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A Multi-Objective Programming Model for Supplier Evaluation and Selection in the Steel Industry Supply Chain (Case Study: Khouzestan Steel Company)

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Abstract

This research focuses on quantitative models for the selection and evaluation of suppliers in the supply chain. It is applied in nature, with the statistical population consisting of 12 experts from Khouzestan Steel Company. Based on this, a fuzzy mathematical model has been proposed for the selection and evaluation of suppliers, aiming to minimize returned goods, late transportation rates, order production costs, and raw material costs. Given the uncertainties present in real-world issues, the demand and capacity parameters, which may not have available or precise values, are considered as fuzzy trapezoidal numbers. Two methods have been employed: the fuzzy ranking method (Jiménez's method) for converting the fuzzy model into a deterministic model, and the Linear Programming (LP)-metric method due to the multi-objective nature of the problem. The computational results obtained from solving the model show that, in the fuzzy model, due to the consideration of flexibility in the model's constraints using various α-cuts (in Jiménez's range method), the model becomes more flexible compared to the deterministic model, resulting in a better objective function value. Additionally, the results of the proposed model provide optimal values for returned goods, late transportation rates, order production costs, and raw materials, enabling managers to select the most suitable supplier. Furthermore, the calculations indicate that the model's fuzziness does not significantly increase computational complexity or problem-solving time.

Keywords: Suppliers, Supply chain, Linear programming-metric, Fuzzy logic.

1 | Introduction

Supply Chain refers to a network of facilities and distributors that perform the operations of sourcing materials, converting materials into semi-finished products, manufacturing final products, and distributing these products among customers [1]. In today's highly competitive world, every active company needs the

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ability to respond quickly to external stimuli in order to survive in the market. On the other hand, no company can operate independently in a competitive market. Given the competitive environment of today's markets, distribution channels, and the selection of appropriate suppliers within these channels, especially in industrial markets, the supply chain of industrial goods and the selection of suitable suppliers are of particular importance [2]. Selecting appropriate suppliers and establishing and maintaining long-term relationships with them is one of the most essential tasks for factories in order to reduce purchasing costs. For this reason, today the concept of Supplier Relationship Management (SRM) has gained more attention than ever before [3], [4]. The supplier selection problem is a process in which a set of the best suppliers is selected by considering a number of quantitative and qualitative criteria. This, in turn, increases the overall efficiency of the supply chain and ultimately improves the competitive position of the chain. In recent years, this issue has received more attention from researchers, indicating its growing importance [5].

Based on the extensive literature review in the field of supplier selection, it can be observed that the approaches and models used to solve the supplier selection problem have always focused on selecting first-tier suppliers, who are directly connected with the leading organization, and have paid little attention to second-tier suppliers or raw material producers. However, it seems that if an organization considers second-tier suppliers, it will have greater assurance regarding the quality and timeliness of its parts [6]. For this reason, in this research, both layers of the supply chain are considered for the evaluation and selection of suppliers.

In today's world, various factories are outsourcing a significant portion of their business processes. These outsourcing activities range from raw material procurement to after-sales services and support, or even the full distribution of products. According to studies in this area, 80% of organizations outsource some of their activities, and most of them spend nearly 45% of their total budget on these activities [7]. Generally, sourcing is one of the most critical operations in the supply chain, with procurement being the most crucial part. When an organization decides to purchase raw materials or outsource part of its components, the main task of the procurement unit is to select suitable suppliers. Supplier selection is a task beyond simply reviewing and determining the proposed prices of a few vendors [6]. This issue involves examining a large number of quantitative and qualitative criteria, and various multi-criteria decision-making methods have been proposed to solve it.

Furthermore, in many cases, a single supplier cannot meet the organization's needs, and a group of suppliers must be chosen to fulfill a specific order. In such situations, the issue of order allocation to each supplier arises, and determining the appropriate size of these orders is critical. This selection involves examining different criteria, many of which have undergone significant changes in the last 50 years (Since 1966) [8]. Additionally, various approaches and models have been employed to address the issue, which have consistently focused on selecting first-tier suppliers directly connected to the buyer, without considering second-tier suppliers. Although this topic has not received attention in the proposed models and academic studies, the type of materials and components used can have a significant impact on the quality and price of the final parts. The remaining structure of the paper is organized as follows: First, the literature review is presented; then, the mathematical model of the problem is formulated. Afterwards, data collection and model validation are conducted, and finally, the discussion and conclusions are provided.

2 | Literature Review

Recently, supply chain management and the supplier selection process have gained significant attention in the business management literature. Throughout the 1990s, many organizations considered collaborating with their suppliers to enhance their managerial performance and competitiveness. Today, the purchasing function has become a strategic issue in organizations, with considerable focus on the relationships between buyers and suppliers. When long-term relationships are established between them, the organization creates a supply chain that makes it very difficult for competitors to enter. The main objectives of the supplier selection process include reducing purchasing risks, increasing value for the buyer, and establishing close and long-term relationships between the buyer and supplier [9]. The increase in and diversification of customer demand, recent advancements in communication technologies and information systems, global competition, reduced government regulations, and growing environmental awareness have compelled companies to focus on supply chain management. The term "supply chain management," which has gained prevalence over the past twenty years, refers to the integration of activities aimed at procuring materials, converting them into work-in-progress and finished goods, and delivering these products to customers [10]. Supply chain management includes all the connections from suppliers to customers, focusing on production [11]. It states that supplier management is one of the key issues in supply chain management because the cost of materials and components constitutes the most considerable portion of costs in this area, and many companies allocate a significant portion of their revenue to purchasing activities. Therefore, selecting suppliers is the most crucial decision-making issue in organizations, as the right choice of suppliers reduces purchasing costs and improves the company's competitive advantages [10]. On the other hand, the supplier selection problem involves trade-offs between multiple criteria, which may be quantitative or qualitative, and even in conflict with each other [12].

A study conducted by Moghaddam [13] in 2015, related to fuzzy multi-objective model for supplier selection and order allocation in reverse logistics systems under supply and demand uncertainty, was carried out. In this research, a fuzzy multi-objective mathematical model was proposed for identifying and ranking suppliers as well as determining the optimal quantity of new components and final products in the configuration of the reverse supply chain network. Beikakhkian et al. [14] examined the application of the ISM Model in Evaluating Agile Supplier Selection Criteria and Supplier Ranking Using Fuzzy AHP and TOPSIS Methods. In this research, the criteria for assessing agile suppliers were first identified. Then, the Interpretive Structural Modeling (ISM) approach was employed to structure and categorize these factors. The results of this method indicated that the delivery speed criterion was positioned at the first level of the model's output and also possessed a strong driving power.

A study conducted by Pourrostaa et al. [15] in 2012, concerning a fuzzy mixed-integer linear programming model for integrated procurement–production–distribution planning in supply chains, was carried out. In their research, supply chain problems involving a single vendor/procurement source and the distribution of products among multiple retailers were investigated. Considering the uncertainties inherent in real-world problems, the parameters of demand, capacity, and cost—which may not always be available or precisely known—were represented as trapezoidal fuzzy numbers, and two ranking methods were employed to handle the uncertainty. A study conducted by Zeydan et al. [16] in 2011, associated with a hybrid method for supplier performance evaluation and selection, was carried out. In this research, a novel approach was introduced and proposed to enhance the quality of supplier evaluation and selection. This new perspective considered both qualitative and quantitative variables in assessing supplier performance, focusing on efficiency and effectiveness in one of Turkey's largest machinery manufacturing plants. The proposed method was examined in two steps: First, a qualitative performance evaluation was conducted through Fuzzy Analytic Hierarchy Process (FAHP) to determine the weights of the criteria; then, Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was employed to rank the suppliers [16].

A study conducted by Jolai et al. [17] in 2011, related to integrating Fuzzy TOPSIS and multi-period Goal Programming (GP) for purchasing multiple products from multiple suppliers, was carried out. This research proposes a two-stage approach for supplier selection and order allocation in a fuzzy environment. In the first stage, the Fuzzy Multi-Criteria Decision-Making (FMCDM) method was applied to obtain the overall ranking of alternative suppliers and to identify the most qualified ones for further evaluation. In the second stage, using the GP approach, a Multi-Objective Mixed-Integer Linear Programming (MOMILP) model was developed to determine the order quantity of each selected supplier for each product in every period. Shadkam and Ghavidel [18] proposed a new hybrid COAW method for multi-objective supplier selection. It focuses on key criteria, including cost, quality, delivery time, and defect rate. The model uses evolutionary optimization techniques to handle complex decision-making. It provides a systematic framework for evaluating multiple suppliers simultaneously. Results indicate improvements in efficiency and reduced procurement risks. The approach can be applied in various industries to enhance supply chain performance.

Kabadayi and Duman [19] introduce a simulation–optimization approach for multi-objective supplier selection. It integrates strategic, operational, quantitative, and qualitative criteria. The model allows decision-makers to evaluate trade-offs among multiple objectives. It is designed to balance cost, quality, and delivery performance effectively. Simulation is used to test different scenarios under uncertainty. The proposed framework enhances the overall robustness of supply chain decisions. Shadkam [20] investigates a multi-objective optimization approach for supplier selection. It incorporates multiple criteria such as cost, quality, and delivery reliability. The model uses mathematical programming techniques for optimization. It helps organizations reduce procurement costs and delivery delays. The approach enhances competitiveness and decision quality in supply chains. It can be adapted for various industries with complex supplier networks.

Kazemi Miyangaskary et al. [21] proposed a multi-objective optimization model developed for closed-loop supply chains. The model considers supplier selection and order allocation under uncertainty. It incorporates both forward and reverse logistics flows in the network. A case study is conducted for retail stores of protein products in Iran. The results show improved cost-efficiency and delivery performance. The model provides a practical tool for decision-making in sustainable supply chains. Seifbarghy and Sadeghi [22] present a stochastic, multi-objective, multi-site supply chain model. It integrates supplier selection with order allocation and transportation planning. The model considers uncertainty in demand, supply, and lead times. Optimization aims to minimize costs and delivery times while maximizing service levels. It provides a flexible framework for complex supply chain networks. The proposed approach can support both strategic and operational decision-making.

3 | Conceptual Model

Based on the review of previous research, the factors that are important in supplier selection and ultimately in fulfilling and delivering requested orders have been examined and discussed in the preceding sections. Accordingly, the conceptual research model can be developed based on the premise that the purchasing company must procure final components from multiple suppliers, while each component can, in turn, be sourced from lower-tier suppliers. This framework can be illustrated as shown in *Fig. 1*.

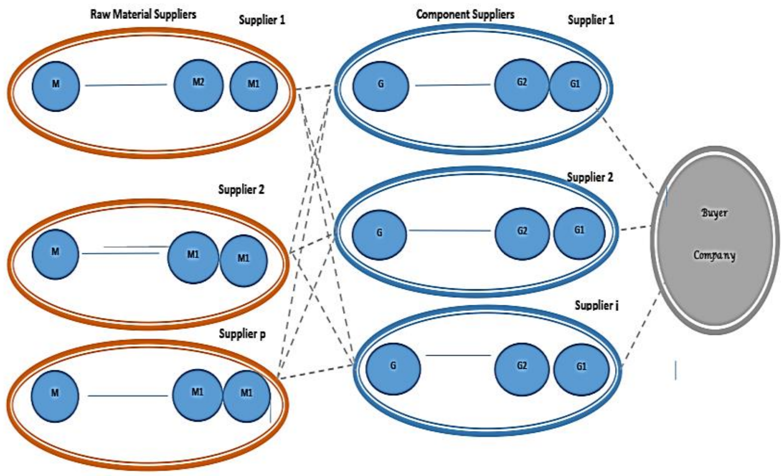

Fig. 1. Research conceptual model.

4 | Methodology

The foundation of any science is its methodology, and the validity and value of scientific laws are based on the methodological approach applied in that science [23]. After defining and designing the study, the researcher must consider the selection of the research method. The purpose of choosing a research method is to enable the researcher to determine which approach and technique will help achieve the research questions' answers as accurately, easily, quickly, and cost-effectively as possible.

Considering that this research aims to apply theories, laws, principles, and techniques of fundamental studies to solve practical and real-world problems, the present study is classified as applied research in terms of nature and objective. It is expected that, through this research, a mechanism for supplier evaluation and selection will be established, which can be utilized by the managers of Khuzestan Steel Company to assess and select suppliers. The statistical population of the present study consists of the managers and experts in the procurement and supplier evaluation departments of Khuzestan Steel Company. The study aims to utilize their opinions and perspectives regarding the criteria for supplier evaluation and selection. According to information obtained from the company's human resources department, the total number of these experts is 12. The model presented in this section consists of four distinct sets:

I. The set of components that the purchasing company orders from first-tier suppliers.

II. The set of first-tier suppliers who provide the required components in various types.

III. The set of raw materials required by first-tier suppliers to produce semi-finished components.

IV. The set of second-tier suppliers who supply the raw materials needed by first-tier suppliers.

Definition of indices

I. i: Index of products produced by first-tier suppliers (component suppliers).

II. j: Index of first-tier suppliers (component suppliers).

III. t: Index of time periods.

IV. r: Index of raw materials produced by second-tier suppliers (raw material suppliers).

V. v: Index of second-tier suppliers (raw material suppliers).

Model variables

I. p_{ijt}: Quantity of product i assigned to first-tier supplier j in period t.

II. B'_{ijt}: Number of batches intended for packaging product p_{ijt} in batch size b_{ijt}.

III. Z'_{ijt}: Equals 1 if supplier j is selected to produce product i; otherwise, 0.

Model parameters

I. g_{ijr}: Amount of raw material r required to produce product i.

II. R'_{rvt}: Maximum available amount of raw material r provided by second-tier supplier v in period t.

III. b_{ijt}: Batch size of product i produced by supplier j in period t.

IV. u_{ij}: Production time per unit of product i by first-tier supplier j.

V. u'_{jt}: Total available time of supplier j in period t for packaging batches B.

VI. D_{it}: Demand for product i in period t.

VII. q_{ijt}: Quantity of returned product i by supplier j in period t.

VIII. I'_{ijt}: Parameter for delayed transportation of product i produced by first-tier supplier j.

IX. f_y: Fixed ordering cost from first-tier supplier j.

X. a_{ij}: Cost per hour of producing one unit of product i by supplier j.

XI. c_{rv}: Unit cost of raw material r produced by second-tier supplier v.

XII. s_{ijt}: Production capacity of first-tier supplier j for product i in period t.

XIII. $\widetilde{D}_{it}$: Fuzzy demand of product i in period t.

XIV. $\tilde{s}_{ijt}$: Fuzzy capacity of first-tier supplier j for product i in period t.

Objective functions

$$\text{Min } Z_1 = \sum_i \sum_j \sum_t q_{ijt}\, p_{ijt}. \tag{1}$$

$$\text{Min } Z_2 = \sum_i \sum_j \sum_t I'_{ijt}\, p_{ijt}. \tag{2}$$

$$\text{in } Z_3 = \sum_i \sum_j \sum_r \sum_v \sum_t g_{ijr}\, c_{rv}\, p_{ijt} + \sum_i \sum_j \sum_t f_j\, Z'_{ijt} + \sum_i \sum_j \sum_t a_{ij}\, u_{ij}\, B_{ijt} M. \tag{3}$$

Objective *Function (1)* minimizes the returned product rate, objective *Function (2)* minimizes delayed transportation, and Objective *Function (3)* minimizes the costs of raw materials, ordering, and production.

Constraints

Constraint 1. Ensures that the total raw material usage does not exceed the available capacity in any period.

$$\sum_i \sum_j g_{ijr} \times p_{ijt \leq \sum_v R'_{rvt}}, \quad \text{for all } t, r. \tag{4}$$

Constraint 2. Balances production based on the number of produced items and batches.

$$p_{ijt} = B'_{ijt}, \quad \text{for all } i, j, t. \tag{5}$$

Constraint 3. Limits the total production time for packaging batches in each period.

$$\sum_i u_{ij} \times B'_{ijt} \leq u'_{jt}, \qquad \text{for all } t, j. \tag{6}$$

Constraint 4. Ensures that first-tier suppliers meet the buyer's demand.

$$p_{ijt} \geq D_{it}, \quad \text{for all } t, i. \tag{7}$$

Fuzzy version of *Function (8)*:

$$p_{ijt} \geq \widetilde{D}_{it}, \qquad \text{for all } t, i. \tag{8}$$

Constraint 5. Ensures that supplier production does not exceed capacity.

$$p_{ijt} \leq s_{ijt} \times z'_{ijt}, \qquad \text{for all } i, j, t. \tag{9}$$

Fuzzy version of *Function (10)*:

$$p_{ijt} \leq \tilde{s}_{ijt} \times Z'_{ijt}, \qquad \text{for all } i, j, t. \tag{10}$$

Constraint 6. Defines the binary nature of selection variables.

$$\sum_j Z'_{ijt} \leq 1, \text{ for all } t, i. \tag{11}$$

Since some parameters, such as $\widetilde{D}_{it}$ and $\tilde{s}_{ijt}$ are considered fuzzy, the fuzzy model must be converted to a crisp model for solution.

Fuzzy number ranking and conversion to a crisp model

Various methods have been developed for solving fuzzy mathematical programming problems, including the Max-Min method, convex combination of Max-Min operators, fuzzy operators, and the Lai-Hwang method. Fuzzy numbers can be ranked based on one or more characteristics, such as the centroid, area under the membership function, or intersection points between sets [13]. One ranking method considers a specific characteristic of fuzzy numbers and ranks them accordingly. Therefore, it is reasonable to expect that different ranking methods may assign different ranks to the same set of fuzzy numbers, which adds complexity to the ranking process. In this study, the fuzzy mixed-integer programming model is converted into a crisp model using the expected interval ranking method.

Converting the fuzzy model to a crisp model

Since the capacity parameter is considered a trapezoidal fuzzy number, the fuzzy model can be converted into a crisp model. For the fuzzy parameter below, fuzzy *Constraint (10)* is transformed into the following crisp constraint:

$$\tilde{s}_{ijt} = \left(s^1_{ijt}, s^2_{ijt}, s^3_{ijt}, s^4_{ijt}\right). \tag{12}$$

$$p_{ijt} \leq \left((1-\alpha)\frac{s^3_{ijt}+s^4_{ijt}}{2} + \alpha\frac{s^1_{ijt}+s^2_{ijt}}{2}\right), \text{for all } t, j, i. \tag{13}$$

The objective functions and other constraints (crisp constraints) remain unchanged.

Linear programming-metric method

Unlike other methods, the LP-metric method does not require prioritizing objectives, assigning weights, or converting objectives into constraints. Depending on the case, this method minimizes the sum of first, second, and order deviations of the objectives from their optimal values. Consider the following Multi-Objective Linear Programming (MOLP) model:

$$\text{optimize} \quad z = f_1(x) \tag{14}$$

$$\text{optimize} \quad z = f_2(x). \qquad \vdots \tag{15}$$

$$\text{optimize} \quad z = f_k(x). \tag{16}$$

$$\text{s.t.} \quad x\epsilon X, X = \left\{ x\epsilon R^n : g_i(x) \begin{bmatrix} \leq \\ \geq \\ = \end{bmatrix} 0, i = 1,2,\dots,m \right\}. \tag{17}$$

In this model, X is the feasible solution space, $g_i(x): i = 1,2,\dots,m$ are the linear constraints, $f_l(x): l = 1,2,\dots,k$ are the linear objective functions, and $x\epsilon R^n$ represents the decision variables. To solve the model, several multi-objective decision-making methods can be used, one of which is the Comprehensive Criteria Method, formulated as follows:

$$\text{Min} \left\{ \sum_{l=1}^{k} \left[\frac{f_l(x^*)-f_l(x)}{f_l(x^*)}\right]^p \right\}^{\frac{1}{p}}, \qquad 1 \leq P \leq \infty, \qquad \text{s.t. } x \in X. \tag{18}$$

If $P = \infty$ (Infinity norm) is considered, the above model will be modified as follows:

$$\text{Min} \left\{ \max \frac{f_l(x^*) - f_l(x)}{f_l(x^*)} \right\}. \tag{19}$$

$$1 \leq l \leq k. \tag{20}$$

$$\text{s.t. } x \in X. \tag{21}$$

The above model can also be expressed as follows:

$$\text{Min } Z. \tag{21}$$

$$\text{s.t.} \quad Z \geq \frac{f_l(x^*)-f_l(x)}{f_l(x^*)}, \quad l = 1,2,\dots,k. \tag{22}$$

$x \in X.$ (23)

$Z \geq 0.$ (24)

Lemma 1. The optimal solution of the above model, if unique, is an efficient solution for the original problem. To solve the problem using the LP-metric method, the new objective function is obtained as follows:

$$\text{Min } Z_4 = \sum_{k=1}^{3} \frac{Z_k^* - Z_k}{Z_k^*}. \tag{25}$$

$$\text{Min } Z_4 = \frac{Z_1^*-Z_1}{Z_1^*} + \frac{Z_2^*-Z_2}{Z_2^*} + \frac{Z_3^*-Z_3}{Z_3^*} = \frac{Z_1^* - \sum_i \sum_j \sum_t q_{ijt}\ p_{ijt}}{Z_1^*} + \frac{Z_2^* - \sum_i \sum_j \sum_t I'_{ijt}\ p_{ijt}}{Z_2^*} + \frac{Z_3^* - \sum_i \sum_j \sum_r \sum_v \sum_t g_{ijr}\ c_{rv}\ p_{ijt} + \sum_i \sum_j \sum_t f_j\ Z'_{ijt} + \sum_i \sum_j \sum_t a_{ij} u_{ij}\ B_{ijt}}{Z_3^*}. \tag{26}$$

The complete solution of the model using the LP-metric method is as follows:

$$\text{Min } Z_4 = \frac{Z_1^* - \sum_i \sum_j \sum_t q_{ijt}\ p_{ijt}}{Z_1^*} + \frac{Z_2^* - \sum_i \sum_j \sum_t I'_{ijt}\ p_{ijt}}{Z_2^*} \\ \frac{Z_3^* - \sum_i \sum_j \sum_r \sum_v \sum_t g_{ijr}\ c_{rv}\ p_{ijt} + \sum_i \sum_j \sum_t f_j\ Z'_{ijt} + \sum_i \sum_j \sum_t a_{ij}\ u_{ij}\ B_{ijt}}{Z_3^*}. \tag{28}$$

$\sum_i \sum_j g_{ijr} \times p_{ijt} \leq \sum_v R'_{rvt},$ for all t, r. (29)

$p_{ijt} = b_{ijt}\ B'_{ijt},$ for all i, j, t. (30)

$\sum_i u_{ij} \times B'_{ijt} \leq u'_{jt},$ for all t, j. (31)

$p_{ijt} \geq D_{it},$ for all t, i. (32)

$p_{ijt} \leq s_{ijt} \times Z'_{ijt},$ for all t, i, j. (33)

$\sum_j Z'_{ijt} \leq 1,$ for all t,i. (34)

5 | Data Collected from the Company

Considering the nature of product demand, product supply, raw material procurement, suppliers, and other factors, this company can be regarded as a supply chain. Therefore, it can be used as a suitable case study for this research. The source of the parameters for this study is Khuzestan Steel Company, and the necessary information was collected through on-site visits. However, due to the large scale and dispersion of products, it was not possible to gather data for all products. Therefore, only information related to two products—rebar and aluminum sheets—from three suppliers over three periods was collected. After ensuring that the model could be solved using random data through GAMS software, the actual data (problem parameters) were collected. The input parameters of the model are presented in *Tables 1-8*.

Table 1. Amount of raw material r required to supply product i.

Product 2			Product 1			Parameter b
Period 3	Period 2	Period 1	Period 3	Period 2	Period 1	
60	50	50	60	50	60	Supplier 1
50	50	50	70	70	70	Supplier 2
60	60	60	60	70	50	Supplier 3

Table 2. Maximum available amount of raw material type r supplied by second-tier supplier v in period.

Product 2			Product 1			Parameter b
Period 3	Period 2	Period 1	Period 3	Period 2	Period 1	
150	150	150	100	100	100	Supplier 1
100	100	100	200	200	200	Supplier 2
250	250	250	100	100	100	Supplier 3

Table 3. Batch size of product i produced by supplier j in period t.

Raw Material 3			Raw Material 2			Raw Material 1			Parameter
Period 3	Period 2	Period 1	Period 3	Period 2	Period 1	Period 3	Period 2	Period 1	R'_{rvt}
80000	80000	80000	85000	85000	85000	90000	90000	90000	Supplier 1
82000	80000	80000	90000	90000	90000	80000	80000	80000	Supplier 2
90000	88000	82500	80000	80000	80000	12000	12000	12000	Supplier 3

Table 4. Production time per unit of product i by first-tier supplier j.

Supplier 3	Supplier 2	Supplier 1	Parameter u
3	3	3	Product 1
4	4	4	Product 2

Table 5. Total available time of supplier j for packaging batches B.

Supplier 3	Supplier 2	Supplier 1	Parameter u
72	72	70	Period 1
60	60	60	Period 2
72	72	72	Period 3

Table 6. Demand for product i in period t.

Period 3	Period 2	Period 1	Parameter D
1550	1610	1500	Product 1
1550	1450	1140	Product 2

Table 7. Quantity of returned product i by supplier j.

Product 2			Product 1			Parameter q
Period 3	Period 2	Period 1	Period 3	Period 2	Period 1	
0.1	0.1	0.1	0.1	0.1	0.1	Supplier 1
0.1	0.1	0.1	0.1	0.1	0.1	Supplier 2
0.05	0.05	0.05	0.05	0.05	0.05	Supplier 3

Table 8. Delayed transportation rate of product i by first-tier supplier j.

Product 2			Product 1			Parameter I'
Period 3	Period 2	Period 1	Period 3	Period 2	Period 1	
0.1	0.1	0.1	0.1	0.1	0.1	Supplier 1
0.1	0.1	0.1	0.05	0.05	0.05	Supplier 2
0.1	0.1	0.1	0.1	0.1	0.1	Supplier 3

6 | Optimal Results of Decision Variables

The binary variable Z' represents the selection of a supplier for product i. If the variable takes a value of 1, it indicates that the supplier is selected for product i in the corresponding period; otherwise, it takes a value of 0. *Table 9* presents the optimal values of this variable based on the data collected from the company.

Table 9. Supplier selection for product i.

Period 3	Period 2	Period 1	Parameter	Z
1	1	1	Supplier 1	Product 1
0	1	0	Supplier 2	Product 2
1	0	1	Supplier 3	Product 2

The variable P represents the quantity of product i assigned to the first-tier supplier j. *Table 10* shows the optimal values of P after solving the model with the collected data.

Table 10. Product allocation to first-tier suppliers.

Period 3	Period 2	Period 1	Parameter	P
1600	1700	1500	Supplier 1	Product 1
0	1500	0	Supplier 2	Product 2
1500	0	1250	Supplier 3	Product 2

The variable B represents the batch sizes for product packaging. *Table 11* presents the optimal values of B after solving the model with the collected data.

Table 11. Batch sizes for product i packaging.

Period 3	Period 2	Period 1	Parameter	B
16	17	15	Supplier 1	Product 1
0	15	0	Supplier 2	Product 2
6	0	5	Supplier 3	Product 2

The optimal values of the objective functions Z1, Z2, Z3, and Z4after solving the model are as follows: Z1=527,500, Z2=830,000, Z3=3,813,300,000, Z4=0.147. As all four objective functions were minimization objectives, these values represent their respective minimum achievable values under the model constraints.

Since evaluating the results obtained from solving the models requires a basis for assessing the performance of each model, in this section, the results of the deterministic and fuzzy models are analyzed using real data collected from Khuzestan Steel Company in 2024. To this end, the objective function values of the deterministic model and the defuzzified model using the Jiménez method are calculated for different values of the α-level, considering variations in two parameters: product demand and total supplier capacity. The values of the product demand parameter D_{it} were presented in *Tables 4-6* in the previous section. The values and Computational Time of the first objective function for different product demand levels are listed in *Tables 12* and *13*.

Table 12. First objective function values of deterministic and defuzzified models for different product demand levels.

Problem No.	D_{it}	Deterministic Method	Jiménez Method		
			$\alpha = 0.2$	$\alpha = 0.5$	$\alpha = 0.7$
1	$D_{it} - 200$	397.500	397.500	397.500	397.500
2	$D_{it} - 100$	437.500	425.000	425.000	437.500
3	$D_{it} - 50$	532.500	442.500	442.500	442.500
4	D_{it}	527.500	527.500	512.500	527.500
5	D_{it} 50	642.500	617.500	617.500	617.500
6	D_{it} 100	642.500	642.500	632.500	642.500
7	$D_{it}+200$	750.000	750.000	750.000	750.000

Table 13. Computational time for the first objective function for different product demand levels (In seconds).

Problem No.	Deterministic Method	$\alpha = 0.2$	$\alpha = 0.5$	$\alpha = 0.7$
		Jimenez	Jimenez	Jimenez
1	0.8	0.5	0.9	0.4
2	0.6	0.5	0.5	0.6
3	0.5	0.4	0.5	0.5
4	0.6	0.5	0.5	0.4
5	0.6	0.4	0.5	0.4
6	0.09	0.9	0.5	0.5
7	0.5	0.04	0.6	0.5

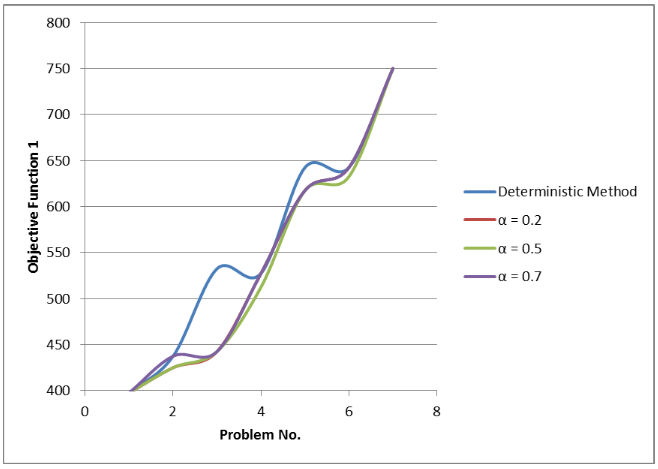

Fig. 2. Comparison of the deterministic and jiménez methods for the first objective function.

The first objective function values improve with variations in product demand. Overall, the results indicate that the first objective function improves with variations in product demand. The second objective function does not change for α=0.2, but shows improvement for α=0.5 and α=0.7. The third objective function deteriorates for α=0.2, but improves for α=0.5 and α=0.7. In general, the fuzzy ranking method proposed by Jiménez provides better solutions compared to those obtained from the deterministic approach.

7 | Conclusion and Recommendations

In this study, a fuzzy logic approach has been employed for modeling. The research conducted by scholars in the field of supply chain management and fuzzy logic was reviewed. Some mathematical models for supplier evaluation and selection were also discussed. This research proposes a new mathematical model for prioritizing and selecting suitable suppliers in the steel industry. The model aims to evaluate and select suppliers with the objectives of minimizing returned products, late deliveries, and costs associated with procurement, production, and ordering. It incorporates fuzzy product demand parameters for product i in period t and fuzzy total capacity of supplier j for producing product i in period t.

The ordering, production, and raw material procurement costs are considered in this study. These costs are incorporated into the objective functions, with the first objective function and the third objective function minimized accordingly. Based on the model solution results presented, the values of these objective functions are as follows: Z1=527,500, Z3=38,133,000. The results indicate that the model effectively minimizes both returned products (Z1) and total procurement, production, and ordering costs (Z3) under the given constraints and parameters. Another essential outcome considered in this study is the penalty for late deliveries, which has been minimized in the second objective function. Based on the model solution results presented, the value of this objective function is as follows: Z2=830,000.

This indicates that the proposed model effectively reduces delivery delays, thereby minimizing associated penalty costs under the given constraints and parameters. Among the practical recommendations resulting from the research, it is worth noting that utilizing multiple suppliers simultaneously can reduce risks. If one supplier faces issues such as financial problems, poor performance, or insufficient inventory, which may disrupt the supply chain, the company can fulfill its requirements through other suppliers. Implementing proper standards ensures accurate assessment of suppliers' performance. Employing competent and specialized personnel for supplier evaluation and selection improves decision-making quality. The model can be extended to evaluate and select suppliers for other products of the company. Applying this research in other organizations and comparing the results with the steel industry can provide valuable insights.

Conflict of Interest Disclosure

The authors declare they have no competing interests as defined by the journal, or other interests that might be perceived to influence the results reported in this paper.

Data Access

Anonymized data can be requested from the corresponding author following the journal's data sharing policies.

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