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A novel hybrid method using fuzzy decision making and multi-objective programming for sustainable-reliable supplier selection in two-echelon supply chain design

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ABSTRACT

Recently, large companies have shown a growing tendency to enhance the reliability and sustainability of their supply chains to increase customers' satisfaction in terms of on-time fulfillment of demands and to be compatible with environmental regulations. Therefore, finding the best approaches to achieve companies' goals is a crucial concern in supply chain management, and the majority of organizations prefer to cooperate with reliable and sustainable companies. In designing a supply chain, the supplier selection problem, order size identification, and order allocation are midterm decisions that are needed to be made separately. To this end, three levels of the supply chain, i.e., suppliers, central warehouses, and wholesalers are considered. In the first level, to address the sustainable supplier selection problem, a novel hybrid approach based on the fuzzy logic is implemented. This approach applies the Fuzzy Analytic Network Process (FANP) method to ranking criteria and sub-criteria, the fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) is applied to identification of the relationships among the main criteria, and the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to prioritizing the suppliers. After prioritizing the suppliers, the obtained weights are considered as the input of a tri-objective model designed to optimize the proposed supply chain. The objectives are minimization of the total cost of the chain, maximization of the weighted value of products by taking the account of suppliers' priorities, and maximization of the reliability of the supply chain. Weighted Goal Programming (WGP) method is then used to deal with multi-objectiveness. To assess the applicability of the suggested methodology, a case study of the lamp supply chain was considered and solved using GAMS/CPLEX solver and optimal policies based on suppliers' sustainability. The reliability of the supply chain was tested, and sensitivity analyses were also performed on the main parameters of the model.

1. Introduction

In recent years, organizations have experienced world-wide changes that emerged with technological developments, market globalization, and customers' preferences. Therefore, they have attempted to improve their performance to survive among the growing number of competitors. In this regard, they perceived that they have to participate in the management of all organizations supplying their inputs (directly or indirectly) and all organizations that are responsible for delivery and after-sale services. Such a perception has resulted in the theory of supply chain. Generally, a supply chain consists of facilities, duties, and activities that exist in the production, delivery, and after-sale services. A supply chain includes four levels of supply, production, distribution, and

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customers, each of which has, in turn, a large number of facilities. Regarding the complexity of the supply chain, the selection of performance evaluation criteria is a concern (Cox, 1999). In the late 1980s, it was revealed that the cost of raw materials and required parts accounted for a considerable amount of the product cost, which could be in some organizations even up to 70% of the total cost (Ghobadian et al., 2016). According to the literature review, it was found that through establishing high technology collaborations, the cost of materials and purchased services can account for even more than 80% of the total cost of the product (Ghodsypour and O'Brien, 2001). The supply chain of a product begins with the entrance of raw materials and ends with the production, distribution, and delivery of the products to customers. In calculating the cost of a product, in addition to the usual costs of production (the cost of transforming raw materials to the final product), other costs such as ordering costs, transporting the product to be delivered to the customer, and services are given to the customer is also considered. Therefore, to reduce the production cost of a product, the corporations must coordinate all activities. In other words, the participants of a supply chain, i.e., suppliers, producers, and distributors cannot pursue exclusively their own profits. Thus, harmonizing the business processes among the members of a network is a vital issue of a supply chain. In most industries, the cost of raw material and the product's components constitute a large portion of its final price. Under these conditions, suppliers can control the efficiency of the organization, have a direct influence on the costs reduction, and increase the profitability and flexibility (Ghodsypour and O'Brien, 1998). Thus, our objective in this study is to help customers, through decision-making and optimization approaches, to select best suppliers and allocate orders where the reliability of and sustainability of suppliers are taken into account.

Two important parts of the chain are a) selecting an appropriate supplier for purchasing raw materials, and b) assigning them some of the internal operations. To this end, researchers found that a corporation must cooperate with other participants to remain active in the market. The major duty of purchasing management is to select appropriate suppliers (Aissaoui et al., 2007). A supply chain is a complicated procurement system in which raw materials are turned into final products and distributed among final consumers. Since the supplier performance directly affects the cost, quality, delivery, and services, supplier selection is regarded as one of the most critical tasks of the purchase management system (Gunasekaran et al., 2004). The supplier selection process is considered as a hierarchical process based on some criteria and a set of available suppliers. The cost of raw materials and parts that construct the final product determine a large percent of the product price. During the supplier selection process, cost minimization is not the only objective, especially in the existing competitive environment, other factors such as the quality of raw materials and on-time delivery are also important, which result in high-quality and on-time delivered products, respectively. Moreover, sustainability is another noteworthy issue that concurrently involves economic, social, and environmental aspects.

Sustainability can be considered as the capability of an organization to make real-time decisions without any disadvantageous impacts on the future condition of the environment, societies, and business stability. According to these features, many researchers have worked on sustainability in supply chain management recently (Amindoust et al., 2012; Sazvar et al., 2018; Govindan, 2018; Govindan et al., 2018; Li et al., 2019). Since the performance of suppliers has a basic effect on the success or failure of the organization, the selection of a sustainable supplier is known as a strategic task. In some cases, suppliers are not capable to cover customers' demand on time due to capacity limitation or it might be more beneficial to lose demand rather than covering it, which is known as a lost sale. Lost sales might help corporations to avoid needless consumption with respect to sustainability issues (Gören, 2018). On the other hand, addressing the concept of reliability at the stage of supply chain design can increase customer satisfaction, bring about a larger market share, and finally augment the sustainability of the supply chain. To the best of our knowledge, this concept has not been investigated in sustainable supplier selection literature. In this study, considering the policy of inventory control, the efficient hybrid methodology is developed to simultaneously solve the problems of supplier selection, lot sizing determination, and order allocation in a supply chain network with three levels (i.e., suppliers, central warehouse, and wholesalers). The primary concentration is on the sustainability criteria of supplier selection and reliability of the network. In summary, the main contributions of the current study are as follow:

I. Implementing a hybrid approach based on the fuzzy logic: the Fuzzy Analytic Network Process (FANP) method is applied to ranking criteria and sub-criteria, the fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) to identifying the relationships of the main criteria, and the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to determining the final priority of suppliers considering sustainability aspects.
II. Developing a novel Multi-Objective Mixed-Integer Linear Programming (MOMILP) model to determine the lot size, program the order allocation, and determine the amount of products transported to wholesalers in a planning horizon, considering the objectives of minimizing the total cost of the supply chain, maximizing the weighted value of products by taking the account of suppliers' priorities, and maximizing the reliability of the supply chain during a planning horizon.
III. Evaluating the suggested methodology on a real case study and studying the sensitivity analyses of the parameters to identify managerial decision aids and optimal policies.

The remaining of the paper is organized as follows. In Section 2, the relevant literature is reviewed and contributions of the present work are verified. Section 3 explains the selection and ranking approach that employs a Multiple-Criteria Decision-Making (MCDM) method based on fuzzy logic. The proposed MOMILP model, which is developed based on the assumptions and real-world conditions, is discussed in Section 4. Section 5 presents the suggested solution technique; i.e., Weighted Goal Programming (WGP). The validation of the model and the results obtained from the case study along with sensitivity analyses are given in Section 6. Finally, the concluding remarks and future research recommendations are provided in Section 7.

2. Literature review

In this section, a brief review is conducted on different methodologies and practical aspects proposed for the supplier selection problem. It was first introduced by Dickson (1966) who extracted 23 criteria through a questionnaire distributed among the managers and purchase staff. When linear programming and computation methods were in their infancy, the problem of supplier selection was first introduced by Moore and Fearon (1973). In a comprehensive review of supplier selection, Weber et al. (1991) considered 74 papers and found that in the multi-criteria supplier selection problem, the significance of criteria depends on the purchase state. Gaballa (1974) was the first researcher who applied linear programming for a real-case supplier selection problem. He formulated the problem as a Mixed-Integer Linear Programming (MILP) model to minimize the total price of products.

Dahel (2003) suggested a MOMILP model to determine the number of suppliers and the allocated order quantity simultaneously. Humphreys et al. (2003) proposed a novel approach to investigate the environmental criteria in the supplier selection process by considering some factors such as quality and flexibility. Kumar et al. (2004) investigated the logistic cost factor as an important factor to select a multi-sourcing supplier using a novel MILP model. Boran et al. (2009) applied the TOPSIS method under the Intuitionistic Fuzzy Set (IFS) for the green supplier selection problem. A fuzzy TOPSIS method was employed for the supplier selection problem with environmental criteria by Awasthi et al. (2010). Dobos and Vörösmarty (2014) employed the Data Envelopment Analysis (DEA) method for solving the problem of green supplier selection. The results of their study divided the relevant factors into two groups: traditional (managemental) factors and environmental (green) factors. To validate the DEA method, they used Common Weights Analysis (CWA) method as a DEA method. Hashemi et al. (2015) integrated Analytic Network Process (ANP) and Grey Relational Analysis (GRA) methods to select and rank the green supplier based on economic and environmental criteria in the machine industry. In developing a green supplier selection problem in a traditional system, Freeman and Chen (2015) considered two phases. In the first phase, the authors conducted a structured interview with the representatives of senior management of electronic machinery manufacturing company. In the second phase, they designed a questionnaire; in the first part, the data was analyzed using Analytical Hierarchy Process (AHP), and in the second part, they collected and analyzed data using the Entropy approach.

Yu et al. (2016) considered business factors, such as price, volume, and time, and also environmental ones, including Carbon Dioxide (CO_2) emission, in supplier selection problem to reduce the damage to the environment. The authors showed the superiority of their proposed method using numerical computations. A multi-product mathematical model was proposed by Azadnia (2016). The proposed quadruple-objective model was aimed at minimizing total cost, maximizing total social, total environmental, and total economic qualitative scores. Fallahpour et al. (2017) presented a problem of sustainable supplier selection through a questionnaire survey and obtained supportive results using a case study. Park et al. (2018) also used a case study to address a two-phase scenario-based supplier selection problem. In the first phase, social and economic factors were considered, and in the second one, regarding the economic and environmental objectives, a MOMILP model was presented. Ghadimi et al. (2018) analyzed the performance of supplier selection at manufacturing companies and presented a model for order allocation. Furthermore, they presented a case study of an industrial company in the electronics sector. Cheraghalipour and Farsad (2018) studied MCDM tools for multi-period supplier selection and order allocation problem. They employed the Best-Worst method (BWM) to calculate the weights of criteria and implemented their suggested technique in a case study of an electronics lamp supply chain whose warehouse was located in the North of Iran.

Yang et al. (2011) introduced probabilistic models for supplier selection problem in which demand was modeled randomly as a nonlinear function, and the model was solved using a genetic algorithm (GA). In another study, Amindoust et al. (2012) used fuzzy logic for sustainable supplier selection and ranking problem; and using an illustrative example, they showed the applicability of their proposed method. After that, using MOMILP and Fuzzy AHP (FAHP), Shaw et al. (2012) addressed the supplier selection problem in which the emission of CO_2 was considered as a supply constraint. The authors included factors such as cost, quality, CO_2 emission, and demand in the model and applied a fuzzy linearization method for determining the criteria weights. Using the fuzzy theory and multi-objective programming, Kannan et al. (2013) considered the green supplier selection and order allocation problem regarding the economic and environmental criteria. They first implemented FAHP to analyze basic data and then proposed a multi-objective mathematical model to maximize profit and minimize the total cost of purchasing. The results showed the superiority of this systematic approach in selecting the green supplier and relevant decisions about order allocations. DEMATEL technique was used by Hsu et al. (2013) to manage the emission of CO_2. The results showed that this could have a substantial effect on improving the performance of suppliers. Fallahpour et al. (2016) proposed an integrated model to select a green supplier selection in a fuzzy environment. They employed DEA and GA for robust modeling and parametric analysis for model validation. Two well-known MCDM techniques, including FAHP and TOPSIS method, were applied by Wang Chen et al. (2016) to green supplier evaluation and ranking problem. They conducted a case study to verify the applicability of the proposed technique. Yazdani et al. (2017) used the DEMATEL method to select a green supplier considering environmental criteria. They conducted a case study to evaluate the reliability of their proposed method. Banaeian et al. (2018) performed the supplier selection problem in a fuzzy context. The authors discussed the problem using TOPSIS, VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) which means Multi-Criteria Optimization and Compromise Solution, and GRA techniques and implemented the model in a case study of the agriculture supply chain. A multi-product mathematical model was proposed by Arabsheybani et al. (2018) based on the fuzzy analysis. They did a case study in the furniture industry using the Failure Modes and Effects Analysis (FMEA) method. Mohammed et al. (2018) designed a method for sustainable supplier selection and order allocation problem regarding the economic, social, and environmental criteria. Their proposed method consisted of four sections. In the first section, they used FAHP to determine the criteria weights. Then, they applied the TOPSIS method to evaluate the suppliers. And the third section included a multi-objective programming model for order allocation. A new model for green supplier selection and allocation order was developed by Lo et al. (2018). They solved the model using the BWM method in a fuzzy context. They also performed a case study at an electronics company and investigated the effective performance of the model in order allocation. Vahidi et al. (2018) provided a multi-objective probabilistic mathematical model for supplier selection and order allocation problem considering the existing risks. The computational results showed that their model performed better than current strategies in terms of reliability and flexibility. A case study was also conducted to assess the flexibility of the model. Another model of green supplier selection under the uncertainty conditions was presented by Yu et al. (2018) considering the objectives of minimizing CO_2 emission and transportation cost along with the maximization of the profit. The numerical computations and comparison of the results showed the superiority of the proposed model. Having conducted a case study, Gören (2018) presented a framework for sustainable supplier selection and order allocation problem. The author implemented the fuzzy DEMATEL method for weight calculation and Taguchi method for ranking suppliers. Recently, Memari et al. (2019) and Moheb-Alizadeh and Handfield (2019) worked on the sustainable supplier selection problem using Intuitionistic fuzzy TOPSIS and MOMILP, respectively.

Table 1 presents a summary of the most important studies carried out on this subject.

Table 1
A summary of the literature.

References	Evaluation criteria				Specific features					Problem conditions		Case Study	Research methodology/Solution technique
	Environmental	Reliability	Social	Economic	Inventory control	Multi-product	Multi-period	Disruption	Order allocation	Deterministic	Uncertain		
Boran et al. (2009)			*	*							*		Intuitionistic fuzzy TOPSIS
Yang et al. (2011)				*		*			*		*		GA
Shaw et al. (2012)	*			*					*		*	*	FAHP and fuzzy MOMILP
Kannan et al. (2013)	*			*					*		*	*	FAHP, fuzzy TOPSIS and Fuzzy Multi-Objective Programming (FMOP)
Azadnia (2016)	*		*	*	*	*	*		*	*		*	Fuzzy Inference Systems (FIS), FAHP and MOMILP
Wang Chen et al. (2016)	*			*							*	*	FAHP and fuzz TOPSIS
Fallahpour et al. (2017)	*		*	*							*	*	Fuzzy Preference Programming (FPP) and fuzzy TOPSIS
Hamdan and Cheaitou (2017)	*			*	*		*		*		*		FAHP, Fuzzy TOPSIS, AHP and MOMILP
Yazdani et al. (2017)	*			*						*		*	DEMATEL and Quality Function Deployment (QFD) model
Park et al. (2018)	*		*	*		*			*		*	*	Multi-Attribute Utility (MAU), FAHP and MOMILP
Ghadimi et al. (2018)	*		*	*	*	*			*	*		*	Multi-Agent Systems (MASS) and FIS
Cheraghalipour and Farsad (2018)	*		*	*	*	*	*	*	*		*	*	BWM and Revised Multi-Choice Goal Programming (RMCGP)
Arabsheybani et al. (2018)	*		*	*	*	*	*		*		*	*	Fuzzy multi-objective optimization model based on the ratio analysis (fuzzy MOORA), FMEA
Mohammed et al. (2018)	*		*	*					*		*	*	FAHP, Fuzzy TOPSIS and FMOP
Lo et al. (2018)	*		*	*		*			*		*	*	BWM, Fuzzy TOPSIS and FMOP
Vahidi et al. (2018)	*			*		*		*	*		*	*	ϵ-constraint method and metaheuristics
Yu et al. (2018)	*			*		*			*	*			Eclipse IDE for java developers and ILOG CPLEX
Gören (2018)	*		*	*	*	*	*		*		*	*	Fuzzy DEMATEL, Taguchi and MOMILP
Memari et al. (2019)	*		*	*							*	*	Intuitionistic fuzzy TOPSIS
Moheb-Alizadeh and Handfield (2019)	*		*	*	*	*	*		*	*		*	ε-constraint method, Benders decomposition algorithm, DEA
Current research	*	*	*	*	*	*	*		*		*	*	Fuzzy DEMATEL, fuzzy ANP, fuzzy TOPSIS and MOMILP

According to literature, the majority of the studies have focused on the supplier selection and order allocation problem with the assumption that all demands of customers are covered. However, in real-world conditions, it is possible that suppliers do not succeed in fulfilling the orders of all customers. In addition, the possibility of lost sales has not been adequately investigated in the literature. Furthermore, only a few studies have addressed the sustainability conditions, and no one has considered the reliability concept of the supply chain. Table 2 lists the abbreviations used in this paper.

Table 2
List of abbreviations.

Abbreviations	Descriptions
AHP	Analytical Hierarchy Process
ANP	Analytic Network Process
BWM	Best-Worst Method
CO_2	Carbon Dioxide
CWA	Common Weights Analysis
DEA	Data Envelopment Analysis
DEMATEL	Decision Making Trial and Evaluation Laboratory
FAHP	Fuzzy AHP
FANP	Fuzzy Analytic Network Process
FMOP	Fuzzy Multi-Objective Programming
FMEA	Failure Modes and Effects Analysis
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
GP	Goal Programming
GRA	Grey Relational Analysis
IFS	Intuitionistic Fuzzy Set
LED	Light-Emitting Diode (LED)
MASS	Multi-Agent Systems
MAU	Multi-Attribute Utility
MCDM	Multiple Criteria Decision-Making
MILP	Mixed-Integer Linear Programming
MOMILP	Multi-Objective Mixed-Integer Linear Programming
MOORA	Multi-Objective Optimization model based on the Ratio Analysis
MOPSO	Multi-Objective Particle Swarm Optimization
NSGA-II	Non-dominated Sorting Genetic Algorithm II
QA	Quality Assurance
RMCGP	Revised Multi-Choice Goal Programming
TOPSIS	The technique for Order of Preference by Similarity to Ideal Solution
VIKOR	Visekriterijumska Optimizacija I Kompromisno Resenje
WGP	Weighted Goal Programming

3. Ranking suppliers

In this research, fuzzy ANP is implemented to rank criteria and sub-criteria, then fuzzy DEMATEL is employed to identify the relationships among the main criteria, and finally, fuzzy TOPSIS is used to rank the suppliers. To analyze the available data, this study makes use of Excel software, Visual Basic, and Super Decision software. The results are presented in this section.

3.1. Identifying the priority of the model components by ANP

ANP method is a general form of AHP. It has been developed for analyzing complicated problems with mutual dependencies of criteria (Xu et al., 2015). In the first step, the criteria and sub-criteria of the model are identified and selected. The main criteria are economic factors, environmental factors, and social factors. For each basic criterion, a number of sub-criteria are determined (totally 21 sub-criteria). There are several criteria and sub-criteria in terms of social, environmental, and economic aspects, which are needed to select and assess the best sustainable-reliable supplier. To do this, a survey was performed based on the literature review, questionnaire, and interview to select significant criteria and sub-criteria to assess sustainable-reliable suppliers. To select and assess the significant criteria and sub-criteria of the sustainable-reliable supplier, there is a need to perform a decision on a hierarchical framework in a way to guide the process of evaluating these suppliers and then ensure that the selected criteria and sub-criteria are capable of covering all aspects of this framework. Therefore, this study presented a framework to show the most important criteria for selection of the best sustainable-reliable suppliers (see Table 3 and Fig. 1). In the second step, this paper developed a questionnaire to show the significance and applicability of selected criteria and sub-criteria to the evaluation of sustainable-reliable suppliers. In this step, the experts responded and assessed the selected criteria and sub-criteria. In this regard, the questionnaire was sent to some experts from industry and academia (production, marketing, and quality assurance (QA) departments). In order to conduct the content validation to ensure that the selected criteria are suitable and applicable to evaluating sustainable-reliable suppliers, the research works of Fallahpour et al. (2017), Arabsheybani et al. (2018) and Gören (2018) were taken into account as the main exemplars. Table 3 represents these criteria and sub-criteria according to the assigned notations.

Moreover, Fig. 1 provides the related hierarchical tree structure of ANP for supplier selection in the case study problem.

The following steps are performed to determine the criteria weights using the ANP technique:

Step 1: Prioritizing the main criteria through the paired comparisons.
Step 2: Identifying the internal relationships of the main criteria using the DEMATEL approach.
Step 3: Prioritizing each sub-criterion in its corresponding cluster through paired comparisons.
Step 4: Identifying the internal relationships of the sub-criteria using DEMATEL approach.
Step 5: Calculating the preliminary supermatrix, weighted supermatrix, and the limit supermatrix.

Accordingly, the final priority of criteria was then obtained. The details of all operations implemented in sub-sections of Section 3 have been provided in Supplemental Material.

3.2. The prioritization of the main criteria based on the objectives

Based on the steps explained in the previous subsection, the priority of the main criteria is identified as follows (see Fig. 2).

The inconsistency ratio of the performed comparisons is

Table 3
The research criteria and sub-criteria.

Major Criteria		Sub-criteria	Symbols
Economic	C1	Automation	S11
		Supply chain cost	S12
		Return cost	S13
		Product shelf life	S14
		Design cost	S15
		Resource cost	S16
		Production cost	S17
		Flexibility of supply chain	S18
Environmental	C2	Integration and partnership	S21
		Process integration	S22
		Market imbalances recognition	S23
		Dangerous factors for workplace and community	S24
		Environmental pollution	S25
Social	C3	Performance of advertising marketing	S31
		Appropriate packing and delivery	S32
		Quality improvement	S33
		On-time delivery	S34
		Customer status	S35
		Trust and communication between buyer and seller	S36
		Human rights	S37
		Development of culture and technology	S38

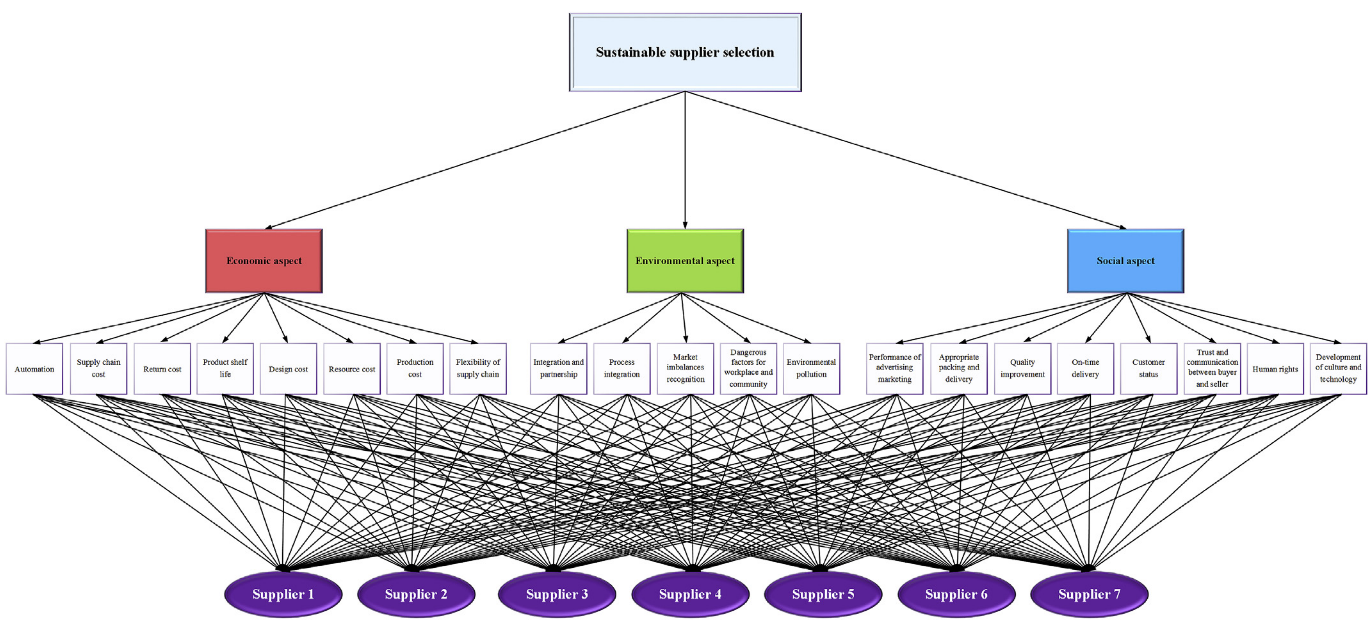


Fig. 1. Hierarchical tree structure of ANP for sustainable supplier selection of the study.

0.001 < 0.1; therefore, they can be trusted.

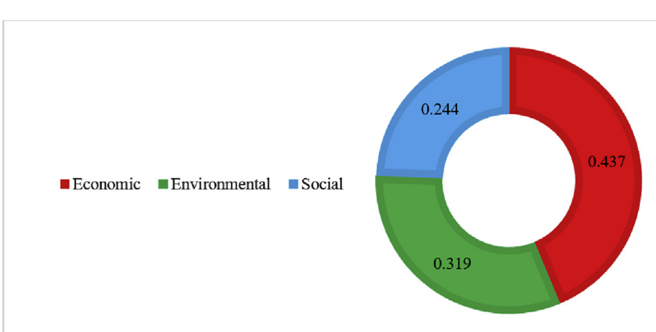


Fig. 2. Obtained weights to prioritize the main criteria.

3.3. The comparison and prioritization of sub-criteria

In the second step of ANP, the sub-criteria of each criterion are pair-wisely compared. The priorities of economic, environmental, and social sub-criteria are determined in the following.

3.3.1. The priority of the economic sub-criteria

Since 8 economic sub-criteria are defined based on Table 3, there is a need for 28 paired comparisons. The inconsistency ratio of the comparisons was obtained 0.083, which was less than 0.1; thus, the results were found trustable. As can be seen in Fig. 3, the criteria of resource cost, automation, and supply chain cost are placed at the first to third priorities.

3.3.2. The priority of the environmental sub-criteria

Since 5 environmental sub-criteria are taken into account based

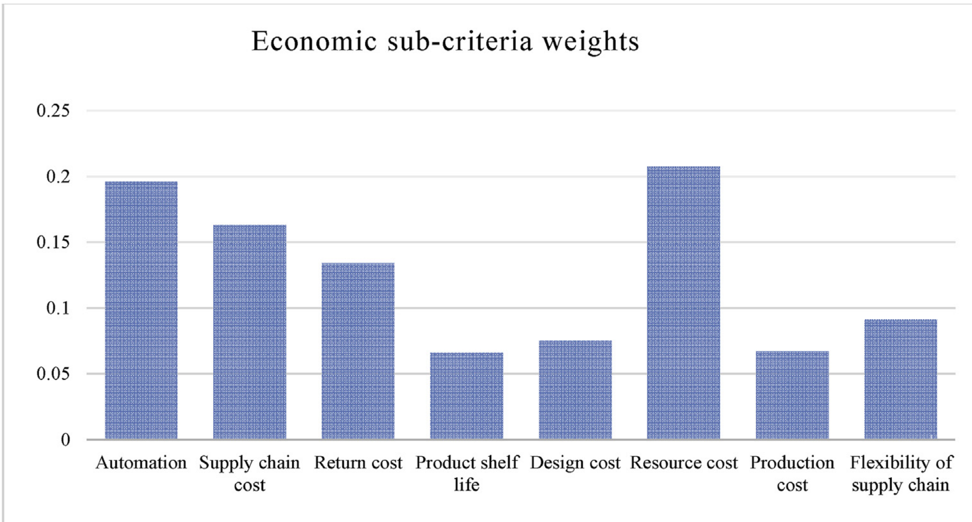


Fig. 3. Defuzzified values of the economic sub-criteria weights.

on Table 3, 10 paired comparisons are required to be performed. The inconsistency ratio of these comparisons is 0.072, which is trustable, too. As can be seen in Fig. 4, the sub-criteria of process integration, integration and partnership, and market imbalance recognition have the first to third priorities.

3.3.3. *The priority of the social sub-criteria*

Since 8 social sub-criteria are regarded, 28 paired comparisons need to be done. The inconsistency ratio of these comparisons is 0.008; therefore, we can trust the results. As can be seen in Fig. 5, trust and communication between buyer and seller, customer status, and performance of advertising marketing are placed at the first to third priorities.

3.4. *Calculating the internal relationships by fuzzy DEMATEL*

DEMATEL was introduced by Gabus and Fontela (1973) as a comprehensive approach for constructing a structural model to test the causal relationship of complex factors. The next step of the proposed approach is to calculate the internal relationships of the identified criteria. To reflect this internal relationship, the fuzzy DEMATEL technique is applied, based on which the practitioners can express their opinions about the interactions (their direction and intensity) with higher efficiency. Accordingly, the matrix obtained from the DEMATEL approach (the interrelations matrix) represents both the cause and effect relationship between criteria and the effects of variables on each other. The final results are reported in Table 4.

According to Table 4, we have the following interpretations:

1. Each row sum (D) denotes the impact of that factor on the other factors. Accordingly, the factors are flexibility of supply chain, automation, return cost, supply chain cost, production cost, environmental pollution, integration and partnership, appropriate packing and delivery, understanding the market imbalance, process integration, trust and communication between

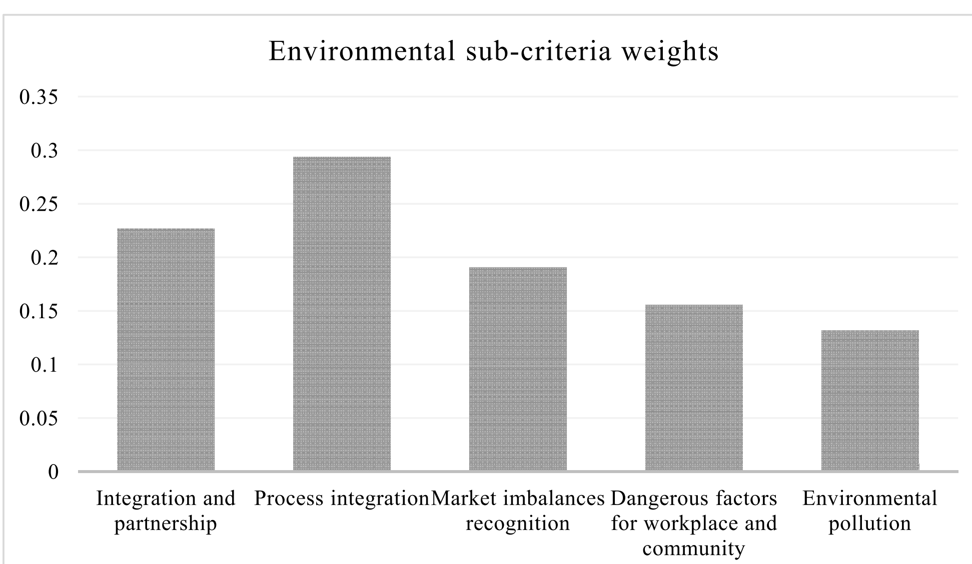


Fig. 4. Defuzzified values of the environmental sub-criteria weights.

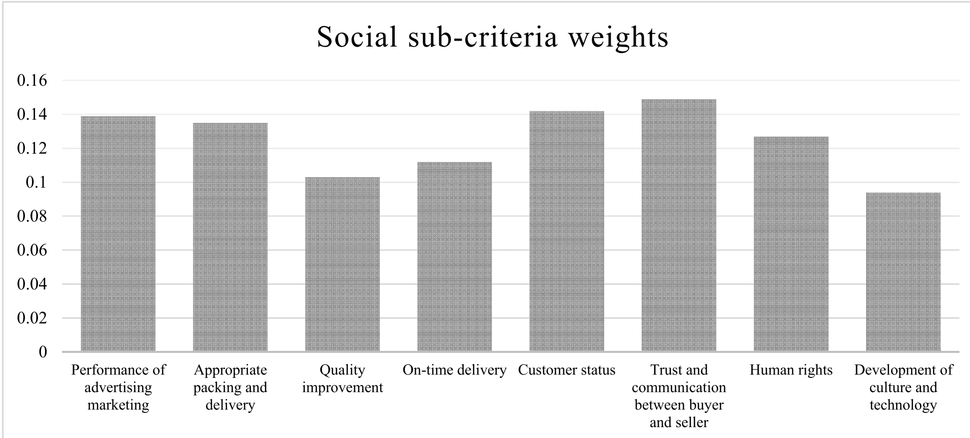


Fig. 5. Defuzzified values of the social sub-criteria weights.

Table 4
The causal relationships of the research criteria.

Sub-criteria	D	R	D + R	D-R
Automation	2.83	3.84	6.67	−1.02
Supply chain cost	4.16	3.93	8.09	0.22
Return cost	3.84	3.58	7.42	0.26
Product shelf life	3.49	3.39	6.88	0.11
Design cost	3.65	3.54	7.19	0.11
Resource cost	3.48	3.66	7.14	−0.18
Production cost	3.4	3.03	6.43	0.36
Flexibility of supply chain	3.54	3.52	7.07	0.02
Integration and partnership	3.39	3.04	6.43	0.35
Process integration	3.29	3.39	6.67	−0.1
Market imbalances recognition	3.11	3.72	6.82	−0.61
Dangerous factors for workplace and community	3.49	4	7.49	−0.51
Environmental pollution	3.38	3.67	7.05	−0.29
Performance of advertising marketing	4.05	3.17	7.22	0.89
Appropriate packing and delivery	3.72	3.89	7.61	−0.17
Quality improvement	3.5	3.88	7.38	−0.38
On-time delivery	3.84	3.1	6.94	0.74
Customer status	3.42	3.69	7.11	−0.27
Trust and communication between buyer and seller	3.6	3.86	7.46	−0.26
Human rights	3.89	3.16	7.05	0.73
Development of culture and technology	3.43	3.08	6.51	0.35

buyer and seller, performance of advertising marketing, resource cost, product durability, design cost, on-time delivery, dangerous factors for workplace and community, human rights, and development of culture and technology.

2. Each column sum (R) indicates the influence each factor receives from the others. Accordingly, the factors are trust and communication between buyer and seller, flexibility of supply chain, environmental pollution, customer status, appropriate packing and delivery, development of culture and technology, human rights, quality improvement, on-time delivery, performance of advertising marketing, production cost, integration and partnership, understanding the market imbalance, process integration, dangerous factors for workplace and community, automation, return cost, supply chain cost, resource cost, design cost, and product durability.
3. The horizontal vector (D + R) indicates the interaction each factor has with the other factors of the system. According to this index, the factors are flexibility of supply chain, environmental pollution, trust and communication between buyer and seller, appropriate packing and delivery, production cost, customer status, automation, integration and partnership, performance of advertising marketing, quality improvement, understanding the market imbalance, return cost, on-time delivery, supply chain cost, process integration, human rights, dangerous factors for workplace and community, development of culture and technology, resource cost, design cost, product durability.
4. The vertical vector (D − R) specifies the impact power of each factor. Generally, if D − R is a positive value, the variable is considered as a causal variable, and if D − R is a negative value, the variable is supposed to be a caused variable. In this model, the casual variables are automation, supply chain cost, return cost, product durability, resource cost, design cost, production cost, integration and partnership, the flexibility of supply chain, and understanding the market imbalance. The caused variables are dangerous factors for workplace and community, environmental pollution, performance of advertising marketing, appropriate packing and delivery, quality improvement, human rights, customer status, on-time delivery, trust and communication between buyer and seller, and development of culture and technology.

3.5. The final priorities of sub-criteria by FANP

To determine the weights and final priority of criteria, the output of comparing major criteria based on the objective and interrelations of criteria is presented in a supermatrix. The final priority of the criteria is given in Table 5.

According to the performed calculations and limit supermatrix, the output of Super Decision software provides the final priority of criteria and sub-criteria. Accordingly, the final weight of model criteria is calculated using FANP. These weights can be used as a guideline for managerial decisions. According to the output of the FANP technique, it can be seen that including interrelations of research variables can alter their importance and ranking. The integration of processes with a weight of 0.107 is the first priority. The integration and cooperation with a weight of 0.083 and the resources cost with a weight of 0.079 occupy the second and third priorities, respectively.

3.6. Determining the best supplier using the fuzzy TOPSIS

In this case study, the TOPSIS technique is adopted for the purpose of supplier prioritization. This technique was first introduced by Yoon and Hwang and Yoon (1981) and is known as one of the best MCDM techniques. The best alternative has the maximum distance from negative factors and minimum distance from positive factors. Seven suppliers were prioritized using the fuzzy TOPSIS technique. The results are given in Table 6 and Fig. 6.

In Table 6, the amounts of normalized weight were calculated using CI values. According to these results, it can be concluded that Supplier 4 is the best alternative with the normalized weight of 0.169, and Supplier 5 is the second priority with the normalized weight of 0.161.

In the next section, the weights of suppliers are taken into account as an input parameter to the proposed mathematical model.

4. Problem definition and model development

In this section, a novel MOMILP model is developed for the proposed supply chain network based on the problem definition and its main assumptions. The main motivation is to design a reliable supply chain network to fulfill the demands of customers over different time periods through determining the optimal order allocation plan of products to the best suppliers. The intended supply chain has three levels of suppliers, warehouses, and wholesalers. In the warehouses' level, there is a central warehouse that handles some potential temporary warehouses. The objective is to determine the order size and order allocation at the central warehouse in such a way that the demand of wholesalers of different products at each period can be satisfied with a minimized ordering cost, lost sales, and holding inventory. The size of total orders released to the suppliers is based on the order of the central warehouse, which itself is a function of wholesalers' demand. On the other hand, the total amount of products sent by the central

Table 6
The distance of alternatives from the positive and negative ideal solutions.

#Supplier	+D	-D	CI	Normalized weight	Ranking
Supplier 1	0.228	0.141	0.382	0.119	7
Supplier 2	0.215	0.154	0.417	0.130	5
Supplier 3	0.204	0.166	0.448	0.140	4
Supplier 4	0.169	0.199	0.541	0.169	1
Supplier 5	0.179	0.19	0.516	0.161	2
Supplier 6	0.217	0.152	0.412	0.129	6
Supplier 7	0.189	0.181	0.488	0.152	3

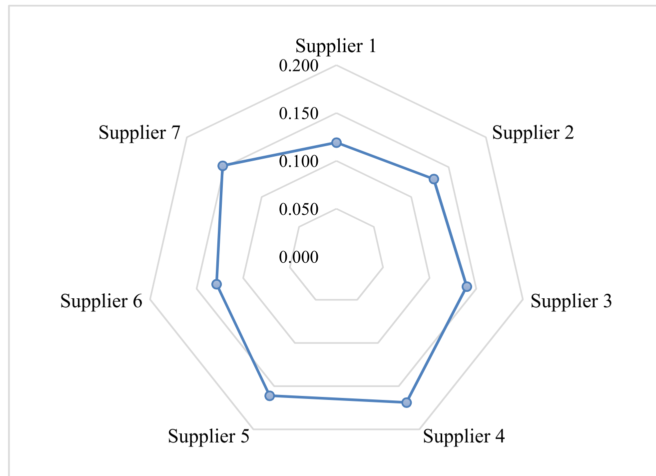


Fig. 6. The final priority of suppliers based on normalized weights.

Table 5
The final priority of sub-criteria based on the limit supermatrix.

Symbol	Sub-criteria	Overall weight	Normal weight	Ideal weight	Rating
S11	Automation	0.037	0.0742	0.692	4
S12	Supply chain cost	0.031	0.0617	0.575	6
S13	Return cost	0.025	0.0508	0.473	8
S14	Product shelf life	0.013	0.025	0.233	20
S15	Design cost	0.014	0.0284	0.265	17
S16	Resource cost	0.039	0.0788	0.734	3
S17	Production cost	0.013	0.0254	0.237	19
S18	Flexibility of supply chain	0.017	0.0345	0.321	14
S21	Integration and partnership	0.041	0.0829	0.772	2
S22	Process integration	0.054	0.1073	1	1
S23	Market imbalances recognition	0.035	0.0697	0.65	5
S24	Dangerous factors for workplace and community	0.029	0.0569	0.531	7
S25	Environmental pollution	0.024	0.0482	0.449	9
S31	Performance of advertising marketing	0.018	0.0356	0.332	12
S32	Appropriate packing and delivery	0.017	0.0346	0.322	13
S33	Quality improvement	0.013	0.0264	0.246	18
S34	On-time delivery	0.014	0.0287	0.267	16
S35	Customer status	0.018	0.0364	0.339	11
S36	Trust and communication between buyer and seller	0.019	0.0381	0.356	10
S37	Human rights	0.016	0.0325	0.303	15
S38	Development of culture and technology	0.012	0.0241	0.224	21

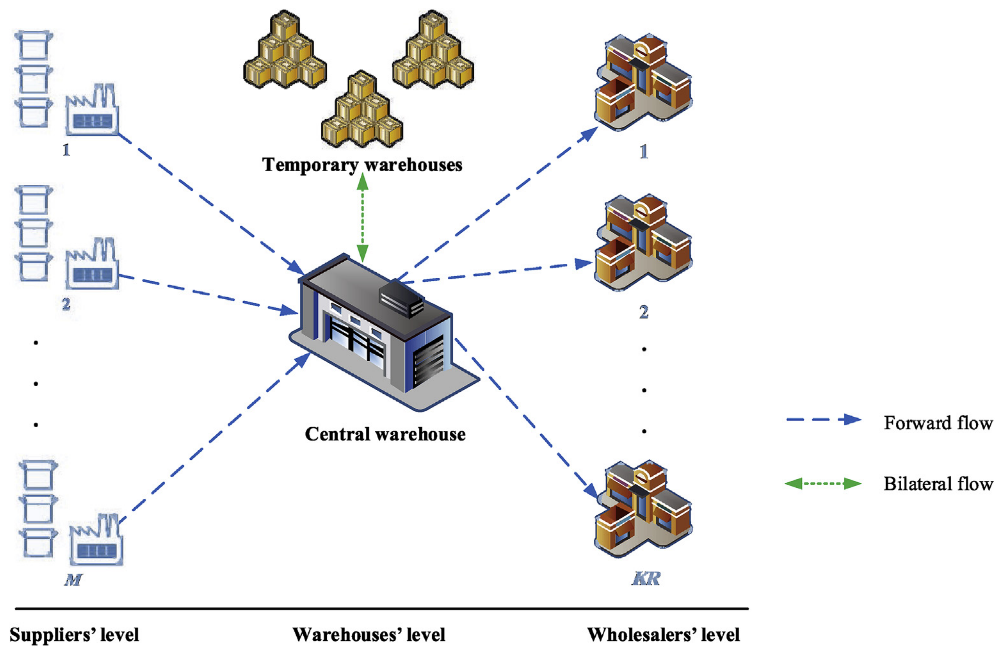


Fig. 7. The schematic view of the proposed supply chain network.

warehouse to the wholesalers is determined regarding its inventory and the wholesalers' demand. Due to the fluctuations of the wholesalers' demand in real-world conditions, the construction of temporary warehouses has been also anticipated considering the capacity and construction cost. For further investigation, Fig. 7 depicts the proposed two-echelon supply chain.

On the other hand, sometimes there may be delays, disruptions, or sudden changes in the activities of suppliers and central warehouse, which affect the reliability of the supply process. In fact, these factors lead to a decrease in the average amount of products to be delivered. Therefore, the time required to have a failure in the ith supplier activities at period T_i is supposed to be a variable following exponential distribution with the parameterλ_{it}.Here, λ_{it}denotes the failure rate of ith supplier at tth period. Thus, the reliability of activities of the ith supplier (R_i) is obtained as follows (Pasandideh et al., 2015):

$$R_i = P(T_i > \tau) = e^{-\lambda_{it}\tau} (i = 1, 2, ..., M) \tag{1}$$

where τ is the minimum time during which no failure takes place. Likewise, the parameter$\lambda'_t$is defined for the failure of the central warehouse in tth period and its reliability expression is defined similarly.

To present the proposed mathematical model, first, the sets of indices, variables, objective functions, and constraints are given as follows:

4.1. Sets and indices

I	Set of suppliers,
J	Set of products,
K	Set of wholesalers,
T	Set of time periods,
$i = 1, 2, ..., M$	Index of suppliers,
$j = 1, 2, ..., PR$	Index of products,
$k = 1, 2, ..., KR$	Index of wholesalers,
$t = 1, 2, ..., PE$	Index of time periods.

4.2. Parameters

UR	Maximum number of potential temporary warehouses at each period,
W_i	Normalized weight of ith supplier (see Table 6),
C_{ijt}	Capacity of ith supplier for supplying jth product at tth period,
SC_{jt}	Maximum capacity of the central warehouse to supply jth product at tth period,
SO_j	Maximum capacity of supplying jth product at each temporary warehouse,
PO	Establishment cost of each temporary warehouse,
P_{ij}	Unit purchasing price of ith supplier for jth product,
st_{ij}	Setup time of jth product at ith supplier including production time and delivery time,
LT_{jt}	Delivery lead time for jth product in tth period,
O_{ij}	Ordering cost of ith supplier for jth product,
DO_k	Products unit transportation cost to wholesaler k,
DK_{kjt}	Demand of wholesaler k for jth product in tth period,
h_j	Unit holding cost of jth product,
LS_j	Unit lost sale cost of jth product at the suppliers' level,
LW_j	Unit lost sale cost of jth product at the central warehouse,
qa_i	Average defect rate of ith supplier,
Qa_j	Maximum acceptable defect rate for jth product,
$L_{\max}$	Maximum level of lost sales,
λ_{it}	Exponential distribution parameter indicating the failure rate of ith supplier at tth period,
λ'_t	Exponential distribution parameter indicating the failure rate of the central warehouse at tth period,
τ	A certain time period in which the supply chain does not fail,
BM	An optional big number.

4.3. Variables

X_{ijt}	Amount of jth product ordered to ith supplier in tth period,
XK_{kjt}	Amount of jth product dispatched by the central warehouse to wholesaler k in tth period,
D_{jt}	Demand of the central warehouse for jth product in tth period,
I_{jt}	Inventory amount of jth product in tth period,
LO_{jt}	Lost sales amount of jth product at the end of tth period for the suppliers' level,
LO'_{jt}	Lost sales amount of jth product at the end of tth period for the central warehouse,
OX_t	Number of temporary warehouses established in tth period,
Y_{ijt}	Binary variable taking the value of 1 when ith supplier is selected to supply jth product in tth period; otherwise, it is equal to 0,
	Binary variable taking the value of 1 when the demand of all wholesalers is satisfied for jth product in tth period; otherwise, it is equal to 0.

Finally, the proposed MOMILP model is presented as follows:

$$\text{minimize} Z_1 = \sum_{j=1}^{PR}\sum_{i=1}^{M}\sum_{t=1}^{PE}(P_{ij}.X_{ijt}) + \sum_{j=1}^{PR}\sum_{t=1}^{PE}(h_j.I_{jt}) + \sum_{i=1}^{M}\sum_{j=1}^{PR} \times \sum_{t=1}^{PE}(O_{ij}.Y_{ijt}) + \sum_{j=1}^{PR}\sum_{t=1}^{PE}(LS_j.LO_{jt}) + \sum_{j=1}^{PR}\sum_{t=1}^{PE}(LW_j.LO'_{jt}) + \sum_{k=1}^{KR} \times \sum_{j=1}^{PR}\sum_{t=1}^{PE}\left(DO_k.XK_{kjt}\right) + \sum_{t=1}^{PE}(PO.OX_t)\Bigg) \tag{2}$$

$$\text{maximize} Z_2 = \sum_{i=1}^{M}\sum_{j=1}^{PR}\sum_{t=1}^{PE}(W_i \cdot X_{ijt}) \tag{3}$$

$$\text{maximize} Z_3 = \sum_{i=1}^{M}\sum_{j=1}^{PR}\sum_{t=1}^{PE}(e^{-\lambda_{it}\tau} \cdot X_{ijt}) + \sum_{k=1}^{KR}\sum_{j=1}^{PR} \times \sum_{t=1}^{PE}\left(e^{-\lambda'_t\tau} \cdot XK_{kjt}\right) \tag{4}$$

subject to

$$\sum_{i=1}^{M} X_{ijt} + I_{jt-1} + LO_{jt} - \sum_{k=1}^{KR} XK_{kjt} = I_{jt} \qquad \forall j \in J;\ \forall t \in T, \tag{5}$$

$$D_{jt} = \sum_{k=1}^{KR} DK_{kjt}.B_{kjt} \qquad \forall j \in J;\ \forall t \in T, \tag{6}$$

$$LO_{jt} \le BM\left(1 - B_{kjt}\right) \qquad \forall j \in J;\ \forall k \in K;\ \forall t \in T, \tag{7}$$

$$LO_{jt} \le D_{jt} \qquad \forall j \in J;\ \forall t \in T, \tag{8}$$

$$\sum_{i=1}^{M}(X_{ijt}.qa_i) \le Qa_j.D_{jt} \qquad \forall j \in J;\ \forall t \in T, \tag{9}$$

$$X_{ijt} \le C_{ijt} \qquad \forall i \in I;\ \forall j \in J;\ \forall t \in T, \tag{10}$$

$$\sum_{i=1}^{M} st_{ij} Y_{ijt} \le LT_{jt} \qquad \forall j \in J;\ \forall t \in T, \tag{11}$$

$$\sum_{i=1}^{M} X_{ijt} + I_{jt-1} \le SC_{jt} + SO_j.OX_t \qquad \forall j \in J;\ \forall t \in T, \tag{12}$$

$$XK_{kjt} + LO'_{jt} = DK_{kjt} \qquad \forall j \in J;\ \forall k \in K;\ \forall t \in T, \tag{13}$$

$$\sum_{j=1}^{PR}\sum_{t=1}^{PR} LO_{jt} \le L_{\max}.\sum_{j=1}^{PR}\sum_{t=1}^{PR} D_{jt} \tag{14}$$

$$OX_t \le UR \qquad \forall t \in T, \tag{15}$$

$$X_{ijt} \le BM.Y_{ijt} \qquad \forall i \in I;\ \forall j \in J;\ \forall t \in T, \tag{16}$$

$$X_{ijt}, XK_{kjt}, I_{jt}, LO_{jt}, LO'_{jt}, D_{jt} \ge 0;\ OX_t \in Z^+;\ Y_{ijt}, B_{kjt} \in \{0,1\} \quad \forall i \in I;\ \forall j \in J;\ \forall k \in K;\ \forall t \in T. \tag{17}$$

The first objective function, i.e., Eq. (2), includes seven terms minimizing the total cost of the supply chain that contains purchasing cost of products, holding the cost of products, ordering cost of products, cost of lost sales of suppliers, cost of lost sales of the central warehouse, total transportation cost of products, and establishment cost of temporary warehouses, respectively. The second objective function represented in Eq. (3) maximizes the weighted value of different products purchased from different suppliers over the planning horizon. This objective function is responsible for increasing the quantity of orders allocated to high-priority suppliers. The third objective function represented by Eq. (4) consists of two terms 1) maximizing the reliability of the supply chain network through maximizing the average number of products delivered from suppliers to the central warehouse and 2) the average number of products delivered to wholesalers, respectively. Equation (5) defines the inventory balance concept. That is, the inventory of each product at the end of each period must be equal to the total number of products purchased from suppliers plus the inventory of the previous period and the lost sales of that product minus the total number of products transported to the wholesalers. Equation (6) calculates the demand for each product at each period. Equation (7) represents the relationship between the continuous variable of the total number of lost sales and the binary variable of satisfying the demand of the wholesalers. Actually, if the demand of the central warehouse is not satisfied, there will be lost sales, and it cannot satisfy the demand of the wholesalers. Equation (8) denotes the maximum level of lost sales, which is equal to the demand of the central warehouse of each product at each period. Equation (9) represents the qualitative constraints, which guarantees the average defect percent of the ordered products will not exceed a certain limit. Equation (10) indicates that the total number of products ordered from a supplier must not exceed its capacity. Equation (11) guarantees the product submission during the considered lead-time. Based on the maximum supply capacity of the central warehouse, Equation (12) identifies whether or not temporary warehouses are established. For each period, Equation (13) ensures that the total number of a product transported from the central warehouse to each wholesaler plus its lost sales must be equal to the demand of the wholesalers of that product. Equation (14) states that the maximum level of lost sales for the suppliers must not exceed a certain limit (a percentage of the central warehouse demand at all periods) for all products over all periods. As is obvious, we have a restriction on the total amount of lost sales for the suppliers to consider the best suppliers. In this equation, $1-L_{\max}$ denotes the service level. Equation (15) ensures that the number of established temporary warehouses should not exceed the maximum number of allowable temporary warehouses. Equation (16) represents the relationships between the variables of order quantity and order allocation. It means that an order can be placed while a supplier is already selected. Finally, Eq. (17) shows the type of the variables.

5. Goal programming

The goal programming (GP) approach was introduced by Charnes and Cooper (1977) as one of the most important multi-objective programming models. This method was proposed for solving problems with multiple contradictory objectives. All GP-based methods have a common structure with the ultimate goal of minimizing unfavorable deviations from the objective functions.

This method considers expectation levels for the objective functions and attempts to minimize the sum of deviations from these levels. In modeling problems using this method, three basic components are needed:

1. System constraints, which demonstrate the resources constraints and constraints imposed by the decision environment.
2. Goal constraints, which indicate the management policies and different levels of objectives pursued by decision-makers.
3. The objective function, which minimizes the deviations from the desired levels of objectives, considering the specified ranking.

When we make use of GP, the objectives are formulated based on three concepts:

1. Deviation variables: the difference between the obtained values of objective functions and their desired values is called deviation. Here, d_y^+ and d_y^- denote the positive and negative, respectively. The purpose is to minimize the sum of these variables according to the GP approach.
2. Priority factors: these factors determine the objective functions that must be optimized sooner.
3. Giving weight to deviation variables at the same level of priority; on some occasions, it is necessary to weight deviation variables that are at the same level of priority.

5.1. Weighted goal programming

The general model of weighted GP (WGP) method is as follows:
minimize $\sum_{y=1}^{Y} We_y(d_y^+ + d_y^-)$
subject to

$$h_k(X) = (\leq \text{or} \geq)0 \qquad (k = 1, 2, ..., q),$$

$$f_y - d_y^+ + d_y^- = b_y \qquad \left(y = 1, 2, ..., Y\right),$$

$$d_y^+, d_y^- \geq 0 \qquad \left(y = 1, 2, ..., Y\right) \tag{18}$$

where in profit goals, negative deviations (d_y^-); and in cost goals, positive deviations (d_y^+) must be minimized. In Eq. (18), $h_k(X)$and $b_y$denote the kth constraint set and the desired value of yth goal, and f_y represents the yth goal. Furthermore, the positive and negative deviations are calculated as follow:

$$d_y^- = \begin{cases} b_y - f_y, & \text{if } f_y < b_y, \\ 0, & \text{otherwise}, \end{cases}$$

$$d_y^+ = \begin{cases} f_y - b_y, & \text{if } f_y > b_y, \\ 0, & \text{otherwise}. \end{cases} \tag{19}$$

Here, We_ydenotes the positive weight indicating the importance of goals. It should be noted that these weights are determined by experience and using experts' opinions and must be summed to one ($\sum_{y=1}^{Y} We_y = 1$).

Therefore, the following adjustments are made in the model to simultaneously consider the three objectives of the proposed model:

$$\text{minimize}\left(we_1\frac{d_1^+}{b_1}\right) + \left(we_2\frac{d_2^-}{b_2}\right) + \left(we_3\frac{d_3^-}{b_3}\right). \tag{20}$$

Since the first objective is of minimization type, while the second and third ones are of maximization type, the objective function of the GP model is formulated as a weighted sum of positive deviation for the first objective and negative deviation for the second and third objectives.

The three following constraints are also added to the problem constraints:

$$f_1 - d_1^+ + d_1^- = b_1, \tag{21}$$

$$f_2 - d_2^+ + d_2^- = b_2, \tag{22}$$

$$f_3 - d_3^+ + d_3^- = b_3. \tag{23}$$

where b_y, $y = 1, 2, 3$ can be determined by solving the single-objective model with yth objective function.

6. Numerical results

In this section, a case study is investigated to validate the mathematical model and analyze the applicability of the proposed methodology. It has seven potential suppliers and distributes three types of electronic lamps (Gas-discharge lamp, light-emitting diode (LED) lamp, and Incandescent light bulb) though a central warehouse located at Sari in Iran. The information of this supply chain is presented in Appendix A. We describe step by step how the case study problem was solved using the GP method. Our proposed MILP model is validated and solved by GAMS/CPLEX solver.

In this regard, the values of b_y are determined first and shown in Table 7. The weights considered for the deviations from goals are 0.5, 0.3, and 0.2 for the first, second, and third objective, respectively.

Therefore, the objective functions and constraints added to the model are as follow:

$$\text{minimize } Z_{GP} = \left(0.5d_1^+\right) + \left(0.3d_2^-\right) + \left(0.2d_3^-\right)$$

subject to (24)

Table 7
Desired values of the goals.

Goals	Values
b_1	1288765.014
b_2	50.445
b_3	55.997

Table 8
Values of the goal variables.

Variables	Z_{GP}	f_1	f_2	f_3	d_1^+	d_1^-	d_2^+	d_2^-	d_3^+	d_3^-
Values	0.191	1340033.014	30.633	40.993	51268.000	0.000	0.000	19.812	0.000	15.004

$$f_1 - d_1^+ + d_1^- = 1288765.014\,, \tag{25}$$

$$f_2 - d_2^+ + d_2^- = 50.445\,, \tag{26}$$

$$f_3 - d_3^+ + d_3^- = 55.997\,. \tag{27}$$

After executing the model in GAMS software, the outputs results for the goal variables are obtained (see Table 8).

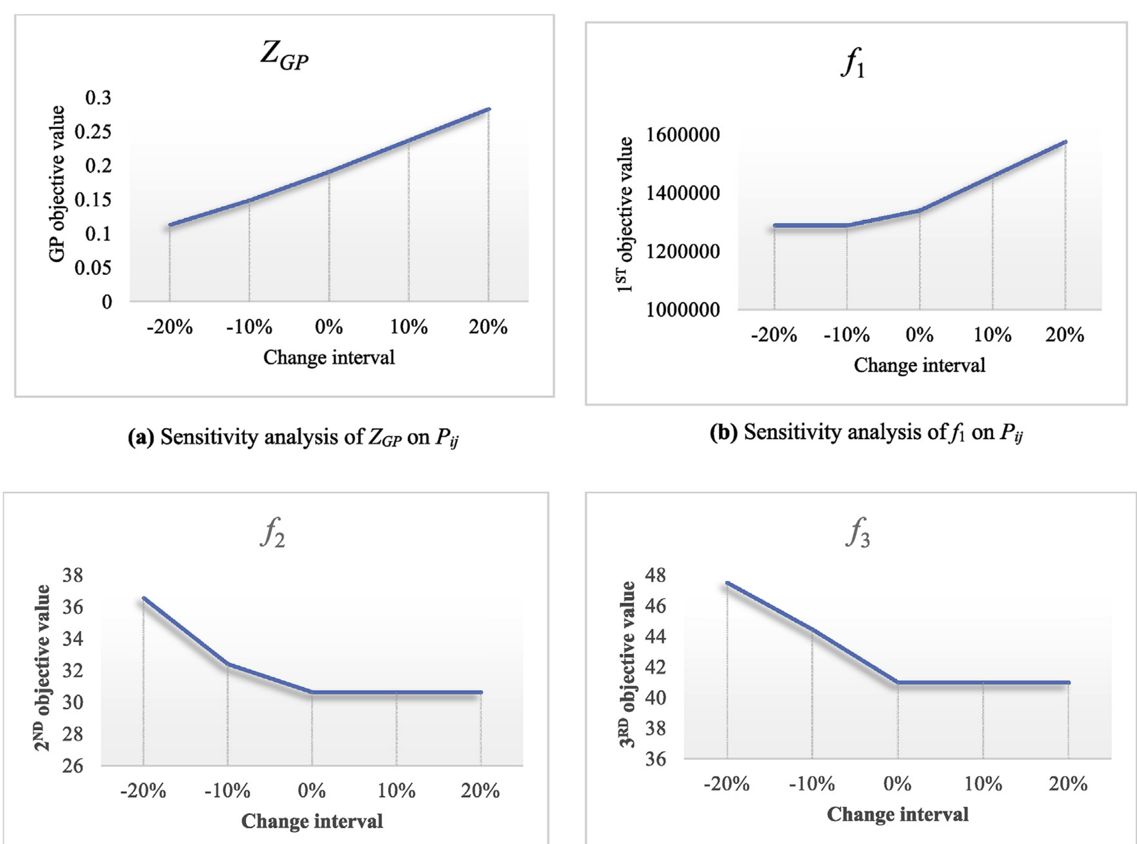
As can be seen in Table 8, the objectives in the optimal policy have the values of 1340033.014, 30.633, and 40.993, respectively. The value of the third objective (reliability) is greater than that of the second objective (the weighted amount of the products transported from the suppliers to the central warehouse). Based on the proposed model, the reliability in the first and second echelons is optimized concurrently. More results including the amount of products transported between the different levels and the inventory at the end of each period have been provided in Appendix B. The other results are as follow:

- Only one temporary warehouse is constructed in the second period.
- There is no lost sale at any period.

6.1. Sensitivity analysis

In this section, to investigate the real-world conditions of the problem, a sensitivity analysis is conducted on the most sensitive parameters (which have been selected after testing all parameters), namelyP_{ij},DK_{kjt} andτ to detect the behavior of the objective functions. In this regard, the parameters of the case study problem undergo changes from 20% decrease to a 20% increase and the results are given in Figs. 8–10. The analytical charts are also provided for the objectives.

As can be seen in Fig. 8, different objective functions, including the GP objective function and the first to third objective functions all experienced substantial changes in response to P_{ij} parameter. Generally, the largest changes have occurred in the GP objective function and in case of an increase in this parameter, the second and third objective functions have experienced no change. However, the first objective function is substantially dependent on the increase in this parameter and a 10% decrease causes it to reach its goal, which requires managers to have special care in controlling cost. On the other hand, by reducing this parameter, the second and third objective functions have increased substantially, and in case of a 20% decrease, they are at the most desirable level. Overall, it is concluded that the price parameter is one of the most effective



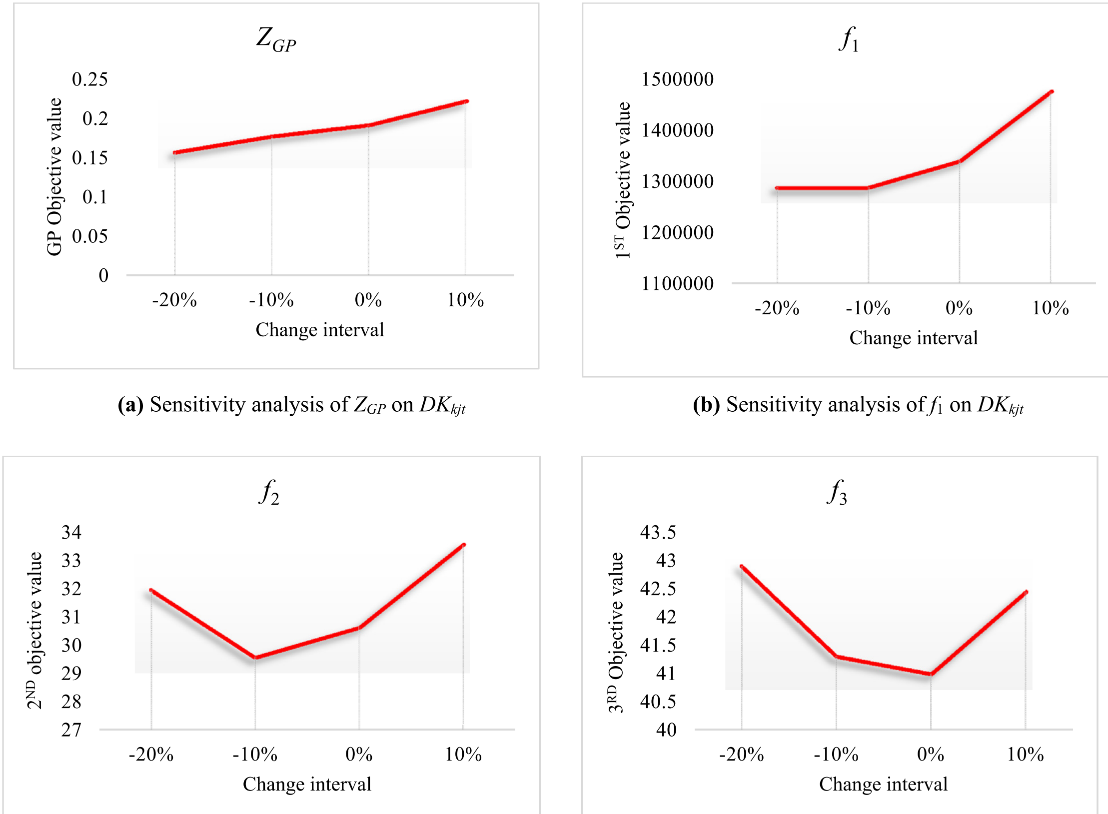
(a) Sensitivity analysis of Z_{GP} on P_{ij}

(b) Sensitivity analysis of f_1 on P_{ij}

(c) Sensitivity analysis of f_2 on P_{ij}

(d) Sensitivity analysis of f_3 on P_{ij}

Fig. 8. The sensitivity analysis of the purchasing price parameter.



(a) Sensitivity analysis of Z_{GP} on DK_{kjt}

(b) Sensitivity analysis of f_1 on DK_{kjt}

(c) Sensitivity analysis of f_2 on DK_{kjt}

(d) Sensitivity analysis of f_3 on DK_{kjt}

Fig. 9. The sensitivity analysis of the wholesalers' demand parameter.

parameters that has a central role in determining the value of objective functions.

As can be seen in Fig. 9, different objective functions have shown considerable changes against the change in one of the most key decision-making parameters, i.e., the parameter of DK_{kjt}. Generally, the least changes have occurred in the GP objective function, and in the range of 10% increase in this parameter, all objective functions have increased; GP and the first and second objective functions had the highest change in this range. One of the interesting points here is that the problem is infeasible for a 20% increase in this parameter. In other words, it is not possible to fulfill the demand of all wholesalers considering the capacity of the potential suppliers. With a 10% decrease in demand, the value of the first objective functions reaches its goal.

As can be seen in Fig. 10, different objective functions have shown different manners against the reliability parameter of the supply chain. Generally, as it was expected, the biggest changes have occurred in the third objective function; it decreased monotonically with the increase of this parameter. The behavior of the GP objective function was absolutely in opposition to the third objective function. In the range of 10% and 20% increase in this parameter, the first and second objective functions showed no sensitivity. However, for a 10% decrease in this parameter, the first objective function reached its utmost value, while the second objective function reached its minimum value.

Therefore, based on the presented figures, it is revealed that the objective functions are sensitive to the changes in the parameters, and this fact must be considered in management decisions and making policies.

7. Conclusion and future research directions

This study addressed the sustainability criteria in supplier selection problem and reliability in designing a supply chain comprising suppliers, a central warehouse, and wholesalers. The main aims were to find the best suppliers and determine the optimal order allocation plan by taking into consideration an inventory control policy. To this end, we integrated decision-making and optimization processes to provide an efficient methodology. In this regard, first, a hybrid MCDM method based on the fuzzy approach (i.e., Fuzzy ANP, Fuzzy DEMATEL, and Fuzzy TOPSIS) was developed to select sustainable suppliers. Then, based on the score of each supplier, a MOMILP model was designed to determine the optimal size of orders and order allocation as the main variables and to make decision about the quantity of orders transported to wholesalers, lost sales and inventory of the central warehouse, the construction of temporary warehouses, and the demand of the central warehouse, as the secondary variables, in a planning horizon. The considered objective functions were the minimization of the total cost, maximization of the weighted value of products by taking the account of suppliers' priorities, and maximization of the supply chain reliability. Then, the multi-objective problem was transferred to a single objective one using WGP technique. To validate the applicability of the proposed methodology, a case study of the electronics lamp supply chain was investigated including seven suppliers, three types of products and four

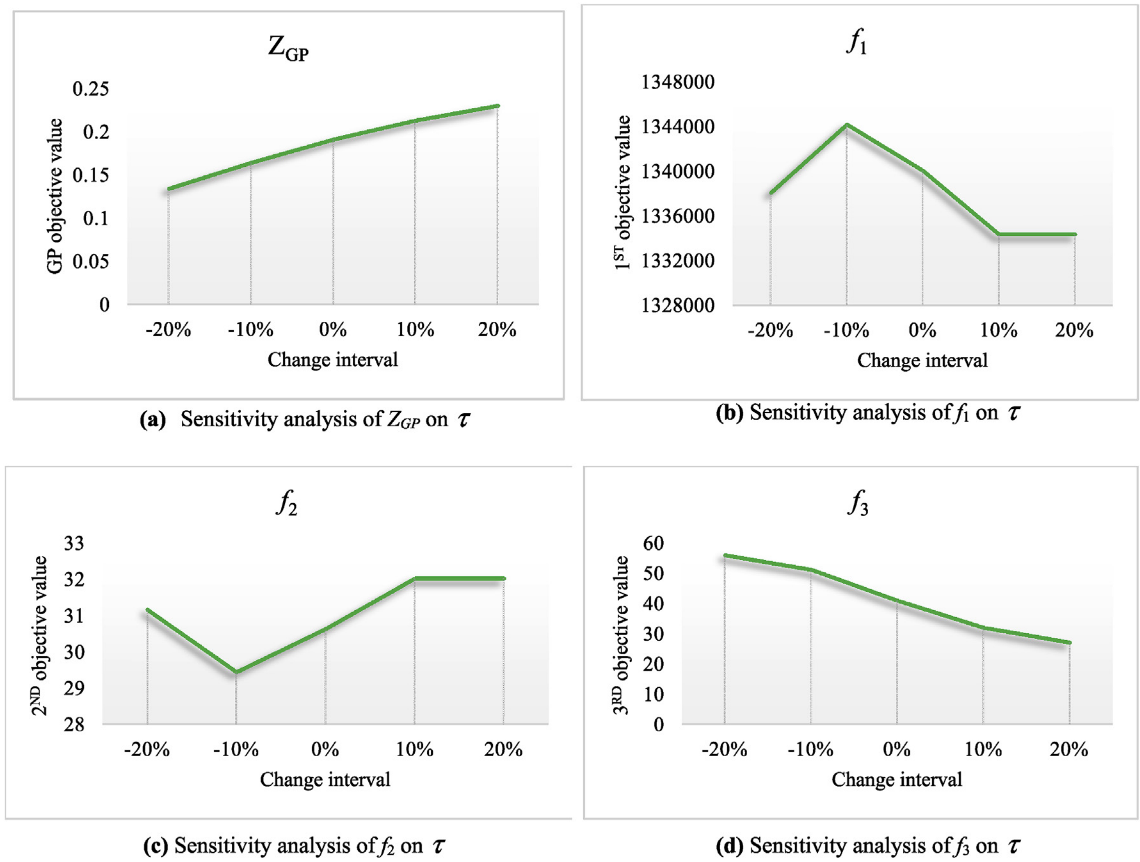


Fig. 10. The sensitivity analysis of the reliability parameter of the supply chain.

planning periods. The optimal policy was determined and discussed by performing sensitivity analyses of the key parameters, i.e., the product purchasing price, wholesalers' demand and the reliability of the supply chain was conducted.

One of the limitations faced by our proposed MOMILP model is that all parameters are considered to be deterministic. As an opportunity for future research, we can extend it using uncertain optimization techniques such as fuzzy programming (Babaee Tirkolaee et al., 2019), robust optimization (Golpîra and Tirkolaee, 2019; Babaee Tirkolaee et al., 2019; Sangaiah et al., 2019; Tirkolaee et al., 2019, Tirkolaee et al., 2020) and stochastic programming (Golpîra, 2016; Temoçin and Weber, 2014) to make it closer to the real-life situation. To solve the small-sized problems, the ε-constraint method can be employed to provide Pareto optimal points, and multi-objective Pareto-based heuristic/metaheuristic algorithms such as non-dominated sorting genetic algorithm (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) can be implemented to solve large-sized problems. Moreover, examining other variables such as transportation planning along with the supply chain design and also greenhouse gas emissions can be areas for future research.

Author contributions section

Erfan Babaee Tirkolaee proposed the method and worked on the analysis, Abbas Mardani worked on the literature, framewrok and discussion, Zahra Dashtian worked on research method and references, Mehdi Soltani worked on the introduction and analysis, Gerhard-Wilhelm Weber worked on conclusion, rewrited and edited the paper.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript.

Appendix A. Input parameters of the case study problem.

Input information regarding the case study problem is presented in the following tables for all parameters.

Table A1
Information about parameters not related to the index.

Parameters	M	PR	PE	KR	UR	L_{max}	BM	PO	τ	λ_{it}	λ'_t
Value	7	3	4	16	5	10%	106	20000000	12	uniform(0.1,0.5)	uniform(0.8,1)

Table A2
Maximum capacity of the central warehouse to supply products in each period.

SC_{jt}	Period 1	Period 2	Period3	Period 4
Product 1	2400	2500	2500	2000
Product 2	2200	2000	2200	2400
Product 3	2400	2400	2000	2100

Table A3
Maximum capacity of products' supply at each temporary warehouse (SO_j).

Product	Value
1	300
2	300
3	250

Table A4
Capacity of suppliers for products in each period.

C_{ijt}		Period 1	Period 2	Period 3	Period 4
Supplier 1	Product 1	17000	20000	16000	13000
	Product 2	20000	20000	17000	15000
	Product 3	20000	20000	18000	15000
Supplier 2	Product 1	21000	20000	20000	15000
	Product 2	17000	16000	16000	14000
	Product 3	18000	17000	16000	16000
Supplier 3	Product 1	22000	20000	21000	19000
	Product 2	17000	17000	16000	12000
	Product 3	17000	17000	18000	13000
Supplier 4	Product 1	17000	16000	17000	11000
	Product 2	19000	17000	21000	23000
	Product 3	22000	21000	21000	13000
Supplier 5	Product 1	13000	15000	17000	15000
	Product 2	14000	16000	15000	23000
	Product 3	14000	16000	17000	14000
Supplier 6	Product 1	17000	16000	15000	17000
	Product 2	21000	23000	17000	23000
	Product 3	21000	13000	17000	23000
Supplier 7	Product 1	23000	20000	20000	16000
	Product 2	19000	13000	17000	20000
	Product 2	20000	20000	23000	22000

Table A5
Demand of wholesalers for different products in each period.

DK_{kjt}		Period 1	Period 2	Period 3	Period 4
Wholesaler 1	Product 1	0	90	0	0
	Product 2	0	0	170	90
	Product 3	0	0	330	0
Wholesaler 2	Product 1	0	260	0	260
	Product 2	240	0	0	250
	Product 3	380	123	240	0
Wholesaler 3	Product 1	90	260	90	260
	Product 2	250	170	0	250
	Product 3	300	220	280	220
Wholesaler 4	Product 1	170	90	150	150
	Product 2	340	208	100	208
	Product 3	200	100	100	208
Wholesaler 5	Product 1	190	150	192	192
	Product 2	0	40	192	192
	Product 3	0	260	90	90
Wholesaler 6	Product 1	90	0	240	230
	Product 2	0	0	330	220
	Product 3	0	0	260	200
Wholesaler 7	Product 1	90	170	0	0
	Product 2	0	0	240	230
	Product 3	260	90	90	90
Wholesaler 8	Product 1	90	177	90	0
	Product 2	170	90	0	90
	Product 3	220	330	110	330
Wholesaler 9	Product 1	177	90	90	177
	Product 2	240	170	0	170
	Product 3	330	0	110	0
Wholesaler 10	Product 1	177	260	177	0
	Product 2	90	170	170	0
	Product 3	110	110	220	110
Wholesaler 11	Product 1	260	90	0	0
	Product 2	170	240	240	170
	Product 3	0	220	220	110
Wholesaler 12	Product 1	90	260	177	0
	Product 2	240	170	240	250

Table A5 (*continued*)

DK_{kjt}		Period 1	Period 2	Period 3	Period 4
	Product 3	0	110	110	200
Wholesaler 13	Product 1	260	260	90	260
	Product 2	90	0	0	0
	Product 3	330	110	0	210
Wholesaler 14	Product 1	0	90	260	270
	Product 2	90	0	240	0
	Product 3	110	330	220	0
Wholesaler 15	Product 1	180	90	180	250
	Product 2	250	0	90	90
	Product 3	0	330	100	210
Wholesaler 16	Product 1	0	90	0	0
	Product 2	0	0	170	90
	Product 3	0	0	330	0

Table A6
Unit purchasing price of suppliers for each product.

P_{ij}	Product 1	Product 2	Product 3
Supplier 1	5000	3900	6000
Supplier 2	4500	4000	6200
Supplier 3	4700	4100	6000
Supplier 4	4800	4000	5800
Supplier 5	4800	3900	5700
Supplier 6	4800	4200	6100
Supplier 7	3600	4800	6100

Table A7
Setup time of products at each supplier.

st_{ij}	Product 1	Product 2	Product 3
Supplier 1	8	7	9
Supplier 2	7	8	9
Supplier 3	9	7	10
Supplier 4	9	8	9
Supplier 5	9	7	10
Supplier 6	8	7	10
Supplier 7	8	7	10

Table A8
Unit holding cost, lost sale cost, and maximum acceptable defect ratio.

Parameter	Product 1	Product 2	Product 3
h_j	60	55	65
LW_j	6000	5000	7000
Qa_j	0.02	0.03	0.06

Table A9
Ordering cost of suppliers for each product.

O_{ij}	Product 1	Product 2	Product 3
Supplier 1	1250	1250	1200
Supplier 2	1250	1300	1100
Supplier 3	1200	1100	900
Supplier 4	1400	1000	1300
Supplier 5	1100	1050	1150
Supplier 6	1300	1150	1150
Supplier 7	1250	1300	1350

Table A10
Average defect rate of suppliers (qa_i).

Supplier	Value
1	2
2	3
3	5
4	4
5	5
6	4
7	2

Table A11
Unit transportation cost of products to wholesalers (DO_k).

Wholesaler	Value
1	3.788
2	4.923
3	1.957
4	4.570
5	2.998
6	1.957
7	3.994
8	3.964
9	4.968
10	2.973
11	4.650
12	4.996
13	2.811
14	1.988
15	4.615
16	2.436

Table A12
Delivery lead-time for products in each period (hrs).

LT_{jt}	Period 1	Period 2	Period 3	Period 4
Product 1	24	24	48	24
Product 2	72	12	72	72
Product 3	12	72	48	48

Table A13
Weight of suppliers specified in Section 3(W_i).

Supplier	Value
1	0.169
2	0.129
3	0.117
4	0.105
5	0.099
6	0.098
7	0.082

Appendix B. Values obtained for the main decision variables of the case study problem.

Table B1
Amount of products ordered to suppliers in each period (X_{ijt}).

t i, j	1	2	3	4
1, 1	13	13.73	0	0
1, 2	23	21	0	0
1, 3	22	0	0	0
2, 1	0	0	20	0
2, 3	0	8.87	13	0
5, 2	0	0	13.15	0
5, 3	0	0	10.853	0
6, 1	16	0	0	0
7, 3	0	14	22.877	0
9, 1	0	0	17	0
9, 2	0.57	20	0	0

Table B2
Amount of products dispatched to the wholesalers in each period (XK_{kjt}).

t k, j	1	2	3	4
1, 1	0	0	0.85	0
1, 2	0.85	1.69	0	0
1, 3	0	3.31	0	0
2, 1	2.62	0	2.62	0
2, 2	2.54	0	0	2.54
2, 3	0	2.54	1.23	3.77
3, 1	2.62	0.85	2.62	0.85
3, 2	2.54	0	1.69	2.54
3, 3	2.15	3.31	2.15	3.31
4, 1	1.77	1.77	0.85	1.77
4, 2	2.08	1	2.08	3.08
4, 3	2.08	1	1	2.08
5, 1	1.92	1.92	0.92	1.92
5, 2	1.92	1.92	0.92	0
5, 3	0.85	0.85	2.62	0
6, 1	2.54	2.54	0	0.85
6, 2	2.15	3.31	0	0
6, 3	1.77	2.62	0	0.85
7, 1	0	0	1.69	0.85
7, 2	2.54	2.54	0	0
7, 3	0.85	0.85	0.85	2.62
8, 1	0	0.85	1.77	0.85
8, 2	0.85	0	0.85	1.69
8, 3	3.31	1.08	3.31	2.15
9, 1	1.77	0.85	0.85	1.77
9, 2	1.69	0	1.69	2.54
9, 3	0	1.08	0	3.31
10, 1	0	1.77	2.62	1.77
10, 2	0	1.69	1.69	0.85
10, 3	2.15	1.08	1.08	1.08
11, 1	0	0	0.85	2.62
11.2	1.69	2.54	2.54	1.69
11, 3	1.8	2.15	2.15	0
12, 1	0	1.77	2.62	0.85
12, 2	2.54	2.54	1.69	2.54
12, 3	2.15	1.08	1.08	0
13, 1	2.62	0.85	2.62	2.62
13, 2	0	0	0	0.85
13, 3	2.15	0	1.08	3.31
14, 1	2.62	2.62	0.85	0
14, 2	0	2.54	0	0.85
14, 3	0	2.15	3.31	1.08
15, 1	2.62	1.77	0.85	1.77
15, 2	0.85	0.85	0	2.54
15, 3	2.15	1.08	3.31	0

Table B3
Demand of the central warehouse for different products in each period.

D_{jt}	Period 1	Period 2	Period 3	Period 4
Product 1	21.1	17.56	20.81	1.77
Product 2	22.24	20.62	13.15	2.54
Product 3	19.62	25.25	23.17	1.08

Table B4
Inventory amount of products at the central warehouse in each period.

I_{jt}	Period 1	Period 2	Period 3	Period 4
Product 1	7.9	4.07	18.49	0
Product 2	1.33	21.71	21.71	0
Product 3	2.38	0	23.56	0

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