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A multi-objective optimization model of a closed-loop supply chain for supplier selection and order allocation under uncertainty: A case study of retail stores for protein products

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Abstract

The supply chain plays an essential role in the competition between companies. Supplier selection is of great importance considering the influence on the quality of the final product, the return rate, the price of the product, and the sustainability of the whole supply chain. Moreover, the real world is facing much uncertainty. In this uncertain environment, applying fuzzy decision support systems is promising. The main objective of this study is to develop an optimization model to choose suppliers and determine the number of orders for perishable protein products in uncertain conditions in a retail store. A fully fuzzy multi-objective model for a retailer company's closed-loop supply chain is developed to minimize costs and waste and maximize profit, customer satisfaction, quality, and margin under uncertainty. The proposed model is applied in a real case study of Iranian retail stores for protein products. The results proved the potential of the proposed model to improve the closed-loop supply chain's sustainability performance.

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Keywords: Supplier Selection, Fully Fuzzy Multi-Objective Programming, Sustainable Closed-Loop Supply Chain ;

1. Introduction

The increasing population and changing people's lifestyles significantly have augmented the importance of the food sector and made it one of the leading players in the global economy. Sustainable Food Supply Chain Management (SFSCM) is an institutional component of this sector that optimizes supply chain performance by balancing economic, social, and environmental criteria.

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The three principal components of the food supply chain are suppliers, distributors, and retailers. The supplier in the SFSCM plays an essential role due to its influences on the safety, quality, perishability, and sensory characteristics of products.

Moreover, evaluating and selecting suppliers is critical in SFSCM because they significantly impact enterprises' strategic and operational performance. Furthermore, it is an influential factor in product price, quality, and return rate (Hamdan & Cheaitou, 2017). The supplier selection problem can be divided into two types (Dary & Bagherzadeh, 2017):

- A supplier meets the buyer's needs, such as demand, quality, lead time, etc. In this case, there is no limit to the choice of supplier (individual sourcing).
- None of the suppliers satisfy the buyer's needs owing to their limitations in capacity, quality, etc., and the buyer must fulfill his demand from different suppliers (multiple sourcing). In this case, the management must first select the top suppliers and decide how much to buy.

In the real world, supplier selection is a challenging issue because most input parameters are uncertain and cannot be precisely determined; therefore, deterministic supplier selection methods lose their effectiveness. Hence, there is a need to use techniques and strategies to consider ambiguity, indecision, and uncertainty. The fuzzy approach is one of the common methods to deal with environmental uncertainty. Fuzzy mathematical programming is a powerful tool for allocating resources under various constraints to achieve goals such as saving costs and increasing profits (Lu et al., 2021). To the best of our knowledge, the review of the research literature has also shown that previous studies have not considered the sustainability criteria of an SFSCM in a fully fuzzy environment for supplier selection.

This research aims to present a fully fuzzy multi-objective model to improve the performance of a retail company's sustainable supply chain of protein products. With this aim, by taking into account economic, social, and environmental criteria in a fully fuzzy multi-objective model, the best suppliers are selected, and the optimal order of each product from each supplier is determined. In addition, to get closer to the real-world problem in the proposed model, all values, including the number of orders, the safety stock, product costs, demand, return rate, product quality, customer satisfaction, and supplier capacity, are considered as the trapezoidal fuzzy number. Finally, optimal fuzzy order amounts are determined by minimizing costs and quantity of waste and maximizing profit, customer satisfaction, quality, and profit margin. This study uses a retail store for protein products in Iran to verify the proposed model.

The rest of the paper is organized as follows. In Section 2, the background of the research is critically reviewed. Section 3 is dedicated to designing the fully fuzzy multi-objective mathematical model. In Section 4, the proposed model is transformed into a deterministic linear programming single-objective problem using Sharma and Agarwal's method (Sharma & Aggarwal, 2018). Section 5 presents research findings based on a real case study and finally, section 6 concludes with some remarks and the future research direction.

2. Literature review

The following subsections review previous studies on supplier selection, order allocation problems, and fuzzy mathematical optimization methods.

2.1. Supplier selection and order allocation problem

As discussed, the selection of suppliers and distribution of orders significantly impacts various facets of organizational functioning, a fact widely recognized in academic over the past several decades. Different methodologies, encompassing Multi-Criteria Decision-Making (MCDM) (Luthra et al., 2017; Stević et al., 2020), Mathematical Modeling (Ng, 2008), and Heuristic Algorithms (Alejo-Reyes et al., 2021), have been leveraged to optimize these processes. However, a prevalent issue in these approaches remains the lack of accommodation for uncertainty, which can affect the accuracy of the developed model’s output. In response to this challenge, Fuzzy Systems Theory has employed in recent years, facilitating a more accurate representation of uncertainty in supplier selection and order allocation. In the following, authors critically discussed the methodology of the studies that benefited fuzzy system theory in this regard.

Babbar & Amin (2018) have developed a mathematical model for supplier selection and order allocation in a soft drink company based on bio-environmental criteria. They used a two-stage model, including a two-stage fuzzy QFD and a Stochastic multi-objective mathematical model. Goli et al (2020) presented a method for ranking, selecting, and allocating supplier orders. They used the concept of fuzzy quality performance expansion and network analysis to evaluate and rank the suppliers and use the mathematical programming model to allocate the demand to the suppliers. Their proposed model gives the order to the supplier to minimize costs, returned goods, and delays in the network and maximize the value of the customer's purchase. Oroojeni Mohammad Javad et al (2020) identified the criteria and selection of green suppliers in the steel industry using the combination of BWM and Fuzzy TOPSIS. They implemented the proposed method in Khuzestan Steel Company. Zekhnini et al (2020) developed supplier selection using an adaptive fuzzy-neuro approach. They considered fundamental performance indicators such as cost, delivery time, quality integrated resiliency, sustainability, and intelligence criteria (technological capacity).

Mosavi, (2021) employed the gray fuzzy VICOR method to pick resilient suppliers. The proposed model combines fuzzy logic, gray relation analysis, and compromise solution. Tavana et al.(2021) developed a model to select the best suppliers by integrating the Fuzzy Best-Worst Method (BWM) with the fuzzy multi-objective optimization based on ratio analysis, full multiplicative form, fuzzy complex proportional assessment of alternatives (COPRAS), and fuzzy TOPSIS. The fuzzy BWM approach is utilized to calculate the importance weights of the digital criteria. In addition, various prioritization methods, including the fuzzy full multiplicative form, fuzzy COPRAS, and fuzzy TOPSIS methods, are applied to rank suppliers. Finally, they used Maximize Agreement Heuristic (MAH) to achieve the final ranking. Aghababayi & Shafiei Nikabadi (2021) presented an integrated fuzzy model for resilient supplier selection in the electronics industry. In the generated model, the weight of each criterion is calculated by the FBMW method, and then the problem is solved using goal programming. Kao et al.(2022) identified sustainable suppliers in the apparel industry using a fuzzy MCDM model, but the optimal number of orders from each supplier has been determined. Pamucar et al.(2022) developed a novel decision-making approach using a combination of the Measuring Attractiveness Categorical-Based Evaluation Technique (MACBETH) and a new combinative distance-based assessment method to address the supplier selection problem during the COVID-19 pandemic.

In conclusion, most of the conducted research that benefited from fuzzy systems theory to cope with the uncertainty in the evaluation and ranking of suppliers and order allocation mainly used three approaches fuzzy multi-criteria decision-making techniques, fuzzy mathematical programming, and fuzzy meta-heuristic (Jiang et al., 2018; Khalilzadeh et al., 2020). However, they rarely strived to optimize an order allocation in a fully fuzzy environment. For instance, most of the model's parameters, such as purchase costs, transportation, inventory holding, and product quality, were fuzzy numbers. Still, the decision variables, like the order amount, were definite and crisp, which contradicts the nature of the fuzzy environment (Lu et al., 2021).

2.2. Fuzzy mathematical optimization methods

In this section, the different fuzzy mathematical optimization methods are examined.
In 1965, Lotfi A. Zadeh introduced the fuzzy theory (Zadeh, 1965). This theory can mathematically model many imprecise and vague concepts, variables, and systems in uncertain conditions. Bellman and Zadeh first used this theory in decision-making. In 1978, Zimmermann formulated the fuzzy linear programming problem (Zimmermann, 1978). Different types of fuzzy mathematical programming methods have been developed to solve multi-objective or single-objective problems with fuzzy parameters or variables (Bigdeli et al., 2019; Cheng et al., 2013; Dubey & Mehra, 2014; Ghosh & Chakraborty, 2015; Goli et al., 2020; Hernández-Jiménez et al., 2021; Sun, 2020); However, none of them were fully fuzzy. A model is fully fuzzy programming if all parameters and decision variables are simultaneously fuzzy. Researchers have presented various methods to solve fully fuzzy single-objective problems (Ezzati et al., 2015; Hosseinzadeh Lotfi et al., 2009; Kaur & Kumar, 2013; Khan et al., 2013; Kumar & Kaur, 2011; Momeni & Hosseinzadeh, 2012; Nasseri et al., 2014). However, real-world problems are mostly multi-objective, so there is a need for appropriate solution methods for Fully Fuzzy Multi-Objective Problems (FFMOP). Table 1 briefly presents

various fuzzy methods for solving the FFOMP problem.

Table 1. Literature on fuzzy methods for solving the FFMOP Problem

Author	Method	Ability to solve fuzzy numbers			Limitation
		triangular	trapezoidal	Other LR flat	
(Kandasamy et al., 2012)	They used linear membership function and max-min approach to finding the fuzzy Pareto optimal solution of FFMOP.	*			1
(Aggarwal & Sharma, 2013)	They found the fuzzy Pareto optimal solution Using the ranking function and deviation degree of two fuzzy triangular numbers.	*			1
(Hadi-Vencheh et al., 2014)	The utility vector approach transfers the multi-objective optimization problem to a single objective programming.	*			1
(Jayalakshmi & Pandian, 2014)	The total objective-segregation method is developed for finding a proper solution.		*		1
(Das, 2017)	The author converted the *k* fuzzy objective function into the *3k* crisp objective functions, *m* fuzzy constraints into *3m* constraints, and *n* fuzzy variables into *n* constraints to find the fuzzy optimal solution of the FFMOP.	*			2
(Aggarwal & Sharma, 2016)	They converted the FFMOP into a nonlinear programming problem by using the deviation degree of two closed intervals and then found an optimal solution.	*			3
(Bharati et al., 2018)	They developed a new distance function between two trapezoidal fuzzy numbers that have been used to solve the FFMOP.		*		1
(Van Hop, 2020)	Authors defined fuzzy dominant degrees to solve the FFMOP.	*			1
(Arya et al., 2020)	They proposed a ranking function and the weighted approach to solve the FFMOP problem.	*			1
(Sharma & Aggarwal, 2018)	Authors converted FFMOP to MOILP using fuzzy slack variables, fuzzy surplus variables, nearest interval approximation of fuzzy numbers, and Interval Programming. Then, they used the scalarization technique to transfer MOILP into a Crisp Linear Programming (CLP) problem.	*	*	*	-

Limitation:
1. It only solves triangular or trapezoidal fuzzy number.
2. It only solves triangular fuzzy number and inequal constraint and to find the Pareto-fuzzy optimal solution with the k objective function, the decision maker should solve (2k+1) linear programming problems.
3. It only solves triangular fuzzy number and to achieve the Pareto-fuzzy optimal solution of the FFMOLP problem with the k objective function, (2k+1) nonlinear programming problems should be solved.

According to Table 1, Sharma & Aggarwal (2018) proposed an efficient model for solving all types of LR flat fuzzy numbers. To find the Pareto-fuzzy optimal solution to the FFMOP problem, the decision maker only needs to solve a crisp linear programming problem. The method proposed by Sharma & Aggarwal (2018) is used in this study to solve the proposed model because it is more flexible than previous approaches and has less computational complexity.

3. Model description and formulation

Designing the configuration of the supply chain network is the first step of supply chain optimization. To do that, literature is reviewed as well as structure of supply chain of food retailers was probed. Then, a three-echelon closed-loop supply chain, including suppliers, retailer, and final customers is designed. Figure 1 illustrates the flow of the supply chain. As it is demonstrated, there are forward and backward flows. In the forward flows, the retailer company, based on market demand and its policy, purchases its required products from suppliers and collects them in a central warehouse. Then, the purchased products are distributed between stores. In the backward flow, returned products collected from the stores also return to the central warehouse. This study aims to select the best supplier and optimal order allocation. In the developed model, the central warehouse and stores are considered as a unit, and the flow of products between them is not considered.

The following defines assumptions, notations, parameters, and the decision variables used in our proposed model.

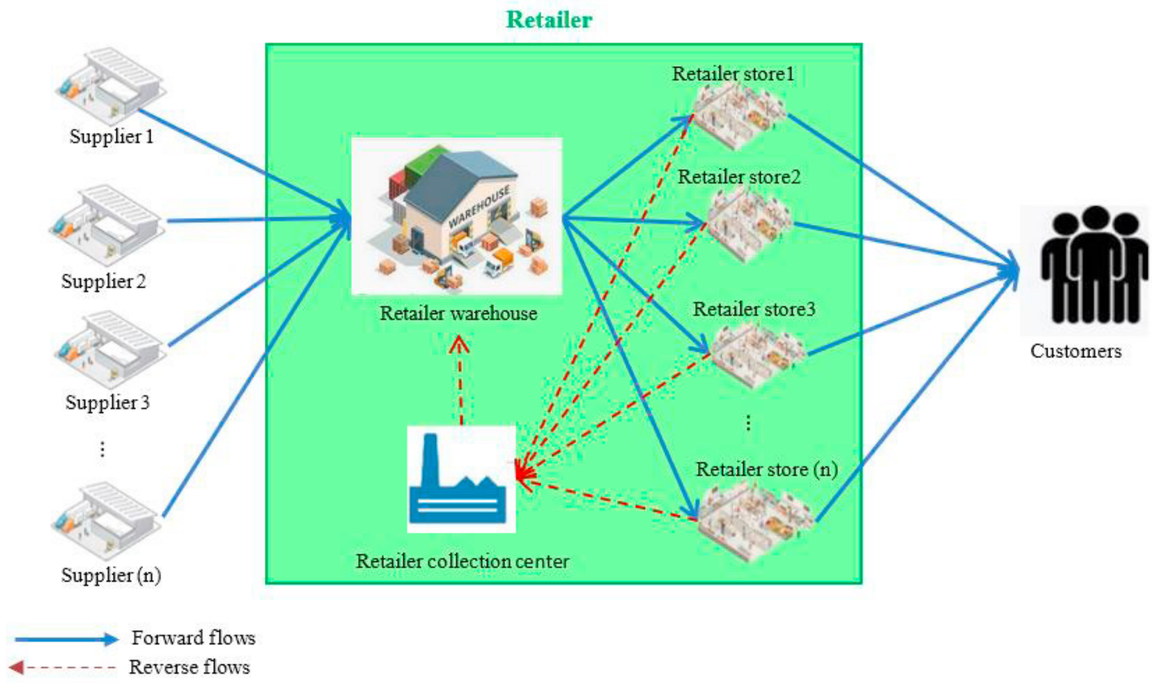

Figure 1. A structure of the closed-loop supply chain of the company

3.1. Model assumptions

- All the facilities have limited and identified capacities.
- The location of all centers (suppliers and stores) is fixed.
- Shortage of products to meet customer's demand is allowed.
- Purchased goods are the final products, and they are not processed.
- Forward flow is elastic and dependent on customer demand, and the reverse flow is pushy and depends on the amount of returned product.
- The quantity of purchases from suppliers is limited (according to the company's policies, a minimum purchase is considered for some suppliers).
- Several products are considered in the model.
- Quantity discounts are not considered in the purchase.
- There is uncertainty in demand, price, costs, return rate, quality, capacity, and order amount.

It should be noted that the symbol tilde (~) is used whenever there is a fuzzy parameter or fuzzy variable.

3.2. Sets

Symbols	Definition	Index
J	Set of suppliers	$\forall\ j \in J$
S	Set of products	$\forall\ s \in S$
C	Set of customers	$\forall\ c \in C$
L	Set of retailers	$\forall\ l \in L$

3.3. Parameters

Symbols	Definition
$\tilde{p}_{sj}$	The unit purchase cost of the product *s* from the supplier center *j*
$\widetilde{ps}_{sj}$	The unit sales price of the product *s* from the supplier center *j*
$\tilde{\gamma}_s$	Inventory holding cost of product s
$\tilde{O}_{sj}$	Ordering cost of the product s from supplier center *j*
$\tilde{D}_s$	The demand for product *s*
$\tilde{C}_{sj}$	The capacity of supplier *j* for product *s*
$\tilde{A}_{sj}$	Lower limit purchase of product *s* from supplier *j*
$\widetilde{SC}_{sj}$	Satisfaction (brand popularity) of the product s from supplier center *j*
$\tilde{Q}_{sj}$	Quality of product **s** ordered from supplier *j*
$\tilde{R}_{sj}$	Return percentage of the product *s* from supplier *j*
$\widetilde{Shc}_s$	Shortage cost of product s
$\tilde{I}_s$	Safety inventory of product s

3.4. Decision variables

Symbols	Definition
$\tilde{x}_{sj}$	quantity of product *s* ordered from supplier *j*

3.5. Mathematical Model

The following presents the mathematical model of the fully fuzzy multi-objective problem in this study:

$$\text{Max } F_1(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \widetilde{SC}_{sj} \otimes \tilde{X}_{sj} \qquad (1)$$

$$\text{Max } F_2(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \tilde{Q}_{sj} \otimes \tilde{X}_{sj} \qquad (2)$$

$$\text{Max } F_3(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n}(\widetilde{PS}_{sj} \ominus \tilde{P}_{sj}) \otimes \tilde{x}_{sj} \quad (3)$$

$$\text{Max } F_4(\tilde{X}) = \sum_{s=1}^{n}\frac{\sum_{j=1}^{m}\tilde{X}_{sj}}{D_s} \quad (4)$$

$$\text{Min } F_5(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n}\tilde{R}_{sj} \otimes \tilde{x}_{sj} \quad (5)$$

$$\text{Max } F_6(\tilde{X}) = \left[\sum_{j=1}^{m}\sum_{s=1}^{n}\widetilde{PS}_{sj} \otimes (1 \ominus \tilde{R}_{sj}) \otimes \tilde{x}_{sj}\right] \ominus \left[(\sum_{s=1}^{n}\widetilde{Shc}_s \otimes (\tilde{D}_s \ominus \sum_{j=1}^{m}\tilde{x}_{sj})) \oplus (\sum_{s=1}^{n}\tilde{\gamma}_s \otimes \tilde{I}_s) \oplus (\sum_{j=1}^{m}\sum_{s=1}^{n}\tilde{O}_{sj} \otimes \tilde{x}_{sj}) \oplus (\sum_{j=1}^{m}\sum_{s=1}^{n}\widetilde{PS}_{sj} \otimes \tilde{x}_{sj})\right] \quad (6)$$

st:

$$\tilde{X}_{sj} \le \tilde{C}_{sj} \qquad \forall s = 1,2,\dots,n \ ,\forall j = 1,2,\dots,m \quad (7)$$

$$\tilde{X}_{sj} \ge \tilde{A}_{sj} \qquad \forall s = 1,2,\dots,n \ ,\forall j = 1,2,\dots,m \quad (8)$$

$$\sum_{j=1}^{m}\tilde{X}_{sj} \le \tilde{D}_s \qquad \forall s = 1,2,\dots,n \quad (9)$$

$$\tilde{X}_{sj} \ge 0 \qquad \forall s = 1,2,\dots,n \ ,\forall j = 1,2,\dots,m \quad (10)$$

In equations 1 to 6, the objectives of the problem are stated. Objective functions (1), (2), and (3) maximize total satisfaction (brand popularity), quality, and profit margin, respectively. The objective function (4) aims to maximize the final customer's satisfaction, defined as the ratio of satisfied demand to total demand. Equation (5) is to minimize the company's total returns. Equation (6) is to maximize the retailer's expected profit. This objective function consists of two parts. The first part of this relationship shows the company's income by considering the return rate of each product. And the second part is related to the total cost, which includes shortage, inventory holding, ordering, and purchase costs. Constrain (7) shows each supplier's product's capacity. According to the company's policies and the existing conditions for some suppliers, there is a limit on the minimum order amount. Constrain (8) guarantees the implementation of this restriction. Constrain (9) provides the order limit so that the total order of each product must be less than the total market demand that predicts. Constrain (10) is non-negative problem variables.

Regarding sustainability, objective functions 1 (brand popularity), 2 (quality), and 4 (service level) are considered social criteria. In fact, the mentioned functions maximize end customers satisfaction in the food supply chain (Ada, 2022; Kao et al., 2022; Kazemi Miyangaskari et al., 2023). Furthermore, objective functions 3 and 6 maximizes profits which are related to economic criteria of sustainable development (Pamucar et al., 2023; Zekhnini et al., n.d.). Finally, objective function 5 by minimizing wastes decrease environmental impacts of food supply chain (Ada, 2022; Oroojeni

Mohammad Javad et al., 2020).

4. Solution approach

As stated in the literature, different methods have been developed to solve FFMOP problems. This research uses the technique of (Sharma & Aggarwal, 2018) to solve the proposed FFMOP model due to the following advantages.

- In this method, unlike (Das, 2017; Sharma & Aggarwal, 2018), to obtain the optimal solution with the k objective functions, solving a crisp linear programming problem (CLP) is enough. Therefore, the computational complexity is decreased significantly.
- This method is capable of solving problems with triangular and trapezoidal fuzzy numbers and can be used for other LR flat fuzzy numbers.

To solve the problem, through the following five steps, the proposed FFMOP model is converted into a CLP model.
Step 1: The fuzzy surplus variables and fuzzy slack are added to the fuzzy inequality constraints and then converted to the fuzzy equality constraints.

$$\text{Max } F_1(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \widetilde{SC}_{sj} \otimes \tilde{X}_{sj}$$

$$\text{Max } F_2(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \tilde{Q}_{sj} \otimes \tilde{X}_{sj}$$

$$\text{Max } F_3(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \left(\widetilde{PS}_{sj} \ominus \tilde{P}_{sj}\right) \otimes \tilde{x}_{sj}$$

$$\text{Max } F_4(\tilde{X}) = \sum_{s=1}^{n} \frac{\sum_{j=1}^{m} \tilde{X}_{sj}}{D_s}$$

$$\text{Min } F_5(\tilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \tilde{R}_{sj} \otimes \tilde{x}_{sj}$$

$$\text{Max } F_6(\tilde{X}) = \left[\sum_{j=1}^{m}\sum_{s=1}^{n} \widetilde{PS}_{sj} \otimes \left(1 \ominus \tilde{R}_{sj}\right) \otimes \tilde{x}_{sj}\right] \ominus \left[\left(\sum_{s=1}^{n} \widetilde{Shc}_s \otimes \left(\tilde{D}_s \ominus \sum_{j=1}^{m} \tilde{x}_{sj}\right)\right) \oplus \left(\sum_{s=1}^{n} \tilde{\gamma}_s \otimes \tilde{I}_s\right) \oplus \left(\sum_{j=1}^{m}\sum_{s=1}^{n} \tilde{O}_{sj} \otimes \tilde{x}_{sj}\right) \oplus \left(\sum_{j=1}^{m}\sum_{s=1}^{n} \widetilde{PS}_{sj} \otimes \tilde{x}_{sj}\right)\right]$$

st:

$$\tilde{X}_{sj} \oplus \tilde{S}_{1sj} = \tilde{C}_{sj} \qquad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$\tilde{X}_{sj} \ominus \tilde{S}_{2sj} = \tilde{A}_{sj} \qquad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$\sum_{j=1}^{m} \tilde{X}_{sj} \oplus \tilde{S}'_s = \tilde{D}_s \qquad \forall s = 1,2,\dots,n$$

$$\widetilde{X}_{sj} \geq \tilde{0} \quad \text{where} \quad \widetilde{X} = \left[\tilde{x}_{sj}\right]_{n*m} \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$\widetilde{S} \geq \tilde{0} \;\; \text{where}\; \widetilde{S} = \left[\tilde{S}_{psj}\right]_{P*1} \qquad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m, \;\; \forall p = 1,2,3$$

$$\widetilde{S'} \;\geq \tilde{0} \;\; \text{where}\; \widetilde{S'} = \left[\widetilde{S'}_s\right]_{n*1} \qquad \forall s = 1,2,\dots,n$$

Step 2: Suppose we have LR fuzzy numbers using algebraic operations:

$$\text{Max/Min}\; F_q(\widetilde{X}) = \sum_{j=1}^{m}\sum_{s=1}^{n} \tilde{C}_{sj} \otimes \widetilde{X}_{sj} \;= (u_q, v_q, \gamma_q, \delta_q)_{LR} \quad \forall q = 1,2,\dots,k$$

$$\widetilde{X}_{sj} \oplus \tilde{S}_{1sj} \;= (m_{sj}, n_{sj}, \alpha_{sj}, \beta_{sj})_{LR}$$

$$\widetilde{X}_{sj} \ominus \tilde{S}_{2sj} \;= (m'_{sj}, n'_{sj}, \alpha'_{sj}, \beta'_{sj})_{LR}$$

$$\sum_{j=1}^{m} \widetilde{X}_{sj} \oplus \widetilde{S'}_s \;= (m''_s, n''_s, \alpha''_s, \beta''_s)_{LR}$$

Then the model obtained in step (1) can be rewritten as follows:

$$\begin{aligned}
&\text{Max}\; F_1(\widetilde{X}) = (u_1, v_1, \gamma_1, \delta_1)_{LR}\\
&\text{Max}\; F_2(\widetilde{X}) = (u_2, v_2, \gamma_2, \delta_2)_{LR}\\
&\text{Max}\; F_3(\widetilde{X}) = (u_3, v_3, \gamma_3, \delta_3)_{LR}\\
&\text{Max}\; F_4(\widetilde{X}) = (u_4, v_4, \gamma_4, \delta_4)_{LR}\\
&\text{Min}\; F_5(\widetilde{X}) = (u_5, v_5, \gamma_5, \delta_5)_{LR}\\
&\text{Max}\; F_6(\widetilde{X}) = (u_6, v_6, \gamma_6, \delta_6)_{LR}
\end{aligned}$$

st:

$$\begin{cases}
(m_{sj}, n_{sj}, \alpha_{sj}, \beta_{sj})_{LR} \cong (c_{1sj}, c_{2sj}, \xi_{sj}, \eta_{sj})_{LR} & \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m\\
\left(m'_{sj}, n'_{sj}, \alpha'_{sj}, \beta'_{sj}\right)_{LR} \cong (A_{1sj}, A_{2sj}, \xi'_{sj}, \eta'_{sj})_{LR} & \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m\\
\left(m''_s, n''_s, \alpha''_s, \beta''_s\right)_{LR} \cong (D_{1sj}, D_{2sj}, \xi''_{sj}, \eta''_{sj})_{LR} & \forall s = 1,2,\dots,n\\
\widetilde{X}_{sj} \geq \tilde{0} \quad \text{where} \quad \widetilde{X} = \left[\tilde{x}_{sj}\right]_{n*m} & \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m\\
\widetilde{S} \geq \tilde{0} \;\; \text{where} \quad \tilde{S} = \left[\tilde{S}_{psj}\right]_{P*1} & \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m, \forall p = 1,2\\
\widetilde{S'} \;\geq \tilde{0} \;\; \text{where} \quad \widetilde{S'} = \left[\widetilde{S'}_s\right]_{n*1} & \forall s = 1,2,\dots,n
\end{cases}$$

Step 3: The model achieved in step (2) is transformed into a Multi-objective Interval Linear Programming (MOILP) by using the definition of the Nearest Interval Approximation (NIA). Law Grzegorzewski (2002) defined the NIA of the numbers $\widetilde{A}$ concerning metric d as follows:

$$C_d(\widetilde{A}) = \left[\int_0^1 \widetilde{A}_l(\alpha)d\alpha, \int_0^1 \widetilde{A}_u(\alpha)d\alpha\right] = \left[(C_d(\widetilde{A}))_l, (C_d(\widetilde{A}))_u\right]$$

Therefore, according to the definition above and $\widetilde{X}_{sj} = (x_{sj}, y_{sj}, u_{sj}, v_{sj})$, $\tilde{S}_{sjp} = (s_{1sjp}, s_{2sjp}, s_{3sjp}, s_{4sjp})$ and $\tilde{S}'_s = (s'_{1s}, s'_{2s}, s'_{3s}, s'_{4s})$ which are trapezoidal fuzzy numbers, the MOILP model is presented as follows:

$$\text{Max } F_1(\widetilde{X}) = [Z_1^L, Z_1^U]$$
$$\text{Max } F_2(\widetilde{X}) = [Z_2^L, Z_2^U]$$
$$\text{Max } F_3(\widetilde{X}) = [Z_3^L, Z_3^U]$$
$$\text{Max } F_4(\widetilde{X}) = [Z_4^L, Z_4^U]$$
$$\text{Min } F_5(\widetilde{X}) = [Z_5^L, Z_5^U]$$
$$\text{Max } F_6(\widetilde{X}) = [Z_6^L, Z_6^U]$$

st:

$$[B_{sj1}^L, B_{sj1}^U] = [C_{sj}^L, C_{sj}^U] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$[B'^L_{sj2}, B'^U_{sj2}] = [A_{sj}^L, A_{sj}^U] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$[Q_s^L, Q_s^U] = [D_s^L, D_s^U] \quad \forall s = 1,2,\dots,n$$

$$x_{sj}, y_{sj} - x_{sj}, u_{sj} - y_{sj}, v_{sj} - u_{sj} \geq 0 \quad \forall s, j$$

$$s_{1sjp}, s_{2sjp} - s_{1sjp}, s_{3sjp} - s_{2sjp}, s_{4sjp} - s_{3sjp} \geq 0 \quad \forall s, j, p$$

$$s'_{1s}, s'_{2s} - s'_{1s}, s'_{3s} - s'_{2s}, s'_{4s} - s'_{3s} \geq 0 \quad \forall s$$

$$[Z_q^L, Z_q^U] = C_d\left(\left(u_q, v_q, \gamma_q, \delta_q\right)_{LR}\right) \; \forall q = 1,2,\dots,k$$

$$[B_{sjp}^L, B_{sjp}^U] = C_d\left((m_{sj}, n_{sj}, \alpha_{sj}, \beta_{sj})_{LR}\right) \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$[B'^L_{sj}, B'^U_{sj}] = C_d\left((m'_{sj}, n'_{sj}, \alpha'_{sj}, \beta'_{sj})_{LR}\right) \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$[Q_s^L, Q_s^U] = C_d\left((m''_s, n''_s, \alpha''_s, \beta''_s)_{LR}\right) \quad \forall s = 1,2,\dots,n$$

$$[C_{sj}^L, C_{sj}^U] = C_d\left((c_{1sj}, c_{2sj}, \xi_{sj}, \eta_{sj})_{LR}\right) \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$[A_{sj}^L, A_{sj}^U] = C_d\left((A_{1sj}, A_{2sj}, \xi_{sj}', \eta_{sj}')_{LR}\right) \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$
$$[D_s^L, D_s^U] = C_d\left((D_{1sj}, D_{2sj}, \xi_{sj}'', \eta_{sj}'')_{LR}\right) \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

Step 4: According to the definition of Sengupta et al.(2001), if $A = [a^L, a^U]$ is a closed interval number, the centre and length of A are equal to $m(A) = \frac{a^L + a^U}{2}$ and $w(A) = \frac{a^U - a^L}{2}$ respectively. Also, A can be displayed as $A = (m(A), w(A))$.

According to this definition, the model developed in the step 3, can be written as follows.

$$\text{Max } F_1(\widetilde{X}) = [m(F_1(\widetilde{X})), w(F_1(\widetilde{X}))]$$
$$\text{Max } F_2(\widetilde{X}) = [m(F_2(\widetilde{X})), w(F_2(\widetilde{X}))]$$
$$\text{Max } F_3(\widetilde{X}) = [m(F_3(\widetilde{X})), w(F_3(\widetilde{X}))]$$

$$\text{Max } F_4(\widetilde{X}) = [m(F_4(\widetilde{X})), w(F_4(\widetilde{X}))]$$
$$\text{Min } F_5(\widetilde{X}) = [m(F_5(\widetilde{X})), w(F_5(\widetilde{X}))]$$
$$\text{Max } F_6(\widetilde{X}) = [m(F_6(\widetilde{X})), w(F_6(\widetilde{X}))]$$

st:

$$\left[\frac{B^L_{sj1}+B^U_{sj1}}{2}, \frac{B^u_{sj1}-B^u_{sj1}}{2}\right] =_{mw} \left[\frac{C^L_{sj}+C^U_{sj}}{2}, \frac{C^U_{sj}-C^L_{sj}}{2}\right] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$\left[\frac{B'^L_{sj2}+B'^U_{sj2}}{2}, \frac{B'^U_{sj2}-B'^L_{sj2}}{2}\right] =_{mw} \left[\frac{A^L_{sj}+A^U_{sj}}{2}, \frac{A^U_{sj}-A^L_{sj}}{2}\right] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$

$$\left[\frac{Q^L_s+Q^U_s}{2}, \frac{Q^U_s-Q^L_s}{2}\right] =_{mw} \left[\frac{D^L_s+D^U_s}{2}, \frac{D^U_s-D^L_s}{2}\right] \quad \forall s = 1,2,\dots,n$$

$$x_{sj}, y_{sj}-x_{sj}, u_{sj}-y_{sj}, v_{sj}-u_{sj} \geq 0 \quad \forall s, j$$

$$s_{1sjp}, s_{2sjp}-s_{1sjp}, s_{3sjp}-s_{2sjp}, s_{4sjp}-s_{3sjp} \geq 0 \quad \forall s, j, p$$

$$s'_{1s}, s'_{2s}-s'_{1s}, s'_{3s}-s'_{2s}, s'_{4s}-s'_{3s} \geq 0 \quad \forall s$$

Step 5: if $A = [a^L, a^U]$ and $B = [b^L, b^U]$ are closed intervals number, the order relations between two closed intervals A and B are defined as follow (Ishibuchi & Tanaka, 1990):

- If $A \leq_{mw} B$ then $m(A) \leq m(B), w(A) \geq w(A)$
- If $A <_{mw} B$ then $m(A) < m(B), w(A) > w(A)$
- If $A =_{mw} B$ then $m(A) = m(B), w(A) = w(A)$.

According to the above definition and scalarization technique, the MOILP model is converted to a CLP model.

$$\text{Max } F(X) = \sum_{q=1}^{k} \lambda_q m(F_q(\widetilde{X})) - \sum_{q=1}^{k} \mu_q w(F_q(\widetilde{X}))$$

st:

$$\left[\frac{B^L_{sj1}+B^U_{sj1}}{2}\right] = \left[\frac{C^L_{sj}+C^U_{sj}}{2}\right] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$
$$\left[\frac{B^u_{sj1}-B^u_{sj1}}{2}\right] = \left[\frac{C^U_{sj}-C^L_{sj}}{2}\right] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$
$$\left[\frac{B'^L_{sj2}+B'^U_{sj2}}{2}\right] = \left[\frac{A^L_{sj}+A^U_{sj}}{2}\right] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$
$$\left[\frac{B'^U_{sj2}-B'^L_{sj2}}{2}\right] = \left[\frac{A^U_{sj}-A^L_{sj}}{2}\right] \quad \forall s = 1,2,\dots,n \;, \forall j = 1,2,\dots,m$$
$$\left[\frac{Q^L_s+Q^U_s}{2}\right] = \left[\frac{D^U_s-D^L_s}{2}\right] \quad \forall s = 1,2,\dots,n$$
$$\left[\frac{Q^U_s-Q^L_s}{2}\right] = \left[\frac{D^U_s-D^L_s}{2}\right] \quad \forall s = 1,2,\dots,n$$

$$\sum_{q=1}^{k} \lambda_q = 1$$

$$\sum_{q=1}^{k} \mu_q = 1$$

$$\lambda_q, \mu_q \geq 0 \qquad q = 1,2,\dots,k$$

$$x_{sj}, y_{sj} - x_{sj}, u_{sj} - y_{sj}, v_{sj} - u_{sj} \geq 0 \qquad \forall s, j$$

$$s_{1sjp}, s_{2sjp} - s_{1sjp}, s_{3sjp} - s_{2sjp}, s_{4sjp} - s_{3sjp} \geq 0 \qquad \forall s, j, p$$

$$s'_{1s}, s'_{2s} - s'_{1s}, s'_{3s} - s'_{2s}, s'_{4s} - s'_{3s} \geq 0 \qquad \forall s$$

In the above model, λ_q and μ_q are the weights of the central and length of the objective, respectively. Industry experts determine these values according to the importance of each objective. It also proved that the optimal solution obtained from the above final CLP model is the Pareto-fuzzy optimal solution of the original FFMOP (Sharma and Aggarwal, 2018). Eventually, the final CLP model is solved using GAMS software, and the optimal order quantity of each product from each supplier is calculated.

5. Case study

5.1. CLSC configuration

This research uses a retail company as a case study in Iran. This company owns 500 retail stores and 12 central warehouses across the country. Around 8 main suppliers supply 15 protein foods for them. But according to the sales amount, the main four products are Sausage, Bologna, Hamburger, and Pizza cheese, which are in order products 1, 2, 3, and 4. So, this study is carried out to develop an optimization method for these four products. The company's closed-loop supply chain configuration is as follows:

- First, the company calculates its demand and sends orders to suppliers.
- Then, the suppliers deliver the placed order to the central warehouses.
- Next, received orders are distributed between retailer stores.
- Finally, the wastes are gathered from the stores and returned to the collection centre for disposal.

5.2. Data

A food retailer's data is used as a case study from June 2021 to 2022. The required data are collected from either historical company data or interviews with company experts. The retailer can buy its protein products from eight leading suppliers. The problem is designed for four products on a monthly basis. Also, the values of the model parameters are defined as trapezoidal fuzzy numbers. Table 2 presents the model's parameters and their Trapezoidal fuzzy numbers. A fuzzy number of the model's quantitative parameters are calculated based on the company's historical data. The fuzzy number of qualitative parameters is computed using Table 3 and according to interviews with experts.

Table 2.The sample of data

Symbol	Parameter	Unit	Resource	Type	Trapezoidal fuzzy numbers (m_1, m_2, m_3, m_4)
$\widetilde{D}_s$	Demand	Ton	Company	Quantitative	(110,120,140,170)
$\tilde{p}_{sj}$	Purchase cost	Million Rials	Company	Quantitative	(1.8,2.1,2.3,2.5)
$\widetilde{ps}_{sj}$	Sales price	Million Rials	Company	Quantitative	(2.7,3,3.5,3.8)
$\tilde{C}_{sj}$	Capacity	Ton	Company	Quantitative	(30,45,70,80)
$\tilde{\gamma}_s$	Inventory holding cost	Million Rials	Company	Quantitative	(0.1,0.2,0.3,0.4)
$\widetilde{O}_{sj}$	Ordering cost	Million Rials	Company	Quantitative	(0.001,0.002,0.025,0.003)
$\widetilde{Shc}_s$	Shortage cost	Million Rials	Company	Quantitative	(0.67,0.75,0.87,0.95)
$\tilde{I}_s$	Safety inventory	Ton	Company	Quantitative	(2,3,5,6)
$\widetilde{R}_{sj}$	Return (%)		Company	Quantitative	(0.07,0.08,0.1,0.1)
$\widetilde{SC}_{sj}$	Satisfaction (brand popularity)	-	Interview	Qualitative	(0.72,0.78,0.92,0.97)
$\widetilde{Q}_{sj}$	Quality of product	-	Interview	Qualitative	(0.32,0.41,0.58,0.65)

Table 3. The relationship between trapezoidal fuzzy numbers and degrees of linguistic importance (Delgado et al., 1998)

Low/high levels	Trapezoidal fuzzy numbers
Very low	(0.001,0.01,0.02,0.07)
Low	(0.04,0.1,0.18,0.23)
Slightly low	(0.17,0.22,0.36,0.42)
Middle	(0.32,0.41,0.58,0.65)
High	(0.72,0.78,0.92,0.97)
Very high	(0.93,0.98,0.98,0.999)

5.3. Results

After implementing the steps described in section 4, the final CLP model is solved using GAMS 24.8.3 software, and the optimal order quantity of each product from each supplier is calculated. The optimal order quantities after fuzzification are shown in Table 4.

Table 4. Optimal order quantities from the proposed model

	Optimum order quantity of product 1 (kg)	Optimum order quantity of product 2 (kg)	Optimum order quantity of product 3 (kg)	Optimum order quantity of product 4 (kg)
Supplier 1	40185824	62319836	19297564	12815951
Supplier 2	21056935	53174276	18709467	12621771
Supplier 3	19160701	17150566	6034458	6195591
Supplier 4	13387556	13329912	4196454	5900000
Supplier 5	10379216	7202340	2400780	-
Supplier 6	8497300	2473245	1236623	-
Supplier 7	6060807	1816020	605340	-
Supplier 8	5963272	-	-	-
Total	124691611	157464194	52462686	37533313

The results of developing the model are as follows:

- To supply product 1, 32% of the order is from supplier 1, 17% is from supplier 8, 15% is from supplier 7, 11% is from supplier 3, and the rest of the demand is from four suppliers.
- Regarding to product 2, suppliers 1 and 2 supply about 75% of the demand, 40%, and 34%, respectively.
- Regarding product 3, about 84% of the total order comes from three suppliers, 1, 2, and 7, and the remaining 16% of orders come from four suppliers, 3, 4, 5, and 6 are provided. Also, buying product 3 from supplier 8 is not cost-effective considering all the conditions and restrictions.
- To meet the monthly demand of product 4, buying 16%, 34%, 17%, and 34% from suppliers 1,2, 4, and 6, respectively, is the most optimal order combination.

The Figure 2 displays the result of supplier selection and order allocation.

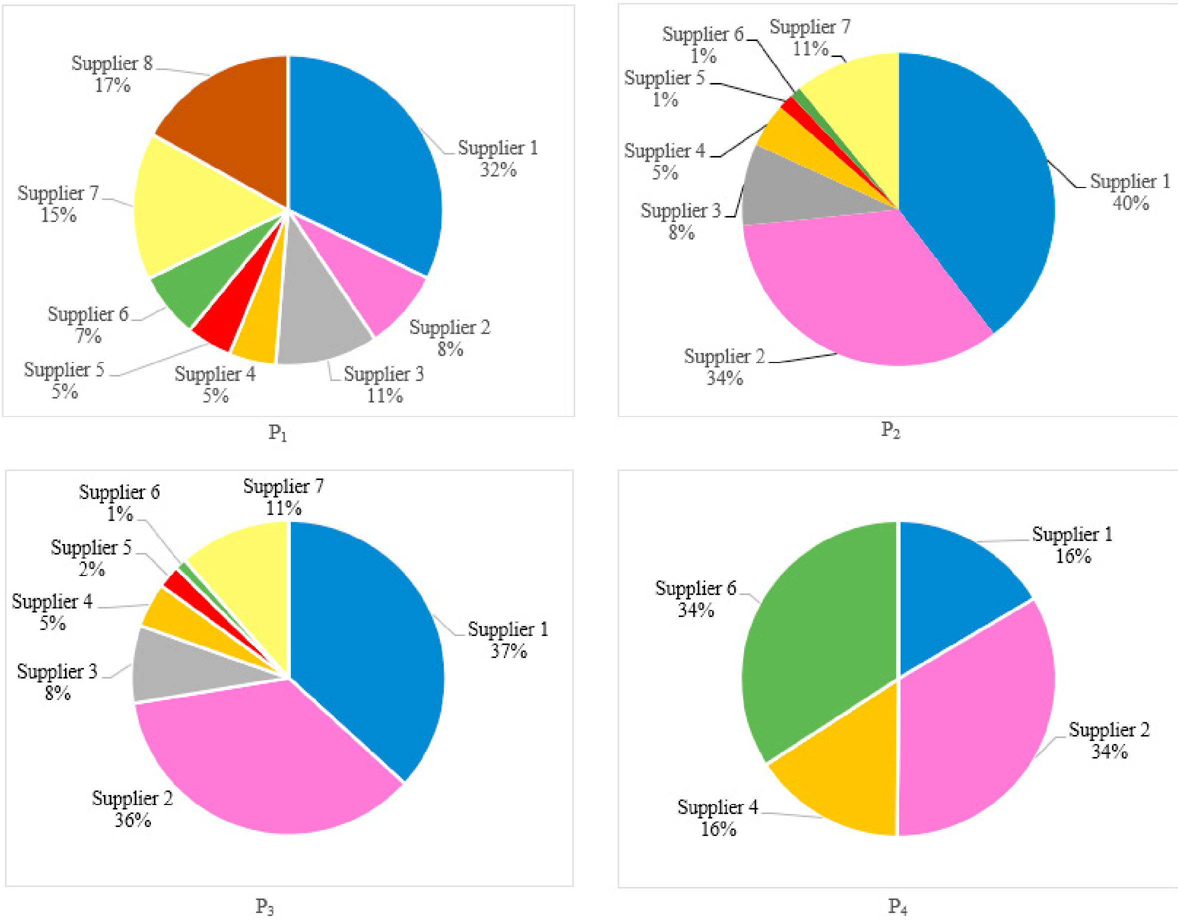

Figure 2. Share of suppliers in p1: product 1, p2: product 2, p3: product 3, p4: product 4 and relative order allocations

Also, the relationship between the model's output and waste was examined. The waste for a product is defined as the differences between the quantity of ordered and sales. The waste has various environmental and economic influences. For instance, augmenting waste is equal to increasing garbage disposal. Furthermore, it indirectly affects the cost of transportation and inventory holding. Accordingly, the optimal amount of order and the real-world allocated orders come from the historical data and are compared with the sales data. Figure 3 depicts the comparison result.

- The optimal quantity of the order for item 1 was around 124 tons, while the actual order amount for the same month was about 178 tons. The comparison of these two values with the sales amount shows that the model's order is only 8% more than the sales, while this difference for historical order is about 36%.
- Regarding product 2, the optimal order is about 157 tons, and the company's actual order was approximately 169 tons. But according to the sales data of the month under review, only 150 tons of this product have been sold. This means that the difference between the sales and optimal order amounts is approximately 4.5%, and the company's actual order amount is about 12%.
- The proposed model has estimated the optimal order amount for product 3 to be approximately 52 tons, which is only 4% different from the company's actual sales this month. Still, this difference is about 13% for the company's exact order amount.
- Regarding product 4, unlike the previous three items, the difference between the optimal order amount and the company's actual order amount with the company's substantial sales amount has a minimal difference, which is 1% and 2%, respectively.

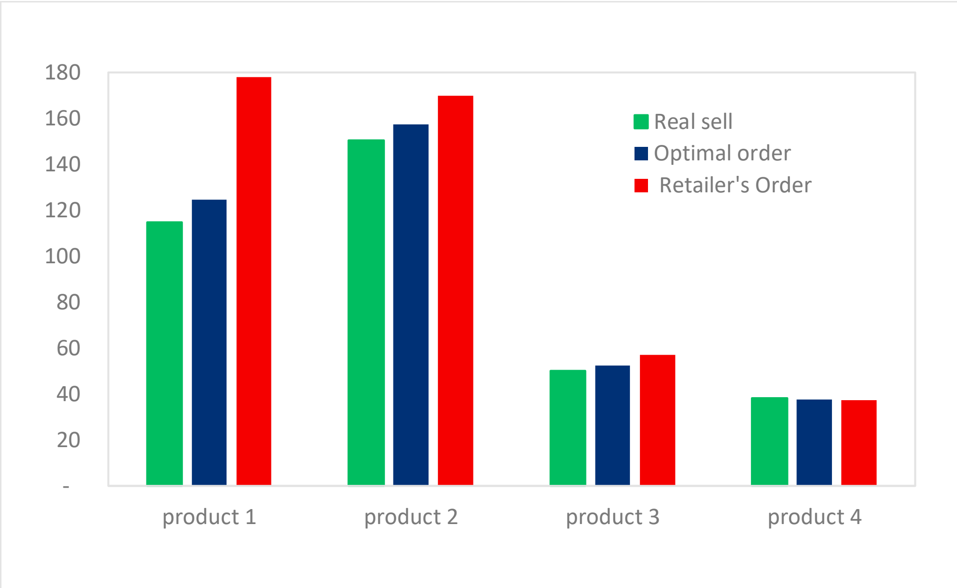

Figure 3. The quantity of real sell, optimal order, retailer's order in each product

In general, the comparison of the optimal order values and the real order of the company with the real number of sales shows that the use of the proposed model to place order allocation not only leads to the reduction of the company's ordering, inventory hold, and purchase of costs but also decrease the total wastes.

6. Conclusion

Supplier selection is the foundation of a successful supply chain because suppliers significantly affect strategic success and, specifically, a company's performance. This research uses a fully fuzzy multi-objective model to select the appropriate supplier and allocate the optimal order in the sustainable food supply chain. To be closer to the real world, the variables and parameters of the proposed model are considered trapezoidal fuzzy numbers. The influences of the model on waste were explored. To this end, the output of the model and the real quantity of the order allocation is compared with the real-world number of sales. It was proved that the proposed method is much closer than the amount of sale, so allocating the order using the proposed model could decrease wastes and economic implications.

Choosing a supplier in a way that simultaneously considers the sustainable criteria, explained in section 3.5, in a completely fuzzy environment and also calculates the optimal order amount of each product from each supplier is one of the most important achievements of this research. In addition, the proposed model can be flexible enough to be implemented in various industries, such as dairy, dried fruit, etc., to procure and sell multiple products from potential suppliers.

The primary constraint of this research is data availability. The study lacked details on factors including the return rate percentage, brand receptivity, product quality control, among others. To compensate for this deficiency, the researchers conducted interviews with experts. Consequently, there is a possibility that the expert perspectives might have influenced the final outcomes of the model. Moreover, obtaining data on Greenhouse Gas (GHG) emissions relevant to supply chain management processes is crucial for the development of a sustainable supply chain. In addition, information about road networks, such as slope, is important for calculating vehicle emissions and transportation costs (Yarahmadi et al., 2023). However, this aspect was not considered in the present study due to the absence of necessary information.

Also, the following points are suggested for future studies:

- The current research model is designed to supply the required products in a certain amount of demand and a specific period of time. So, in future research, both can be dynamic parameters.
- It is suggested to use simulation-based optimization to design and solve the problem of supplier selection and order allocation.
- It is also valuable to include the discount to calculate the purchase price.

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