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A new multi-criteria model based on interval type-2 fuzzy sets and EDAS method for supplier evaluation and order allocation with environmental considerations

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ABSTRACT

Nowadays environmental performance of suppliers becomes more important because of competitive conditions. Besides, the economic performance has been a significant factor for companies to choose their suppliers. In this paper, a new integrated model is proposed for supplier evaluation and order allocation which considers both environmental and economic factors. We use the EDAS (Evaluation based on Distance from Average Solution) method and interval type-2 fuzzy sets for evaluation of suppliers with respect to environmental criteria. According to this evaluation two parameters are defined for each supplier: positive score and negative score. These parameters, together with cost parameters, are utilized to propose a multi-objective mathematical model for determination of order quantity from each supplier. A numerical example is used in this paper to show the applicability of the proposed integrated model. Also, a sensitivity analysis is made to examine the effect of weighting environmental criteria on total purchasing cost and quantity of order from each supplier. The results show that the proposed model is efficient and applicable for real-world problems.

1. Introduction

Companies are forced to improve their performance and optimize their business processes because of today's competitive environment (Chiu & Chiou, 2016; Otay & Çebi, 2016). In such an environment, companies are confronted with many challenges from different perspectives like demographic changes, emergence of disruptive technologies, digitalization and environmental issues. Demographic changes can lead to significant changes in labor market and labor costs in terms of increase or decrease in the size of the workforce, and accordingly it can affect quality and/or price of products or services of companies (Du & Yang, 2014; Richter, 2014). Disruptive innovations and technologies which can create new markets and value networks are another challenge for companies in a competitive environment. Companies should make dynamic strategies like a dynamic commercialization strategy and flexibility in R&D management to prevail over this challenge (Guo, Tan, Sun, Cao, & Zhang, 2016; Marx, Gans, & Hsu, 2014). Integration of digital technologies in different processes or digitalization usually increases the performance of companies. Therefore, using information technology (IT) management can help companies to overcome their rivals in a competitive environment. IT can be used to reduce costs by improving productivity and efficiency and increase revenues by exploiting opportunities through existing customers or finding new customers (Mithas & Rust, 2016; Ye & Wang, 2013).

The attention of consumers, businesses and governments to the environmental issues has been increased in recent years. Societies are concerned with the environmental impact of human activities on natural resources (Toro, Franco, Echeverri, & Guimarães, 2017). Today, companies cannot ignore environmental issues because of increasing public awareness in environmental protection and government regulation about these issues. If they disregard the environmental issues in their business processes, they will probably face with serious problems in competing with other companies in the global market (Hänninen & Karjaluoto, 2017). Accordingly, companies are learning to purchase raw materials, products and services from suppliers that can provide them with low cost and at the same time with environmental responsibility (Lee, Kang, Hsu, & Hung, 2009; Sinha & Anand, 2017). Specifically, new envi-

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ronmental legislations such as RoHS Directive (Restriction of Hazardous Substances Directive), WEEE Directive (Waste Electrical and Electronic Equipment Directive) and EuP (Eco-design Requirement for Energy-using Product) increase the pressure on companies to make their processes more environmentally friendly (Akman, 2015).

Evaluation of suppliers and selection of appropriate ones for procurement of needed materials can be an important activity for improvement and optimization of processes in many companies (Valipour Parkouhi & Safaei Ghadikolaei, 2017). In supply chain management, selection of appropriate suppliers is a strategic decision that can affect the quality and price of the final product of a company (Chai & Ngai, 2015; Dey, Bhattacharya, Ho, & Clegg, 2015; Razmi, Kazerooni, & Sangari, 2016). The current research focuses on the environmental aspects as a competitive advantage.

Supplier evaluation and selection problem can be considered as a multi-criteria decision-making (MCDM) problem because it usually involves some alternatives that are evaluated with respect some criteria (Ho, Xu, & Dey, 2010). Evaluation process in the MCDM problems is usually interlocked with uncertainty of information. The fuzzy sets theory is the most common tool to deal with the uncertainty of information in many MCDM problems (Mardani, Jusoh, Zavadskas, Khalifah, & Nor, 2015; Mardani, Zavadskas, Khalifah, Jusoh, & Nor, 2016). The type-2 fuzzy sets (T2FSs) are an extension of ordinary fuzzy sets which were proposed by Zadeh (1975). The T2FSs are very flexible to model the uncertainty of information because the membership values of them are also fuzzy sets (Keshavarz Ghorabaee, Amiri, Kazimieras Zavadskas, & Antuchevičienė, 2017; Mendel, 2007). An interval type-2 fuzzy set (IT2FS) is a special case of type-2 fuzzy set which has been used in MCDM problems by many researchers (Mohammadi, Farahani, Noroozi, & Lashgari, 2017; Olfat, Amiri, Bamdad Soufi, & Pishdar, 2016).

Many methods have been proposed to handle decision-making problems with multiple criteria in the past years (Mardani et al., 2015). The EDAS (Evaluation based on Distance from Average Solution) method is a new and efficient method which proposed by Keshavarz Ghorabaee, Zavadskas, Olfat, and Turskis (2015) and applied to the inventory classification problem. Keshavarz Ghorabaee, Zavadskas, et al. (2015) demonstrated the efficiency of the EDAS method by comparing it with some other MCDM methods. Fuzzy extension of the EDAS was proposed by Keshavarz Ghorabaee, Zavadskas, Amiri, and Turskis (2016) and applied to supplier selection problem. Also, Kahraman et al. (2017) developed an intuitionistic fuzzy EDAS method and used it for selection of solid waste disposal site. Peng and Liu (2017) proposed some algorithms for soft decision-making with neutrosophic sets based on the EDAS method, new similarity measure soft set. Peng, Dai, and Yuan (2017) developed some interval-valued fuzzy soft decision making methods based on MABAC (Multi-Attributive Border Approximation area Comparison), similarity measure and EDAS method. Stanujkic, Zavadskas, Keshavarz Ghorabaee, and Turskis (2017) presented an extension of the EDAS method based on interval grey numbers. This method has also been used in some other real-world MCDM problems (Ecer, 2017; Stević, Vasiljević, & Vesković, 2016; Trinkūnienė et al., 2017; Turskis & Juodagalvienė, 2016; Zavadskas, Cavallaro, Podvezko, Ubarte, & Kaklauskas, 2017).

In this study, a new integrated model based on IT2FSs and the EDAS method is proposed for supplier evaluation and order allocation with environmental consideration. Some steps of the EDAS method and arithmetic operations of IT2FSs are used to evaluate suppliers with respect to environmental criteria. The outcome of this evaluation process is two parameters for each supplier: positive scores and negative scores. The purchasing costs and the parameters determined are utilized to formulate a multi-objective linear programming for determination of the quantity of order from each supplier. We use a fuzzy programming approach to solve this multi-objective model. A sensitivity analysis is also performed to examine impact of changing weights of environmental criteria on total purchasing cost and order quantity from each supplier. The results show that the integrated proposed model is applicable to real-world problems.

The rest of this paper is organized as follows. In Section 2, we present a brief review of the literature on supplier evaluation with environmental considerations, supplier evaluation and order allocation and applications of IT2FSs in MCDM problems. In Section 3, the proposed methodology is described in detail. In Section 4, we apply the proposed model to an example of supplier evaluation and order allocation with environmental considerations. A sensitivity analysis is made in Section 5. Section 6 presents discussion and future directions. Finally, conclusions are presented in Section 7.

2. Literature review

In this section, a brief review of the recent literature is presented in three sub-section including supplier evaluation with environmental considerations, supplier evaluation and order allocation and applications of IT2FSs in MCDM problems.

2.1. Supplier evaluation with environmental considerations

In recent years, environmental criteria have been used by many researchers in the process of evaluation of suppliers. "Green supplier" and "sustainable supplier" are the most common terms which have been used in the studies of this field. Some researchers have performed reviews on green and sustainable supplier evaluation studies that interested readers can refer to their studies. For example, Govindan, Rajendran, Sarkis, and Murugesan (2015) presented a review of multi criteria decision making approaches for green supplier evaluation and selection, and Zimmer, Fröhling, and Schultmann (2016) conducted a review of models for supporting sustainable supplier selection, monitoring and development. In the following some of recent studies in this field are reviewed.

Banaeian, Mobli, Fahimnia, Nielsen, and Omid (2016) compared the application of technique for order preference by similarity to an ideal solution (TOPSIS), VIKOR (in Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje) and grey relational analysis (GRA) methods in supplier selection problem. Then they applied these methods to a green supplier evaluation and selection study for an actual company from the agri-food industry in fuzzy environment.

Liao, Fu, and Wu (2016) proposed a new integrated fuzzy MCDM approach based on three methods including fuzzy AHP, fuzzy additive ratio assessment (ARAS) and multi-segment goal programming (MSGP) to handle green supplier selection problems. Their method allows decision makers to set multiple segment aspiration levels for green supplier selection problems. They applied the proposed model to a problem in a watch manufacturing company.

Shahryari Nia, Olfat, Esmaeili, Rostamzadeh, and Antuchevičienė (2016) developed an MCDM approach based on intuitionistic fuzzy sets (IFSs) and interval-valued intuitionistic fuzzy sets (IVIFSs). They used the Choquet integral operator and fuzzy measures for evaluation of suppliers with respect to environmental criteria and applied their approach to a manufacturing company.

Govindan, Kadziński, and Sivakumar (2016) presented a novel approach based on PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) method and Simos procedure for evaluation of green suppliers using a group compromise ranking. They showed the applicability of their approach with a case study in an Indian food industry.

Qin, Liu, and Pedrycz (2017) developed an extended TODIM (an acronym in Portuguese of interactive and multi-criteria decision making) based on IT2FSs for multi-criteria group decision making. They introduced a new distance measure based the α-cuts of the IT2FSs and extended TODIM method based on this distance measure and prospect theory. Then they used the proposed method for evaluation of suppliers with respect to environmental criteria.

Mathivathanan, Kannan, and Haq (2017) examined the interrelated influences among sustainable supply chain management practices with a particular look at the automotive industry. They proposed a framework based on the Decision Making Trial and Evaluation Laboratory (DEMATEL) method, for evaluation of automotive industry supply chain management practices in an emerging economy like India.

Tseng, Lim, Wu, Zhou, and Bui (2017) proposed a hybrid method to enhance green supply chain practices. They used the fuzzy Delphi method to screen the evaluation criteria and then a converged interval-valued triangular fuzzy numbers-grey relation analysis (IVTFN-GRA) weighting method used to handle the uncertainty and incomplete information with interdependence relations. They applied their method to a Taiwanese electronic focal firm.

Luthra, Govindan, Kannan, Mangla, and Garg (2017) developed a framework for evaluation of sustainable suppliers by integration of the AHP and VIKOR methods. Based on the literature and experts' opinions, they identified 22 criteria in economic, environmental, and social dimensions, which are the sustainability dimensions, for evaluation of supplier. The AHP method was used to weight the criteria and the VIKOR method was utilized to rank the suppliers.

Yazdani, Chatterjee, Zavadskas, and Hashemkhani Zolfani (2017) proposed a framework to address the relationship between customer requirements and evaluation criteria for green supplier selection problem. They used the DEMATEL method to construct a relationship structure, the quality function deployment (QFD) to identify degree of relationship and the complex proportional assessment (COPRAS) method to rank the suppliers.

Sen, Datta, and Mahapatra (2017) developed a novel decision support framework to deal with supplier selection problems with green and resiliency criteria. Their framework included a dominance-based method with the fuzzy sets theory. The dominance-based method used by them was a simplified version of the PROMETHEE and TODIM methods with lower computational steps. By using a numerical example, they compared the proposed approach with the fuzzy TOPSIS and fuzzy VIKOR methods.

2.2. Supplier evaluation and order allocation

The supplier evaluation and order allocation problem includes two main processes. The evaluation of suppliers is the first process of this problem, and the second process is related to allocation of order to suppliers with respect to the evaluation result of them. This problem usually involves two stages of a supply chain. However, it is very important problem because of its effects on all stages. Although there are some review papers in this field (Aissaoui, Haouari, & Hassini, 2007; Amindoust, Ahmed, & Saghafinia, 2013; Molinè & Coves, 2013; Setak, Sharifi, & Alimohammadian, 2012), a comprehensive review has not been made yet. Here we review some recent studies in this field.

Singh (2014) presented a hybrid approach for prioritization of suppliers and allocation of demand among the suppliers. Their approach was based on the TOPSIS method and mixed-integer linear programming (MILP). The objective function of their model was maximization of total purchase value of items with some constraints including demand condition, budget, lead-time of delivery, and supplier capacity.

Scott, Ho, Dey, and Talluri (2015) proposed an integrated method to handle supplier selection and order allocation problem in a stochastic environment with multiple stakeholders and multiple criteria. They used a combined analytic hierarchy process–quality function deployment (AHP–QFD) approach and a chance constrained optimization algorithm for evaluation of suppliers and allocation of optimal orders among them. They applied the proposed decision support system to the bioenergy industry.

Moghaddam (2015) developed a model for evaluation of suppliers and determination of the optimal quantity of refurbished parts and final products in a reverse logistics network. The proposed model was based on fuzzy multi-objective programming approach and AHP. The Monte Carlo simulation was used to obtain Pareto-optimal solutions of the problem and a computational study was done to validate the model.

Arabzad, Ghorbani, Razmi, and Shirouyehzad (2015) proposed a two-phase approach for supplier evaluation and order allocation problem with respect to both qualitative and quantitative criteria. The criteria were defined based on strengths, weaknesses, opportunities, and threats (SWOT) analysis. Then a fuzzy TOPSIS method was used to determine the evaluation score of suppliers. The results of the fuzzy TOPSIS method were used as inputs for a linear programming model to allocate the orders.

Çebi and Otay (2016) presented a two-stage approach for supplier evaluation and order allocation problem in an uncertain environment. In the first stage, a fuzzy MULTIMOORA (multi-objective optimization by ratio analysis plus the full multiplicative form) method was utilized to evaluate suppliers with respect to some subjective criteria. Then a fuzzy goal programming was used to obtain optimal order from each supplier in a multi-product problem.

PrasannaVenkatesan and Goh (2016) introduced a new approach for evaluation of suppliers and optimization of their order allocation under disruption risk. Performance score values of suppliers were obtained using the fuzzy AHP and fuzzy PROMETHEE methods, and a mixed-integer linear programming approach was used to formulate the mathematical model. They applied the particle swarm optimization (PSO) algorithm to determine Pareto-optimal solutions.

Hu, Xiong, You, and Yan (2016) proposed a hybrid approach to handle supplier evaluation and order allocation problem. They used the fuzzy analytic hierarchy process and mixed integer programming in their proposed approach. To show the feasibility of the proposed approach they applied it to supplier evaluation and order allocation of a plastic and textile manufacturing company.

Govindan and Sivakumar (2016) proposed an integrated MCDM approach for supplier evaluation and order allocation problem. The evaluation of suppliers was done with respect to green criteria, and the fuzzy TOPSIS method was used to prioritize the suppliers. They formulated a multi-objective MILP model to determine optimal order from each supplier, and a weighted additive model was used to solve it.

Kumar, Rahman, and Chan (2016) considered the dimensions of sustainability (economic, social and environmental) in the supplier evaluation and order allocation problem. They presented an integrated MCDM approach based on fuzzy AHP and fuzzy multi-objective linear programming to deal with this problem. The proposed approach was applied to an example of Indian automobile company.

Hamdan and Cheaitou (2017) developed an integrated MCDM approach for supplier evaluation and order allocation problem based on fuzzy AHP, fuzzy TOPSIS and multi-objective mathematical modelling. To evaluate suppliers, they used two types of criteria including green and traditional criteria. The weighted global criterion method and branch-and-cut algorithm were utilized to solve the model.

2.3. Applications of IT2FSs in MCDM problems

As previously mentioned, interval type-2 fuzzy sets are very efficient and flexible to handle uncertainties in comparison to ordinary fuzzy sets. This type of fuzzy sets has been used in MCDM problems by many researchers in recent years. Celik, Gul, Aydin, Gumus, and Guneri (2015) performed a comprehensive review on the applications of IT2FSs in multi-criteria decision-making problems. Interested readers are referred to this article for further information. Some of the recent studies in this field are reviewed in the following.

Kiliç and Kaya (2016) proposed a new model for city-ranking in Turkey. They simultaneously used IT2FSs and crisp sets to address ambiguities and relativities of the problem. The proposed model was utilized for multi-criteria decision-making process of grants allocation, and the applicability of it was assessed by data of a real case in the Middle Black Sea Development Agency in Turkey.

Celik and Taskin Gumus (2016) developed an outranking multi-criteria decision-making method based on interval type-2 fuzzy sets to evaluate preparedness and response ability of non-governmental humanitarian relief organizations. They used interval type-2 fuzzy AHP to determine the weights of some critical success factors as the criteria of the problem. Then the PROMETHEE (stands for: Preference Ranking Organization METHod for Enrichment of Evaluations) method was utilized to evaluate some organizations in Turkey.

Keshavarz Ghorabaee, Zavadskas, Amiri, and Antucheviciene (2016b) introduced a new ranking method for IT2FSs and compared it with some other ranking methods to show the efficiency of it. They developed a new method of assessment based on fuzzy ranking and aggregated weights (AFRAW) to deal with group decision-making problems with IT2FSs. Subjective weights expressed by decision-makers and objective weights calculated based on a deviation-based method were used to determine the aggregated weights of criteria.

Soner, Celik, and Akyuz (2017) integrated the AHP and VIKOR method under interval type-2 fuzzy environment. They demonstrated the proposed approach using a hatch cover design selection problem. In structure of bulk carrier ships, this problem is very important to protect cargo from the external damages and prevent water ingress. In their approach the AHP and VIKOR methods were used to determine weights of criteria and rank the alternatives, respectively.

Deveci, Demirel, and Ahmetoğlu (2017) addressed a planning problem of an airline company in Turkey to launch a new route at an airport in the North American region. They proposed an MCDM approach based on the TOPSIS method and interval type-2 fuzzy sets to select a new route from five different destinations. The results of their research show the feasibility of the proposed approach.

Baykasoğlu and Gölcük (2017) developed a new interval type-2 fuzzy multi-criteria decision making model based on the TOPSIS and DEMATEL methods. Their model uses hierarchical decomposition approach to reduce complexity of problems, DEMATEL to consider interdependencies among criteria and hierarchical TOPSIS to rank alternatives.

Senturk, Erginel, and Binici (2017) introduced a new approach based on the analytic network process (ANP) and interval type-2 fuzzy sets for evaluation of third-party logistics providers. The inner/outer dependencies among criteria and pairwise comparison between criteria/sub-criteria were modelled in their approach using IT2FSs.

Chen (2017) developed a prioritized interval type-2 fuzzy aggregation operator and applied it to multi-criteria decision-making with prioritized criteria. Relationship between criteria was considered in a situation that a lack of satisfaction by higher priority criteria cannot be compensated by lower priority criteria. The proposed method was applied to a landfill site selection problem.

Yu, Wang, and Wang (2017) presented a new multi-attributive border approximation area comparison (MABAC) method based on IT2FSs. They first introduced an algorithm to decompose IT2FSs into embedded ordinary fuzzy numbers, and then used the algorithm to determine the likelihood of IT2FSs. Finally the MABAC method was utilized to rank alternatives based on the likelihood of IT2FSs. They applied their method to an example of selecting hotels from a tourism website.

Celik (2017) proposed a proactive multi-criteria decision-making tool to locate temporary shelters in disaster operations management. The proposed method was based on the DEMATEL method and interval type-2 fuzzy sets. For evaluation of the cause and effect factors, 14 criteria were considered by 9 disaster operation managers, and results showed practical benefits of the proposed method.

Çolak and Kaya (2017) presented an integrated decision-making model for prioritization of renewable energy alternatives in Turkey. Their decision-making model was based on the interval type-2 fuzzy AHP and hesitant fuzzy TOPSIS methods. Interval type-2 fuzzy AHP method was used to obtain the weights of decision criteria, and hesitant fuzzy TOPSIS method was applied to rank renewable energy alternatives.

Kundu, Kar, and Maiti (2017) introduced a new method based on relative preference index and generalized credibility measure to rank interval type-2 fuzzy sets. Using the proposed ranking method, they developed a new method to solve fuzzy MCDM problems with linguistic variables which are based on IT2FSs. They applied the proposed method to a transportation mode selection problem and showed the efficiency of their approach.

Zhong and Yao (2017) extended an ELECTRE (stands for: ELimination Et Choix Traduisant la REalité) method using interval type-2 fuzzy sets. They proposed an α-based distance method to measure the proximity between the interval type-2 fuzzy numbers. Then an IT2FS entropy measure and an entropy weight model were developed to obtain the criteria weights without any subjective information. The feasibility and applicability of the proposed approach were examined by using a supplier selection problem.

Görener, Ayvaz, Kuşakcı, and Altınok (2017) proposed a three-phase hybrid approach based on the IT2FSs to address the supplier evaluation problem in the aviation industry. In the first stage the most significant evaluation criteria were defined. Then they used an interval type-2 fuzzy AHP method to determine the importance of the criteria defined. Finally, an interval type-2 fuzzy TOPSIS method was utilized for evaluation of the performance of suppliers in Turkish airlines.

2.4. Summary

Based on the literature, environmental criteria are very important in the evaluation process of suppliers in a supply chain. The supplier evaluation and order allocation problem can involve uncertainty of information. Using interval type-2 fuzzy sets can help us to handle higher degrees of uncertainty in multi-criteria decision-making problem. Although some studies have considered uncertainty and environmental criteria in the supplier evaluation and order allocation problem, there has been no study in the literature which uses interval type-2 fuzzy sets to deal with the uncertainty of this problem. Also, most of the related researches have only defined one score function for evaluation of suppliers. In this study, we can define positive and negative score functions by the EDAS method to formulate a multi-objective mathematical model for order allocation. The structure of the proposed model can help to capture more degrees of uncertainty and consider environmental criteria as two objectives.

3. Methodology

In this section, we present the preliminaries of the proposed approach first, and then the steps of the proposed approach are described in detail.

3.1. Preliminaries

3.1.1. Interval type-2 fuzzy sets

The type-2 fuzzy sets were introduced as an extension of fuzzy sets (Zadeh, 1975). This type of fuzzy sets can capture more degrees of uncertainty and lead to more rational model in an uncertain environment. In the following, some of the important descriptions related to this type of fuzzy sets are presented.

An interval type-2 fuzzy set is defined based on two levels of membership functions ($\mu(x)$) including upper membership function (UMF) and lower membership function (LMF) which form footprint of uncertainty (Mendel, John, & Feilong, 2006). An IT2FS which has the UMF and LMF with trapezium (or trapezoidal) shapes is called trapezium (or trapezoidal) interval type-2 fuzzy set (TIT2FS). Let us denote by $\tilde{\tilde{E}}$ a TIT2FS. An example of this type of fuzzy sets is shown in Fig. 1, and the mathematical representation of it can be defined as follows:

$$\tilde{\tilde{E}} = (\tilde{E}_\ell | \ell \in \{L, U\}) = (e_{\ell 1}, e_{\ell 2}, e_{\ell 3}, e_{\ell 4}; h^E_{\ell 1}, h^E_{\ell 2} | \ell \in \{L, U\}) \tag{1}$$

In this representation, $\tilde{E}_L$ shows the LMF and $\tilde{E}_U$ represents the UMF of $\tilde{\tilde{E}}$. Moreover, $h^E_{\ell 1}$ and $h^E_{\ell 2}$ denote the membership values of $e_{\ell 2}$ and $e_{\ell 3}$, respectively ($\ell \in \{L, U\}$).

Suppose that $\tilde{\tilde{E}}$ and $\tilde{\tilde{G}}$ are two TIT2FSs and d is a crisp number. The arithmetic operations of this type of fuzzy sets are defined as follows (Chen & Lee, 2010; Keshavarz Ghorabaee, Amiri, Salehi Sadaghiani, & Hassani Goodarzi, 2014; Keshavarz Ghorabaee, Amiri, Salehi Sadaghiani, & Zavadskas, 2015):

- Addition

$$\tilde{\tilde{E}} \oplus \tilde{\tilde{G}} = \big(e_{\ell 1} + g_{\ell 1}, e_{\ell 2} + g_{\ell 2}, e_{\ell 3} + g_{\ell 3}, e_{\ell 4} + g_{\ell 4}; \min(h^E_{\ell 1}, h^G_{\ell 1}), \quad \min(h^E_{\ell 2}, h^G_{\ell 2}) | \ell \in \{L, U\}\big) \tag{2}$$

$$\tilde{\tilde{E}} + d = \big(e_{\ell 1} + d, e_{\ell 2} + d, e_{\ell 3} + d, e_{\ell 4} + d; h^E_{\ell 1}, h^E_{\ell 2} | \ell \in \{L, U\}\big) \tag{3}$$

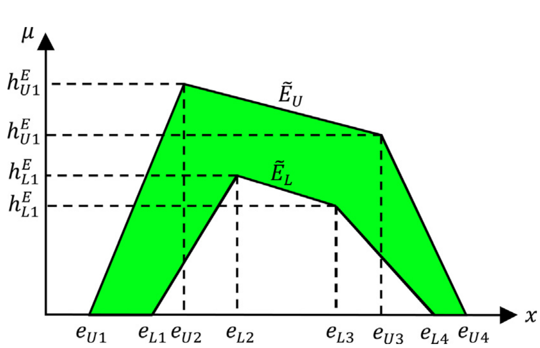

Fig. 1. An example of TIT2FS.

- Subtraction

$$\tilde{\tilde{E}} \ominus \tilde{\tilde{G}} = \big(e_{\ell 1} - g_{\ell 4}, e_{\ell 2} - g_{\ell 3}, e_{\ell 3} - g_{\ell 2}, e_{\ell 4} - g_{\ell 1}; \min(h^E_{\ell 1}, h^G_{\ell 1}), \min(h^E_{\ell 2}, h^G_{\ell 2}) | \ell \in \{L, U\}\big) \tag{4}$$

$$\tilde{\tilde{E}} - d = (e_{\ell 1} - d, e_{\ell 2} - d, e_{\ell 3} - d, e_{\ell 4} - d; h^E_{\ell 1}, h^E_{\ell 2} | \ell \in \{L, U\}) \tag{5}$$

- Multiplication

$$\tilde{\tilde{E}} \otimes \tilde{\tilde{G}} = \big(m_{\ell 1}, m_{\ell 2}, m_{\ell 3}, m_{\ell 4}; \min(h^E_{\ell 1}, h^G_{\ell 1}), \min(h^E_{\ell 2}, h^G_{\ell 2}\big) | \ell \in \{L, U\}) \tag{6}$$

where

$$m_{\ell i} = \begin{cases} min(e_{\ell i} g_{\ell i}, e_{\ell i} g_{\ell (5-i)}, e_{\ell (5-i)} g_{\ell i}, e_{\ell (5-i)} g_{\ell (5-i)}) \ \ if \ i = 1, 2 \\ max\big(e_{\ell i} g_{\ell i}, e_{\ell i} g_{\ell (5-i)}, e_{\ell (5-i)} g_{\ell i}, e_{\ell (5-i)} g_{\ell (5-i)}\big) \ \ if \ i = 3, 4 \end{cases} \tag{7}$$

$$\tilde{\tilde{E}}.d = \begin{cases} \big(e_{\ell 1} d, e_{\ell 2} d, e_{\ell 3} d, e_{\ell 4} d; h^E_{\ell 1}, h^E_{\ell 2} | \ell \in \{L, U\}\big) \ if \ k \geqslant 0 \\ \big(e_{\ell 4} d, e_{\ell 3} d, e_{\ell 2} d, e_{\ell 1} d; h^E_{\ell 1}, h^E_{\ell 2} | \ell \in \{L, U\}\big) \ if \ k < 0 \end{cases} \tag{8}$$

Division of a TIT2FS by a crisp number l can be defined using $d = 1/l$ and $l \neq 0$.

- Defuzzification

$$\mathcal{T}(\tilde{\tilde{E}}) = \frac{1}{2}\left(\sum_{\ell \in \{L,U\}} \frac{e_{\ell 1} + (1 + h^E_{\ell 1}) e_{\ell 2} + (1 + h^E_{\ell 2}) e_{\ell 3} + e_{\ell 4}}{4 + h^E_{\ell 1} + h^E_{\ell 2}} \right) \tag{9}$$

where $\mathcal{T}(\tilde{\tilde{E}})$ denote the crisp score of $\tilde{\tilde{E}}$.

3.1.2. Ranking TIT2FSs

In this paper, an efficient method which were proposed by Keshavarz Ghorabaee, Zavadskas, Amiri, and Antucheviciene (2016a) is used to determine ranking scores of TIT2FSs in the process of the proposed approach. We summarize this method as follows.

This method is based on the membership area of the subtraction of two TIT2FSs. Suppose that $\tilde{\tilde{E}}_s$ and $\tilde{\tilde{E}}_t$ are two TIT2FSs. Firstly, the total area under the UMF and LMF of $\tilde{\tilde{E}}_s$ and $\tilde{\tilde{E}}_t$ is calculated. These areas are symbolized by SE^U_k and SE^L_k ($k \in \{s, t\}$) and shown in Fig. 2.

Secondly, the subtraction of two TIT2FSs ($\tilde{\tilde{E}}_s \ominus \tilde{\tilde{E}}_t$) is calculated and denoted by $\tilde{\tilde{D}}$. Then the areas under the UMF and LMF of $\tilde{\tilde{D}}$ for positive and negative domains are computed. SD^p_ℓ and SD^n_ℓ ($\ell \in \{L, U\}$) represent the areas for positive and negative domains, respectively. These parameters are depicted in Fig. 3.

According to these areas, the possibility degree of $\tilde{\tilde{E}}_s$ over $\tilde{\tilde{E}}_t$ is calculated as follows:

$$p(\tilde{\tilde{E}}_s \geqslant \tilde{\tilde{E}}_t) = \frac{W_p + (\mathcal{K}(W_p - W_n) \times P_s)}{W_p + W_n + \mathcal{K}(W_p - W_n)} \tag{10}$$

where

$$W_p = (h^D_{L2} \times SD^p_L) + (h^D_{U2} \times SD^p_U) \tag{11}$$

$$W_n = (h^D_{L1} \times SD^n_L) + (h^D_{U1} \times SD^n_U) \tag{12}$$

$$P_s = \frac{SE^U_s + SE^L_s}{SE^U_s + SE^L_s + SE^U_t + SE^L_t} \tag{13}$$

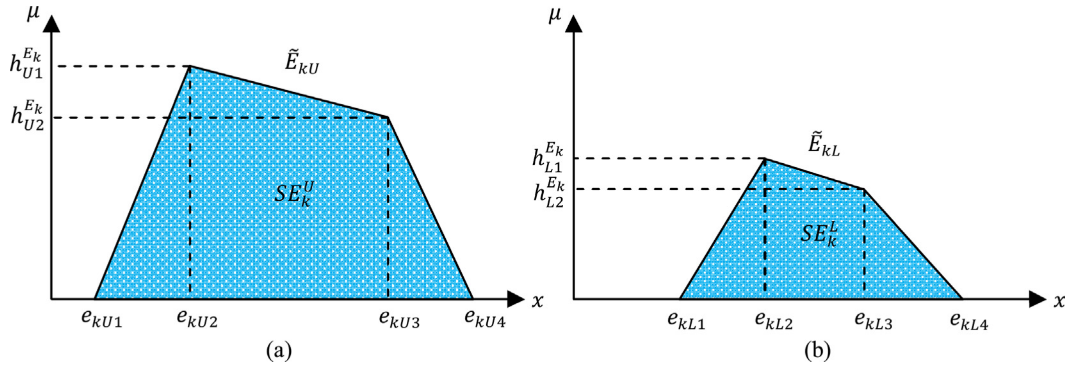

Fig. 2. (a) Total area under the UMF of $\tilde{\tilde{E}}_k$, (b) total area under the LMF of $\tilde{\tilde{E}}_k$.

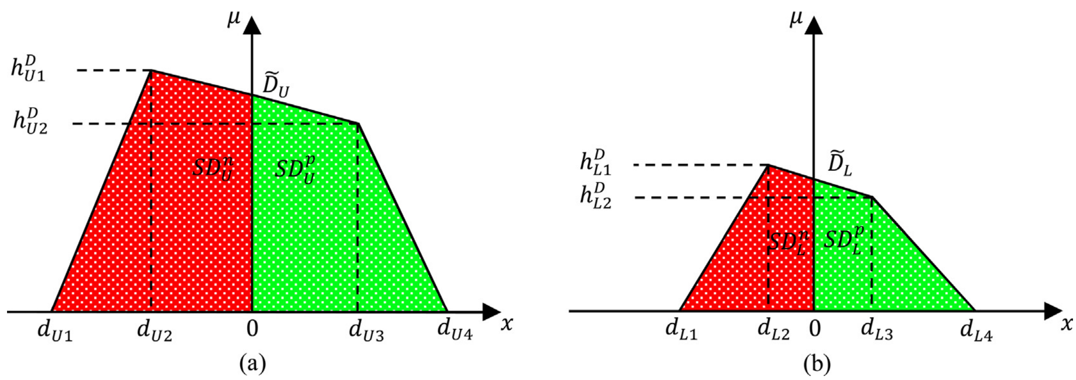

Fig. 3. (a) The area under the UMF of $\tilde{\tilde{D}}$, (b) the area under the LMF of $\tilde{\tilde{D}}$.

and $\mathcal{K}(x)$ is a simple function which is defined as follows:

$$\mathcal{K}(x) = \begin{cases} 1 \text{ if } x = 0 \\ 0 \text{ if } x \neq 0 \end{cases} \tag{14}$$

In a special case, when all elements of $\tilde{\tilde{E}}_s$ and $\tilde{\tilde{E}}_t$ ($e_{k\ell 1}$ to $e_{k\ell 4}$, $\ell \in \{L, U\}$ and $k \in \{s, t\}$) are equal to zero, the possibility degree of $\tilde{\tilde{E}}_s$ over $\tilde{\tilde{E}}_t$ is assumed to be equal to 0.5 ($p(\tilde{\tilde{E}}_s \geqslant \tilde{\tilde{E}}_t) = 0.5$).

Suppose that we have n TIT2FSs, using the possibility degrees and the formula presented by Xu (2001) we can calculate the ranking score of each TIT2FS as follows:

$$\mathcal{R}(\tilde{\tilde{E}}_i) = \frac{1}{n(n-1)}\left(\sum_{j=1}^{n} p(\tilde{\tilde{E}}_i \geqslant \tilde{\tilde{E}}_j) + \frac{n}{2} - 1\right) \tag{15}$$

3.1.3. The EDAS method

The EDAS method is a new and efficient multi-criteria decision-making method which proposed by Keshavarz Ghorabaee, Zavadskas, et al. (2015). Evaluation process in this method is based on positive and negative distances from the average solution. Suppose that we have an MCDM problem with n alternatives and m criteria, and the decision-matrix is defined as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{im} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nj} & \cdots & x_{nm} \end{bmatrix} \tag{16}$$

where x_{ij} denote the performance value (rating) of ith alternative on jth criterion ($i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$). Also, we define the weight of jth criterion by w_j, where $0 < w_j < 1$ and $\sum_{j=1}^{m} w_j = 1$. The steps of using this method are presented as follows:

Step 1. Determine the average solution elements ($\mathcal{V}_j$) with respect to each criterion shown as follows:

$$\mathcal{V}_j = \frac{\sum_{i=1}^{n} x_{ij}}{n} \tag{17}$$

Step 2. Calculate the positive distance ($\mathcal{Pd}_{ij}$) and negative distance ($\mathcal{Nd}_{ij}$) of each elements of the decision-matrix from the calculated elements of the average solution using the following equations:

$$\mathcal{Pd}_{ij} = \begin{cases} \frac{max(0, x_{ij} - \mathcal{V}_j)}{\mathcal{V}_j} & \text{if } j \in BC \\ \frac{max(0, \mathcal{V}_j - x_{ij})}{\mathcal{V}_j} & \text{if } j \in NC \end{cases} \tag{18}$$

$$\mathcal{Nd}_{ij} = \begin{cases} \frac{max(0, \mathcal{V}_j - x_{ij})}{\mathcal{V}_j} & \text{if } j \in BC \\ \frac{max(0, x_{ij} - \mathcal{V}_j)}{\mathcal{V}_j} & \text{if } j \in NC \end{cases} \tag{19}$$

where BC and NC are the sets of beneficial and non-beneficial criteria, respectively.

Step 3. Compute the weighted summation of the calculated positive and negative distances for each alternative as follows:

$$\mathcal{SP}_i = \sum_{j=1}^{m} w_j \mathcal{Pd}_{ij} \tag{20}$$

$$\mathcal{NP}_i = \sum_{j=1}^{m} w_j \mathcal{Nd}_{ij} \tag{21}$$

Step 4. Calculate the normalized values of $\mathcal{SP}_i$ and $\mathcal{NP}_i$ as follows:

$$\mathcal{SP}_i^{(n)} = \frac{\mathcal{SP}_i}{\max\limits_k \mathcal{SP}_k} \quad (22)$$

$$\mathcal{NP}_i^{(n)} = 1 - \frac{\mathcal{NP}_i}{\max\limits_k \mathcal{NP}_k} \quad (23)$$

Step 5. Calculated the appraisal score of each alternative using the following equation:

$$\mathcal{AS}_i = \frac{1}{2}(\mathcal{SP}_i^{(n)} + \mathcal{NP}_i^{(n)}) \quad (24)$$

Step 6. Rank the alternatives according to decreasing values of $\mathcal{AS}_i$.

According to the steps of the EDAS method, increase in the values of $\mathcal{SP}_i$ and decrease in the values of $\mathcal{NP}_i$ lead to increasing the desirability of an alternative. In other words, the values of $\mathcal{SP}_i$ and $\mathcal{NP}_i$ should be maximized and minimized, respectively.

3.2. The proposed model for supplier evaluation and order allocation

In this section, a new integrated model is proposed for supplier evaluation and order allocation. Firstly, we use TIT2FSs and some steps of the EDAS method to evaluate suppliers and determine positive and negative scores of them. Then a multi-objective linear programming model is developed to allocate orders to each supplier. A fuzzy programming approach is utilized to solve the multi-objective model and obtain final solution. The proposed model can be used to answer the following questions:

- Which supplier should we select for procurement of raw material with respect to environmental and economic criteria?
- How much raw material should we order from each selected supplier with respect to environmental and economic criteria?
- How can environmental criteria affect the order quantity of selected suppliers?
- How can environmental criteria affect the total purchasing cost of raw material?

Moreover, a company which aims to use the proposed model should meet the following conditions:

- The company should be able to appoint some experts as decision-makers which are familiar with the supplier evaluation and order allocation problem.
- The decision-makers should be able to identify some potential suppliers for procurement of raw material. Also, they should be agreed on the identified suppliers for evaluation process.
- The decision-makers should be able to define some environmental criterial for evaluation of suppliers. They should be agreed on the selected criteria and their definitions.
- The parameters of the order allocation problem like purchasing cost and average defect rate of each supplier should be defined by the decision-makers.

The steps of the proposed model are as follows:

Step 1. Formation of a group of decision-makers and identification of potential suppliers and related criteria for evaluation process.

Step 2. Evaluation of the importance of each criterion and also the performance value of each supplier on each criterion by each decision-maker.

In this step, the elements of fuzzy decision matrix and fuzzy weights of criteria are determined with respect to each decision-maker using TIT2FSs. Suppose that we have *n* suppliers, *m* criteria and *k* decision-makers in the evaluation process. Then the following equations describe these elements:

$$X_p = [\tilde{\tilde{x}}_{ijp}]_{n\times m} \quad (25)$$

$$W_p = [\tilde{\tilde{w}}_{jp}]_{1\times m} \quad (26)$$

where $\tilde{\tilde{x}}_{ijp}$ symbolizes the performance value of *i*th supplier on *j*th criterion given by the *p*th decision-maker, and $\tilde{\tilde{w}}_{jp}$ represents the weight of *j*th criterion given by the *p*th decision-maker.

Step 3. Calculation of aggregated values for the performance value of each supplier on each criterion and also the weight of each criterion.

To obtain aggregated values, the average opinion of decision-makers is calculated as follows:

$$\tilde{\tilde{x}}_{ij} = \frac{1}{k}\bigoplus_{p=1}^{k}\tilde{\tilde{x}}_{ijp} \quad (27)$$

$$\tilde{\tilde{w}}_{j} = \frac{1}{k}\bigoplus_{p=1}^{k}\tilde{\tilde{w}}_{jp} \quad (28)$$

Step 4. Determination of the elements of average solution.

As previously mentioned, the evaluation process in the EDAS method is based on distance from the average solution. According to Step 1 of the EDAS method and aggregated performance values, we can use the following equation to determine these elements:

$$\tilde{\tilde{\mathcal{V}}}_j = \frac{1}{n}\bigoplus_{i=1}^{n}\tilde{\tilde{x}}_{ij} \quad (29)$$

Step 5. Calculation of the positive and negative distances from the average solution.

In this step, we first define a function to compare a TIT2FS with zero and determine the maximum value, shown as follows:

$$\mathcal{Z}(\tilde{\tilde{E}}) = \begin{cases} \tilde{\tilde{E}} \text{ if } T(\tilde{\tilde{E}}) > 0 \\ 0 \text{ if } T(\tilde{\tilde{E}}) \leqslant 0 \end{cases} \quad (30)$$

Then the following equations are used to calculate the positive and negative distances:

$$\widetilde{\widetilde{\mathcal{P}d}}_{ij} = \begin{cases} \frac{\mathcal{Z}(\tilde{\tilde{x}}_{ij}\ominus\tilde{\tilde{\mathcal{V}}}_j)}{\mathcal{T}(\tilde{\tilde{\mathcal{V}}}_j)} \text{ if } j \in BC \\ \frac{\mathcal{Z}(\tilde{\tilde{\mathcal{V}}}_j\ominus\tilde{\tilde{x}}_{ij})}{\mathcal{T}(\tilde{\tilde{\mathcal{V}}}_j)} \text{ if } j \in NC \end{cases} \quad (31)$$

$$\widetilde{\widetilde{\mathcal{N}d}}_{ij} = \begin{cases} \frac{\mathcal{Z}(\tilde{\tilde{\mathcal{V}}}_j\ominus\tilde{\tilde{x}}_{ij})}{\mathcal{T}(\tilde{\tilde{\mathcal{V}}}_j)} \text{ if } j \in BC \\ \frac{\mathcal{Z}(\tilde{\tilde{x}}_{ij}\ominus\tilde{\tilde{\mathcal{V}}}_j)}{\mathcal{T}(\tilde{\tilde{\mathcal{V}}}_j)} \text{ if } j \in NC \end{cases} \quad (32)$$

where *BC* and *NC* are the sets of beneficial and non-beneficial criteria, respectively.

Step 6. Calculation of the weighted sums of positive and negative distances for all suppliers, shown as follows:

$$\widetilde{\widetilde{\mathcal{SP}}}_i = \bigoplus_{j=1}^{m}(\tilde{\tilde{w}}_j \otimes \tilde{\tilde{\mathcal{P}d}}_{ij}) \quad (33)$$

$$\widetilde{\widetilde{\mathcal{NP}}}_i = \bigoplus_{j=1}^{m}(\tilde{\tilde{w}}_j \otimes \tilde{\tilde{\mathcal{N}d}}_{ij}) \quad (34)$$

Step 7. Determination of positive scores ($\mathcal{R}(\widetilde{\widetilde{\mathcal{SP}}}_i)$) and negative scores ($\mathcal{R}(\widetilde{\widetilde{\mathcal{NP}}}_i)$) of each supplier using the ranking method presented in Section 3.1.2.

Step 8. Formulation of a mathematical linear programming model for allocation of order among suppliers.

The following notations are used in the model:

x_i	Order quantity of ith supplier
y_i	Binary variable of allocation ($y_i = 1$ if $x_i > 0$, and otherwise $y_i = 0$)
$\mathcal{R}(\widetilde{\widetilde{\mathcal{SP}}}_i)$	Positive score of ith supplier
$\mathcal{R}(\widetilde{\widetilde{\mathcal{NP}}}_i)$	Negative score of ith supplier
C_i^P	Purchasing cost of ith supplier
p_i	Average defect rate of ith supplier
l_i	Average rate of lateness (in delivery) of ith supplier
CAP_i	Maximum capacity of ith supplier
$Qmin_i$	Minimum allowable order quantity of ith supplier
$Pmax$	Maximum allowable defected material
$Lmax$	Maximum allowable lateness
D^T	Total demand
Z_1	Total positive score of supplied material
Z_2	Total negative score of supplied material
Z_3	Total purchasing cost

According to the parameters of the EDAS method and the other parameters and variables, the following multi-objective linear programming model is proposed to determine order allocation.

$$Max\ Z_1 = \sum_{i=1}^{n} \mathcal{R}(\widetilde{\widetilde{\mathcal{SP}}}_i) x_i \tag{35}$$

$$Min\ Z_2 = \sum_{i=1}^{n} \mathcal{R}(\widetilde{\widetilde{\mathcal{NP}}}_i) x_i \tag{36}$$

$$Min\ Z_3 = \sum_{i=1}^{n} C_i^P x_i \tag{37}$$

Subject to:

$$\sum_{i=1}^{n} x_i = D^T \tag{38}$$

$$\sum_{i=1}^{n} p_i x_i \leqslant Pmax \tag{39}$$

$$\sum_{i=1}^{n} l_i x_i \leqslant Lmax \tag{40}$$

$$x_i \geqslant y_i Qmin_i \quad \forall i \tag{41}$$

$$x_i \leqslant y_i CAP_i \quad \forall i \tag{42}$$

$$x_i \geqslant 0 \text{ and } y_i \in \{0, 1\} \tag{43}$$

Step 9. Solving the mathematical model using the fuzzy multi-objective programming approach proposed by Zimmermann (1978).

To obtain a solution for the mathematical model (Eqs. (35)–(43)), we first define the membership functions of the objectives as follows:

$$\mu(Z_1) = \begin{cases} 0 & for \quad Z_1 \leqslant Z_1^{min} \\ 1 + \frac{Z_1 - Z_1^{max}}{Z_1^{max} - Z_1^{min}} & for \quad Z_1^{min} \leqslant Z_1 \leqslant Z_1^{max} \\ 1 & for \quad Z_1^{max} \leqslant Z_1 \end{cases} \tag{44}$$

$$\mu(Z_2) = \begin{cases} 0 & for \quad Z_2^{max} \leqslant Z_2 \\ 1 - \frac{Z_2 - Z_2^{min}}{Z_2^{max} - Z_2^{min}} & for \quad Z_2^{min} \leqslant Z_2 \leqslant Z_2^{max} \\ 1 & for \quad Z_2 \leqslant Z_2^{min} \end{cases} \tag{45}$$

$$\mu(Z_3) = \begin{cases} 0 & for \quad Z_3^{max} \leqslant Z_3 \\ 1 - \frac{Z_3 - Z_3^{min}}{Z_3^{max} - Z_3^{min}} & for \quad Z_3^{min} \leqslant Z_3 \leqslant Z_3^{max} \\ 1 & for \quad Z_3 \leqslant Z_3^{min} \end{cases} \tag{46}$$

Then the following model is solved.

$$Max\ \lambda \tag{47}$$

Subject to:

$$\lambda \leqslant 1 + \frac{Z_1 - Z_1^{max}}{Z_1^{max} - Z_1^{min}} \tag{48}$$

$$\lambda \leqslant 1 - \frac{Z_2 - Z_2^{min}}{Z_2^{max} - Z_2^{min}} \tag{49}$$

$$\lambda \leqslant 1 - \frac{Z_3 - Z_3^{min}}{Z_3^{max} - Z_3^{min}} \tag{50}$$

And Eqs. (38)–(43).

It should be noted that Z_r^{max} and Z_r^{min} ($r = 1, 2, 3$) denote the maximum and minimum values of objective functions, respectively, and these values are determined by solving the original model as single-objective models.

To clear the steps of the proposed model, a flowchart is depicted in Fig. 4.

4. Application of the model with environmental criteria

In this section, the proposed integrated model is applied to supplier evaluation and order allocation with respect to environmental criteria in a tissue paper manufacturing company which is called XYZ in this paper. XYZ produces different types of tissue paper including facial tissues, paper towels, table napkins, etc. The company employs more than 160 people including managers and technical workers. The production capacity of XYZ is approximately 5000 tons per annum, and the total net sales revenue of the company was about \$31 million in 2016. XYZ has markets in more than 30 countries including 62 customers (27 retailers and 35 independent distributers). It has been certified to many standards like ISO 9001:2015, ISO 10002:2014 and ISO 10668. Because of the possible effect of the paper products on environment, XYZ has begun a plan since 2015 to improve its processes with respect to environmental aspects and get ISO 14001 certification. This company purchases its raw material annually, and the tonnage of the raw material is approximately equal to the production capacity. As a part of its environmental plan, XYZ decided to supply the needed raw material of a year from some suppliers according to environmental criteria. In the past 10 years, the company has purchased the raw material from more than 14 suppliers, but some of them have not met the required quality of XYZ. Therefore, the company decided to limit the number of suppliers and choose suppliers which have higher rates of quality, lower rates of lateness and adherence to environmental principles. For this aim, the board of directors of the company formed a group of five experts (Dm_1 to

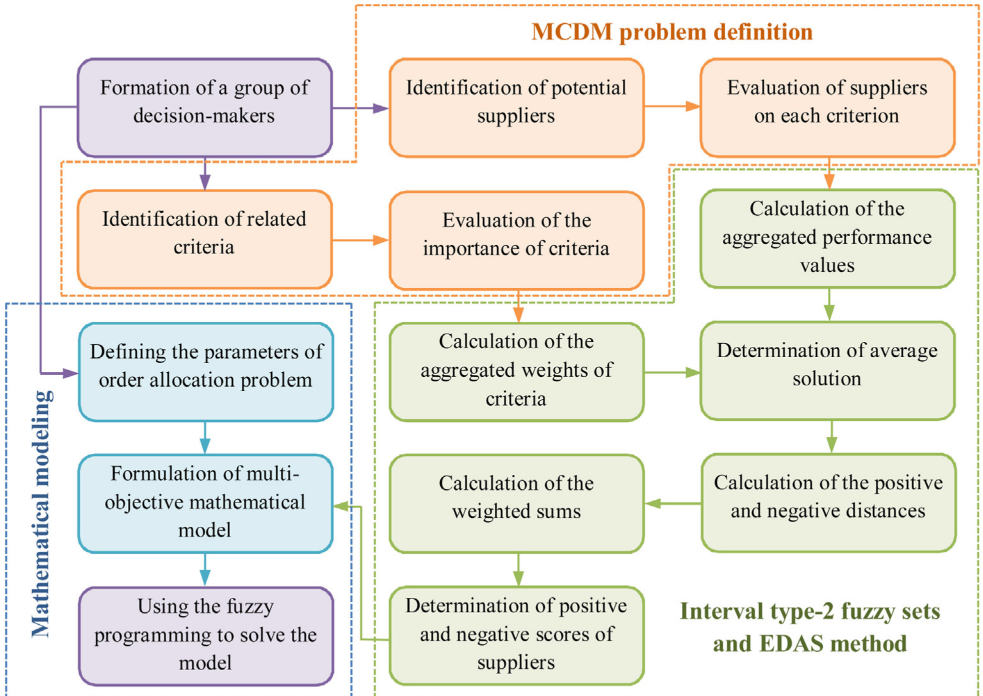

Fig. 4. Flowchart of the proposed MCDM model.

Dm_5) from different departments (production, research and development, purchasing, marketing and human resource management). Afterwards, the proposed integrated model is applied to this example as follows:

Step 1. First mission of the group of experts, which is defined as decision-makers, was to identify potential suppliers and define some environmental criteria. According the literature (Govindan et al., 2015b; Nielsen, Banaeian, Golińska, Mobli, & Omid, 2014), the decision-makers defined seven criteria (C_1 to C_7) which are represented in Table 1. Then they estimated the average defect rates and the average rates of lateness for each supplier and also the amount of raw material (total demand) according to the historical data of the company. The data of the company which was used to define the problem is provided in Table 2.

Step 2. In this step, each decision-maker should express the importance of each criterion and also the performance value of each supplier with respect to each criterion. The linguistic variables which are defined based on TIT2FSs are used by decision-makers to express their evaluations. The linguistic variables and the corresponding TIT2FSs are presented in Table 3.

The importance of each criterion and ratings of alternatives expressed by each decision-maker are shown in Tables 4 and 5, respectively.

Step 3. The aggregated weights of the criteria and performance values of the suppliers (elements of the decision matrix) are calculated using Eqs. (27) and (28). The results are represented in Tables 6 and 7.

Step 4. According to Table 7 and Eq. (29), we can calculate the elements of the average solution. Table 8 presents the TIT2FSs related to the elements of the average solution.

Step 5. The values of positive and negative distances from the average solution are calculated using Eqs. (30)–(32). The

Table 1
The environmental evaluation criteria and their definitions.

Criteria		Definition
C_1	Environmental pollution	This criterion is related to the estimated level of emission of air pollutants, harmful materials, solid wastes, emission of air pollutants waste water, which releases by a supplier in its production process
C_2	Resource consumption	This criterion is related to the estimated level of raw material consumption, energy consumption and water consumption during the process of production
C_3	Ecological innovation	This criterion is related to the development of processes and products that can help to sustainable development using the commercial application of knowledge to reach direct or indirect ecological improvements
C_4	Environmental management system	This criterion is related to planning of resources for developing, organizational structure and implementing policies for environmental protection. ISO 14000 and ISO14001 are the most widely used standards in an environmental management system
C_5	Commitment of managers to environmental improvements	This criterion is related to the direct participation of the highest level managers of a company to improve environmental management practices and performance
C_6	Using green technologies in production processes	This criterion is related to the application of environmental science and green electronic devices to model, monitor and conserve the natural resources of the environment and to control the negative effects to the environment
C_7	Using green materials in production processes	This criterion is related to the estimated level of using recyclable material in all processes of production of the firm including packaging, manufacturing, etc.

Table 2
The data of the company related to the problem.

		Year										Average
		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
Amount of raw material (ton)		4633	5109	4701	5472	4600	5428	4726	4914	5944	4069	4959.6
Purchasing cost ($\times 10^2$ \$/ton)	S_1	3.85	3.8	4.3	4.45	4	4.8	4.9	4.8	4.9	5.1	4.49
	S_2	5.5	5.9	6.3	6.2	6.2	6.4	6.6	6.5	6.7	7.1	6.34
	S_3	5.7	5.8	5.7	6	6.1	6.1	6.2	6.4	6.5	6.9	6.14
	S_4	2.5	2.6	2.7	2.9	3.2	3.4	3.5	3.5	3.6	3.6	3.15
	S_5	5.2	5.4	5.3	5.65	5.5	5.8	6	6.2	6.1	6.45	5.76
Defect rate (%)	S_1	0.30	0.19	0.24	0.26	0.30	0.21	0.28	0.21	0.30	0.25	0.25
	S_2	0.25	0.18	0.15	0.22	0.19	0.22	0.30	0.19	0.22	0.10	0.20
	S_3	0.10	0.11	0.10	0.11	0.08	0.14	0.10	0.09	0.09	0.10	0.10
	S_4	0.29	0.33	0.38	0.35	0.31	0.38	0.45	0.31	0.35	0.33	0.35
	S_5	0.18	0.18	0.16	0.10	0.19	0.14	0.17	0.12	0.17	0.12	0.15
Rate of lateness (%)	S_1	0.10	0.06	0.12	0.11	0.09	0.11	0.10	0.11	0.11	0.05	0.10
	S_2	0.27	0.24	0.24	0.26	0.22	0.27	0.26	0.21	0.30	0.20	0.25
	S_3	0.23	0.25	0.28	0.10	0.24	0.32	0.25	0.25	0.26	0.28	0.25
	S_4	0.17	0.13	0.13	0.19	0.12	0.16	0.18	0.16	0.15	0.12	0.15
	S_5	0.08	0.08	0.09	0.10	0.12	0.09	0.09	0.10	0.11	0.12	0.10
Capacity (ton)	S_1	1200	1400	1100	1700	1200	1000	1000	1200	1100	1100	1200
	S_2	1000	1500	1700	1600	1500	1400	1400	1700	1600	1600	1500
	S_3	1200	2300	1500	1800	1200	2000	1900	1500	1700	1900	1700
	S_4	1100	1350	1650	1500	1000	1200	1800	1700	1200	1500	1400
	S_5	1000	1100	1250	1350	1600	1800	1700	1800	1800	1600	1500
Minimum allowable order (ton)	S_1	50	50	50	100	150	200	100	100	100	100	100
	S_2	100	100	200	200	150	150	150	150	150	150	150
	S_3	150	150	150	100	100	200	200	150	150	150	150
	S_4	100	100	100	100	100	100	100	100	100	100	100
	S_5	50	50	50	150	150	150	100	100	100	100	100

Table 3
Linguistic variables and the corresponding TIT2FSs.

Usage	Linguistic variable	TIT2FSs
For weighting criteria	Very low (VL)	((0,0,0,0.1;1,1),(0,0,0,0.05;0.9,0.9))
	Low (L)	((0,0.1,0.15,0.3;1,1),(0.05,0.1,0.15,0.2;0.9,0.9))
	Medium low (ML)	((0.1,0.3,0.35,0.5;1,1),(0.2,0.3,0.35,0.4;0.9,0.9))
	Medium (M)	((0.3,0.5,0.55,0.7;1,1),(0.4,0.5,0.55,0.6;0.9,0.9))
	Medium high (MH)	((0.5,0.7,0.75,0.9;1,1),(0.6,0.7,0.75,0.8;0.9,0.9))
	High (H)	((0.7,0.85,0.9,1;1,1),(0.8,0.85,0.9,0.95;0.9,0.9))
	Very high (VH)	((0.9,1,1,1;1,1),(0.95,1,1,1;0.9,0.9))
For rating alternatives	Very poor (VP)	((0,0,0,1;1,1),(0,0,0,0.5;0.9,0.9))
	Poor (P)	((0,1,1.5,3;1,1),(0.5,1,1.5,2;0.9,0.9))
	Medium poor (MP)	((1,3,3.5,5;1,1),(2,3,3.5,4;0.9,0.9))
	Fair (F)	((3,5,5.5,7;1,1),(4,5,5.5,6;0.9,0.9))
	Medium good (MG)	((5,7,7.5,9;1,1),(6,7,7.5,8;0.9,0.9))
	Good (G)	((7,8.5,9,10;1,1),(8,8.5,9,9.5;0.9,0.9))
	Very good (VG)	((9,10,10,10;1,1),(9.5,10,10,10;0.9,0.9))

Table 4
The importance of the criteria by each decision-maker.

Criteria	Decision-makers				
	Dm_1	Dm_2	Dm_3	Dm_4	Dm_5
C_1	VH	H	VH	MH	H
C_2	H	H	M	H	M
C_3	L	M	ML	M	M
C_4	H	M	H	H	M
C_5	L	ML	ML	ML	VL
C_6	ML	MH	MH	MH	ML
C_7	M	MH	MH	MH	M

TIT2FSs related to the positive and negative distances are presented in Tables 9 and 10, respectively.

Step 6. The weighted sums of positive and negative distances for each supplier are determined according to Eqs. (33) and (34). Here, we can present the TIT2FSs related to the weighted sums. Tables 11 and 12 represent the elements of $\widetilde{\widetilde{\mathcal{SP}}}_i$ and $\widetilde{\widetilde{\mathcal{NP}}}_i$ of suppliers, respectively.

Table 5
The performance values of the suppliers by each decision-maker.

Decision-makers	Suppliers	Criteria						
		C_1	C_2	C_3	C_4	C_5	C_6	C_7
Dm_1	S_1	F	MG	F	F	MP	P	MP
	S_2	G	VG	MG	MG	MG	MP	MG
	S_3	VG	F	MG	G	MP	F	F
	S_4	P	MP	F	P	MG	P	MP
	S_5	G	MG	G	MG	P	MP	MP
Dm_2	S_1	F	MP	G	P	MG	P	P
	S_2	F	G	G	MG	G	MP	F
	S_3	VG	F	MG	VG	F	MG	MP
	S_4	VP	MP	MG	F	MP	MP	MP
	S_5	F	F	F	G	P	F	MP
Dm_3	S_1	MP	MP	MG	F	MG	P	P
	S_2	F	VG	MG	G	MG	F	MP
	S_3	G	F	MG	MG	MG	G	MG
	S_4	VP	MP	MP	F	F	F	P
	S_5	F	MP	F	G	MP	F	MP
Dm_4	S_1	F	F	MG	MP	F	VP	P
	S_2	F	MG	MG	MG	F	F	MG
	S_3	G	MG	F	VG	F	F	MG
	S_4	VP	P	F	P	MP	F	F
	S_5	MG	MP	F	MG	F	MP	MP
Dm_5	S_1	P	F	G	MP	F	P	P
	S_2	G	MG	VG	F	MG	MP	MG
	S_3	G	G	MG	G	F	MG	MP
	S_4	P	MP	MG	F	F	MP	F
	S_5	MG	F	G	G	MP	F	F

Table 6
The aggregated weights of the criteria.

	$\tilde{w}_{jL}$						$\tilde{w}_{jU}$					
	w_{jL1}	w_{jL2}	w_{jL3}	w_{jL4}	$h_{L1}^{w_j}$	$h_{L2}^{w_j}$	w_{jU1}	w_{jU2}	w_{jU3}	w_{jU4}	$h_{U1}^{w_j}$	$h_{U2}^{w_j}$
$\tilde{\tilde{w}}_1$	0.74	0.88	0.91	0.98	1	1	0.82	0.88	0.91	0.94	0.9	0.9
$\tilde{\tilde{w}}_2$	0.54	0.71	0.76	0.88	1	1	0.64	0.71	0.76	0.81	0.9	0.9
$\tilde{\tilde{w}}_3$	0.2	0.38	0.43	0.58	1	1	0.29	0.38	0.43	0.48	0.9	0.9
$\tilde{\tilde{w}}_4$	0.54	0.71	0.76	0.88	1	1	0.64	0.71	0.76	0.81	0.9	0.9
$\tilde{\tilde{w}}_5$	0.06	0.2	0.24	0.38	1	1	0.13	0.2	0.24	0.29	0.9	0.9
$\tilde{\tilde{w}}_6$	0.34	0.54	0.59	0.74	1	1	0.44	0.54	0.59	0.64	0.9	0.9
$\tilde{\tilde{w}}_7$	0.42	0.62	0.67	0.82	1	1	0.52	0.62	0.67	0.72	0.9	0.9

Steps 7 and 8. The ranking method, which proposed in the methodology section (Eqs. (10)–(15)), is used in this step to calculate the positive and negative scores of each supplier with respect to the considered environmental criteria. These values and the other parameters of the problem, which are used to formulate the multi-objective model, are provided in Table 13.

According to the parameters provided in Table 13 and Eqs. (35)–(43), the following multi-objective linear programming model is formulated.

$$Max\ Z_1 = 0.1616x_1 + 0.2369x_2 + 0.2569x_3 + 0.1402x_4 + 0.2044x_5$$

$$Min\ Z_2 = 0.2519x_1 + 0.1483x_2 + 0.1541x_3 + 0.2548x_4 + 0.1910x_5$$

$$Min\ Z_3 = 4.5x_1 + 6.3x_2 + 6.1x_3 + 3.1x_4 + 5.8x_5$$

Subject to:

$$x_1 + x_2 + x_3 + x_4 + x_5 = 5000$$

$$0.25x_1 + 0.2x_2 + 0.1x_3 + 0.35x_4 + 0.15x_5 \leqslant 12$$

$$0.1x_1 + 0.25x_2 + 0.25x_3 + 0.15x_4 + 0.1x_5 \leqslant 18$$

$$x_1 \geqslant 100y_1, x_2 \geqslant 150y_2, x_3 \geqslant 150y_3, x_4 \geqslant 100y_4, x_5 \geqslant 100y_5$$

$$x_1 \leqslant 1200y_1, x_2 \leqslant 1500y_2, x_3 \leqslant 1700y_3, x_4 \leqslant 1400y_4, x_5 \leqslant 1500y_5$$

$$x_1, x_2, x_3, x_4, x_5 \geqslant 0$$

$$y_1, y_2, y_3, y_4, y_5 \in \{0, 1\}$$

Step 9. By solving the formulated model of the previous step as single-objective models, we first determine the maximum and minimum values of each objective separately. These values are: $Z_1^{max} = 1147.167$, $Z_1^{min} = 909.954$, $Z_2^{max} = 1084.057$, $Z_2^{min} = 846.406$, $Z_3^{max} = 29870$ and $Z_3^{min} = 23930$. Then the multi-objective model is transformed to the following single-objective model according to Eqs. (44)–(50).

$$Max\ \lambda$$

Subject to:

$$\lambda \leqslant 1 + \frac{Z_1 - 1147.167}{237.213}$$

$$\lambda \leqslant 1 - \frac{Z_2 - 846.406}{237.651}$$

Table 7
The aggregated performance values of the suppliers.

	$\tilde{x}_{ijL}$						$\tilde{x}_{ijU}$					
	x_{ijL1}	x_{ijL2}	x_{ijL3}	x_{ijL4}	$h_{L1}^{x_{ij}}$	$h_{L2}^{x_{ij}}$	x_{ijU1}	x_{ijU2}	x_{ijU3}	x_{ijU4}	$h_{U1}^{x_{ij}}$	$h_{U2}^{x_{ij}}$
$\tilde{\tilde{x}}_{11}$	2	3.8	4.3	5.8	1	1	2.9	3.8	4.3	4.8	0.9	0.9
$\tilde{\tilde{x}}_{12}$	2.6	4.6	5.1	6.6	1	1	3.6	4.6	5.1	5.6	0.9	0.9
$\tilde{\tilde{x}}_{13}$	5.4	7.2	7.7	9	1	1	6.4	7.2	7.7	8.2	0.9	0.9
$\tilde{\tilde{x}}_{14}$	1.6	3.4	3.9	5.4	1	1	2.5	3.4	3.9	4.4	0.9	0.9
$\tilde{\tilde{x}}_{15}$	3.4	5.4	5.9	7.4	1	1	4.4	5.4	5.9	6.4	0.9	0.9
$\tilde{\tilde{x}}_{16}$	0	0.8	1.2	2.6	1	1	0.4	0.8	1.2	1.7	0.9	0.9
$\tilde{\tilde{x}}_{17}$	0.2	1.4	1.9	3.4	1	1	0.8	1.4	1.9	2.4	0.9	0.9
$\tilde{\tilde{x}}_{21}$	4.6	6.4	6.9	8.2	1	1	5.6	6.4	6.9	7.4	0.9	0.9
$\tilde{\tilde{x}}_{22}$	7	8.5	8.8	9.6	1	1	7.8	8.5	8.8	9.1	0.9	0.9
$\tilde{\tilde{x}}_{23}$	6.2	7.9	8.3	9.4	1	1	7.1	7.9	8.3	8.7	0.9	0.9
$\tilde{\tilde{x}}_{24}$	5	6.9	7.4	8.8	1	1	6	6.9	7.4	7.9	0.9	0.9
$\tilde{\tilde{x}}_{25}$	5	6.9	7.4	8.8	1	1	6	6.9	7.4	7.9	0.9	0.9
$\tilde{\tilde{x}}_{26}$	1.8	3.8	4.3	5.8	1	1	2.8	3.8	4.3	4.8	0.9	0.9
$\tilde{\tilde{x}}_{27}$	3.8	5.8	6.3	7.8	1	1	4.8	5.8	6.3	6.8	0.9	0.9
$\tilde{\tilde{x}}_{31}$	7.8	9.1	9.4	10	1	1	8.6	9.1	9.4	9.7	0.9	0.9
$\tilde{\tilde{x}}_{32}$	4.2	6.1	6.6	8	1	1	5.2	6.1	6.6	7.1	0.9	0.9
$\tilde{\tilde{x}}_{33}$	4.6	6.6	7.1	8.6	1	1	5.6	6.6	7.1	7.6	0.9	0.9
$\tilde{\tilde{x}}_{34}$	7.4	8.8	9.1	9.8	1	1	8.2	8.8	9.1	9.4	0.9	0.9
$\tilde{\tilde{x}}_{35}$	3	5	5.5	7	1	1	4	5	5.5	6	0.9	0.9
$\tilde{\tilde{x}}_{36}$	4.6	6.5	7	8.4	1	1	5.6	6.5	7	7.5	0.9	0.9
$\tilde{\tilde{x}}_{37}$	3	5	5.5	7	1	1	4	5	5.5	6	0.9	0.9
$\tilde{\tilde{x}}_{41}$	0	0.4	0.6	1.8	1	1	0.2	0.4	0.6	1.1	0.9	0.9
$\tilde{\tilde{x}}_{42}$	0.8	2.6	3.1	4.6	1	1	1.7	2.6	3.1	3.6	0.9	0.9
$\tilde{\tilde{x}}_{43}$	3.4	5.4	5.9	7.4	1	1	4.4	5.4	5.9	6.4	0.9	0.9
$\tilde{\tilde{x}}_{44}$	1.8	3.4	3.9	5.4	1	1	2.6	3.4	3.9	4.4	0.9	0.9
$\tilde{\tilde{x}}_{45}$	2.6	4.6	5.1	6.6	1	1	3.6	4.6	5.1	5.6	0.9	0.9
$\tilde{\tilde{x}}_{46}$	1.6	3.4	3.9	5.4	1	1	2.5	3.4	3.9	4.4	0.9	0.9
$\tilde{\tilde{x}}_{47}$	1.6	3.4	3.9	5.4	1	1	2.5	3.4	3.9	4.4	0.9	0.9
$\tilde{\tilde{x}}_{51}$	4.6	6.5	7	8.4	1	1	5.6	6.5	7	7.5	0.9	0.9
$\tilde{\tilde{x}}_{52}$	2.6	4.6	5.1	6.6	1	1	3.6	4.6	5.1	5.6	0.9	0.9
$\tilde{\tilde{x}}_{53}$	4.6	6.4	6.9	8.2	1	1	5.6	6.4	6.9	7.4	0.9	0.9
$\tilde{\tilde{x}}_{54}$	6.2	7.9	8.4	9.6	1	1	7.2	7.9	8.4	8.9	0.9	0.9
$\tilde{\tilde{x}}_{55}$	1	2.6	3.1	4.6	1	1	1.8	2.6	3.1	3.6	0.9	0.9
$\tilde{\tilde{x}}_{56}$	2.2	4.2	4.7	6.2	1	1	3.2	4.2	4.7	5.2	0.9	0.9
$\tilde{\tilde{x}}_{57}$	1.4	3.4	3.9	5.4	1	1	2.4	3.4	3.9	4.4	0.9	0.9

Table 8
The elements of the average solution.

	$\tilde{v}_{jL}$						$\tilde{v}_{jU}$					
	v_{jL1}	v_{jL2}	v_{jL3}	v_{jL4}	$h_{L1}^{v_j}$	$h_{L2}^{v_j}$	v_{jU1}	v_{jU2}	v_{jU3}	v_{jU4}	$h_{U1}^{v_j}$	$h_{U2}^{v_j}$
$\tilde{\tilde{v}}_1$	3.8	5.24	5.64	6.84	1	1	4.58	5.24	5.64	6.1	0.9	0.9
$\tilde{\tilde{v}}_2$	3.44	5.28	5.74	7.08	1	1	4.38	5.28	5.74	6.2	0.9	0.9
$\tilde{\tilde{v}}_3$	4.84	6.7	7.18	8.52	1	1	5.82	6.7	7.18	7.66	0.9	0.9
$\tilde{\tilde{v}}_4$	4.4	6.08	6.54	7.8	1	1	5.3	6.08	6.54	7	0.9	0.9
$\tilde{\tilde{v}}_5$	3	4.9	5.4	6.88	1	1	3.96	4.9	5.4	5.9	0.9	0.9
$\tilde{\tilde{v}}_6$	2.04	3.74	4.22	5.68	1	1	2.9	3.74	4.22	4.72	0.9	0.9
$\tilde{\tilde{v}}_7$	2	3.8	4.3	5.8	1	1	2.9	3.8	4.3	4.8	0.9	0.9

$$\lambda \leqslant 1 - \frac{Z_3 - 23930}{5940}$$

$$Z_1 = 0.1616x_1 + 0.2369x_2 + 0.2569x_3 + 0.1402x_4 + 0.2044x_5$$

$$Z_2 = 0.2519x_1 + 0.1483x_2 + 0.1541x_3 + 0.2548x_4 + 0.1910x_5$$
$$Z_3 = 4.5x_1 + 6.3x_2 + 6.1x_3 + 3.1x_4 + 5.8x_5$$

$$x_1 + x_2 + x_3 + x_4 + x_5 = 5000$$

$$0.25x_1 + 0.2x_2 + 0.1x_3 + 0.35x_4 + 0.15x_5 \leqslant 12$$
$$0.1x_1 + 0.25x_2 + 0.25x_3 + 0.15x_4 + 0.1x_5 \leqslant 18$$
$$x_1 \geqslant 100y_1, x_2 \geqslant 150y_2, x_3 \geqslant 150y_3, x_4 \geqslant 100y_4, x_5 \geqslant 100y_5$$
$$x_1 \leqslant 1200y_1, x_2 \leqslant 1500y_2, x_3 \leqslant 1700y_3, x_4 \leqslant 1400y_4, x_5 \leqslant 1500y_5$$
$$x_1, x_2, x_3, x_4, x_5 \geqslant 0$$
$$y_1, y_2, y_3, y_4, y_5 \in \{0, 1\}$$

Table 9
The TIT2FSs related to the positive distances.

	$\widetilde{\mathcal{P}d}_{ijL}$						$\widetilde{\mathcal{P}d}_{ijU}$					
	$\mathcal{P}d_{ijL1}$	$\mathcal{P}d_{ijL2}$	$\mathcal{P}d_{ijL3}$	$\mathcal{P}d_{ijL4}$	$h_{L1}^{\mathcal{P}d_{ij}}$	$h_{L2}^{\mathcal{P}d_{ij}}$	$\mathcal{P}d_{ijU1}$	$\mathcal{P}d_{ijU2}$	$\mathcal{P}d_{ijU3}$	$\mathcal{P}d_{ijU4}$	$h_{U1}^{\mathcal{P}d_{ij}}$	$h_{U2}^{\mathcal{P}d_{ij}}$
$\widetilde{\widetilde{\mathcal{P}d}}_{11}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{12}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{13}$	−0.4547	0.0029	0.1457	0.6062	1	1	−0.1836	0.0029	0.1457	0.3468	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{14}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{15}$	−0.6854	0.0000	0.1970	0.8666	1	1	−0.2954	0.0000	0.1970	0.4806	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{16}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{17}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{21}$	−0.4146	0.1407	0.3073	0.8144	1	1	−0.0925	0.1407	0.3073	0.5220	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{22}$	−0.0147	0.5082	0.6482	1.1344	1	1	0.2946	0.5082	0.6482	0.8692	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{23}$	−0.3381	0.1049	0.2332	0.6645	1	1	−0.0816	0.1049	0.2332	0.4197	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{24}$	−0.4482	0.0576	0.2113	0.7043	1	1	−0.1601	0.0576	0.2113	0.4162	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{25}$	−0.3703	0.2954	0.4924	1.1424	1	1	0.0197	0.2954	0.4924	0.7760	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{26}$	−0.9871	−0.1069	0.1425	0.9566	1	1	−0.4885	−0.1069	0.1425	0.4834	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{27}$	−0.5012	0.3759	0.6265	1.4534	1	1	0.0000	0.3759	0.6265	0.9773	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{31}$	0.1777	0.6404	0.7700	1.1476	1	1	0.4627	0.6404	0.7700	0.9477	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{32}$	−0.5303	0.0663	0.2431	0.8397	1	1	−0.1841	0.0663	0.2431	0.5009	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{33}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{34}$	−0.0640	0.3617	0.4834	0.8644	1	1	0.1921	0.3617	0.4834	0.6563	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{35}$	−0.7642	−0.0788	0.1182	0.7879	1	1	−0.3742	−0.0788	0.1182	0.4018	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{36}$	−0.2748	0.5801	0.8294	1.6180	1	1	0.2239	0.5801	0.8294	1.1703	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{37}$	−0.7017	0.1754	0.4260	1.2530	1	1	−0.2005	0.1754	0.4260	0.7768	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{41}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{42}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{43}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{44}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{45}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{46}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{47}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{51}$	−0.4146	0.1592	0.3258	0.8514	1	1	−0.0925	0.1592	0.3258	0.5405	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{52}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{53}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{54}$	−0.2561	0.2177	0.3714	0.8323	1	1	0.0320	0.2177	0.3714	0.5762	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{55}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{P}d}}_{56}$	−0.8853	−0.0051	0.2442	1.0583	1	1	−0.3867	−0.0051	0.2442	0.5851	0.9	0.9
$\widetilde{\widetilde{\mathcal{P}d}}_{57}$	0	0	0	0	1	1	0	0	0	0	1	1

The result of solving this model is presented in Table 14. For comparison, the result of solving a classic single-objective cost-based model which minimizes only the total purchasing cost (Z_3) is also shown in this table.

As can be seen in Table 14, the value of total purchasing cost obtained by optimization of the proposed model is greater than that of the other model. However, the values of total positive and negative scores of suppliers are improved in the proposed model. Moreover, if we only minimize the total purchasing cost, the quantity of order from suppliers can be significantly different from those determined by the proposed model. In the current problem, we can see that the order quantity from second supplier will be equal to zero if the total purchasing cost is minimized. This is due to the good environmental scores of this supplier and the high purchasing cost of it.

5. Sensitivity analysis

In this section, we examine the effect of changing the weights of environmental criteria on order quantity allocated to each supplier and total cost of purchasing. The analysis is made for each of the criteria separately. For this aim, the weight of a criterion, which is considered for the analysis, is changed, and equal weights are given to the other criteria. To clear the analysis process, suppose that we want to examine effect of changing the weight of gth criterion ($g \in \{1, 2, \ldots, m\}$). Then we set the weight of this criterion to w_g, and the other criteria weights are calculated as follows:

$$w_j = \frac{1 - w_g}{m - 1} j \in \{1, 2, \ldots, m\} \text{ and } j \neq g \tag{51}$$

For example, in the problem of this study, if we set w_3 to 0.3, the weights of the other criteria (w_1, w_2, w_4, w_5, w_6 and w_7) will be equal to 0.1167 ($\frac{1-0.3}{7-1}$). By changing the value of w_g (increasing or decreasing), we can get the effect of gth criterion on solution.

Here we choose nine values (from 0.1 to 0.9) for the weight of each environmental criterion and analyze the effect of variation of the weights. To perform this analysis, the proposed model is solved 63 (9 × 7) times.

Table 10
The TIT2FSs related to the negative distances.

	$\widetilde{\mathcal{N}d}_{ijL}$						$\widetilde{\mathcal{N}d}_{ijU}$					
	$\mathcal{N}d_{ijL1}$	$\mathcal{N}d_{ijL2}$	$\mathcal{N}d_{ijL3}$	$\mathcal{N}d_{ijL4}$	$h_{L1}^{\mathcal{N}d_{ij}}$	$h_{L2}^{\mathcal{N}d_{ij}}$	$\mathcal{N}d_{ijU1}$	$\mathcal{N}d_{ijU2}$	$\mathcal{N}d_{ijU3}$	$\mathcal{N}d_{ijU4}$	$h_{U1}^{\mathcal{N}d_{ij}}$	$h_{U2}^{\mathcal{N}d_{ij}}$
$\widetilde{\widetilde{\mathcal{N}d}}_{11}$	−0.3702	0.1740	0.3406	0.8958	1	1	−0.0407	0.1740	0.3406	0.5923	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{12}$	−0.5819	0.0331	0.2099	0.8250	1	1	−0.2247	0.0331	0.2099	0.4788	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{13}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{14}$	−0.1601	0.3489	0.5026	0.9924	1	1	0.1441	0.3489	0.5026	0.7203	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{15}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{16}$	−0.1425	0.6462	0.8701	1.4450	1	1	0.3053	0.6462	0.8701	1.0990	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{17}$	−0.3508	0.4761	0.7267	1.4033	1	1	0.1253	0.4761	0.7267	1.0024	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{21}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{22}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{23}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{24}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{25}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{26}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{27}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{31}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{32}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{33}$	−0.5479	−0.0583	0.0845	0.5712	1	1	−0.2594	−0.0583	0.0845	0.3002	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{34}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{35}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{36}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{37}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{41}$	0.3702	0.8588	0.9699	1.2660	1	1	0.6441	0.8588	0.9699	1.0920	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{42}$	−0.2136	0.4014	0.5782	1.1565	1	1	0.1436	0.4014	0.5782	0.8287	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{43}$	−0.3731	0.1166	0.2594	0.7461	1	1	−0.0845	0.1166	0.2594	0.4751	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{44}$	−0.1601	0.3489	0.5026	0.9604	1	1	0.1441	0.3489	0.5026	0.7043	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{45}$	−0.7091	−0.0394	0.1576	0.8430	1	1	−0.3230	−0.0394	0.1576	0.4530	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{46}$	−0.8548	−0.0407	0.2086	1.0380	1	1	−0.3816	−0.0407	0.2086	0.5648	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{47}$	−0.8520	−0.0251	0.2255	1.0525	1	1	−0.3759	−0.0251	0.2255	0.5764	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{51}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{52}$	−0.5819	0.0331	0.2099	0.8250	1	1	−0.2247	0.0331	0.2099	0.4788	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{53}$	−0.4896	−0.0291	0.1137	0.5712	1	1	−0.2302	−0.0291	0.1137	0.3002	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{54}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{55}$	−0.3151	0.3545	0.5515	1.1581	1	1	0.0709	0.3545	0.5515	0.8076	0.9	0.9
$\widetilde{\widetilde{\mathcal{N}d}}_{56}$	0	0	0	0	1	1	0	0	0	0	1	1
$\widetilde{\widetilde{\mathcal{N}d}}_{57}$	−0.8520	−0.0251	0.2255	1.1026	1	1	−0.3759	−0.0251	0.2255	0.6014	0.9	0.9

Table 11
The weighted sum of positive distances from the average solution.

	$\widetilde{\mathcal{SP}}_{iL}$						$\widetilde{\mathcal{SP}}_{iU}$					
	$\mathcal{SP}_{iL1}$	$\mathcal{SP}_{iL2}$	$\mathcal{SP}_{iL3}$	$\mathcal{SP}_{iL4}$	$h_{L1}^{\mathcal{SP}_i}$	$h_{L2}^{\mathcal{SP}_i}$	$\mathcal{SP}_{iU1}$	$\mathcal{SP}_{iU2}$	$\mathcal{SP}_{iU3}$	$\mathcal{SP}_{iU4}$	$h_{U1}^{\mathcal{SP}_i}$	$h_{U2}^{\mathcal{SP}_i}$
$\widetilde{\widetilde{\mathcal{SP}}}_1$	−0.52	0.00	0.11	0.68	1	1	−0.17	0.00	0.11	0.31	0.9	0.9
$\widetilde{\widetilde{\mathcal{SP}}}_2$	−2.29	0.79	1.66	5.14	1	1	−0.38	0.79	1.66	2.97	0.9	0.9
$\widetilde{\widetilde{\mathcal{SP}}}_3$	−1.46	1.27	2.06	5.15	1	1	0.20	1.27	2.06	3.25	0.9	0.9
$\widetilde{\widetilde{\mathcal{SP}}}_4$	0.00	0.00	0.00	0.00	1	1	0.00	0.00	0.00	0.00	0.9	0.9
$\widetilde{\widetilde{\mathcal{SP}}}_5$	−1.29	0.29	0.72	2.35	1	1	−0.31	0.29	0.72	1.35	0.9	0.9

The effect of varying the weight of C_1 (environmental pollution) on the order quantities is depicted in Fig. 5. As can be seen, increasing the weight of C_1 leads to decrease in the order from the S_1 (x_1) and increase in the order from the S_5 (x_5). Little variation can also be seen in the values of x_4. However, the values of x_2 and x_3 is completely stable.

Table 12
The weighted sum of negative distances from the average solution.

	$\widetilde{\mathcal{NP}}_{iL}$						$\widetilde{\mathcal{NP}}_{iU}$					
	$\mathcal{NP}_{iL1}$	$\mathcal{NP}_{iL2}$	$\mathcal{NP}_{iL3}$	$\mathcal{NP}_{iL4}$	$h_{L1}^{\mathcal{NP}_i}$	$h_{L2}^{\mathcal{NP}_i}$	$\mathcal{NP}_{iU1}$	$\mathcal{NP}_{iU2}$	$\mathcal{NP}_{iU3}$	$\mathcal{NP}_{iU4}$	$h_{U1}^{\mathcal{NP}_i}$	$h_{U2}^{\mathcal{NP}_i}$
$\widetilde{\widetilde{\mathcal{NP}}}_1$	−1.41	1.07	1.85	4.70	1	1	0.07	1.07	1.85	2.95	0.9	0.9
$\widetilde{\widetilde{\mathcal{NP}}}_2$	0.00	0.00	0.00	0.00	1	1	0.00	0.00	0.00	0.00	0.9	0.9
$\widetilde{\widetilde{\mathcal{NP}}}_3$	−0.32	−0.03	0.04	0.33	1	1	−0.12	−0.03	0.04	0.14	0.9	0.9
$\widetilde{\widetilde{\mathcal{NP}}}$	−1.87	1.28	2.13	5.49	1	1	0.06	1.28	2.13	3.40	0.9	0.9
$\widetilde{\widetilde{\mathcal{NP}}}_5$	−1.61	0.07	0.49	2.40	1	1	−0.55	0.07	0.49	1.20	0.9	0.9

Table 13
The parameters of the problem.

Parameters	S_1	S_2	S_3	S_4	S_5
$\mathcal{R}(\widetilde{\widetilde{\mathcal{SP}}}_i)$	0.1616	0.2369	0.2569	0.1402	0.2044
$\mathcal{R}(\widetilde{\widetilde{\mathcal{NP}}}_i)$	0.2519	0.1483	0.1541	0.2548	0.1910
C_i^P ($\times 10^2$ \$/Ton)	4.5	6.3	6.1	3.1	5.8
p_i (%)	0.25	0.2	0.1	0.35	0.15
l_i (%)	0.1	0.25	0.25	0.15	0.1
CAP_i (Ton)	1200	1500	1700	1400	1500
$Qmin_i$ (Ton)	100	150	150	100	100
$Pmax$	12 (0.24% of total demand)				
$Lmax$	18 (0.36% of total demand)				
D^T	5000				

Table 14
The optimization results.

Variables	Minimization of total purchasing cost	Optimization of the proposed model
Z_1	928.0232	1058.92
Z_2	1084.057	933.39
Z_3	23930	26139.91
x_1	1200	261.61
x_2	0	1500
x_3	900	1700
x_4	1400	1400
x_5	1500	138.39

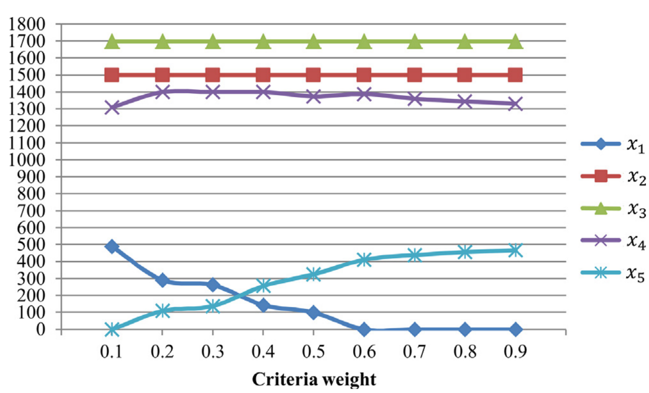

Fig. 5. Effect of changing the weight of "environmental pollution".

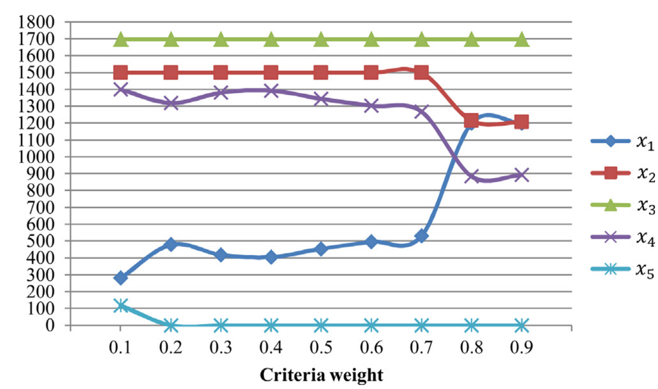

Fig. 6. Effect of changing the weight of "resource consumption".

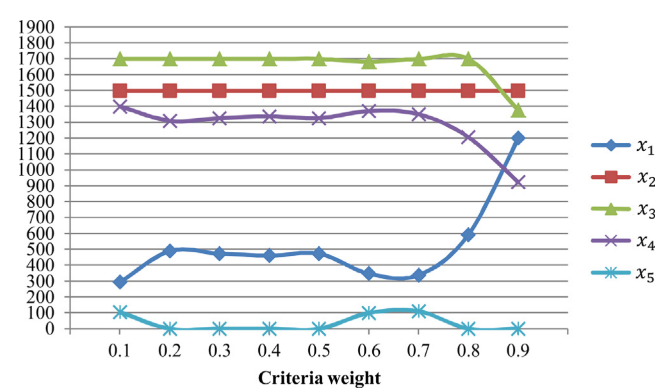

Fig. 7. Effect of changing the weight of "ecological innovation".

Fig. 6 shows the effect of changing the weight of C_2 (resource consumption). Maximum effect of this criterion can be seen in the order quantity from S_1 and S_4 (x_1 and x_4). If the weight of this criterion is set to a high value, the value of x_1 increases sharply. Also the order quantity from S_2 and S_4 decreases in high values of the weight of this criterion.

We can see in Fig. 7 the effect of changing the weight of C_3 (ecological innovation). The effects of this criterion appear in high values of its weight. It can be seen that the weight of this criterion affects the order quantity from S_1 more than the order quantity

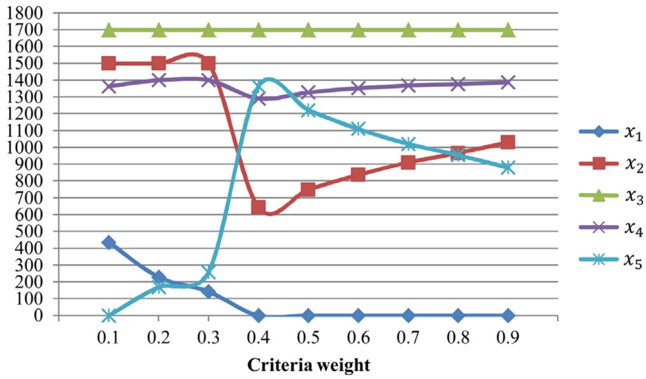

Fig. 8. Effect of changing the weight of "environmental management system".

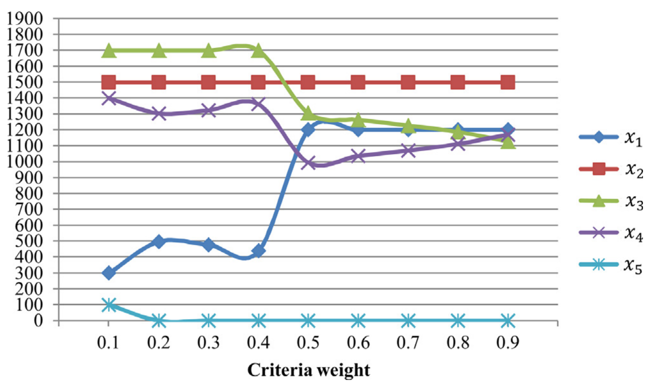

Fig. 9. Effect of changing the weight of "commitment of managers to environmental improvements".

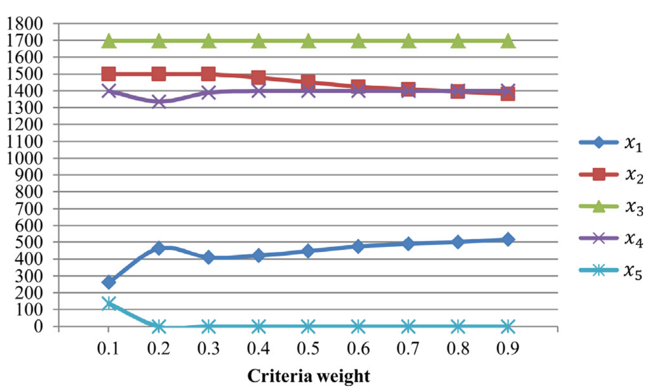

Fig. 10. Effect of changing the weight of "using green technologies in production processes".

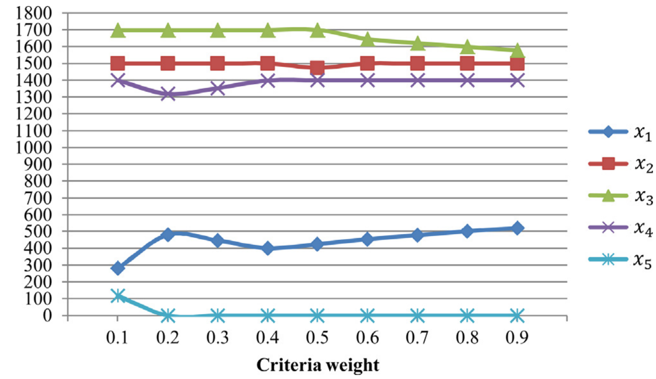

Fig. 11. Effect of changing the weight of "using green materials in production processes".

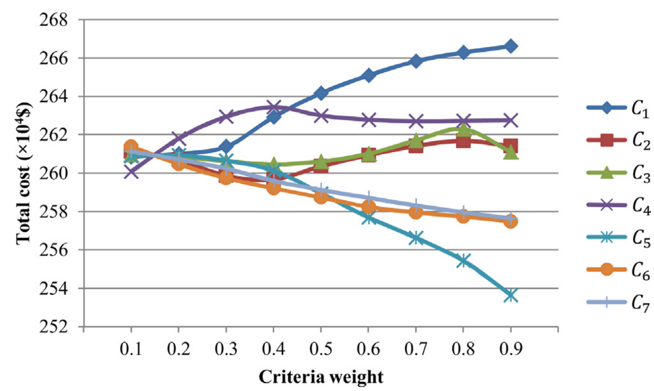

Fig. 12. Effect of changing weight of the criteria on total purchasing cost.

from the other suppliers. Moreover, high values of the weight of C_3 decreases the values of x_3 and x_4.

The effect of changing the weight of C_4 (environmental management system) is shown in Fig. 8. As can be seen in this figure, the quantity of order from S_2 and S_5 is very sensisitive to the weight of this criterion. Also we can see that increasing the weight of this criterion leads to reduction in the value of x_1.

In Fig. 9, we can see the effect of changing the weight of C_5 (commitment of managers to environmental improvements). The values of x_1, x_3 and x_4 are sensitive to changing the weight of this criterion. The domain of variation in the values of x_1 is about 900 within the range considered for the weight, and it shows that the quantity of order from S_1 is the most sensitive variable when the weight of C_5 is changed.

We represent the effect of changing the weights of C_6 (using green technologies in production processes) and C_7 (using green materials in production processes) in Figs. 10 and 11, respectively. As can be seen in these figures, these criteria have little effect on quantity of order purchased from the suppliers. However, the value of x_1 relatively increases by increasing the weights of C_6 and C_7.

The effect of changing the weights of each criterion on total purchasing cost is also depicted in Fig. 12. It can be seen that increase in the weights of C_5 (commitment of managers to environmental improvements), C_6 (using green technologies in production processes) and C_7 (using green materials in production processes) leads to reduction in total purchasing cost. Among these criteria, C_5 has more impact on the cost than C_6 and C_7. On the other hand, increasing the weights of C_1 (environmental pollution) and C_4 (environmental management system) increases the total purchasing cost. In this case, C_1 has more effect than C_4. Although changing the weights of C_2 (resource consumption) and C_3 (ecological innovation) leads to variation in the total purchasing cost, the variation is not so great.

6. Discussion and future directions

Supplier evaluation and order allocation is an important issue for companies which want to have long-term contracts with suppliers. Although economic factors are important in the process of evaluation of suppliers, environmental attributes of suppliers can also be essential for some companies with green strategies. In this paper, we have proposed an integrated model which considers both economic and environmental factors in the process of supplier evaluation and order allocation.

The proposed model consists of two main step including evaluation of suppliers with respect to environmental criteria and order allocation according to this evaluation and economic objective. The evaluation of suppliers with respect to environmental criteria has been made by some experts (decision-makers) subjectively. Because of uncertainty of information in a subjective evaluation, the fuzzy sets theory has been used to model the opinions of experts. Linguistic variables defined by interval type-2 fuzzy sets have been utilized to quantify the experts' opinions. This type of fuzzy sets is very flexible to capture the uncertainty of information because of its characteristics. Based on the experts' opinions and some steps of the EDAS method two parameters are defined for each supplier with respect to considered environmental criteria: the positive score and negative score of supplier. According to the environmental scores of the suppliers and economic parameters, a multi-objective linear programming has been formulated. By using this multi-objective model, we can determine the quantity of order from each supplier. In this study a fuzzy multi-objective programming approach has been used to determine the final solution. As shown in the sensitivity analysis section, by changing the weight of each criterion using the proposed pattern, we can examine the effect of each environmental criterion on total purchasing cost and quantity of order from each supplier. However, we have to determine the values of Z_1^{max}, Z_1^{min}, Z_2^{max} and Z_2^{min} if the fuzzy multi-objective programming approach is used to solve the model. According to the above-mentioned discussion, the proposed model has two main advantages as follows:

- Using IT2FSs helps us to consider more degrees of uncertainty in the process of supplier evaluation.
- Using the EDAS method enables us to define environmental criteria as two scores (positive and negative) to determine the quantity of order from each supplier.

On the other hand, the proposed model has two main disadvantages as follows:

- Using IT2FSs in the evaluation process of suppliers requires a considerable amount of computations.
- Solving the proposed multi-objective model only yield one Pareto optimal solution, while in such a problem we need to determine the Pareto front (trade-off solutions).

The proposed model can provide us with a decision support mechanism in the buyer–supplier relationship. We can have a long-term buyer–supplier relationship if the evaluation process of suppliers is carried out correctly, and the proposed model helps to optimize this process. Moreover, Lee and Klassen (2008) indicated that buyers' supply chain management can initiate and enable the improvement of suppliers' environmental capabilities. The buyer–supplier relationship can be established in the supply chain of many industries. Accordingly, if we can define appropriate environmental criteria for evaluation of suppliers in an industry, the proposed model can be applicable in that industry. However, the proposed model can only be used in a single-product and single-period supply chain. The application area of the proposed model includes many manufacturing industries such as automotive industry, food industry, clothing industry, and pulp and paper industry.

Sustainable development or sustainability has been described regarding three dimensions, i.e. economic, environmental and social. Each of these dimensions includes many criteria and sub-criteria which can significantly affect the competitive environment of companies (Manea, Titan, Boboc, & Anoaica, 2016; Popescu, Boboc, Stoian, Zaharia, & Ladaru, 2017). These criteria and sub-criteria may be changed over time. The proposed model has been established based on the economic and environmental dimensions and can be extended to include the social dimension. However, the changeable feature of the criteria and sub-criteria related to the sustainability dimensions requires flexibility in the proposed model for identification of evaluation criteria. This flexibility depends on the level of expertise of the decision-makers.

Based on the proposed model, we can give some recommendations for future research. To determine the positive and negative scores of the suppliers with respect to environmental criteria, we have used a ranking method of interval type-2 fuzzy sets which proposed by Keshavarz Ghorabaee et al. (2016a). The other ranking methods can also be used in this step in future research. The proposed multi-objective model can also yield the trade-off solutions with respect to environmental and economic objectives. Future research can apply the other multi-objective programming methods like ε-constraint method to obtain the trade-off solutions. Moreover, the proposed model is formulated for a single-product and single-period situation. Future research can also extend the model to a multi-product and multi-period model.

7. Conclusion

In this paper we have proposed an integrated model for supplier evaluation and order allocation with respect to environmental criteria. Based on the EDAS method and interval type-2 fuzzy sets, a process has been developed to evaluate suppliers and determine positive and negative scores of each supplier. Then a multi-objective linear programming model has been formulated for determination of order quantity from each supplier that maximizes total positive score and minimizes total negative score and total purchasing cost. By using a fuzzy multi-objective programming approach an auxiliary model has been presented to solve the proposed multi-objective model. The proposed integrated model has been applied to a numerical example of supplier evaluation and order allocation with five suppliers and seven environmental criteria, and the optimal solution has been determined. Also we have performed a sensitivity analysis to examine the effect of variation in the weights of the environmental criteria on the quantity of order and total purchasing cost. The results of this analysis show that "resource consumption," "ecological innovation," "environmental management system" and "commitment of managers to environmental improvements" are four criteria that have more impact on the order quantity than the other criteria. More over the effects of "environmental pollution" and "commitment of managers to environmental improvements" on total purchasing cost are more than the other environmental criteria for the company considered in this study.

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