventory cost, lose control (quality, delivery, etc.), and negative impact on employees' motivation. In addition, managers must deal with other issues arising from outsourcing e.g., (1) reducing employment, (2) changes in facility requirements, (3) potential adjustments to quality control systems and manufacturing processes, and (4) expanding logistics issues, including insurance, tariffs, customs, and timing (Perlekar and Thakkar, 2019). Especially in the past few years, natural disasters have increased the attention to disruption risks in supply chains, such as the Covid-19 pandemic. Another risk of outsourcing overseas is the political backlash that results from moving jobs to foreign countries (Van Wyk, 2011). Table 1 lists a number of identified research on outsourcing risks.

Table 1 - Key research on risks factors associated with outsourcing

Research	**Risk factors**
Aloini et al. (2012)	Technological, managerial, Psychological and Sociological risks
Li and Zeng (2016)	Cost, Delivery, Quality and Service
Chen and Wu (2013)	Cost, Quality, Deliverability, Technology, Productivity and Service
Hu et al. (2012)	Organizational, Environmental, User related, Requirement, Project complexity, Planning and control and Team risk
Rajagopal et al. (2017)	Quality, Capacity/Inventory, Supply, Demand, Information, Transportation, Commodity price fluctuation, Exchange rate, Credit, Environment and Reputation
Lee et al. (2012)	Demand risk, Delay risk, Disruption risk, Inventory risk, Manufacturing process, Breakdown risk, Physical plan risk, System risk, Sovereign risks and Transportation risks
Sinha et al. (2004)	Lack of raw material Availability, Conflict in matrix utilized, Uncertainty in technology, Conflict in OEM requirements, Competing in cost, Lack of information, Transparency, Possibility of collaborator becoming competitor, Difference in communication standards, Uncertainty in market, Poor quality, Dependence on vendors and Excessive holding of inventory
Viswanadham and Samvedi (2013)	Supply chain-related Risk, Resource-related risk, Institutional Risk and Delivery infrastructure-related risk
Lacity et al. (2010)	Loss of fearing control, Technical, political, Transaction & Security-related risks, Scalability, Uncertainty, Asset specificity, Switching costs, Vendor opportunism and Task complexity
Song et al. (2017)	Operational risk, Economic risk, Environmental risk and Social risk
Dong and Cooper (2016)	Machine breakdowns, order fluctuation, urgent orders, exchange rate fluctuation, low supplier integration, inaccurate shipment from suppliers, inaccurate shipment to customers, raw parts scarcity, transportation bottlenecks, market requirements transformation, vendor lock, hurricanes, low supplier

	transparency, information distortion, security of information sharing, broken contract, supplier bankruptcy, products damaged in transits, customer defection, political policy, earthquake, war, warranty policy, terrorism, financial crisis, transport provider's fragmentation, and inaccurate demand forecast.

As shown in Table 1, outsourcing is associated with several risks, that require an efficient risk management approach. However, management thinker Peter Drucker says, "*you cannot manage what you cannot measure*". Therefore, the risk management approach should provide experts with measurable information that is based on linguistic experts 'opinions. Furthermore, it should be user-friendly, simple and timely.

2.3 Quantitative approaches in supply chain risk management

In order to facilitate decision makers to make outsourcing decisions, quantitative methods are needed to provide quantifiable measurement and evaluation. Heckmann, et al. (2015) summarized the quantitative methods and related theories of evaluating and analyzing supply chain risk. Rajagopal et al. (2017) reviewed the decision-making methods and models of risk assessment in supply chain environment. Therefore, many scholars have carried out a variety of studies on it.

Sarwar et al. (2021) proposed a novel risks analysis approach that integrates the rough set theory and ELimination and Choice Translating REality (ELECTRE) II method to cope with vagueness and subjectivity in experts' opinions. Dong and Cooper (2016) proposed an AHP-based approach evaluate sourcing risks for a telecommunication equipment and service firm. Ramkumar et al. (2016) employed SWOT analysis to identify risks in e-procurement context. Fang et al. (2016) formulated supply chain operational risks and disruption risks as a multi-objective programming problem. Sreedevi and Saranga (2017) proposed a Structural Equation Modelling combined with partial least square approach to explore the correlation between ecological uncertainties/supply risk and the impact of supply chain flexibility reduction. Rao et al. (2017) explored risks in supplier selection by using a two-stage method comprising of multi-auction and grey correlation degree. Song et al. (2017) employed the rough weighted DEMATEL-based methodology to investigate relationships and relative importance of possible risk factors towards sustainable supply chain. Qazi et al. (2017) conducted a supply risks evaluation study by using three methods: failure mode effect analysis, Bayesian Belief Networks, and Cooperative Game Theory.

However, in most decision-making conditions, sometimes experts or decision makers can not accurately state the opinions or judgments (Wu et al., 2021). The function of fuzzy sets is to help experts express their judgments accurately. In view of this, the method used for outsourcing decision analysis and evaluation should be able to deal with such imprecision and uncertainty. Arantes and Carpinetti (2019) conducted a review study on fuzzy MCDM approaches used for risk assessment in supply chains.

Leng et al. (2014) developed an integrated fuzzy VIKOR-game theory method to solve supplier selection and order allocation considering possible risk factors. Khemiri et al. (2017) employed fuzzy The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to plan tactical supply chain network operations considering risk decision factors. Zarbakhshnia et al. (2018) proposed decision support model based on fuzzy stepwise weight assessment ratio analysis (SWARA) and fuzzy complex proportional assessment of alternatives (COPRAS) for risks and sustainability of a third party reverse logistic provider (3PRLP). Towards the same purpose of evaluating outsourcing suppliers, Perçin (2019) employed fuzzy SWARA. Mokrini and Aouam (2020) developed fuzzy-based MCDM method to evaluate and rank risks when experts 'opinions are uncertain.

Fuzzy set theory and its expansions (e.g., interval-valued fuzzy sets and type-2 fuzzy sets) put forward a set of approaches to deal with the uncertainty in various real industrial problems. Recently, hesitant fuzzy sets were presented as a new approach of fuzzy set theory to efficiently handle hesitant states compared with previous developed approaches. It improves the fuzzy sets extensions (i.e., Fuzzy Multisets, Nonstationary fuzzy sets and Intuitionistic Fuzzy Sets) in providing a function that presents elements memberships in different values in the domain (Torra, 2010). In other words, in the presence of a MCDM problem, multi-experts are limited by small or finite values. The hesitant fuzzy sets hereby handle this limitation by considering all possible values rather than an aggregated operator (Torra, 2010; Nujoom et al., 2016; Torra and Narukawa, 2007). It can be inferred that the hesitant fuzzy sets are sufficient for collecting or aggregating hesitant experts' opinions for elements in the data set (Torra, 2010, Torra, Narukawa, 2009). Arguably, in real life decision-making problem, commonly, experts are hesitated in giving or aggregating their evaluations regarding individual elements for a problem (Dinçer et al., 2012; Sun et al., 2018; and Akram et al., 2019). Thus, since the hesitant fuzzy sets development, its application has gained a rapid growing interest of scholars because of the existence of hesitant situations in various real-world problems, and also its capability to deal with uncertainty and vagueness triggered by hesitation (Zhou and Xu, 2019; Rodríguez et al., 2014; and Naz and Akram, 2019). Recently, Akram et al. (2020) proposed a novel decision-making approach that merges hesitant fuzzy sets with the ELECTRE-II algorithm to evaluate and rank alternatives. In the decision-making context, Akram and Adeel (2019) used the hesitant fuzzy sets, m-polar fuzzy sets and TOPSIS to handle a group decision-making process under an uncertain environment.

2.4 Literature gaps and research contributions

Based on the analyzed literature, the following research notes are proposed: 1. The chemical sector is less concerned about outsourcing. 2. There are a few considerations for assessing and analyzing risks related to outsourcing providers. 3. Scare literature was found on assessing and quantifying outsourcing risks via mathematical models. 4. Risk factors associated with outsourcing providers need to be identified from academic and industry perspectives. This research contributes to the existing literature in proposing a new evaluation approach for outsourcing providers in the chemical sector. In this paper, to the best of our knowledge, the fuzzy hesitant theory and F-FMEA and the combined compromise solution (CoCoSo) methods are combined to evaluate outsourcing risk for the first time. Despite the big pool of MCDM methods available in the literature, the CoCoSo method is featured in its accuracy, easy to understand, and detailed and structure-based anatomy that attracts decision experts to implement it. It acts under an integrated, simple additive weighting, and exponentially weighted product model. Also, this method is expressed as a combination of compromise decision-making approach with the aggregation strategies. Furthermore, its distance measures that is originated from the grey relational coefficients makes its decision outputs more flexible. The aggregation strategies (equations 18, 19 and 20) produce the alternatives' weights. Arguably, none of the other MCDM methods offer these characteristics, simultaneously.

3. The proposed F-FMEA-CoCoSo approach

3.1 Triangular fuzzy hesitant sets

Some general definitions and expressions of TFHS are shown as follows (Torra, 2010; Rodríguez et al., 2014):

Definition 1. Let $M = \{\mu_1, \ldots, \mu_N\}$ be a set of membership functions with *N* members. A HFS h_M related to *M* is defined as follows:

$$h_M(x) = \cup_{\mu \in M}\{\mu(x)\} \quad (1)$$

Definition 2. Suppose that X is a fixed set, a TFHS $\tilde{E}$ on X can be denoted by:

$$\tilde{E} = \{\langle x, \tilde{f}_{\tilde{E}}(x)\rangle : x \in X\} \tag{2}$$

where $\tilde{f}_{\tilde{E}}(x)$ indicates the function that returns various triangular fuzzy values, one of which called a triangular fuzzy hesitant number (TFHN). It is used to express the possible fuzzy membership degree of an element $x \in X$ to $\tilde{E}$.

Definition 3. Assume that $\tilde{f}_1 = (A_1, B_1, C_1)$ and $\tilde{f}_2 = (A_2, B_2, C_2)$ are the two TFHNs, then the classical operations between them can be defined as:

$$\tilde{f}_1 + \tilde{f}_2 = (A_1 + A_2 - A_1.A_2, B_1 + B_2 - B_1.B_2, C_1 + C_2 - C_1.C_2) \tag{3}$$

$$\tilde{f}_1 \times \tilde{f}_2 = (A_1.A_2, B_1.B_2, C_1.C_2) \tag{4}$$

$$\tilde{f}_1 - \tilde{f}_2 = (A_1 - A_2 + A_1.A_2, B_1 - B_2 + B_1.B_2, C_1 - C_2 + C_1.C_2) \tag{5}$$

$$n\tilde{f} = (1 - (1 - A)^n, 1 - (1 - B)^n, 1 - (1 - C)^n)) \tag{6}$$

$$f^n = (A^n, B^n, C^n), for\ n > 0 \tag{7}$$

Let $\tilde{f}_j (j = 1,2,..,n)$ as a set of TFHNs and $w(w_1, w_2, \dots, w_n)^T$ as a set of the importance (weights) of TFHNs, while $0 \le w_j \le 1$ and $\sum_{j=1}^{n} w_j = 1$. The aggregation operators for TFHNs with weights are defined using below expressions.

Definition 4. The Triangular Fuzzy Hesitant Weighted Averaging (TFHWA) operator and Triangular Fuzzy Hesitant Weighted Geometric (TFHWG) operator are defined as follow:

$$TFHWA(\tilde{f}_j) = \oplus_{j=1}^{n} (w_j \tilde{f}_j) = (1 - \prod_{j=1}^{n} (1 - A_j)^{w_j}, 1 - \prod_{j=1}^{n} (1 - B_j)^{w_j}, 1 - \prod_{j=1}^{n} (1 - C_j)^{w_j}) \tag{8}$$

$$TFHWG(\tilde{f}_j) = \otimes_{j=1}^{n} (\tilde{f}_j^{w_j}) = (\prod_{j=1}^{n} A_j^{w_j}, \prod_{j=1}^{n} B_j^{w_j}, \prod_{j=1}^{n} C_j^{w_j}\}) \tag{9}$$

Definition 5. The deffuziffied value for a TFHN $\tilde{f}_i = (A_i, B_i, C_i)$ can be obtained by:

$$def(\tilde{f}_i) = \frac{A_i + 4 * B_i + C_i}{6} \tag{10}$$

3.2 A proposed approach (F-FMEA-CoCoSo)

Our proposed F-FMEA-CoCoSo approach contains two phases.

Phase 1: The TFHN OSD (Occurence*Severity*Detection) score of each risk criterion for each alternative is determined based on the group experts' evaluation.

Suppose that we have a set of n alternatives $A_1, A_2, \dots, A_n$, a set of m risk criteria $c_1, c_2, \dots, c_m$ and k experts (decision-makers) $d_1, d_2, \dots, d_k$. In this section, we use an improved and more fuzzy formulation (OSD_{ijp} $i \in n, j \in m, p \in k$) for risk measurement rather than traditional FMEA results (Arabsheybani et al. 2018). The TFHN OSD score is defined as follows:

$$OSD_{ijp} = \tilde{f}_{ijp}(O) * \tilde{f}_{ijp}(S) * \tilde{f}_{ijp}(D) \tag{11}$$

where $\tilde{f}_{ijp}(O)$ is the fuzzy likelihood value of occurrence of alternative A_i on the risk criterion c_j assigned by the expert d_p, $\tilde{f}_{ijp}(S)$ is the fuzzy severity value, $\tilde{f}_{ijp}(D)$ is the fuzzy detection value.

Actually, the output of F-FMEA evaluation for all risk criteria will be a TFHN matrix X_p for the expert d_p composed as follows:

$$X_p = [\tilde{X}_{ijp}]_{n\times m} = \begin{bmatrix} \tilde{X}_{11p} & \tilde{X}_{12p} & \cdots & \tilde{X}_{1mp} \\ \tilde{X}_{21p} & \tilde{X}_{22p} & \cdots & \tilde{X}_{2mp} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{X}_{n1p} & \tilde{X}_{n2p} & \cdots & \tilde{X}_{nmp} \end{bmatrix} \tag{12}$$

where $\tilde{X}_{ijp}$ denotes the OSD score of alternatives A_i on the criterion c_j assigned by the pth expert. In next phase, we will extend CoCoSo (Yazdani et al. 2019a) algorithm to deal with TFHNs in multi-criteria group decision-making problems.

***Phase 2*:** The ranking of all alternatives are determined by CoCoSo algorithm based on the TFHN matrix.

Step 1. Normalize TFHN matrix through compromise normalisation expressions.

$$\tilde{r}_{ij} = \frac{\tilde{X}_{ij} - \min_i \tilde{X}_{ij}}{\max_i \tilde{X}_{ij} - \min_i \tilde{X}_{ij}}; \text{ for the benefit criterion } c_j \tag{13}$$

$$\tilde{r}_{ij} = \frac{\max_i \tilde{X}_{ij} - \tilde{X}_{ij}}{\max_i \tilde{X}_{ij} - \min_i \tilde{X}_{ij}}; \text{ for the cost criterion } c_j \tag{14}$$

where $\tilde{X}_{ij}$ denotes the TFHN OSD score of alternative A_i on the risk criterion c_j for all experts.

Step 2. Get the weights $w = (\tilde{w}_1, \tilde{w}_2, \dots, \tilde{w}_m)^T$ of the risk criteria from the all experts' evaluation.

$$\tilde{w}_j = \left((\tilde{w}_{j1} \oplus \dots \oplus \tilde{w}_{jp} \oplus \dots \oplus \tilde{w}_{jk})/k\right) \tag{15}$$

where $\tilde{w}_{jp}$ denotes the weight of the risk criterion c_j assigned by the pth expert.

Step 3. Construct the weighted average TFHN matrix $\tilde{S}_i$ and power weighted TFHN matrix $\tilde{P}_i$ for each alternative A_i based on TFHWA operator and TFHWG operator that are defined in expression (8) and (9):

$$\tilde{S}_i = \sum_{j=1}^{n} (\tilde{w}_j \, \tilde{r}_{ij}) \tag{16}$$

$$\tilde{P}_i = \sum_{j=1}^{n} (\tilde{r}_{ij})^{\tilde{w}_j} \tag{17}$$

Step 4. Build the relative weights matrix for alternatives using the three aggregation strategies:

$$\tilde{k}_{i1} = \frac{\tilde{P}_i+\tilde{S}_i}{\sum_{i=1}^{m}(\tilde{P}_i+\tilde{S}_i)} \tag{18}$$

$$\tilde{k}_{i2} = \frac{\tilde{S}_i}{\min_i \tilde{S}_i} + \frac{\tilde{P}_i}{\min_i \tilde{P}_i} \tag{19}$$

$$\tilde{k}_{i3} = \frac{\lambda\tilde{S}_i+(1-\lambda)(\tilde{P}_i)}{\lambda \max_i \tilde{S}_i+(1-\lambda)(\max_i \tilde{P}_i)}, \text{ for } 0 \le \lambda \le 1 \tag{20}$$

where $\tilde{k}_{i1}$ is the arithmetic mean of sum of relative scores of $\tilde{S}_i$ and $\tilde{P}_i$, $\tilde{k}_{i2}$ is the sum of relative scores of $\tilde{S}_i$ and $\tilde{P}_i$ compared to the best, and $\tilde{k}_{i3}$ is the balanced compromise of $\tilde{S}_i$ and $\tilde{P}_i$ scores, respectively. In expression (20), parameter λ is determined by experts that interprets the flexibility and stability of the CoCoSo algorithm, normally set to λ=0.5. However, the flexibility and stability of the *CoCoSo* algorithm may rely on different values of parameter λ.

Step 5. Integrate three relative weights matrix for alternatives as follow:

$$\tilde{K}_i = (\tilde{k}_{i1} * \tilde{k}_{i2} * \tilde{k}_{i3})^{\frac{1}{3}} + \frac{1}{3}(\tilde{k}_{i1} + \tilde{k}_{i2} + \tilde{k}_{i3}) \tag{21}$$

Step 6. Rank the $\tilde{K}_i$ values and sort them from best to worst.

The final ranking of the alternatives based on the *CoCoSo* algorithm is determined by $\tilde{K}_i$ values (as more significant as better).

4. Case study

4.1. Case background: Chemical sector

In order to prove the practicability of the proposed F-FMEA-CoCoSo approach, we apply it to a practical case. The case company has been developing a wide range of chemical products for more than 40 years, with highest technology and manufacturing systems to fit modern production facilities. It has achieved considerable market share and advanced its leadership in the long run. It is a long-established private manufacturing group consisting of 14 companies operating in Iran. There is a powerful commitment to bring trust to stakeholders, consumers, and communities. The company employed more than 1500 full-time and part-time employees and aims to be one of the leaders in the Iranian Chemical market. In 2015, it generated about $230 million in sales revenue. The CEO focuses on international competition and leading position in the domestic market. Compared with highest technical and production facilities, the company benefits from skillful R&D team providing qualified products, innovative marketing operations, and extensive distribution channels. Three main types of products are provided, including automotive, household, and personal care, packaging and adhesive products. They work closely with international companies on licensing and partnering agreements for many products. The section of the company for household products produces a wide range of insect killers, cleaners, air fresher and polishes. In the next few months, the company seems to have too much demand and orders. However, company is currently unable to expand the capacity of such products for a variety of reasons. Therefore, one option is to outsource part of the production to some external companies (outsourcing providers). There is sort of outsourcing providers in the market that can potentially collaborate. In this case, finding a fit outsourcing provider is a fundamental and strategic task for purchasing and business department due to facing complex variables, elements, and consequences. This leads to company managers looking for a solution and find the best outsourcing provider under several factors. The company hereby approaches one of the research team members seeking joint research collaboration to merge the outsourcing into the production strategy in a safe manner.

Our research showed that outsourcing is even a risky process for the case company, so, we choose outsourcing providers that have less risky operations. Some researchers showed that in supply chain, the risk can be measured by three variables: occurrence, severity and detection (Lee et al. 2012; Li and Zeng, 2016; Safari et al. 2016). Purchasing managers and outsourcing managers in the case company have discussed this and agreed to plan a measurement system based on these variables. Therefore, a questionnaire was developed and distributed among evaluation experts. In order to get a balanced and qualified study, we have carried out different weights for the three variables, and also assigned the different weights for the different experts according to their experience, roles and influence on the evaluation process. The information of experts is described in results section. These risk criteria selected from a series of factors proposed by the research team member to the production manager, maintenance manager and supply chain manager. Based on this, managers determined the relative possible risks based on their experts' opinion. This filtering process was conducted via an individual interview (lasting for about 1 hour). Finally, we will use the following ten risk criteria to analyze and evaluate outsourcing providers $\boldsymbol{C}_1$: increased logistic and inventory cost, $\boldsymbol{C}_2$: loss of control (quality, delivery, etc.), $\boldsymbol{C}_3$: negative impact on employees motivation, decreasing job security, $\boldsymbol{C}_4$:political backlash, $\boldsymbol{C}_5$: adjustment and communication in terms of any change in product design, formula etc, C_6 reduced employment levels, C_7 expanded logistics issues, including insurance, tariffs, customs, and timing, C_8 dependability to outsources in emergencies, C_9 risk of losing formulas, knowledge and capital investment, and C_{10} losing competitive capacities due to incorrect outsourcing.

4.2. Application of the Proposed Approach

In this section, the proposed F-FMEA-CoCoSo approach is applied on the real case study for evaluating the outsourcing providers based on risk criteria. Figure depicts the two main phases followed for evaluating outsourcing providers as a holistic framework.

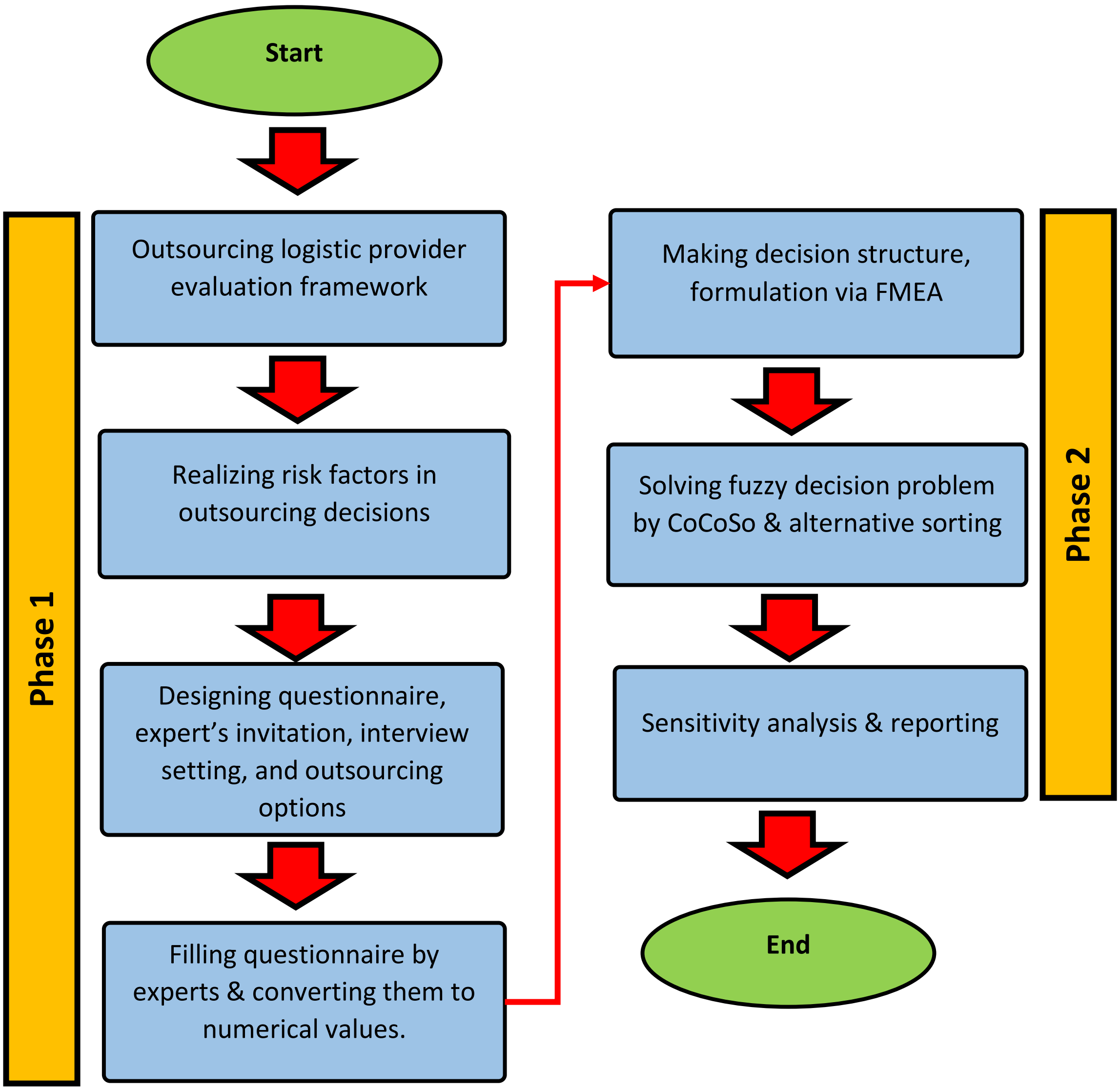


Figure 1- A Holistic framework for analyzing and evaluating outsourcing providers.

Phase 1: Evaluate the TFHN OSD values of outsourcing providers.

Step1. Identifying a group of experts, the risk evaluation criteria, and candidate outsourcing providers.

After a screening, the case company managers identified 10 risk criteria $\{c_j|j \in 1 \cdots 10\}$ and 5 candidate outsourcing providers $\{A_i|i \in 1 \cdots 5\}$. They also nominated three candidate experts $\{d_p|p \in 1 \cdots 3\}$ (Expert 1, Expert 2 and Expert 3) for evaluating five candidate outsourcing providers. Table 2 clarifies the information of experts, their knowledge, and experiences. The case experts have different experience, knowledge, and skills, and thus the weights of 0.2, 0.5, and 0.3 were assigned, accordingly.

Table 2- Experts information

Expert	Gender	Age	Education level	Experience	Job responsibility
Expert 1	Male	46	Bachelor's in Information technology	10 years	Risk analyzer, supply chain planner
Expert 2	Male	55	Master's in industrial & systems engineering	20 years	Operations planning and production manager
Expert 3	Female	49	Master's in Chemical engineering	more than 15 years	Manager of chemical process and quality control expert

Step 2. Evaluating all outsourcing providers by each expert.

First, we introduce the evaluation process to three experts in the form of meetings. They are familiar with risk measurement and evaluation process of FMEA. Three experts have to evaluate the severity, occurrence and detection of each risk criteria of each outsourcing provider utilizing linguistic terms (see Table 3). The questionnaire is sent to the experts by email as an excel file, and they are required to fill in the questionnaire according to the linguistic terms. All experts returned the completed questionnaire on time. Then, the severity, occurrence and detection evaluation results of outsourcing providers shown in Table 4. Due to space constraints, only the evaluation results of Expert 1 are proposed.

Table 3 - Linguistic terms and relevant triangular fuzzy values

Linguistic terms	Triangular fuzzy values
Very low (VL)	(0,0,0.1)
Low (L)	(0,0.1,0.3)

Medium low (ML)	(0.1,0.3,0.5)
Medium (M)	(0.3,0.5,0.7)
Medium High (MH)	(0.5,0.7,0.9)
High (H)	(0.7,0.9,1)
Very High (VH)	(0.9,1,1)

Table 4 – Experts' evaluation of linguistic OSD for outsourcing providers

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Expert.1					*Severity*					
A_1	M	L	VL	ML	M	M	ML	M	MH	M
A_2	L	ML	M	MH	H	M	ML	M	L	M
A_3	ML	ML	M	M	H	L	L	ML	M	MH
A_4	VH	ML	MH	ML	ML	M	M	M	L	M
A_5	M	ML	M	L	M	H	MH	M	ML	M
					Occurrence					
A_1	L	M	M	L	MH	H	ML	MH	M	L
A_2	H	ML	M	M	M	M	MH	ML	M	M
A_3	ML	MH	MH	ML	M	M	M	H	ML	L
A_4	ML	M	M	MH	M	M	MH	M	M	M
A_5	L	M	M	H	ML	L	L	ML	ML	MH
					Detection					
A_1	M	M	M	M	MH	L	L	ML	M	MH
A_2	ML	M	H	ML	ML	M	M	M	L	M
A_3	M	L	M	MH	MH	M	L	MH	M	L
A_4	H	MH	ML	M	M	M	M	L	M	M
A_5	M	ML	M	L	ML	MH	H	VL	L	MH
					…..					

Step 3. Transforming the experts' linguistic variables into TFHN.

The given linguistic evaluation, on the risk criteria of outsourcing providers, were converted into TFHN according to the corresponding relationship shown in Table 3. Next, the three TFHN matrices (occurrence, severity, detection), of each expert, were integrated into the TFHN OSD matrix according to expression (11). The weight of 0.25, 0.4 and 0.35 were given to severity (S), occurrence (O), and detection (D), respectively. Then, the TFHN OSD matrix was obtained by using expressions (4), (6) and (11). The TFHN OSD matrix for each expert is shown in Table 5.

Table 5 - TFHN OSD matrix for Expert 1

Expert.1	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A_1	(0,0.0014, 0.0118)	(0,0.001, 0.0112)	(0,0,0.0034)	(0,0.0008, 0.0073)	(0.0044,0.0209, 0.087)	(0,0.0035, 0.0305)	(0,0.0004, 0.0045)	(0.0007,0.0071, 0.0337)	(0.0025,0.0136, 0.0575)	(0,0.0023, 0.0191)
A_2	(0,0.0018, 0.018)	(0,0.0024, 0.0132)	(0.004,0.0213, 0.099)	(0,0.0074, 0.036)	(0.0013,0.0124, 0.0823)	(0.0013,0.0083, 0.0342)	(0.0007,0.007, 0.0329)	(0.0004,0.0046, 0.0216)	(0,0.0002, 0.0038)	(0.0013,0.0083, 0.0342)
A_3	(0.0001,0.0024, 0.0132)	(0,0.0012, 0.0112)	(0.0024, 0.0131, 0.054)	(0,0.0073, 0.035)	(0.0074,0.0364, 0.2115)	(0,0.0014, 0.0112)	(0,0.0002, 0.0038)	(0.0021,0.0177, 0.088)	(0.0004,0.0046, 0.0216)	(0,0.0004, 0.0068)
A_4	(0.0062,0.0736, 0.242)	(0,0.0071, 0.0336)	(0,0.0074, 0.036)	(0,0.007, 0.033)	(0,0.0044, 0.0209)	(0.0013,0.0083, 0.0342)	(0.0024,0.0131, 0.0538)	(0,0.0014, 0.0117)	(0,0.0014, 0.0112)	(0.0013,0.0083, 0.0342)
A_5	(0,0.0014, 0.0119)	(0,0.0024, 0.0131)	(0.0013,0.008, 0.0342)	(0,0.0006, 0.01)	(0,0.0025, 0.0136)	(0,0.0062, 0.0736)	(0,0.006, 0.0582)	(0,0,0.0023)	(0,0.0004, 0.0045)	(0.0044,0.0209, 0.0866)

Step 4. Aggregating all TFHN OSD matrices into the TFHN OSD matrix for all experts.

Now, the weight of each expert (based on their experience) need be integrated into the decision process. These weights are 0.2, 0.5, and 0.3 for Expert 1, Expert 2 and Expert 3, respectively. Then, we integrated the TFHN OSD matrices and the weights of experts into the TFHN OSD matrix by using expression (9). To end this step, the aggregated TFHN OSD matrix for all experts was obtained by TFHWG operator as shown in Table 6. It should be noted that the aggregated TFHN OSD matrix is used for the Fuzzy CoCoSo algorithm in the next phase.

Table 6 – Aggregated TFHN OSD matrix for all experts

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A_1	(0,0004,0,0024, 0.0107)	(0,0.0005, 0.0046)	(0,0004,0,0024, 0.0107)	(0,0.0003, 0.0028)	(0.0005,0.0029, 0.0125)	(0.0001,0.002, 0.0154)	(0,0.0002, 0.0026)	(0,0.0005,0.003)	(0,0007,0.0039, 0.0171)	(0,0005,0.0029, 0.0127)
A_2	(0,0006,0.0037, 0.0173)	(0,0.0005,0.004)	(0,0003,0.0017, 0.0091)	(0,0002,0.0018, 0.0088)	(0,0003,0.0025, 0.0128)	(0,0002,0.0014, 0.0066)	(0,0.0006, 0.004)	(0,0005,0.0031, 0.0142)	(0,0001,0.0009, 0.005)	(0,0001,0.0012, 0.0064)
A_3	(0.0003,0.0019, 0.0086)	(0,0.0002,0.002)	(0.0002,0.0018, 0.0084)	(0.0001,0.001, 0.0065)	(0.0008,0.0051, 0.028)	(0.0008,0.0038, 0.0172)	(0,0.0003, 0.0023)	(0.0004,0.0027, 0.0132)	(0.0004,0.0032, 0.0209)	(0,0.0002, 0.0023)
A_4	(0.0014,0.0126, 0.0704)	(0.0001,0.0012, 0.0061)	(0.0001,0.001, 0.0054)	(0.0003,0.002, 0.0096)	(0.0002,0.0018, 0.0083)	(0.0003,0.0021, 0.001)	(0.0002,0.0013, 0.0069)	(0,0.0004,0.0038)	(0.0001,0.0009, 0.0055)	(0.0005,0.0026, 0.0116)
A_5	(0,0.0004, 0.0038)	(0,0.0003,0.0024)	(0.0002,0.0016, 0.0078)	(0.0004,0.0023, 0.0108)	(0,0.0003, 0.0027)	(0,0.0008,0.0087)	(0,0001,0,0012, 0.0086)	(0.0007,0.0036, 0.0177)	(0,0.0002,0.0017)	(0,0.0004, 0.0038)
Min	(0,0.0004, 0.0038)	(0,0.0002, 0.002)	(0.0001,0.001, 0.0054)	(0,0.0003, 0.0028)	(0,0.0003, 0.0027)	(0,0.0008, 0.0066)	(0,0.0002, 0.0023)	(0,0.0004, 0.003)	(0,0.0002, 0.0017)	(0,0.0002, 0.0023)
Max	(0.0014,0.0126, 0.0704)	(0.0001,0.0012, 0.0061)	(0.0004,0.0022, 0.0095)	(0.0004,0.0023, 0.0108)	(0.0008,0.0051, 0.0282)	(0.0008,0.0038, 0.0172)	(0.0002,0.0013, 0.0086)	(0.0007,0.0036, 0.0177)	(0.0007,0.004, 0.0209)	(0.0005,0.0029, 0.0127)

Phase 2 **:** Determine the ranking of all alternatives by the CoCoSo algorithm.

Step 1. Normalizing TFHN OSD matrix using expression (13).

First, max and min TFHN OSD values for each risk criterion were achieved as shown in the last two lines of Table 6. In this study, all the risk criteria were considered to be beneficial where the highest level represents the riskiest outsourcing provider. Then, the normalized TFHN OSD matrix was formed using expression (13).

Step 2. Evaluating the weights of all risk criteria.

The weight of each risk criterion was evaluated as in this step. It is used to compute the weighted average TFHN matrix $\tilde{S}_i$ and power weighted TFHN matrix $\tilde{P}_i$ for each outsourcing provider A_i. First, experts were requested to fill Table 7 with linguistic variables in addition to the associated probability. For example, Expert 2 evaluates the importance of C_5 with 50% medium high and 50% low. Second, the TFHN weights of risk criteria were obtained from experts, as shown in the last line of Table 7, via expressions (3-5). Third, the TFHN weights needed to be deffuzified to facilitate the computation process. We used expression (10) to complete deffuzziffication process and get the normalized weights of all risk criteria: w_1= 0.0913, w_2= 0.1071, w_3= 0.0232, w_4= 0.0489, w_5= 0.1366, w_6= 0.0533, w_7= 0.1816, w_8= 0.1415, w_9= 0.076 and w_{10}= 0.1405.

Table 7 – Weight of all risk criteria with linguistic variables and associated probability

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Expert1	L / 0.5	M / 0.6	VL / 0.7	ML / 0.8	H / 0.3	L/0.4	H /0.3	L / 0.5	L / 0.35	L / 0.4
	ML / 0.5	MH / 0.4	ML / 0.3	L / 0.2	ML / 0.7	ML, 0.6	M / 0.7	H / 0.5	MH / 0.65	MH / 0.6
Expert2	M / 0.6	ML / 0.7	VL / 0.8	L / 0.9	MH / 0.5	L/0.6	M /0.4	ML / 0.7	M / 0.2	ML / 0.5
	L / 0.4	MH / 0.3	L / 0.2	M / 0.1	L / 0.5	ML / 0.4	M / 0.6	H / 0.3	ML / 0.8	M / 0.5
Expert3	MH / 0.7	ML / 0.5	L / 0.2	ML / 0.6	M / 0.3	M/0.6	H /0.2	L / 0.4	ML / 0.4	H / 0.3
	M / 0.3	MH / 0.5	ML / 0.8	M / 0.4	M / 0.7	ML/ 0.4	H / 0.8	ML / 0.6	ML / 0.6	M / 0.7
Aggregated TFHN weights	(0.137,0.256, 0.431)	(0.164,0.302, 0.495)	(0.016,0.06, 0.149)	(0.047,0.135, 0.265)	(0.168,0.303,1)	(0.054,0.149, 0.28)	(0.282,0.471,1)	(0.163,0.326,1)	(0.095,0.215, 0.372)	(0.174,0.319,1)

Step 3. Constructing the weighted average TFHN matrix $\tilde{S}_i$ and power weighted TFHN matrix $\tilde{P}_i$ for each alternative A_i.

Table 8 presents the weighted average TFHN matrix and power weighted TFHN matrix $\tilde{P}_i$ by utilizing expression (16) and (17), orderly. Then, the deffuzified values of $\tilde{S}_i$ and $\tilde{P}_i$ can be shown in Table 8.

Table 8 – Weighted average and power weighted TFHN matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Weighted average TFHN matrix										
A_1	(0.0006,0.0027,0.01)	(0,0.0086,0.995)	(0.0016,0.0083,1)	(0,0,0)	(0.0028,0.0141,0.0641)	(0.0007,0.0068,0.092)	(0,0,0.007)	(0.0005,0.0008,0.0001)	(0.0026,0.0163,0.1165)	(0.0065,0.0406,1)
A_2	(0.0008,0.0045,0.0206)	(0.0002,0.0103,0.0676)	(0.0011,0.0043,0.0547)	(0.0011,0.0097,0.0676)	(0.0017,0.0118,0.0666)	(0.0008,0.0033,0.0002)	(0.0014,0.0118,0.0542)	(0.0047,0.0281,0.186)	(0.0003,0.0028,0.0138)	(0.0018,0.0143,0.0683)
A_3	(0.0004,0.002,0.007)	(0,0,0.0001)	(0.0009,0.005,0.0318)	(0.0003,0.0044,0.0308)	(0.0043,0.0277,1)	(0.0039,0.0175,1)	(0,0.0001,0.0002)	(0.0038,0.023,0.155)	(0.0017,0.013,1)	(0,0,0.0001)
A_4	(0.002,0.0181,1)	(0.0031,0.0321,1)	(0,0,0.0002)	(0.0018,0.0114, 0.0916)	(0.0013,0.0081,0.0335)	(0.0017,0.0072,0.02)	(0.0047,0.0313,0.2065)	(0,0,0.008)	(0.0003,0.0031,0.0166)	(0.0065,0.0365,0.6)
A_5	(0,0,0)	(0.0002,0.004,0.0093)	(0.0009,0.004,0.0204)	(0.0026,0.0142,1)	(0,0,0)	(0,0,0.012)	(0.0022,0.0307,1)	(0.0064,0.0336,1)	(0,0,0)	(0.0052,0.0322,0.2737)
Power weighted TFHN matrix										
A_1	(0.627,0.724,0.813)	(0,0.761,0.951)	(0.94,0.98,1)	(0,0.574,0.712)	(0.586,0.73,0.88)	(0.794,0.893,1)	(0,0.123,0.552)	(0.447,0.48,0.35)	(0.774,0.883,0.984)	(0.65,0.83,1)
A_2	(0.652,0.76,0.87)	(0.515,0.775,0.924)	(0.931,0.96,1)	(0.83,0.92,0.99)	(0.55,0.712,0.881)	(0.798,0.86,0.746)	(0.415,0.605,0.785)	(0.616,0.786,0.963)	(0.656,0.78,0.873)	(0.54,0.72,0.89)
A_3	(0.605,0.705,0.79)	(0,0.275,0.477)	(0.927,0.96,1)	(0.783,0.887,0.97)	(0.622,0.794,1)	(0.87,0.935,1)	(0,0.268,0.278)	(0.6,0.766,0.95)	(0.75,0.87,1)	(0,0.18,0.35)
A_4	(0.704,0.86,1)	(0.684,0.867,1)	(0.73,0.823,0.89)	(0.85,0.93,0.993)	(0.529,0.68,0.813)	(0.832,0.896,0.94)	(0.515,0.717,0.942)	(0,0.203,0.663)	(0.66,0.784,0.884)	(0.65,0.815,1)
A_5	(0,0.31,0.47)	(0.515,0.703,0.77)	(0.926,0.96,0.99)	(0.864,0.935,1)	(0.068,0.187,0.329)	(0,0.6,0.92)	(0.447,0.715,1)	(0.643,0.804,1)	(0,0.36,0.513)	(0.63,0.802,0.985)

Table 9 –$\tilde{S}_i$ and $\tilde{P}_i$ and their Deffuzified values

Alternatives	$\tilde{S}_i$	Deffuzified value	$\tilde{P}_i$	Deffuzified value
A_1	(0.015,0.098,2.389)	0,4661	(4.814,6.955,8.139)	6,7955
A_2	(0.014,0.101,0.6)	0,1695	(6.48,7.8,8.6)	7,7082
A_3	(0.015,0.093,3.225)	0,6018	(5.154,6.638,7.763)	6,5786
A_4	(0.021,0.148,2.976)	0,5983	(6.15,7.53,8.75)	7,5053
A_5	(0.017,0.119,3.315)	0,6346	(4.1,6.36,7.9)	6,2418

Step 4. Building the relative weights matrix for alternatives using the three aggregation strategies:

Based on step 3, the relative weights matrix for each alternative should be measured. It is evident that $\tilde{k}_{i1}$ $\tilde{k}_{i2}$ and $\tilde{k}_{i3}$ are obtained via expression (18), (19) and (20).

Step 5. Integrating three relative weights matrix for outsourcing providers.

Finally, the value of $\widetilde{K}_i$ was computed for alternative outsourcing provider and the results shown in Table 10. The priority of outsourcing providers based on risk criteria is ranked as follows:

$$A_2 > A_3 > A_4 > A_5 > A_1$$

The CoCoSo algorithm allows us to perform a sensitivity analysis for the obtained ranking by varying the λ values that are shown in Table 11. It is indicated that each pair of λ, does not change the original ranking ($\lambda = 0.5$), except one case (i.e., when $\lambda = 0.9$) and this interprets the stability of the model and confidential results.

Table 10 – Final ranking of alternatives

Alternatives	$\tilde{k}_{i1}$	$\tilde{k}_{i2}$	$\tilde{k}_{i3}$ (λ =0.5)	$\widetilde{K}_i$	Ranking
A_1	0,1947	2,932	0,8704	2,1245	1
A_2	0,2112	1,2067	0,0203	0,6524	5
A_3	0,1925	3,727	0,0721	1,7032	4
A_4	0,2173	3,731	0,0717	1,7273	3
A_5	0,1844	3,911	0,0761	1,7705	2

Table 11 – Sensitivity analysis under different λ values

Ranking	λ values								
	(0,1)	(0,2)	(0,3)	(0,4)	(0,5)	(0,6)	(0,7)	(0,8)	(0,9)
A_1	1	1	1	1	**1**	1	1	1	4
A_2	5	5	5	5	**5**	5	5	5	5
A_3	4	4	4	4	**4**	4	4	4	3
A_4	3	3	3	3	**3**	3	3	3	2
A_5	2	2	2	2	**2**	2	2	2	1

4.3. Sensitivity analysis of criteria weights

In this section, 50 tests were performed in changing the weights of risk criteria. We selected the different weights by a systematic replacement of random values. Figure 2 shows the list of tests along with their weight's setting.

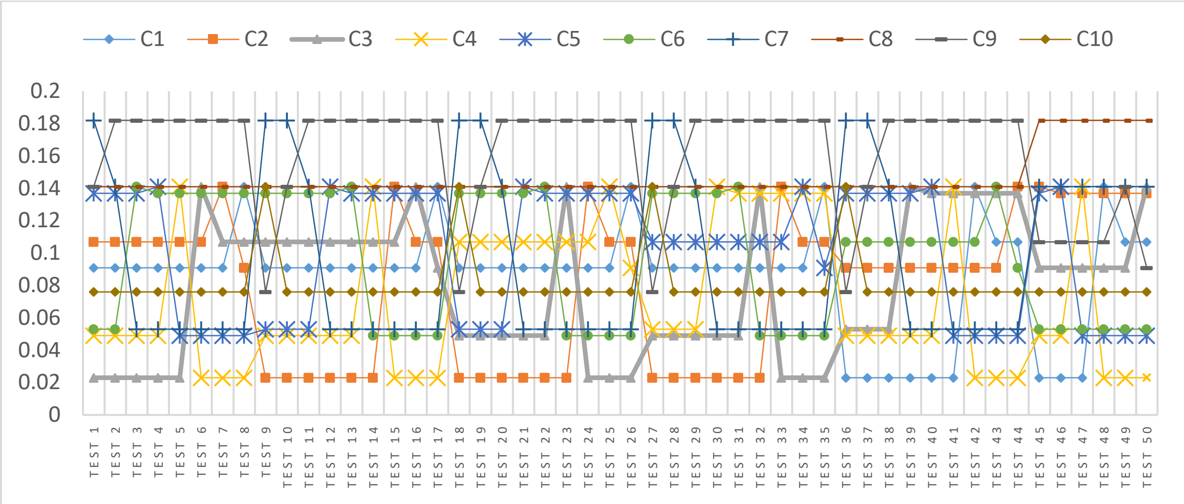
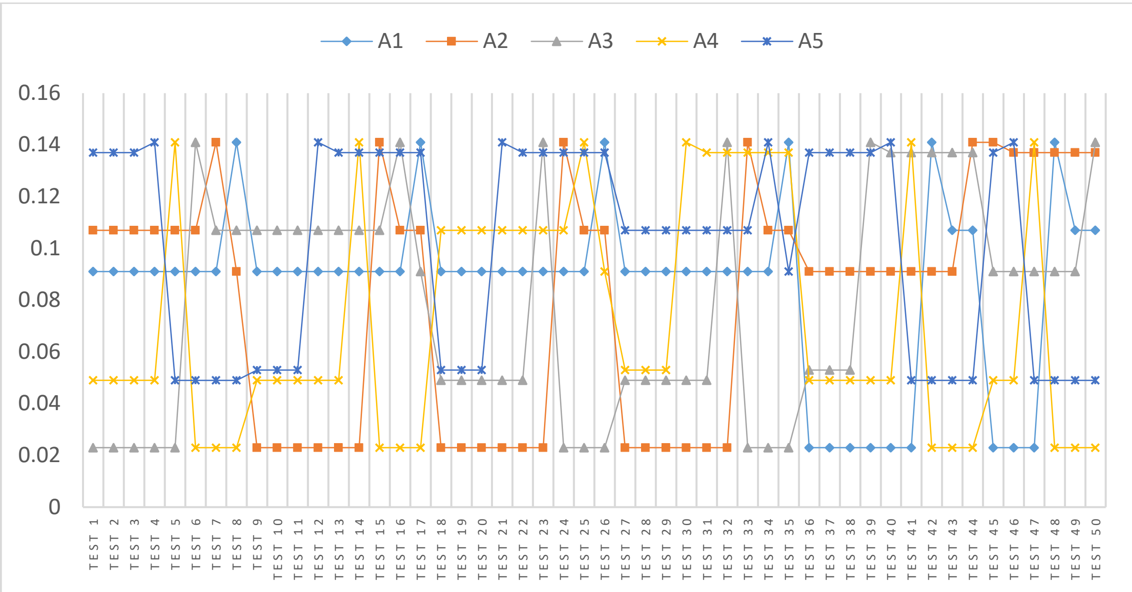


Figure 2 – Sensitivity analysis under different risk criteria weights

The results of the sensitivity analysis are generated using the CoCoCo algorithm in which Figure 3 shows the corresponding priority of the outsourcing providers. In all the fifty tests, the A_2 is the best one and A_1 is the worst one among all outsourcing providers. This is the same as the original ranking obtained in Table 10. During this sensitivity analysis, we set λ =0.5. Comparing the correlation between the original ranking and the tests, the result shows that $\lambda \leq 0.7$ that is acceptable area. Based on these evidences, we can prove that our decision is correct and the results are highly confidential.

Figure 3 – Rankings of alternative providers based on various sensitivity tests



5. Managerial Implication

The aim of this paper is to study outsource risk management and its effects on outsourcing provider selection problem in the chemical industry. In the outsource risk management, we should pay attention to the following problems.

First, risks in outsource are uncertainty in nature. Therefore, it is very difficult to evaluate the risk accurately, and it needs to rely on the qualitative evaluation of experts. In risk evaluation problems, there are two kinds of uncertainties in the expert judgments. The first uncertainty comes from the complexity of risk, the occurrence, severity, detection of risks keeps changing. The second uncertainty comes from different evaluations by experts because of their cognitive limitations. These two uncertainties must be solved to effectively evaluate the risk level of outsourcing provider. Otherwise, these uncertainties will turn into new risks.

Second, the risk criteria should be measurable information by experts. There are many risk criteria, and it is impossible for company to evaluate all risk criteria due to its limited resources. Therefore, measurability is the most important standard for the selection of risk evaluation criteria. "*You cannot manage what you cannot measure*". In this paper, only 10 criteria are selected through the measurability principle, which improves the efficiency of evaluation and reduces the cost of evaluation. Outsourcing providers should also pay attention to risk management, especially these measurable risk criteria, to improve their probability of being selected. Moreover, outsourcing providers only can improve these measurable risk criteria based on the measurement and evaluation.

Third, outsource risk management problem inherently involve multiple criteria, managers should develop multi-criteria methods to address risk management issues in the context of outsourcing provider selection. The weight relationship among multiple criteria will affect the final result. Therefore, how to set the criteria weights scientifically is an important problem to solve the multi-attribute problem. The CoCoCo algorithm considers different weight calculation methods at the same time, which can effectively consider the criteria weight without affecting the final result due to different calculation methods.

Forth, outsourcing provider selection need be completed in a group decision setting. Since risk evaluation involves multiple risk criteria, each criterion involves multiple dimensions (e.g. severity, occurrence, detection). Therefore, the risk assessment needs to consider the opinions of multiple experts, who will evaluate the risk criteria from different perspectives according to their own experience (Bai et al., 2019). Only by synthesizing the opinions of many experts can we effectively evaluate the degree of risk. This hybrid group decision method can be applied to quantitatively express all experts' opinion in a group decision and in an uncertain environment.

In all, the proposed group fuzzy multi-criteria decision-making approach for evaluating the outsourcing providers on the risk criteria can be applied by managers for deciding which outsourcing provider to adopt. It can also be used in the outsourcing provider's own evaluation to find its own risk points and then improve them.

6. Conclusion, limitations, and future research avenues

Over the last two decades, outsourcing activities are increasing dramatically all over the world due to the growing competitiveness among businesses. Thus, managing associated risks has become an important and primary concerns for outsourcing decision-makers. Current literature examines the research area regarding outsource management from the outsourcing provider selection perspective, whereas only few papers consider aspects of outsourcing risks. In addition, potential outsourcing risks management approaches should deliver quantifiable risks-related information that accommodates decision-makers' linguistic opinions of group experts.

This work aims to analyze outsourcing risks associated with the outsourcing provider selection decision. To this end, a multi-phase, multi-method, multi-criteria and multi-expert approach is proposed. This includes a novel fuzzy group multiple-criteria decision-making approach that embraces triangular fuzzy hesitant sets and Failure Mode and Effect Analysis and the combined compromise solution algorithm. The latter is employed to analyze outsourcing risks by evaluating the risks levels associated with outsourcing providers. This work could be concluded in four points:

1. A thorough literature was conducted for identifying outsourcing risks in collaboration with experts in the chemical industry. This point not only supports managers in evaluating outsourcing providers, but also providers to recognize the roots of outsourcing risks. Also, it can be argued that experts should analyze and evaluate outsourcing decisions considering different dimensions (e.g. severity, occurrence, detection). The number and dimensions of evaluation criteria evident the complexity of analyzing outsourcing risks.

2. A two-phase, fuzzy and group decision-support process is constructed by embracing FMEA and CoCoSo along with TFHS. The latter is used when experts are doubtful about linguistic opinions regarding a risk level associated with a risk criterion or an alternative. The FMEA and the CoCoSo approach were merged to deal with risk

levels of criteria and outsourcing providers. Each risk criterion, of outsourcing providers, was hereby given a TFHS OSD score via the FMEA theory. Then, the CoCoSo algorithm was applied to reveal outsourcing provider scores. This phase helps managers in analyzing and evaluating relative importance of possible outcrossing risk criteria and risks levels of outsourcing providers towards the lowest outsourcing risk activity.

3. The proposed outsourcing risks management approach was implemented and demonstrated on a practical-case of an Iranian chemical company. The results demonstrate the capability of the proposed approach in identifying the most desirable outsourcing provider (A1, for the case company) under an uncertain evaluation process environment. Thus, this approach managed to handle vague or uncertain input information within the outsourcing decision process for the case company. However, this approach is re-applicable subject to the approval of the case experts for the risks criteria.

4. A sensitivity analysis was conducted to prove the robustness and reliability of the proposed outsourcing decision-making approach. The results hereby reveled almost no changes in the rank of the best outsourcing provider.

Arguably, this paper provides a valuable approach that provides managerial insights and analysis regarding the risk level of outsourcing providers, mainly in the chemical industry, under uncertainty and group decision-making environment. As a matter of fact, this study has some limitations that paves avenues for further research in the outsource risk management area. First, the risk criteria, for evaluating outsourcing providers, was identified from the risk management perspective. Thus, future research works should consider building a more comprehensive identification that accommodates economic, environmental and social in addition to the risk performance criteria. This potential evaluation framework will provide a comprehensive understanding of outsourcing providers' performance. Also, this paper developed an approach that considers each expert's uncertain judgments and the difference between experts' judgments. Future research might handle expert's psychological characteristics under risk and uncertain environments by using cumulative prospect theory. Furthermore, the quantification process of risk criteria was accomplished by experts; and thus it would be worthy using other methods (e.g., AHP, Rough Set Theory, and Best Worst Method) towards more accurate weights that are based on the subjective evaluation of experts.

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