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A novel fuzzy multi-objective circular supplier selection and order allocation model for sustainable closed-loop supply chains

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ABSTRACT

Maximizing the value of resources and producing less waste are strategic decisions affecting sustainability and competitive advantage. Sustainable closed-loop supply chains (CLSCs) are designed to minimize waste by circling back (repairing, reselling, or dismantling for parts) previously discarded products into the value chain. This study presents a novel two-stage fuzzy supplier selection and order allocation model in a CLSC. In Stage 1, we use the fuzzy best-worst method (BWM) to select the most suitable suppliers according to economic, environmental, social, and circular criteria. In Stage 2, we use a multi-objective mixed-integer linear programming (MOMILP) model to design a multi-product, multi-period, CLSC network, and inventory-location-routing, vehicle scheduling, and quantity discounts considerations. In the proposed MOMILP, the total network costs, the undesired environmental effects, and the lost sales are minimized while job opportunities and sustainable supplier purchases are maximized. A fuzzy goal programming approach is proposed to transform the MOMILP into a single objective model. We present a case study to demonstrate the applicability of the proposed method in the garment manufacturing and distribution industry.

1. Introduction

Companies need to adopt different strategies to survive due to fierce competition in the market. Increasing customers' awareness and excessive use of natural resources have forced companies to focus on environmental consciousness when selecting an optimum strategy. However, eco-friendly and sustainable strategies cannot be chosen in isolation and must be supplemented with social factor considerations (Yu and Cruz, 2019). The triple bottom line concept suggests sustainability should consider economic, environmental, and social factors. With a rapidly changing environment, companies are under pressure to incorporate circular economy (CE) in their strategies and supply chains. The main idea in CE is to utilize the products, components, and materials at maximum level and reach zero-waste idealism. Therefore, biological products can be safely returned to the biosphere. Besides biological products, other products can be remanufactured, recycled, and refurbished to attain minimum waste (Farooque et al., 2019). Genovese et al. (2017) and Nasir et al. (2017) have shown that integrating CE into supply chain management has tremendous sustainability benefits to the firms.

There are differences between the circular supply chain (CSC) and the sustainable supply chain. The first one is that there are restorative and regenerative cycles in CSCs so that both biological and technical ingredients can be safely disposed of to gain the maximum utility. The second one is the no waste has been arisen, which is unique to CE philosophy (Farooque et al., 2019). This research topic has recently gained the attention of many researchers (Canning, 2006; Genovese et al., 2017; Nasir et al., 2017). Different applications of supply chain operations combining CE, such as product and service design (Sabaghi et al., 2016; Steenis et al., 2018), procurement (Popa and Popa, 2016; Witjes and

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Lozano, 2016), production (Li and Ma, 2015; Leslie et al., 2016), logistics (Sun, 2017; Bernon et al., 2018) can be found in the literature. Among them, more attention is paid to the procurement function since a supply chain starts with a supplier. However, the literature focusing on circular supplier selection (CSS) is rather limited. Our literature review shows that there are only three studies (Witjes and Lozano, 2016; Popa and Popa, 2016; Govindan et al., 2020) focusing on this problem. Witjes and Lozano (2016) have proposed a procurement framework to reduce raw material utilization and improve lower waste generation using the idea of CE. Likewise, Popa and Popa (2016) have considered resource efficiency through CE. Different from these two studies, Govindan et al. (2020) have proposed an integrated hybrid approach for CSS and closed-loop supply chain (CLSC) network design problem under uncertain demand. However, the authors have focused on single-period and multi-product problem. Considering a single period might not reflect reality, so more realistic problems, as well as solution approaches, are needed to capture the complexity of real-world problems. By focusing on the gaps in the related literature, as illustrated in Table 1, this paper presents a novel hybrid framework for optimizing a sustainable reverse supply chain network considering circular supplier selection and order allocation (CSSOA) in the presence of uncertainty. The contribution of this paper is fivefold. We:

a. Identify relevant supplier evaluation and selection criteria from economic, environmental, circular, and social perspectives,
b. Propose a hybrid approach for designing a sustainable reverse supply chain and CSSOA using the fuzzy best-worst method (BWM) and multi-objective mathematical programming,
c. Formulate a novel multi-objective mixed-integer linear programming (MOMILP) model for designing a forward and reverse network that takes into consideration the inventory-location-routing and cross-docking scheduling problems with uncertain demand, a quantity discount, lost sales, time window, and alternative transportation modes,
d. Develop a novel fuzzy goal programming model to solve the proposed multi-objective model under uncertainty, and
e. Validate the applicability of the proposed model in the garment manufacturing and distribution industry.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature. The proposed approach is presented in Section 3. In Section 4, we present our case study and results. In Section 5, we discuss the results of the sensitivity analysis. In Section 6, we present our managerial implications, and in Section 7, we conclude with our conclusions and future research directions.

2. Literature review

Supplier selection is one of the most widely studied problems in the literature. Aissaoui et al. (2007) presented a comprehensive review of the literature on supplier selection and order allocation (SSOA), focusing on the purchasing process, outsourcing activities, and procurement models. Chai et al. (2013) and Ho et al. (2010) presented comprehensive reviews of the classical supplier selection problems, selection criteria, and proposed solutions. Simić et al. (2017) have shown the application of fuzzy set theory, fuzzy decision making, and hybrid solutions in supplier assessment and selection. Govindan et al. (2015) presented the applications of multi-criteria decision-making (MCDM) models used for solving green supplier selection problems. The literature related to this study can be categorized into the SSOA and supply chain structure.

2.1. Supplier selection and order allocation (SSOA)

The supplier selection problems can be classified into single-sourcing or multi-sourcing problems. Single-sourcing refers to problems with one supplier, and multi-sourcing refers to problems with multiple suppliers. The fundamental objective in both problems is the selection of supplier(s). However, in the multi-sourcing problems, the concerns are selecting suppliers and determining the order quantity. The multi-sourcing problems are generally solved with MCDM methods such as analytic hierarchy process (AHP) (Mafakheri et al., 2011; Scott et al., 2015; Fu, 2019; Qazvini et al., 2019; Kaviani et al., 2020), analytic network process (ANP) (Demirtas and Üstün; Lin, 2009; Tavana et al., 2017; Wang et al., 2020), BWM (Cheraghalipour and Farsad, 2018; Lo et al., 2018; Li et al., 2020), VIKOR (Awasthi and Govindan, 2016; Luthra et al., 2017; Abdel-Baset et al., 2019; Kannan et al., 2020), the technique for order of preference by similarity to ideal solution (TOPSIS) (Rashidi and Cullinane, 2019; Yu et al., 2019; Rabieh et al., 2019; Kilic et al., 2020), entropy (Davoudabadi et al., 2020; Feng and Gong, 2020; Zeng et al., 2020), and decision-making trial evaluation laboratory (DEMATEL) (Hsu et al., 2013; Liu et al., 2018; Kaya and Yet, 2019). Furthermore, many studies combine several MCDM techniques to determine the best alternative (Mohammed et al., 2019; Wu et al., 2019; Govindan et al., 2020).

In recent years, companies have chosen to collaborate with partners to avoid or minimize competition. Within this alignment strategy, sustainability has gained the attention of both practitioners and researchers. Although the literature focusing on selecting sustainable suppliers using the triple bottom line concepts is rich, little research has focused on supplier selection and order allocation problem. Azadnia et al. (2015) have proposed an integrated approach that integrates AHP and multi-objective mathematical programming in a fuzzy environment. Govindan et al. (2015) proposed a novel hybrid approach considering stochastic demand. Aktin and Gergin (2016) have studied the sustainable SSOA (SSSOA) problem in the printing, footwear, and apparel sectors. Trapp and Sarkis (2016) assigned suppliers to both components and products using a new optimization model with the objective function of maximizing a supplier sustainability performance rating. Gupta et al. (2016) proposed a solution approach to integrating fuzzy AHP and multi-objective linear programming with four objectives for vendor selection problem under price-breaks. Another integrated approach consisting of fuzzy AHP and fuzzy multi-objective linear programming has been proposed by Kumar et al. (2017). In this approach, fuzzy AHP was used for estimating the weights of supplier evaluation criteria and the weight of the factors used n linear programming. A case study in the automobile industry has demonstrated the applicability of the method. Shalke et al. (2018) considered quantity discounts such as all-unit and incremental in the SSSOA problem and used a revised multi-choice goal programming approach to solve the problem.

Ghadimi et al. (2018) proposed a multi-agent systems approach for the SSSOA. The proposed system evaluated suppliers and allocated orders to selected suppliers. A three-stage decision framework considering lost sales was proposed by Gören (2018), where the weights of criteria are determined in the first stage using fuzzy DEMATEL. In the second stage, the appropriate suppliers are determined using Taguchi loss functions, and in the last stage, the order sizes are determined using multi-objective mathematical programming. Cheraghalipour and Farsad (2018) focused on quantity discounts under disruption risks and proposed another hybrid approach. Their approach included two stages, whereas the evaluation of the criteria and suppliers is done using the BWM in the first stage, and the sizes of orders are determined using the revised multi-choice goal programming with quantity discounts

Table 1
The literature focusing on sustainable/circular SSOA.

Reference(s)	Technique/method/approach	Structure of supply chain network				Sustainable			Circular supply chain	Location problem	Routing problem	Inventory problem	Lost sales	Cross-docking scheduling problem	Quantity discount	Time window	Transportation mode	Uncertainty
		Multi product	Multi period	Forward	Reverse	Economic	Environmental	Social										
Azadnia et al. (2015)	Rule based fuzzy method and fuzzy AHP	✓	✓	✓		✓	✓	✓										✓
Govindan et al. (2015)	Multi-objective meta-heuristic			✓		✓	✓	✓		✓	✓	✓		✓				✓
Trapp and Sarkis (2016)	Mathematical model	✓		✓		✓	✓	✓										
Aktin and Gergin (2016)	Mixed integer programming model	✓		✓		✓	✓	✓										
Gupta et al. (2016)	Fuzzy AHP and multi-objective linear programming	✓		✓		✓	✓	✓							✓			✓
Witjes and Lozano (2016)	Conceptual framework								✓									
Popa and Popa (2016)	Life cycle assessment								✓									
Kumar et al. (2017)	Fuzzy AHP and multi-objective linear programming			✓		✓	✓	✓										✓
Ghadimi et al. (2018)	Multi-agent systems approach	✓				✓	✓	✓										
Gören (2018)	MCDM and multi-objective mathematical programming	✓	✓	✓		✓	✓	✓					✓					
Cheraghalipour and Farsad (2018)	MCDM and Revised multi-Choice Goal Programming	✓	✓	✓		✓	✓	✓							✓			
Moheb-Alizadeh and Hanfield (2019)	Data envelopment analysis, Benders decomposition and ε-constraint method	✓	✓			✓	✓	✓							✓		✓	
Mohammed et al. (2019)	MCDM and Fuzzy multi-objective optimization	✓	✓			✓	✓	✓			✓						✓	
Kellner and Utz (2019)	Multi-objective mathematical programming and Markowitz portfolio theory		✓	✓		✓	✓	✓										
Govindan et al. (2020)	Fuzzy MCDM and fuzzy mathematical programming	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓						✓
Kannan et al. (2020)	Fuzzy BWM and interval VIKOR					✓	✓	✓	✓									✓
This study	Fuzzy BWM and fuzzy multi-objective mixed integer linear programming model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

and disruption risks in the second stage. Moheb-Alizadeh and Hanfield (2019) evaluated suppliers and allocated orders using a MOMILP model considering multi periods, multi-products, multi-modal transportation, shortages, and discount conditions. Recently, a novel hybrid approach integrating MCDM and fuzzy multi-objective optimization has been proposed by Mohammed et al. (2019). The first stage of the proposed approach assesses and ranks suppliers according to conventional, green, and social criteria, whereas the second stage chooses suppliers and allocates optimal order quantities. Kellner and Utz (2019) also proposed decision support containing a multi-objective model and Markowitz portfolio theory. Different from similar studies, the authors considered risks in the problem.

The SSSOA problem has resulted in CSSOA when considering circularity assumptions. However, the CSSOA problem has not attracted the attention of the researchers. The literature review reveals that only three studies have focused on this problem. Two of them (Witjes and Lozano, 2016; Popa and Popa, 2016) have focused on CE procurement, which is quite different from this study. Govindan et al. (2020) developed a hybrid MCDM and multi-objective mathematical programming model for CSSOA. They used ANP for weighting the criteria and DEMATEL for calculating the interdependencies between criteria. One of the early sustainable circular supplier selection studies was conducted by Kannan et al. (2020). They applied a fuzzy BWM to calculate the criteria weights, and interval VIKOR was used to rank the suppliers.

2.2. Supply chain structure

A supply chain can be forward, reverse, closed-loop, or CSC. In conventional supply chains, the materials and information are transferred from suppliers to production facilities, distribution centers, and customers in a forward manner. The literature focusing on the forward supply chain is very rich. However, these studies are not relevant to our work since we focus on the CLSC. In reverse supply chains, used products are retrieved and disposed of or reused after processing (Chen et al., 2019). One of the first studies in reverse supply chain networks is credited to Jayaraman et al. (1999), who presented mixed-integer linear programming (MILP) to solve this problem. Forward and reverse supply chains are combined in CLSCs.

The main idea here is to maximize the utilization rate of a product. Govindan et al. (2015) and Govindan and Soleiman (2017) have presented review studies focusing on CLSCs considering different perspectives. A CLSC design problem has been addressed by Soleimani et al. (2017) using a genetic algorithm approach where there are suppliers, manufacturers, distribution centers, customers, warehouse, return, and recycling centers. A novel closed-loop approach for a travertine quarry has been proposed in Soleimani (2018). Ghomi-Avili et al. (2018) have presented a bi-objective fuzzy mathematical model considering disruptions in green CLSC network design. The presented model has been illustrated in an empirical study in the filter industry. Another network design has been proposed by Wu et al. (2018) in which four fuzzy optimization approaches have been used with possibilistic programming. The effects of product returns in a CLSC have been explored by Shaharudin et al. (2019).

Different research studies have been carried concerning environmental issues in the CLSC. Zohal and Soleimani (2016) proposed a meta-heuristic approach, ant colony optimization algorithm, for the green CLSC network design problem in the gold industry. Both sustainable and green issues have been addressed in Soleimani et al. (2017) to model and solve a CLSC under fuzzy demand with a genetic algorithm. Mardan et al. (2019) have studied a green multi-product multi-period CLSC problem with two objectives. A mathematical model and an accelerated benders decomposition algorithm were proposed for solving this problem in the wire-and-cable industry. Another bi-objective optimization model has been proposed by Zhen et al. (2019) to develop a green and sustainable CLSC network under uncertain demand. Yavari and Geraeli (2019) have developed a green CLSC network under uncertainty for perishable products. A MILP model was developed, and a new heuristic was used to solve the large-sized problems in this study. Yavari and Zaker (2020) further developed a bi-objective linear programming model for designing a green CLSC considering the disruption of perishable products.

Green and sustainable CLSC problems have been considered in several recent studies by Guo et al. (2020), Mohtashami et al. (2020), and Pourmehdi et al. (2020). Guo et al. (2020) constructed a profit model for a green CLSC by considering the online and off-line sales and customers' green preferences. They studied the computational time required to solve their profit optimization model and used the genetic algorithm and particle swarm optimization to find and compare approximate optimal solutions. Mohtashami et al. (2020) considered the environmental impacts of transportation fleets in green forward and reverse logistic supply chains and proposed a queuing system to optimize the transportation and waiting times in their fleet network. Pourmehdi et al. (2020) studied CLSCs in the steel industry and proposed a multi-objective linear mathematical model under uncertainty in the stochastic environment. Their model optimized several objectives, including total profits, energy consumption, CO_2 emission, water consumption, and job opportunities, among others.

2.3. Summary and research gap

The literature review indicates an increasing trend in the research on sustainable supplier selection, as shown in Table 1.

The summary of the literature review with the research gaps and findings can be given in the following:

- Only two studies have focused on reverse supply chain networks.
- None of the studies have taken into account lost sales and time windows.
- The cross-docking option has been considered in only one study.
- Only three studies with quantity discounts have been found in the literature.
- Transportation mode has only been considered in two studies.
- There are only three CSSOA studies in the literature.

These observations highlight the novelty of this study. The CSSOA problem considered here takes demand uncertainty, time windows, lost sales, quantity discounts, and alternative transportation modes into consideration, in addition to multi-product multi-period inventory-location-routing and vehicle scheduling. To the best of our knowledge, no one has attempted to solve this problem. This study is intended to address the following questions:

a. What are the relevant criteria for sustainable supplier evaluation in a circular supply chain?
b. What is a suitable method for weighting the criteria and evaluating sustainable suppliers in a circular supply chain?
c. What is an effective approach for integrating inventory-location-routing and cross-docking scheduling problems in a sustainable CLSC network?
d. What is a practical method for solving the proposed multi-objective model under uncertainty?
e. What is a reasonably effective method for validating the applicability of the model?

3. Proposed approach

This study aims at presenting an integrated approach composed of MCDM and mathematical programming. This approach encompasses two stages. First, the suppliers in a CSC are evaluated from a sustainable perspective using a fuzzy BWM and, then, SSOA and a sustainable CLSC network are designed in the second stage by using a mathematical programming model. Fig. 1 illustrates the structure of the proposed approach. In the following, the proposed approach has been presented.

Stage 1: In this stage of the proposed approach, sustainable criteria are employed to evaluate the suppliers of a CSC using the fuzzy BWM presented by Guo and Zhao (2017). The pairwise comparison-based methods, such as AHP and ANP, are conventionally used to determine the criteria weights using a hierarchical structure among criteria. However, as the number of criteria increases, the number of pairwise comparisons increases exponentially. The large number of pairwise comparisons in AHP often confuses the experts and reduces their judgments' consistency. The BWM method utilizes a smaller number of pairwise comparisons and results in more consistent judgments. In addition to a reduced number of pairwise comparisons and increased judgment consistency, the integration of BWM with fuzzy theory allows decision-makers (DMs) to take uncertainty and ambiguity of judgments into consideration. The supplier evaluation steps are presented below in 8 steps:

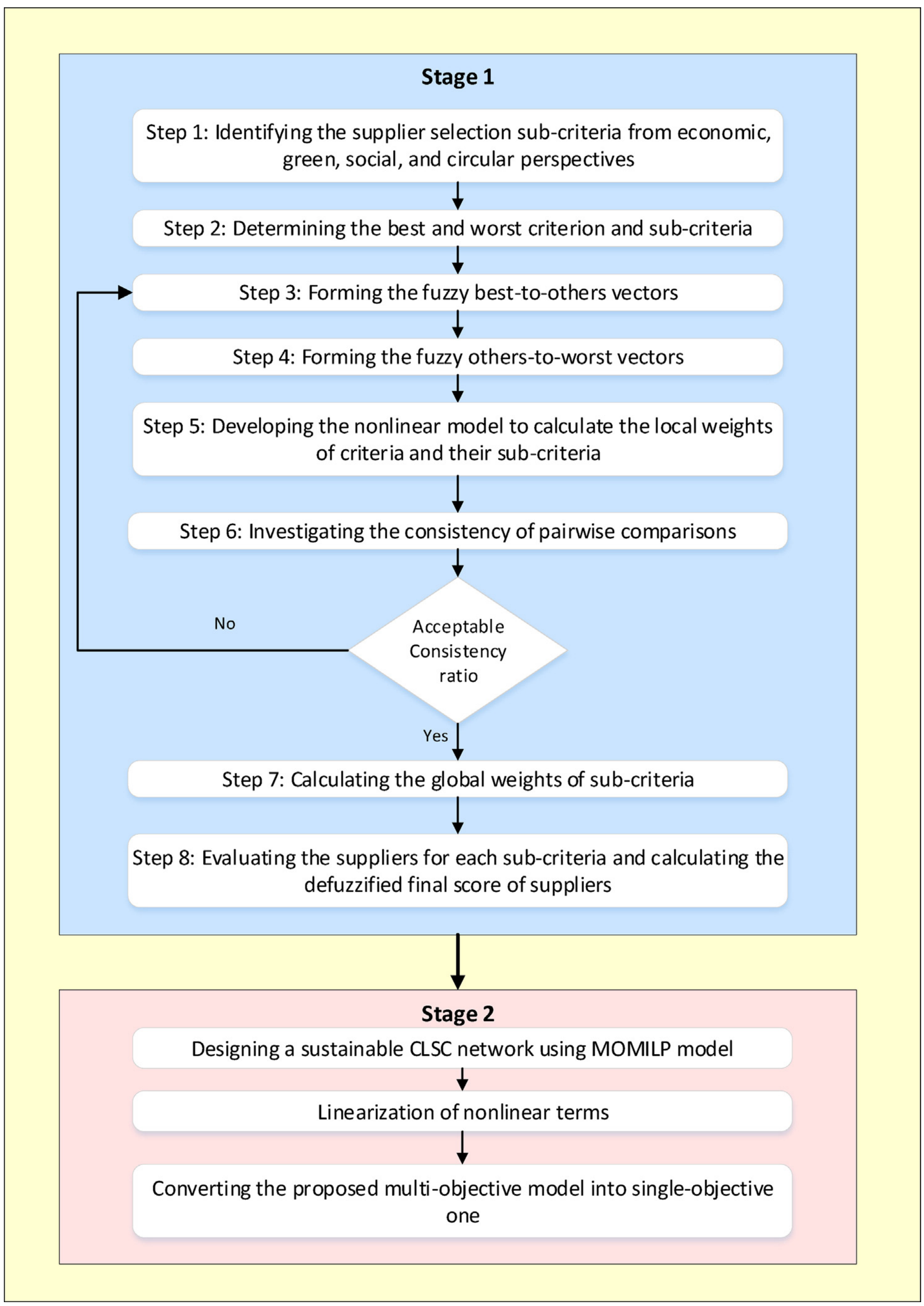

Fig. 1. The proposed approach.

- **Step 1:** In this step, with the help of experts and by reviewing the related literature, supplier evaluation criteria were extracted from the four economic, circular, green, and social aspects, as presented in Table 2.
- **Step 2:** In this step, the most and least important criteria compared to other criteria are selected and are determined as the best and worst criteria, respectively.
- **Step 3:** In this step, the best criterion is compared with other criteria using linguistic terms of Table 3, and the fuzzy best-to-others (FBTO) vector is formed as follows:

$$\tilde{Y}_B = \left(\tilde{y}_{B1}, \tilde{y}_{B2}, \ldots, \tilde{y}_{Bj}, \ldots, \tilde{y}_{Bn}\right) \tag{1}$$

where $\tilde{Y}_B$represents the FBTO vector and $\tilde{y}_{Bj}$shows the fuzzy preference of the best criterion compared to the jth criterion. Obviously, we will have: $\tilde{y}_{BB} = (1, 1, 1)$.

- **Step 4:** In this step, the other criteria are compared with the worst one using linguistic terms of Table 3 and, then, the fuzzy others-to-worst (FOTW) vector is formed as follows:

$$\tilde{Y}_W = \left(\tilde{y}_{W1}, \tilde{y}_{W2}, \ldots, \tilde{y}_{Wj}, \ldots, \tilde{y}_{Wn}\right) \tag{2}$$

where $\tilde{Y}_W$indicates the FOTW vector and the fuzzy preference of the jth criterion compared to the worst criterion. Obviously, we will have: $\tilde{x}_{WW} = (1, 1, 1)$.

- **Step 5:** In this step, the following nonlinear model is employed to calculate the fuzzy local weights of the criteria and sub-criteria:

Table 3
Linguistic terms for pairwise comparison.

Linguistic terms	Triangular fuzzy numbers
Equally importance	(1,1,1)
Weakly importance	(2/3,1,3/2)
Fairly importance	(3/2,2,5/2)
Very importance	(5/2,3,7/2)
Absolutely importance	(7/2,4,9/2)

$$\begin{aligned} & Min\ \vartheta^* \\ & s.t. \\ & \left|\frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{y}_{Bj}\right| \le (\vartheta^*, \vartheta^*, \vartheta^*)\ \forall j \\ & \left|\frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{y}_{jW}\right| \le (\vartheta^*, \vartheta^*, \vartheta^*)\ \forall j \\ & \sum_j R\left(\tilde{w}_j\right) = 1 \end{aligned} \tag{3}$$

where $\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$indicates the fuzzy weight of criterion j and l_j^w, m_j^w, and, $u_j^w$are the pessimistic, most possible, and optimistic elements in triangular fuzzy numbers, respectively. Thus, we will have:

$$\tilde{w}_B = (l_B^w, m_B^w, u_B^w) \tag{4}$$

$$\tilde{w}_W = (l_W^w, m_W^w, u_W^w) \tag{5}$$

$$\tilde{y}_{Bj} = (l_{Bj}, m_{Bj}, u_{Bj}) \tag{6}$$

$$\tilde{y}_{jW} = (l_{jW}, m_{jW}, u_{jW}) \tag{7}$$

With the replacement of Eqs. (4)–(7), the nonlinear model is

Table 2
Evaluation criteria for sustainable suppliers in the CSC.

Criteria	Sub-criteria	References
Economic (ECN)	Quality (ECN1)	Gary Teng and Jaramillo (2005), Chen (2011), Azadnia et al. (2015), Luthra et al. (2017), Ghadimi et al. (2018), Kannan (2018), Guarnieri and Trojan (2019)
	Reputation (ECN2)	Bafrooei et al. (2014), Ghadimi et al. (2018)
	On-time delivery (ECN3)	Gary Teng and Jaramillo (2005), Chen (2011), Azadnia et al. (2015), Luthra et al. (2017), Ghadimi et al. (2018), Guarnieri and Trojan (2019)
	Flexibility (ECN4)	Gary Teng and Jaramillo (2005), Luthra et al. (2017), Kannan (2018), Guarnieri and Trojan (2019)
	Technology capability (ECN5)	Chen (2011), Azadnia et al. (2015), Luthra et al. (2017), Kannan (2018)
	Service and after sales service (ECN6)	Chen (2011), Mina et al. (2014a), Mina et al. (2014b), Kannan (2018)
Circular (CRC)	Utilizing eco-friendly and recyclable raw materials (CRC1)	Mina et al. (2014a), Kannan (2018), Memari et al. (2019), Govindan et al. (2020)
	Using recyclable materials in packaging products (CRC2)	Mina et al. (2014a), Luthra et al. (2017), Guarnieri and Trojan (2019), Qazvini et al. (2019), Govindan et al. (2020)
	Design of products to reuse (CRC3)	Kannan (2018), Govindan et al. (2020)
Green (GRN)	Environmental management systems (GRN1)	Azadnia et al. (2015), Luthra et al. (2017), Gören (2018), Banaeian et al. (2019)
	Managing air pollution resulted from production products (GRN2)	Kannan (2018), Shalke et al. (2018)
	Hazardous waste management (GRN3)	Luthra et al. (2017), Ghadimi et al. (2018), Guarnieri and Trojan (2019)
	Environmental certifications (GRN4)	Mina et al. (2014a), Fallahpour et al. (2017), Guarnieri and Trojan (2019)
	Applying proper and clean technologies (GRN5)	Fallahpour et al. (2017), Kannan (2018), Qazvini et al. (2019), Govindan et al. (2020)
	Green R&D and innovation (GRN6)	Luthra et al. (2017)
Social (SCL)	Creating job opportunities (SCL1)	Kannan (2018), Rashidi and Cullinane (2019)
	Information disclosure (SCL2)	Luthra et al. (2017), Mohammed et al. (2019)
	Occupational health and safety systems (SCL3)	Azadnia et al. (2015), Luthra et al. (2017), Ghadimi et al. (2018), Gören et al. (2018), Memari et al. (2019)
	The rights of stockholders (SCL4)	Luthra et al. (2017), Rashidi and Cullinane (2019)
	The interests and rights of employees (SCL5)	Luthra et al. (2017), Rashidi, K., & Cullinane (2019)

obtained as follows:

$$Min\ \vartheta^*$$

$$s.t.$$

$$\left|\frac{(l_B^w, m_B^w, u_B^w)}{\left(l_j^w, m_j^w, u_j^w\right)} - (l_{Bj}, m_{Bj}, u_{Bj})\right| \le (\vartheta^*, \vartheta^*, \vartheta^*)\,\forall j$$

$$\left|\frac{\left(l_j^w, m_j^w, u_j^w\right)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW})\right| \le (\vartheta^*, \vartheta^*, \vartheta^*)\,\forall j \tag{8}$$

$$\sum_j R\left(\tilde{w}_j\right) = 1$$

$$l_j^w \le m_j^w \le u_j^w$$

$$l_j^w \ge 0$$

The proposed model is run with optimization software to calculate the optimal value of $\vartheta^*$and fuzzy local weights of the criteria and sub-criteria.

- **Step 6:** In this step, Eq. (9) and Table 4 are used to calculate the consistency ratio for the pairwise comparisons. The closer the consistency ratio to zero, the higher the consistency of pairwise comparisons will be.

$$\text{Consistency ratio} = \frac{\vartheta^*}{\text{Consistency index}} \tag{9}$$

- **Step 7:** In this step, the fuzzy local weights of criteria should be multiplied by those of the sub-criteria to calculate the fuzzy global weights of sub-criteria.
- **Step 8:** Here, experts are asked to score suppliers for each sub-criterion using Table 5. Then, the fuzzy final score of suppliers is obtained from the sum of multiplying the fuzzy local weights of sub-criteria by the average supplier evaluation score. Finally, the defuzzified final score of suppliers is calculated by Eq. (10).

$$\text{Defuzzified final score} = \frac{x_i^l + 4 \times x_i^m + x_i^u}{6} \tag{10}$$

where x_i^l, x_i^m, and $x_i^u$are the pessimistic, most possible, and optimistic elements in triangular fuzzy numbers, respectively.

The score obtained for each supplier represents his/her sustainability in the CSC, which will be included as the fifth objective function coefficient in the mathematical model.

Stage 2: The raw materials in this problem are procured from suppliers on the basis of the proposed discounts and shipping to production centers using appropriate transportation modes. The raw materials are first transformed into product components, and then the final products are derived from the combination of product components that are sent to distribution centers as per customer demand. Cross-docking centers utilize optimal routing and vehicle scheduling to collect products from distribution centers, rearrange them, and deliver them to customers after processing (see Fig. 2). Defective products are returned to collection centers, and those that are reusable are sent to remanufacturing centers, and the rest are disposed of. In remanufacturing centers, products are categorized into three groups; the first are the ones that are modified by the repair process and sent to distribution centers. The second category is the products that only some of the components can be used that are sent to the manufacturing centers after the components are disassembled, and the third is products that are severely damaged and discarded during the remanufacturing process. To better understand the problem under study, the model assumptions are explained below, and the structure of the investigated network is shown in Fig. 2.

3.1. Assumptions

- The considered problem encompasses both forward and reverses flows simultaneously.
- Multi-product and multi-period considerations are supported by the network.
- The geographical location of suppliers and customers is predetermined, while the other locations are being optimized.
- The routing problem is between the distribution and cross-docking centers and between cross-docking centers and customers.
- The vehicle routing problem is multi-depot and with capacitated vehicles.
- The hard-time window is considered for returning vehicles to cross-docking centers.
- Visiting the customers with the vehicles is scheduled.
- The unmet demands are treated as lost sales.
- The delivery amounts can be split as a split-delivery problem.
- Customers can keep inventories for the upcoming time periods.
- The vehicle fleets are heterogeneous.
- Logistics of raw material from suppliers to production centers are handled with different transportation modes.
- All the facilities are capacitated.
- Material procurement from suppliers follows discount rules.

3.2. Mathematical model

Given the indices, parameters, and variables presented in Appendices 1, 2, and 3, respectively, we formulate the following mathematical model:

Table 4
Consistency index for fuzzy BWM.

Linguistic terms	Equally important	Weakly important	Fairly important	Very important	Absolutely important
$\tilde{y}_{BW}$	(1,1,1)	(0.667,1,1.5)	(1.5,2,2.5)	(2.5,3,3.5)	(3.5,4,4.5)
Consistency index	3	3.8	5.29	6.69	8.04

Table 5
Fuzzy linguistic values for supplier evaluation (Govindan et al., 2020).

Linguistic values for positive criteria	Linguistic values for negative criteria	Triangular fuzzy numbers
Very weak	Very strong	(0,0,0)
Weak	Strong	(0,0.167,0.333)
Weak-Mid	Mid-Strong	(0.167,0.333,0.5)
Mid	Mid	(0.333,0.5,0.667)
Mid-Strong	Weak-Mid	(0.5,0.667,0.833)
Strong	Weak	(0.667,0.833,1)
Very strong	Very weak	(1,1,1)

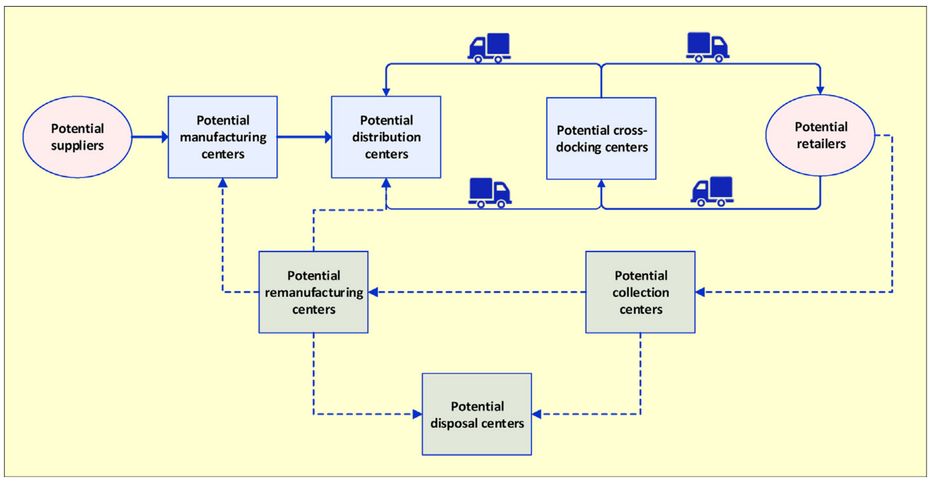

Fig. 2. The structure of supply chain network of this study.

$$
\begin{aligned}
Min\ Obj_1 = {} & \sum_{r,e,s,t} \vartheta_{st}^{SPLR}.\theta_{rest}^{SPLR} + \sum_{m} \vartheta_{m}^{MNF}.\theta_{m}^{MNF} + \sum_{d} \vartheta_{d}^{DSTB}.\theta_{d}^{DSTB} + \sum_{q} \vartheta_{q}^{CRS}.\theta_{q}^{CRS} + \\
& \sum_{g} \vartheta_{g}^{CLCT}.\theta_{g}^{CLCT} + \sum_{a} \vartheta_{a}^{RMNF}.\theta_{a}^{RMNF} + \sum_{b} \vartheta_{b}^{DSP}.\theta_{b}^{DSP} + \sum_{v} \vartheta_{v}^{VH}.\theta_{v}^{VH} + \\
& \sum_{r,e,s,m,f,t} \phi_{rst}^{SPLR}.\mu_{resmft}^{SPLR-MNF} + \sum_{p,m,d,t} \phi_{pmt}^{MNF}.\mu_{pmdt}^{MNF-DSTB} + \sum_{p,v,d,q,t} \phi_{pdt}^{DSTB}.\mu_{pvdqt}^{DSTB-CRS} + \\
& \sum_{p,v,q,k,t} \phi_{pqt}^{CRS}.\mu_{pvqkt}^{CRS-RT} + \sum_{p,k,g,t} \phi_{pgt}^{CLCT}.\mu_{pkgt}^{RT-CLCT} + \sum_{p,g,a,b,t} \phi_{pbt}^{DSP} \cdot \left(\mu_{pgbt}^{CLCT-DSP} + \mu_{pabt}^{RMNF-DSP}\right) + \\
& \sum_{p,g,a,t} \phi_{pat}^{RMNF}.\mu_{pgat}^{CLCT-RMNF} + \sum_{r,e,s,m,f,t} \eta_{rsmft}^{SPLR-MNF}.\mu_{resmft}^{SPLR-MNF} + \sum_{p,m,d,t} \eta_{pmdt}^{MNF-DSTB}.\mu_{pmdt}^{MNF-DSTB} + \\
& \sum_{p,k,g,t} \eta_{pkgt}^{RT-CLCT}.\mu_{pkgt}^{RT-CLCT} + \sum_{p,g,a,t} \eta_{pgat}^{CLCT-RMNF}.\mu_{pgat}^{CLCT-RMNF} + \sum_{p,g,b,t} \eta_{pgbt}^{CLCT-DSP}.\mu_{pgbt}^{CLCT-DSP} + \\
& \sum_{p,a,d,t} \eta_{padt}^{RMNF-DSTB}.\mu_{padt}^{RMNF-DSTB} + \sum_{p,a,b,t} \eta_{pabt}^{RMNF-DSP}.\mu_{pabt}^{RMNF-DSP} + \sum_{c,a,m,t} \eta_{camt}^{RMNF-MNF}.\mu_{camt}^{RMNF-MNF} + \\
& \sum_{p,k,t} \psi_{pkt}^{PST}.\varpi_{pkt}^{PST} + \sum_{p,k,t} \psi_{pkt}^{NGT}.\varpi_{pkt}^{NGT} + \sum_{v,d'>1,d>1,t} \sigma.\gamma_v.\tau_{d'd}^{DSTB}.\alpha_{vd'dt} + \\
& \sum_{v,d>1,q,t} \sigma.\gamma_v.\tau_{dq}^{DSTB-CRS}.(\alpha_{v1dt} + \alpha_{vd1t}).\theta_{vqt} + \sum_{v,k'>1,k>1,t} \sigma.\gamma_v.\tau_{k'k}^{RT}.\alpha'_{vk'kt} + \\
& \sum_{v,q,k>1,t} \sigma \times \gamma_v \times \tau_{kq}^{RT-CRS} \times \left(\alpha'_{v1kt} + \alpha'_{vk1t}\right) \times \theta'_{vqt}
\end{aligned}
\tag{11}
$$

$$Min\ Obj_2 = \sum_m \delta_m^{MNF}.\theta_m^{MNF} + \sum_d \delta_d^{DSTB}.\theta_d^{DSTB} + \sum_q \delta_q^{CRS}.\theta_q^{CRS} + \sum_g \delta_g^{CLCT}.\theta_g^{CLCT} + \sum_a \delta_a^{RMNF}.\theta_a^{RMNF} + \sum_b \delta_b^{DSP}.\theta_b^{DSP} + \sum_{r,s,m,f,t} \delta_{rsmft}^{SPLR-MNF}.\mu_{rsmft}^{SPLR-MNF} \tag{12}$$

$$Max\ Obj_3 = \sum_m \xi_m^{MNF}.\theta_m^{MNF} + \sum_d \xi_d^{DSTB}.\theta_d^{DSTB} + \sum_q \xi_q^{CRS}.\theta_q^{CRS} + \sum_g \xi_g^{CLCT}.\theta_g^{CLCT} + \sum_a \xi_a^{RMNF}.\theta_a^{RMNF} + \sum_b \xi_b^{DSP}.\theta_b^{DSP} \tag{13}$$

$$Min\ Obj_4 = \sum_{p,k,t} \varpi_{pkt}^{NGT} \tag{14}$$

$$Max\ Obj_5 = \sum_{r,e,s,m,f,t} SSR_s.\mu_{resmft}^{SPLR-MNF} \tag{15}$$

s.t.

$$\sum_{m,f} \mu_{rsmft}^{SPLR-MNF} \le \omega_{rst}^{SPLR}\ \forall r,s,t \tag{16}$$

$$\sum_{r,c,s,f} \frac{\mu_{rsmft}^{SPLR-MNF}}{\kappa_{rc}^{RW-CM}.\kappa_{cp}^{CM-PR}} \le \omega_{pmt}^{MNF}\ \forall p,m,t=1 \tag{17}$$

$$\sum_{r,c,s,f} \frac{\mu_{rsmft}^{SPLR-MNF}}{\kappa_{rc}^{RW-CM}.\kappa_{cp}^{CM-PR}} + \sum_{c,a} \frac{\mu_{cam(t-1)}^{RMNF-MNF}}{\kappa_{cp}^{CM-PR}} \le \omega_{pmt}^{MNF}\ \forall p,m,t>1 \tag{18}$$

$$\sum_m \mu_{pmdt}^{MNF-DSTB} \le \omega_{pdt}^{DSTB}\ \forall p,d,t=1 \tag{19}$$

$$\sum_m \mu_{pmdt}^{MNF-DSTB} + \sum_a \mu_{pad(t-1)}^{RMNF-DSTB} \le \omega_{pdt}^{DSTB}\ \forall p,d,t>1 \tag{20}$$

$$\sum_{v,d} \mu_{pvdqt}^{DSTB-CRS} \le \omega_{pqt}^{CRS}\ \forall p,q,t \tag{21}$$

$$\sum_k \mu_{pkgt}^{RT-CLCT} \le \omega_{pgt}^{CLCT}\ \forall p,g,t \tag{22}$$

$$\sum_g \mu_{pgat}^{CLCT-RMNF} \le \omega_{pat}^{RMNF}\ \forall p,a,t \tag{23}$$

$$\sum_g \mu_{pgbt}^{CLCT-DSP} + \sum_a \mu_{pabt}^{RMNF-DSP} \le \omega_{pbt}^{DSP}\ \forall p,b,t \tag{24}$$

$$\sum_{p,d} \mu_{pvdqt}^{DSTB-CRS} \le \omega_v^{VH}\ \forall v,q,t \tag{25}$$

$$\sum_{p,k} \mu_{pvqkt}^{CRS-RT} \le \omega_v^{VH} \quad \forall v,q,t \tag{26}$$

$$\sum_{r,c,s,f} \frac{\mu_{rsmft}^{SPLR-MNF}}{\kappa_{rc}^{RW-CM}.\kappa_{cp}^{CM-PR}} \ge \sum_d \mu_{pmdt}^{MNF-DSTB}\ \forall p,m,t=1 \tag{27}$$

$$\sum_{r,c,s,f} \frac{\mu_{rsmft}^{SPLR-MNF}}{\kappa_{rc}^{RW-CM}.\kappa_{cp}^{CM-PR}} + \sum_{c,a} \frac{\mu_{cam(t-1)}^{RMNF-MNF}}{\kappa_{cp}^{CM-PR}} \ge \sum_d \mu_{pmdt}^{MNF-DSTB}\ \forall p,m,t>1 \tag{28}$$

$$\sum_m \mu_{pmdt}^{MNF-DSTB} \ge \sum_{v,q} \mu_{pvdqt}^{DSTB-CRS}\ \forall p,d,t=1 \tag{29}$$

$$\sum_m \mu_{pmdt}^{MNF-DSTB} + \sum_a \mu_{padt}^{RMNF-DSTB} \ge \sum_{v,q} \mu_{pvdqt}^{DSTB-CRS}\ \forall p,d,t>1 \tag{30}$$

$$\sum_{v,d} \mu_{pvdqt}^{DSTB-CRS} \ge \sum_{v,k} \mu_{pvqkt}^{CRS-RT}\ \forall p,q,t \tag{31}$$

$$\varpi_{pkt}^{PST} - \varpi_{pkt}^{NGT} = \sum_{v,q} \mu_{pvqkt}^{CRS-RT} - \omega_{pkt} - \sum_g \mu_{pkgt}^{RT-CLCT}\ \forall p,k,t=1 \tag{32}$$

$$\varpi_{pkt}^{PST} - \varpi_{pkt}^{NGT} = \varpi_{pk(t-1)}^{PST} + \sum_{v,q} \mu_{pvqkt}^{CRS-RT} - \omega_{pkt} - \sum_g \mu_{pkgt}^{RT-CLCT}\ \forall p,k,t>1 \tag{33}$$

$$\sum_k \mu_{pkgt}^{RT-CLCT} = \sum_a \mu_{pgat}^{CLCT-RMNF} + \sum_b \mu_{pgbt}^{CLCT-DSP}\ \forall p,g,t \tag{34}$$

$$\sum_g \mu_{pkgt}^{RT-CLCT} = \sum_{v,q} \kappa_{pkt}^{RT}.\mu_{pvqkt}^{CRS-RT}\ \forall p,k,t \tag{35}$$

$$\sum_g \mu_{pgat}^{CLCT-RMNF} = \sum_b \mu_{pabt}^{RMNF-DSP} + \sum_{c,m} \frac{\mu_{camt}^{RMNF-MNF}}{\kappa_{cp}^{CM-PR}} + \sum_d \mu_{padt}^{RMNF-DSTB}\ \forall p,a,t \tag{36}$$

$$\sum_{a}\mu_{pgat}^{CLCT-RMNF}=\sum_{k}\kappa_{pgt}^{CLCT}.\mu_{pkgt}^{RT-CLCT}\,\forall p,g,t \tag{37}$$

$$\sum_{b}\mu_{pabt}^{RMNF-DSP}=\sum_{g}\kappa_{pat}^{RMNF-DSP}.\mu_{pgat}^{CLCT-RMNF}\,\forall p,a,t \tag{38}$$

$$\sum_{d}\mu_{padt}^{RMNF-DSTB}=\sum_{g}\kappa_{pat}^{RMNF-DSTB}.\mu_{pgat}^{CLCT-RMNF}\,\forall p,a,t \tag{39}$$

$$\mu_{rsmft}^{SPLR-MNF}\leq M.\theta_{rst}^{SPLR}\,\forall r,s,m,f,t \tag{40}$$

$$\sum_{r,c}\frac{\mu_{rsmft}^{SPLR-MNF}}{\kappa_{rc}^{RW-CM}.\kappa_{cp}^{CM-PR}}\leq M.\theta_{m}^{MNF}\,\forall p,s,m,f,t \tag{41}$$

$$\mu_{pmdt}^{MNF-DSTB}\leq M.\theta_{m}^{MNF}\,\forall p,m,d,t \tag{42}$$

$$\sum_{c}\frac{\mu_{camt}^{RMNF-MNF}}{\kappa_{cp}^{CM-PR}}\leq M.\theta_{m}^{MNF}\,\forall p,a,m,t \tag{43}$$

$$\mu_{pmdt}^{MNF-DSTB}\leq M.\theta_{d}^{DSTB}\,\forall p,m,d,t \tag{44}$$

$$\mu_{padt}^{RMNF-DSTB}\leq M.\theta_{d}^{DSTB}\,\forall p,a,d,t \tag{45}$$

$$\mu_{pvdqt}^{DSTB-CRS}\leq M.\theta_{d}^{DSTB}\,\forall p,v,d,q,t \tag{46}$$

$$\mu_{pvdqt}^{DSTB-CRS}\leq M.\theta_{q}^{CRS}\,\forall p,v,d,q,t \tag{47}$$

$$\mu_{pvqkt}^{CRS-RT}\leq M.\theta_{q}^{CRS}\,\forall p,v,q,k,t \tag{48}$$

$$\mu_{pkgt}^{RT-CLCT}\leq M.\theta_{g}^{CLCT}\,\forall p,k,g,t \tag{49}$$

$$\mu_{pgat}^{CLCT-RMNF}\leq M.\theta_{g}^{CLCT}\,\forall p,g,a,t \tag{50}$$

$$\mu_{pgbt}^{CLCT-DSP}\leq M.\theta_{g}^{CLCT}\,\forall p,g,b,t \tag{51}$$

$$\mu_{pgat}^{CLCT-RMNF}\leq M.\theta_{a}^{RMNF}\,\forall p,g,a,t \tag{52}$$

$$\mu_{padt}^{RMNF-DSTB}\leq M.\theta_{a}^{RMNF}\,\forall p,a,d,t \tag{53}$$

$$\mu_{camt}^{RMNF-MNF}\leq M.\theta_{a}^{RMNF}\,\forall c,a,m,t \tag{54}$$

$$\mu_{pgbt}^{CLCT-DSP}\leq M.\theta_{b}^{DSP}\,\forall p,g,b,t \tag{55}$$

$$\mu_{pabt}^{RMNF-DSP}\leq M.\theta_{b}^{DSP}\,\forall p,a,b,t \tag{56}$$

$$\sum_{d'}\alpha_{vd'dt}=\sum_{d'}\alpha_{vdd't}\,\forall v,d,t \tag{57}$$

$$\sum_{k'}\alpha'_{vk'kt}=\sum_{k'}\alpha'_{vkk't}\,\forall v,k,t \tag{58}$$

$$\sum_{d'}\alpha_{vd'dt}\leq 1\,\forall v,d,t \tag{59}$$

$$\sum_{k'}\alpha'_{vk'kt}\leq 1\,\forall v,k,t \tag{60}$$

$$\sum_{q}\left(\theta_{vqt}+\theta'_{vqt}\right)\leq 1\,\forall v,t \tag{61}$$

$$\mu_{pvdqt}^{DSTB-CRS}\leq M.\theta_{vqt}\,\forall p,v,d,q,t \tag{62}$$

$$\mu_{pvqkt}^{CRS-RT}\leq M.\theta'_{vqt}\,\forall p,v,q,k,t \tag{63}$$

$$\sum_{q}\theta_{vqt}\leq M.\theta_{v}^{VH}\,\forall v,t \tag{64}$$

$$\sum_{q}\theta'_{vqt}\leq M.\theta_{v}^{VH}\,\forall v,t \tag{65}$$

$$\mu_{pvdqt}^{DSTB-CRS}\leq M.\sum_{d'}\alpha_{vd'dt}\,\forall p,v,d,q,t \tag{66}$$

$$\mu_{pvqkt}^{CRS-RT}\leq M.\sum_{k'}\alpha'_{vk'kt}\,\forall p,v,q,k,t \tag{67}$$

$$\mu_{pvdt}+M.(1-\alpha_{vd'dt})\geq\mu_{pvd't}+\mu_{pvd'qt}^{DSTB-CRS}\,\forall p,v,d',d,q,t \tag{68}$$

$$\mu_{pv1t}\geq\sum_{d}\mu_{pvdqt}^{DSTB-CRS}\,\forall p,v,q,t \tag{69}$$

$$\mu'_{vkt}+M.(1-\alpha'_{vk'kt})\geq\mu'_{vk't}+\tau_{vk'k}+UL_{k}\,\forall v,k',k>1,t \tag{70}$$

$$\varphi+M.(1-\alpha'_{vk1t})\geq\mu'_{vkt}+\hat{\tau}_{vkq}\times\theta'_{vqt}+UL_{k}\,\forall v,k>1,q,t \tag{71}$$

$$\mu'_{vkt}-\mu'_{ukt}+M.\chi_{vukt}\geq UL_{k}\,\forall v\neq u,k>1,t \tag{72}$$

$$\mu'_{ukt}-\mu'_{vkt}+M.(1-\chi_{vukt})\geq UL_{k}\,\forall v\neq u,k>1,t \tag{73}$$

$$\mu_{resmft}^{SPLR-MNF}\leq UP_{rest}+M.\left(1-\theta_{rest}^{SPLR}\right)\forall r,e,s,m,f,t \tag{74}$$

$$\mu_{resmft}^{SPLR-MNF}+M.\left(1-\theta_{rest}^{SPLR}\right)>LW_{rest}\,\forall r,e,s,m,f,t \tag{75}$$

$$\sum_{e}\theta_{rest}^{SPLR}\leq 1\,\forall r,s,t \tag{76}$$

The first objective function is devoted to reducing the total costs of the chain as much as possible. These costs include ordering costs to suppliers, costs of establishing manufacturing, distribution, cross-docking, collection, remanufacturing and disposal centers, costs of supplying vehicles, costs of purchasing raw materials from suppliers, costs of production of products in manufacturing centers, costs of processing products in distribution and cross-docking centers, costs of separating products in collection centers, costs of disposing products in disposal centers, costs of processing products in remanufacturing centers, costs of shipping raw materials between suppliers and manufacturers echelons, costs of shipping products between manufacturers and distributors echelons, costs of shipping returned products from customers to collection centers, costs of shipping products from collection centers to remanufacturing centers, costs of shipping products from collection centers to disposal centers, costs of shipping products from remanufacturing centers to distribution centers, costs of shipping products from remanufacturing centers to disposal centers, costs of shipping products components from remanufacturing centers to manufacturing centers, costs of holding products in warehouses of customers, shortage costs and costs of fuel consumption by vehicles.

The second objective function is to minimize the undesired environmental effects arising from opening facilities and using transportation modes. The third objective function is to maximize the employment created by opening the facilities. The fourth objective function minimizes lost sales. The fifth objective function maximizes the procurement value from sustainable suppliers.

Constraint (16) asserts that the amount of raw material purchased from suppliers does not exceed theirs throughout the capacity. Capacity constraints of the manufacturers in the first period and the subsequent periods are shown in Constraints (17) and (18), respectively. Similarly, capacity constraints of distribution centers in the first period and in the subsequent periods are stated in Constraints (19) and (20), respectively. Capacity constraints for cross-docking, collection, remanufacturing and disposal centers, and vehicles' capacities that pick up from distribution centers and deliver to customers are included in Constraints (21) to (26), respectively.

Constraints (27) and (28) represent the balance of inbound and outbound flows in the production centers, respectively, for the first period and the subsequent periods. The same balance in the distribution centers is considered in Constraints (29) and (30), respectively. The balance of material flow at cross-docking centers is guaranteed by the Constraint (31). The balance (inventory level) in the customer inventory for the first period and the subsequent periods is controlled by Constraints (32) and (33), respectively. Constraints (34) and (35) represent the balance of inventory in the collection centers and the calculation of the number of products returned from customers to the collection centers. The balance of inventory in remanufacturing centers is considered in Constraint (36). The amount of product transferred from collection centers to remanufacturing centers, from remanufacturing centers to disposal centers and from remanufacturing centers to distribution centers, is calculated in Constraints (37) to (39), respectively.

The requirement for purchasing raw materials from suppliers is to have a contract with the supplier, which is satisfied by Constraints (40). One of the conditions of location is that inbound and outbound flows are defined for opened facilities. This requirement is applied to manufacturing centers through Constraints (41) to (43). It is also applied for distribution centers in Constraints (44) to (46), for cross-docking centers in Constraints (47) and (48), for collection centers in Constraints (49) to (51), for remanufacturing centers in Constraints (52) to (54) and for disposal centers in Constraints (55) and (56).

One of the classic constraints of a vehicle routing problem is that if vehicles enter a node, they have to exit it; Constraint (57) ensures this requirement for distribution centers, and Constraint (58) states this for customers' site. Each vehicle must not visit each node more than once in each time period; this requirement for distribution centers and customers is guaranteed in Constraints (59) and (60), respectively.

Each vehicle should not be assigned to more than one cross-docking center at a time period. If it is assigned to a cross-docking center, it is used either to collect products from distribution centers or to deliver products to customers. This requirement is considered in Constraint (61). If a vehicle is not given to a cross-docking center, it is not possible to carry products from distribution centers to cross-docking centers and from cross-docking centers to customers' sites. It is ensured in Constraints (62) and (63).

Vehicles can be assigned to cross-docking centers at time periods if they are purchased. Constraints (64) and (65) indicate this prerequisite. Constraint (66) states that the condition for collecting products from distribution centers is to visit distribution centers by vehicles. Similarly, the condition of delivering the product to customers is to visit the customers' by vehicles, as stated by the Constraint (67). The constraints for removing the sub-tour and determining the sequence of visits to distribution centers for product collection are set out in Constraints (68) and (69). Constraints (70) and (71) are also provided for removing the sub-tour and determining the sequencing of customer visits for product delivery. Constraint (71) also expresses the restriction of the delivery hard time window.

Scheduling and sequences of visits to customers are calculated by the Constraints (72) and (73). The amount of raw materials purchased from suppliers in each time period based on the proposed rebates is expressed by Constraints (74) and (75). Constraint (76) indicates that the purchase from any supplier in any given period is possible just at one price level.

3.3. Linearization process

Two terms, $\alpha_{vd'dt} \times \theta_{vqt}$ and $\alpha'_{vk'kt} \times \theta'_{vqt}$, in the first objective function, result in the nonlinearity of the proposed model. Two binary variables, $Y_{vqd'dt}$ and $Y'_{vqk'kt}$, are defined and replaced with the nonlinear terms to linearize the model. The relation between the two new binary variables with the variables used in the linear terms should be determined. In the following, the first objective function is linearized, and the relations between the new binary variables and the nonlinear terms are shown:

$$Min\ Obj_1 = \sum_{r,e,s,t} \vartheta_{st}^{SPLR}.\theta_{rest}^{SPLR} + \sum_{m} \vartheta_{m}^{MNF}.\theta_{m}^{MNF} + \sum_{d} \vartheta_{d}^{DSTB}.\theta_{d}^{DSTB} +$$
$$\sum_{q} \vartheta_{q}^{CRS}.\theta_{q}^{CRS} + \sum_{g} \vartheta_{g}^{CLCT}.\theta_{g}^{CLCT} + \sum_{a} \vartheta_{a}^{RMNF}.\theta_{a}^{RMNF} + \sum_{b} \vartheta_{b}^{DSP}.\theta_{b}^{DSP} +$$
$$\sum_{v} \vartheta_{v}^{VH}.\theta_{v}^{VH} + \sum_{r,e,s,m,f,t} \phi_{rst}^{SPLR}.\mu_{resmft}^{SPLR-MNF} + \sum_{p,m,d,t} \phi_{pmt}^{MNF}.\mu_{pmdt}^{MNF-DSTB} +$$
$$\sum_{p,v,d,q,t} \phi_{pdt}^{DSTB}.\mu_{pvdqt}^{DSTB-CRS} + \sum_{p,v,q,k,t} \phi_{pqt}^{CRS}.\mu_{pvqkt}^{CRS-RT}$$

$$+\sum_{p,k,g,t}\phi_{pgt}^{CLCT}.\mu_{pkgt}^{RT-CLCT}+\sum_{p,g,a,b,t}\phi_{pbt}^{DSP}.\left(\mu_{pgbt}^{CLCT-DSP}+\mu_{pabt}^{RMNF-DSP}\right)$$
$$+\sum_{p,g,a,t}\phi_{pat}^{RMNF}.\mu_{pgat}^{CLCT-RMNF}+\sum_{r,e,s,m,f,t}\eta_{rsmft}^{SPLR-MNF}.\mu_{resmft}^{SPLR-MNF}$$
$$+\sum_{p,m,d,t}\eta_{pmdt}^{MNF-DSTB}.\mu_{pmdt}^{MNF-DSTB}+\sum_{p,k,g,t}\eta_{pkgt}^{RT-CLCT}.\mu_{pkgt}^{RT-CLCT}$$
$$+\sum_{p,g,a,t}\eta_{pgat}^{CLCT-RMNF}.\mu_{pgat}^{CLCT-RMNF}+\sum_{p,g,b,t}\eta_{pgbt}^{CLCT-DSP}.\mu_{pgbt}^{CLCT-DSP}$$
$$+\sum_{p,a,d,t}\eta_{padt}^{RMNF-DSTB}.\mu_{padt}^{RMNF-DSTB}+\sum_{p,a,b,t}\eta_{pabt}^{RMNF-DSP}.\mu_{pabt}^{RMNF-DSP}$$
$$+\sum_{c,a,m,t}\eta_{camt}^{RMNF-MNF}.\mu_{camt}^{RMNF-MNF}+\sum_{p,k,t}\psi_{pkt}^{PST}.\varpi_{pkt}^{PST}+\sum_{p,k,t}\psi_{pkt}^{NGT}.\varpi_{pkt}^{NGT}$$
$$+\sum_{v,d'>1,d>1,t}\sigma.\gamma_v.\tau_{d'd}^{DSTB}.\alpha_{vd'dt}+\sum_{v,d>1,q,t}\sigma.\gamma_v.\tau_{dq}^{DSTB-CRS}.\Big(Y_{vq1dt}$$
$$+Y_{vqd1t}\Big)+\sum_{v,k'>1,k>1,t}\sigma.\gamma_v.\tau_{k'k}^{RT}.\alpha'_{vk'kt}$$
$$+\sum_{v,q,k>1,t}\sigma.\gamma_v.\tau_{kq}^{RT-CRS}.\left(Y'_{vq1kt}+Y'_{vqk1t}\right) \tag{77}$$

s.t.

$$Y_{vqd'dt}\le\alpha_{vd'dt}+M.(1-\theta_{vqt})\,\forall v,q,d',d,t \tag{78}$$

$$Y_{vqd'dt}\le\theta_{vqt}+M.(1-\alpha_{vd'dt})\,\forall v,q,d',d,t \tag{79}$$

$$Y_{vqd'dt}\ge 1+M.(\theta_{vqt}+\alpha_{vd'dt}-2)\,\forall v,q,d',d,t \tag{80}$$

$$Y_{vqd'dt}\le M.(\theta_{vqt}+\alpha_{vd'dt})\,\forall v,q,d',d,t \tag{81}$$

$$Y'_{vqk'kt}\le\alpha'_{vk'kt}+M.\left(1-\theta'_{vqt}\right)\forall v,q,k',k,t \tag{82}$$

$$Y'_{vqk'kt}\le\theta'_{vqt}+M.(1-\alpha'_{vk'kt})\,\forall v,q,k',k,t \tag{83}$$

$$Y'_{vqk'kt}\ge 1+M.\left(\theta'_{vqt}+\alpha'_{vk'kt}-2\right)\forall v,q,k',k,t \tag{84}$$

$$Y'_{vqk'kt}\le M.\left(\theta'_{vqt}+\alpha'_{vk'kt}\right)\forall v,q,k',k,t \tag{85}$$

3.4. Solution approach

Various methods exist in the literature to solve multi-objective problems, one of which is the most prominent method of goal programming (Mirzaee et al., 2018). Especially if there is a high number of objective functions in a mathematical model, the goal programming method would be more efficient because, in this method, an aspiration is targeted for each of the objective functions. It is attempted to bring the undesirable deviations of each objective function to a minimum level (Shahnazari-Shahrezaei et al., 2013).

In the deterministic goal programming model, aspiration levels have to be specifically determined, but in the real world problems, due to uncertainty, this parameter cannot be accurately determined. Fuzzy theory is used to solve this problem and to incorporate the uncertainty (Kim et al., 2000). Therefore, a combination of the goal programming method and the fuzzy theory can be an effective approach for achieving problem goals in the presence of uncertainty. The hybrid solution approach proposed to solve the multi-objective problem in this study is inspired by the Zandkarimkhani et al.'s (2020) method. One of the disadvantages of the method developed by Zandkarimkhani et al. (2020) is that all the goals in their model are assumed equally important, and the DMs cannot assign different importance weights to the more important criteria. However, a weighted fuzzy goal programming approach is proposed in this study to address this shortcoming in the Zandkarimkhani et al.'s (2020) method. This added enhancement allows DMs to weight each goal according to their preferences. In addition, it is possible to obtain a Pareto solution by changing the goals' weights. The following represents the proposed solution approach:

Step 1: Defining the objective function goals

DMs are asked to determine the goal amounts. To this end, the optimal values of each objective function, resulting from the optimization of the model for each objective function individually, are provided to DMs and are asked to assign a goal to each objective function according to its obtained optimal value. Assume that Z_h^* and Z_l^* represent the optimal values of the minimization and maximization objective functions, respectively. And $\hat{v}_h$ and v_h represent their corresponding goals as follows:

$$Z_h^*\le v_h\,\forall h \tag{86}$$

$$Z_l^*\ge\hat{v}_l\,\forall l \tag{87}$$

In our model, there are both minimization and maximization objective functions.

$$\begin{cases} Z_1^*\le v_1\\ Z_2^*\le v_2\\ Z_3^*\ge v_3\\ Z_4^*\le v_4\\ Z_5^*\ge v_5\end{cases} \tag{88}$$

Step 2: Implementing the goal programming model

In this step, the proposed model is presented in the form of goal programming model as follows:

$$Min\ dev_1^+ \tag{89}$$

$$Min\ dev_2^+ \tag{90}$$

$$Min\ dev_3^- \tag{91}$$

$$Min\ dev_4^+ \tag{92}$$

$$Min\ dev_5^- \tag{93}$$

s.t.

$$Z_1 - dev_1^+ + dev_1^- = \upsilon_1 \tag{94}$$

$$Z_2 - dev_2^+ + dev_2^- = \upsilon_2 \tag{95}$$

$$Z_3 - dev_3^+ + dev_3^- = \upsilon_3 \tag{96}$$

$$Z_4 - dev_4^+ + dev_4^- = \upsilon_4 \tag{97}$$

$$Z_5 - dev_5^+ + dev_5^- = \upsilon_5 \tag{98}$$

*System constraints*where $dev_1^+ dev_2^+, dev_3^+, dev_4^+$ and dev_5^+ indicate the positive deviations of goals one to five and $dev_1^- dev_2^-, dev_3^-, dev_4^-$ and dev_5^- show the corresponding negative deviations.

Step 3: Converting MOMILP model to a single objective MILP model

Here, the method proposed by Torabi and Hassini (2008) is used to convert the multi-objective model into a single-objective model.

$$\lambda_0 \le \varphi_3 \le \frac{Z^+_{dev_3^-} - dev_3^-}{Z^+_{dev_3^-} - Z^-_{dev_3^-}} \tag{103}$$

$$\lambda_0 \le \varphi_4 \le \frac{Z^+_{dev_4^+} - dev_4^+}{Z^+_{dev_4^+} - Z^-_{dev_4^+}} \tag{104}$$

$$\lambda_0 \le \varphi_5 \le \frac{Z^+_{dev_5^-} - dev_5^-}{Z^+_{dev_5^-} - Z^-_{dev_5^-}} \tag{105}$$

$$Z_1 - dev_1^+ + dev_1^- = \upsilon_1 \tag{106}$$

$$Z_2 - dev_2^+ + dev_2^- = \upsilon_2 \tag{107}$$

$$Z_3 - dev_3^+ + dev_3^- = \upsilon_3 \tag{108}$$

$$Z_4 - dev_4^+ + dev_4^- = \upsilon_4 \tag{109}$$

Notations

$\hat{\gamma}$	The relative importance of minimum satisfaction degree of objective functions
λ_0	Minimum satisfaction degree of objective functions
w_h	The relative importance weight of the hth objective's degree of satisfaction
φ_h	The satisfaction degree for objective function h
$Z^+_{dev_h^+}$	The upper bound for dev_h^+
$Z^-_{dev_h^+}$	The lower bound for dev_h^-

Mathematical model

$$Max\ \hat{\gamma}.\lambda_0 + (1-\hat{\gamma}).\sum_h w_h.\varphi_h$$

$$St:$$

$$\begin{aligned} &\lambda_0 \le \varphi_h \\ &\varphi_h = \frac{Z^+_{dev_h^+} - dev_h^+}{Z^+_{dev_h^+} - Z^-_{dev_h^+}} \\ &\sum_h w_h = 1 \end{aligned} \tag{99}$$

By developing the proposed model based on Eq. (99) the following formulations are obtained:

$$Max\ \hat{\gamma}.\lambda_0 + (1-\hat{\gamma}).(w_1.\varphi_1 + w_2.\varphi_2 + w_3.\varphi_3 + w_4.\varphi_4 + w_5.\varphi_5) \tag{100}$$

s.t.

$$\lambda_0 \le \varphi_1 \le \frac{Z^+_{dev_1^+} - dev_1^+}{Z^+_{dev_1^+} - Z^-_{dev_1^+}} \tag{101}$$

$$\lambda_0 \le \varphi_2 \le \frac{Z^+_{dev_2^+} - dev_2^+}{Z^+_{dev_2^+} - Z^-_{dev_2^+}} \tag{102}$$

$$Z_5 - dev_5^+ + dev_5^- = \upsilon_5 \tag{110}$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1 \tag{111}$$

Accordingly, the multi-objective model proposed here is transformed into a single-objective model by using a novel fuzzy goal programming approach.

4. Case study

In this part of the study, the validation and efficiency of the proposed approach are investigated using the information and data relating to a suit production and distribution chain in the garment industry. This company was founded with a production capacity of 800,000 m of fabric and 38,000 suits in Alborz Province in 1989. In this chain, the factory purchased two types of raw materials, namely wool fibers and polyester fibers from suppliers and, accordingly, produces three types of woven fabric, including Type 1 fabric (10% wool and 90% polyester), type 2 fabric (20% wool and 80% polyester), and type 3 fabric (45% wool and 55% polyester). Then, three types of suits, regardless of their design, color, and size, are sewn using the manufactured fabrics. The manufactured products at the factory are sent to distribution centers (central warehouses). This chain has provided customers (sales representatives) with the possibility to order their intended products online. Internet distribution centers, which are equivalent to cross-docking centers in this paper, collect the desired products through the optimal routing from the distribution centers according to customers' orders and, then, transfer them to cross-docking centers. Following the processing of products, they are offered to customers

Table 6
The best and worst criteria/sub-criteria.

Criteria	The best criterion/sub-criterion	The worst criterion/sub-criterion
Main criteria	Economic	Circular
Economic sub-criteria	Quality	Flexibility
Circular sub-criteria	Utilizing eco-friendly and recyclable raw materials	Using recyclable materials in packaging products
Green sub-criteria	Environmental management systems	Green R&D and innovation
Social sub-criteria	Occupational health and safety systems	Information disclosure

Table 7
The fuzzy best-to-others vector.

Criteria	Best criteria	Best-to-others criteria vector	Best sub-criteria	Other sub-criteria	Best-to-others sub-criteria vectors
Economic (ECN)	ECN	(1,1,1)	ECN1	ECN1	(1,1,1)
				ECN2	(5/2,3,7/2)
				ECN3	(2/3,1,3/2)
				ECN4	(7/2,4,9/2)
				ECN5	(5/2,3,7/2)
				ECN6	(3/2,2,5/2)
Circular (CRC)		(5/2,3,7/2)	CRC1	CRC1	(1,1,1)
				CRC2	(3/2,2,5/2)
				CRC3	(2/3,1,3/2)
Green (GRN)		(3/2,2,5/2)	GRN1	GRN1	(1,1,1)
				GRN2	(2/3,1,3/2)
				GRN3	(3/2,2,5/2)
				GRN4	(3/2,2,5/2)
				GRN5	(2/3,1,3/2)
				GRN6	(5/2,3,7/2)
Social (SCL)		(2/3,1,3/2)	SCL3	SCL1	(2/3,1,3/2)
				SCL2	(5/2,3,7/2)
				SCL3	(1,1,1)
				SCL4	(3/2,2,5/2)
				SCL5	(3/2,2,5/2)

Table 8
The fuzzy others-to-worst vectors.

Criteria	Worst criteria	Others-to-worst criteria vector	Worst sub-criteria	Other sub-criteria	Others-to-worst sub-criteria vectors
Economic (ECN)	CRC	(5/2,3,7/2)	ECN4	ECN1	(7/2,4,9/2)
				ECN2	(2/3,1,3/2)
				ECN3	(5/2,3,7/2)
				ECN4	(1,1,1)
				ECN5	(2/3,1,3/2)
				ECN6	(3/2,2,5/2)
Circular (CRC)		(1,1,1)	CRC2	CRC1	(3/2,2,5/2)
				CRC2	(1,1,1)
				CRC3	(2/3,1,3/2)
Green (GRN)		(2/3,1,3/2)	GRN6	GRN1	(5/2,3,7/2)
				GRN2	(3/2,2,5/2)
				GRN3	(2/3,1,3/2)
				GRN4	(2/3,1,3/2)
				GRN5	(3/2,2,5/2)
				GRN6	(1,1,1)
Social (SCL)		(3/2,2,5/2)	SCL2	SCL1	(3/2,2,5/2)
				SCL2	(1,1,1)
				SCL3	(5/2,3,7/2)
				SCL4	(2/3,1,3/2)
				SCL5	(2/3,1,3/2)

using optimal routing. The company under study allows customers to return the defective products or the ones not liked by them, then collects them, and put those that have major defects and those whose repair is not cost-effective on sale at a very low price (disposal). Moreover, those returned products that are repairable are modified and returned to the consumption cycle once more. Then, the following is dealt with the evaluation of the function of the proposed approach is validated using the data and information pertaining to 2 raw materials, 3 sub-products, 3 products, 5 suppliers, 3 potential production centers, 4 potential distribution centers, 4 cross-docking centers, 10 customers, 3 potential collection centers, 3 potential reproduction centers, 3 potential disposal centers, 3 price levels, 8 vehicles, 2 transportation modes, and 6 time periods. The steps for implementing the proposed approach are presented below:

Stage 1: At this stage, the knowledge of four experts, namely procurement manager, quality assurance manager, production supervisor, and sales manager were benefited from to evaluate the five suppliers by means of the proposed approach as follows:

Step 1: Here, the criteria and sub-criteria of SCSS were determined by review of the literature and experts' knowledge, as shown in Table 2.

Table 9
The fuzzy local weights of criteria and their sub-criteria.

Criteria	l_j^w	m_j^w	u_j^w	ϑ^*	Sub-criteria	l_j^w	m_j^w	u_j^w	ϑ^*
ECN	0.369	0.376	0.445	0.289	ECN1	0.277	0.308	0.317	0.299
					ECN2	0.083	0.099	0.117	
					ECN3	0.213	0.256	0.286	
					ECN4	0.075	0.082	0.086	
					ECN5	0.083	0.099	0.117	
					ECN6	0.127	0.162	0.196	
CRC	0.139	0.139	0.167		CRC1	0.383	0.405	0.529	0.303
					CRC2	0.237	0.238	0.316	
					CRC3	0.296	0.311	0.424	
GRN	0.160	0.164	0.206		GRN1	0.225	0.260	0.271	0.289
					GRN2	0.165	0.209	0.235	
					GRN3	0.097	0.118	0.142	
					GRN4	0.097	0.118	0.142	
					GRN5	0.165	0.209	0.235	
					GRN6	0.084	0.095	0.102	
SCL	0.249	0.292	0.386		SCL1	0.209	0.264	0.297	0.289
					SCL2	0.106	0.119	0.128	
					SCL3	0.284	0.327	0.342	
					SCL4	0.123	0.149	0.179	
					SCL5	0.123	0.149	0.179	

Table 10
Consistency ratio.

Pairwise comparison among	Consistency ratio
Criteria	0.0432
economic sub-criteria	0.0372
circular sub-criteria	0.0573
green sub-criteria	0.0432
social sub-criteria	0.0432

Step 2: In this step, the criteria and sub-criteria with the lowest and highest values in comparison with the other ones were selected with the help of experts, as shown in Table 6.
Step 3: In this step, it is sought to compare the best criterion with the other ones using Table 3, and the FBTO vector is formed, as presented in Table 7.
Step 4: In this step, the worst criterion is compared with other criteria using Table 3, and the FOTW vector is formed as in Table 8.
Step 5: This step aims at calculating the weights of the criteria and sub-criteria by using the FBTO and the FOTW vectors and the nonlinear model. For example, Tables 7 and 8 are used to develop a nonlinear model for calculating the weights of criteria in Appendix 4. The developed model was run using COUEENE solver in GAMS/24.1.2/Win64 software, which resulted in the calculation of the optimal values of $\vartheta^*$and fuzzy local weights of criteria, as presented in Table 9(a). Thus, the fuzzy local weights of sub-criteria were calculated using the above-mentioned procedure whose results are indicated in Table 9(b).
Step 6: In this step, the consistency ratio for pairwise comparisons is calculated using Table 4 and Eq. (9). In Table 10, the consistency ratios of the criteria and sub-criteria are presented.

According to the results available in Table 10, the consistency ratios for all pairwise comparisons are close to zero; therefore, their consistency is acceptable. Accordingly, the calculated weights of their criteria and sub-criteria are confirmed.

Step 7: In this step, the fuzzy global weights of sub-criteria are calculated by multiplying the fuzzy local weights of criteria by those of the sub-criteria, as observed in Table 11.

Table 11
The fuzzy global weights of sub-criteria.

Sub-criteria	l_j^w	m_j^w	u_j^w
ECN1	0.1022	0.1158	0.1411
ECN2	0.0306	0.0372	0.0521
ECN3	0.0786	0.0963	0.1273
ECN4	0.0277	0.0308	0.0383
ECN5	0.0306	0.0372	0.0521
ECN6	0.0469	0.0609	0.0872
CRC1	0.0532	0.0563	0.0883
CRC2	0.0329	0.0331	0.0528
CRC3	0.0411	0.0432	0.0708
GRN1	0.0360	0.0426	0.0558
GRN2	0.0264	0.0343	0.0484
GRN3	0.0155	0.0194	0.0293
GRN4	0.0155	0.0194	0.0293
GRN5	0.0264	0.0343	0.0484
GRN6	0.0134	0.0156	0.0210
SCL1	0.0520	0.0771	0.1146
SCL2	0.0264	0.0347	0.0494
SCL3	0.0707	0.0955	0.1320
SCL4	0.0306	0.0435	0.0691
SCL5	0.0306	0.0435	0.0691

Step 8: This step is an attempt to address the performance of five suppliers for each sub-criterion using Table 5. For this purpose, each supplier's score for each sub-criterion is obtained using the questionnaire and with the help of the above four experts' knowledge. The mean score of evaluated values for suppliers per sub-criterion is presented in Table 12. From the sum of multiplication results of the mean values evaluated in the fuzzy global weights of sub-criteria, the fuzzy final scores of suppliers are calculated, as presented in Table 13. Then, the defuzzified final scores of suppliers are calculated by Eq. (10), as presented in Table 13.

As it was mentioned earlier, the defuzzified final score will be used as the coefficient of the objective function of purchase from the qualified sustainable suppliers.

Stage 2: In this stage, the proposed mathematical model is coded in GAMS software using the Cplex solver and data in Tables 14–20. Part of the data is extracted from the company's historical databases, and the other part is simulated using experts' knowledge. The data on the geographic and time distance between

Table 12
The fuzzy average supplier evaluation score.

Sub-criteria	Supplier 1			Supplier 2			Supplier 3			Supplier 4			Supplier 5		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
ECN1	0.584	0.750	0.917	0.458	0.625	0.792	0.625	0.792	0.958	0.375	0.542	0.709	0.417	0.584	0.750
ECN2	0.417	0.584	0.750	0.500	0.667	0.833	0.834	0.917	1.000	0.584	0.750	0.917	0.667	0.792	0.917
ECN3	0.458	0.625	0.792	0.417	0.584	0.750	0.667	0.792	0.917	0.458	0.625	0.792	0.834	0.917	1.000
ECN4	0.250	0.417	0.584	0.375	0.542	0.709	0.625	0.792	0.958	0.167	0.333	0.500	0.667	0.833	1.000
ECN5	0.458	0.625	0.792	0.542	0.709	0.875	0.750	0.875	1.000	0.584	0.750	0.917	0.834	0.917	1.000
ECN6	0.375	0.542	0.709	0.333	0.500	0.667	0.500	0.667	0.833	0.417	0.584	0.750	0.458	0.625	0.792
CRC1	0.209	0.375	0.542	0.250	0.417	0.584	0.458	0.625	0.792	0.209	0.375	0.542	0.500	0.667	0.833
CRC2	0.375	0.542	0.709	0.209	0.375	0.542	0.417	0.584	0.750	0.250	0.417	0.584	0.667	0.792	0.917
CRC3	0.167	0.333	0.500	0.250	0.417	0.584	0.417	0.584	0.750	0.209	0.375	0.542	0.417	0.584	0.750
GRN1	0.250	0.417	0.584	0.458	0.625	0.792	0.667	0.792	0.917	0.500	0.667	0.833	0.625	0.792	0.958
GRN2	0.375	0.542	0.709	0.417	0.584	0.750	0.584	0.750	0.917	0.333	0.500	0.667	0.542	0.709	0.875
GRN3	0.250	0.417	0.583	0.458	0.625	0.792	0.500	0.667	0.833	0.542	0.709	0.875	0.417	0.584	0.750
GRN4	0.500	0.667	0.833	0.750	0.875	1.000	0.834	0.917	1.000	0.917	0.958	1.000	1.000	1.000	1.000
GRN5	0.417	0.584	0.750	0.500	0.667	0.833	0.625	0.792	0.958	0.458	0.625	0.792	0.542	0.709	0.875
GRN6	0.458	0.625	0.792	0.917	0.958	1.000	0.834	0.917	1.000	0.417	0.584	0.750	0.500	0.667	0.833
SCL1	0.750	0.875	1.000	0.584	0.750	0.917	0.667	0.833	1.000	0.625	0.792	0.958	0.625	0.792	0.958
SCL2	0.375	0.542	0.709	0.250	0.417	0.584	0.542	0.709	0.875	0.500	0.667	0.833	0.458	0.625	0.792
SCL3	0.500	0.667	0.833	0.417	0.584	0.750	0.625	0.750	0.875	0.458	0.625	0.792	0.542	0.709	0.875
SCL4	0.458	0.625	0.792	0.542	0.709	0.875	0.542	0.709	0.875	0.417	0.584	0.750	0.625	0.792	0.958
SCL5	0.584	0.750	0.917	0.250	0.417	0.584	0.542	0.709	0.875	0.333	0.500	0.667	0.542	0.709	0.875

the nodes is derived from the Internet. The geographic and time distance data between the nodes are determined by placing the origin and destination points in https://www.google.com/maps as shown in Table 20. The proposed multi-objective slrmodel has transformed into a single-objective model one by considerin the aim of each objective function as follows:

Goal 1: The maximum cost of establishing the network is 450,000,000 $.

- Goal 2: The maximum environmental damage is 4.4.
- Goal 3: At least 120 job opportunities should be created.
- Goal 4: The maximum shortage amount is 200 units.
- Goal 5: Purchasing value from sustainable suppliers is at least 9500.

Having implemented the proposed model in GAMS software for $w_1 = 0.4$, $w_2 = 0.15$, $w_3 = 0.15$, $w_4 = 0.15$ and $w_5 = 0.15$ and the abovementioned goals, the optimal values of the first to fifth objective functions are 465,158,249, 4.65, 111, 283 and 8871.38, respectively. Additionally, the network structure is as follows:

- Suppliers 1, 3, and 5 are selected.
- Manufacturing center 3, distribution centers 2 and 3, cross-docking center 3, collection center 1, remanufacturing center 3, and disposal center 3 is established.
- Vehicles 1, 2, 4, 6, 7, and 8 are purchased.

The location-routing problems are NP-hard problems, and increasing the problem's size will significantly increase the complexity. As a result, exact solution methods and tools cannot solve the problem in a reasonable time (Govindan et al., 2019; Yu et al., 2020). The model proposed in this paper is also NP-hard due to the location-routing component of the problem. It took 3543 s to solve this model with the case study data in GAMS software. Increasing any index values in the model will substantially add to the complexity and exponentially increase the solution time. In addition, the $d, k,$ and $t$indices have a higher effect on the solution complexity.

Table 14
Facility establishment cost.

Center	Indices	Establishment cost
Manufacturing center	$m = 1$	$485,200,000
	$m = 2$	$472,500,000
	$m = 3$	$464,800,000
Distribution center	$d = 1$	–
	$d = 2$	$89,000
	$d = 3$	$84,000
	$d = 4$	$90,000
Cross-docking center	$q = 1$	$29,500
	$q = 2$	$30,400
	$q = 3$	$28,000
	$q = 4$	$31,100
Collection center	$g = 1$	$10,300
	$g = 2$	$12,200
	$g = 3$	$11,000
Remanufacturing center	$a = 1$	$25,500
	$a = 2$	$23,900
	$a = 3$	$24,000
Disposal center	$b = 1$	$11,400
	$b = 2$	$12000
	$b = 3$	$10,900

5. Sensitivity analysis

In this section, we conduct a sensitivity analysis to evaluate the proposed model and solution approach's performance and behavior by designing a series of scenarios for the coefficients of objective functions. For this purpose, the coefficients of the three objective functions are kept fixed in each scenario, and the

Table 13
The fuzzy and defuzzified final scores of suppliers.

Final score	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
Fuzzy	(0.341,0.588,1.054)	(0.330,0.571,1.031)	(0.475,0.733,1.239)	(0.330,0.575,1.039)	(0.458,0.711,1.213)
Defuzzified	0.6246	0.6077	0.7742	0.6116	0.7527

Table 15
Raw materials unitary cost per price level and time period.

ϕ^{SPLR}_{rest} (\$)		$t = 1,2,3,4,5$ and 6				
		$s = 1$	$s = 2$	$s = 3$	$s = 4$	$s = 5$
$r = 1$	$e = 1$	$U(2.26, 2.34)$	$U(2.38, 2.47)$	$U(2.55, 2.68)$	$U(2.44, 2.53)$	$U(2.82, 2.87)$
$r = 1$	$e = 2$	$U(2.15, 2.21)$	$U(2.29, 2.36)$	$U(2.44, 2.52)$	$U(2.33, 2.4)$	$U(2.7, 2.8)$
$r = 1$	$e = 3$	$U(2.04, 2.13)$	$U(2.19, 2.29)$	$U(2.35, 2.41)$	$U(2.25, 2.32)$	$U(2.61, 2.67)$
$r = 2$	$e = 1$	$U(13.45, 13.62)$	$U(13.94, 14.03)$	$U(13.67, 13.8)$	$U(14.17, 14.23)$	$U(13.78, 13.85)$
$r = 2$	$e = 2$	$U(13.3, 13.42)$	$U(13.83, 13.91)$	$U(13.58, 13.65)$	$U(14.03, 14.15)$	$U(13.7, 13.77)$
$r = 2$	$e = 3$	$U(13.22, 13.3)$	$U(13.75, 13.81)$	$U(13.45, 13.54)$	$U(13.94, 14.03)$	$U(13.56, 13.63)$

Table 16
Products processing costs in facilities.

ϕ^{MNF}_{pmt}	$t = 1,2,3,4,5$ *and* 6		
	$p = 1$	$p = 2$	$p = 3$
$m = 1$	$U(9.83, 10.05)$	$U(10.12, 10.35)$	$U(10.32, 10.55)$
$m = 2$	$U(10.22, 10.38)$	$U(10.53, 10.69)$	$U(10.73, 10.9)$
$m = 3$	$U(9.27, 9.35)$	$U(9.55, 9.63)$	$U(9.73, 9.82)$
ϕ^{DSTB}_{pdt}	$p = 1$	$p = 2$	$p = 3$
$d = 1$	–	–	–
$d = 2$	$U(2.89, 3)$	$U(2.89, 3)$	$U(2.89, 3)$
$d = 3$	$U(2.58, 2.73)$	$U(2.58, 2.73)$	$U(2.58, 2.73)$
$d = 4$	$U(2.95, 3.12)$	$U(2.95, 3.12)$	$U(2.95, 3.12)$
ϕ^{CRS}_{pqt}	$p = 1$	$p = 2$	$p = 3$
$q = 1$	$U(3.74, 3.85)$	$U(3.74, 3.85)$	$U(3.74, 3.85)$
$q = 2$	$U(3.56, 3.67)$	$U(3.56, 3.67)$	$U(3.56, 3.67)$
$q = 3$	$U(3.34, 3.42)$	$U(3.34, 3.42)$	$U(3.34, 3.42)$
$q = 4$	$U(3.68, 3.77)$	$U(3.68, 3.77)$	$U(3.68, 3.77)$
ϕ^{CLCT}_{pgt}	$p = 1$	$p = 2$	$p = 3$
$g = 1$	$U(1.07, 1.16)$	$U(1.07, 1.16)$	$U(1.07, 1.16)$
$g = 2$	$U(1.24, 1.38)$	$U(1.24, 1.38)$	$U(1.24, 1.38)$
$g = 3$	$U(0.98, 1.11)$	$U(0.98, 1.11)$	$U(0.98, 1.11)$
ϕ^{RMNF}_{pat}	$p = 1$	$p = 2$	$p = 3$
$a = 1$	$U(4.88, 4.97)$	$U(4.88, 4.97)$	$U(4.88, 4.97)$
$a = 2$	$U(4.64, 4.79)$	$U(4.64, 4.79)$	$U(4.64, 4.79)$
$a = 3$	$U(4.93, 5.08)$	$U(4.93, 5.08)$	$U(4.93, 5.08)$
ϕ^{DSP}_{pbt}	$p = 1$	$p = 2$	$p = 3$
$b = 1$	$U(7.19, 7.29)$	$U(7.19, 7.29)$	$U(7.19, 7.29)$
$b = 2$	$U(7.57, 7.72)$	$U(7.57, 7.72)$	$U(7.57, 7.72)$
$b = 3$	$U(7.64, 7.83)$	$U(7.64, 7.83)$	$U(7.64, 7.83)$

Table 17
Number of created job opportunities by established centers.

	$m = 1$	$m = 2$	$m = 3$	
ξ^{MNF}_m	54	49	51	
	$d = 1$	$d = 2$	$d = 3$	$d = 4$
δ^{DSTB}_d	–	13	9	14
	$q = 1$	$q = 2$	$q = 3$	$q = 4$
δ^{CRS}_q	12	13	15	17
	$g = 1$	$g = 2$	$g = 3$	
δ^{CLCT}_g	4	5	4	
	$a = 1$	$a = 2$	$a = 3$	
δ^{RMNF}_a	11	8	14	
	$b = 1$	$b = 2$	$b = 3$	
δ^{DSP}_b	5	6	5	

Table 18
Suppliers sustainability score.

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
Score	0.6246	0.6077	0.7742	0.6116	0.7527

coefficients of the other two objective functions are varied. It is expected that the value of the objective function does not deteriorate by increasing the coefficient of the objective function, and the value of the objective function does not improve by decreasing the coefficient of the objective function. This is a well-established sensitivity analysis approach for evaluating the efficiency and effectiveness of multi-objective mathematical models and their solution approaches (Mardan et al., 2019). For example, if the maximization objective function's coefficient increases, it is expected that the value of that objective function remains constant or increases. On the other hand, if the coefficient of a minimization objective function increases, it is expected that the value of that objective function decreases or remains constant. Unexpected results from implementing these scenarios indicate the proposed model and solution approach do not enjoy an acceptable efficiency. However, meeting reasonable expectations in all scenarios is an indication that the proposed model's behavior and performance are acceptable. The following presents the scenarios:

- **Scenario 1:** This set of scenarios is related to the changes in the coefficients of two objective functions 1 and 2 (those of the other objective functions are kept fixed). It is predicted that by increasing the coefficient of the first objective function and simultaneously decreasing the coefficient of the second one, the first objective function value will not get worse, and the value of the second one will not be improved. In Table 21, scenarios are presented for the change in the coefficients of objective functions 1 and 2, and the optimal values of the objective functions for each scenario. Also, in Figs. 3 and 4, the trend of changes in objective functions 1 and 2 is schematically illustrated.

According to the obtained results in Table 21 and Figs. 3 and 4, as expected by increasing the coefficient of the first objective function and decreasing the coefficient of the second one simultaneously, the first objective function value decreases and the value of the second one increases. Also, by decreasing the coefficient of the first

Table 19
Demand amount.

ω_{pkt}	$p=1$						$p=2$						$p=3$					
	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=6$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=6$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=6$
$k=1$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$k=2$	89	74	116	79	80	83	81	78	97	82	43	94	66	63	79	67	52	76
$k=3$	94	83	100	69	75	85	90	89	81	103	65	104	73	72	65	83	79	84
$k=4$	105	81	78	94	89	71	93	90	103	53	113	82	75	73	83	65	92	66
$k=5$	68	101	108	76	70	87	62	81	105	123	81	98	76	65	84	99	65	79
$k=6$	77	63	59	82	49	68	63	93	109	91	102	98	76	75	88	73	82	79
$k=7$	92	68	105	86	88	99	91	88	105	109	88	65	74	71	85	88	71	80
$k=8$	112	84	93	97	84	76	65	96	108	79	102	83	79	77	87	64	82	67
$k=9$	109	93	79	67	72	83	87	43	63	65	132	47	70	52	77	80	107	57
$k=10$	64	97	78	71	95	104	96	110	91	85	94	55	77	89	73	69	76	67

Table 20
Geographical and time distances among nodes.

Parameter	value
$\tau^{DSTB}_{d'd}(Km)$	https://google.com/maps
$\tau^{DSTB-CRS}_{dq}(Km)$	https://google.com/maps
$\tau^{RT}_{k'k}(Km)$	https://google.com/maps
$\tau^{RT-CRS}_{kq}(Km)$	https://google.com/maps
$\tau_{vk'k}(Minute)$	https://google.com/maps
$\hat{\tau}_{vkq}(Minute)$	https://google.com/maps

objective function and increasing the coefficient of the second objective function, the value of the objective functions are increased and decreased respectively, which was in line with our expectations of the proposed model.

- **Scenario 2:** This section defines scenarios based on changes occurring in the coefficients of objective functions 1 and 3 and keeping fixed coefficients of other objective functions. Table 21 and Figs. 5 and 6 show the trend of changes in objective functions for each scenario.

As expected, with an increase in the coefficient of objective function 1, objective function value decreases, and vice versa. Also, by decreasing and increasing the coefficient of objective function 3, the objective function value is reduced and increased, respectively. The results show the valid performance of the proposed model.

- **The scenario set 3:** This set of scenarios is defined by changes in coefficients of the objective functions 1 and 4 and keeping the other factors fixed. In Table 21, the scenarios resulting from the sensitivity analysis of the coefficients of objective functions 1 and 4, and the optimal values of these objective functions for each scenario are presented.

As shown in Table 21, the changing trend in the objective functions in Figs. 7 and 8 show that by increasing the objective

Table 21
Sensitivity analysis of the objective function coefficients.

w_1	w_2	Scenario set 1 (Objective functions 1 and 2)			Scenario set 2 (Objective functions 1 and 3)			Scenario set 3 (Objective functions 1 and 4)			Scenario set 4 (Objective functions 1 and 4)		
		Scenario	Objective function 1	Objective function 2	Scenario	Objective function 1	Objective function 3	Scenario	Objective function 1	Objective function 4	Scenario	Objective function 1	Objective function 5
0.45	0.1	SC1.1	463,604,006	4.72	SC2.1	463,829,327	102	SC3.1	464,873,565	528	SC4.1	464,871,090	8807.4
0.4	0.15	SC1.2	465,158,249	4.65	SC2.2	465,158,249	111	SC3.2	465,158,249	283	SC4.2	465,158,249	8871.38
0.35	0.2	SC1.3	467,273,098	4.58	SC2.3	465,370,626	116	SC3.3	465,203,674	251	SC4.3	465,611,347	9071.06
0.3	0.25	SC1.4	467,677,312	4.55	SC2.4	465,583,183	120	SC3.4	465,214,933	251	SC4.4	467,222,831	9355.56
0.25	0.3	SC1.5	467,963,781	4.49	SC2.5	467,068,955	162	SC3.5	473,370,973	133	SC4.5	467,374,084	9628.74
0.2	0.35	SC1.6	468,128,110	4.47	SC2.6	467,528,294	173	SC3.6	473,379,307	112	SC4.6	467,571,472	9991.52
0.15	0.4	SC1.7	468,178,463	4.47	SC2.7	467,643,105	181	SC3.7	473,381,428	112	SC4.7	468,276,516	10331.94

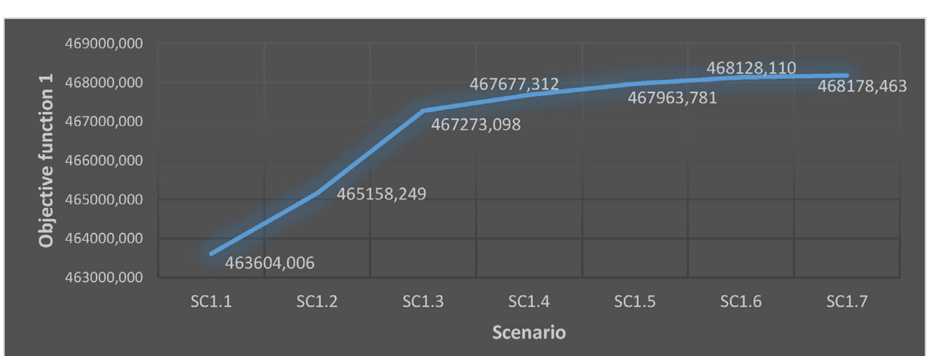

Fig. 3. The sensitivity analysis of objective function 1 regarding the changes in coefficients of objective functions 1 and 2.

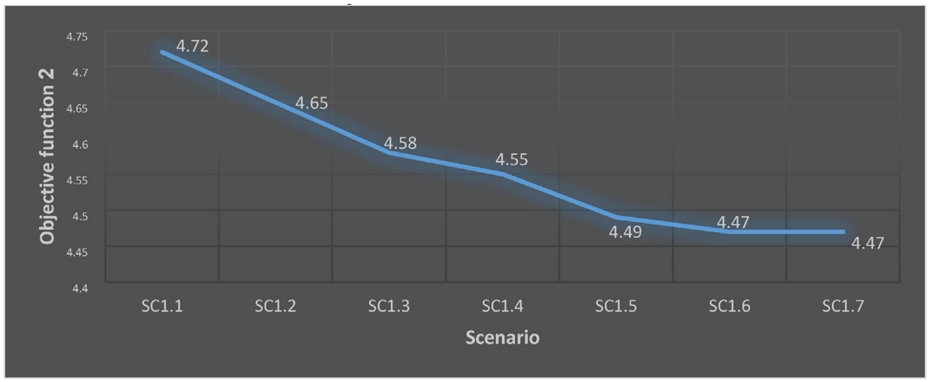

Fig. 4. The sensitivity analysis of objective function 2 based on changes in coefficients of objective functions 1 and 2.

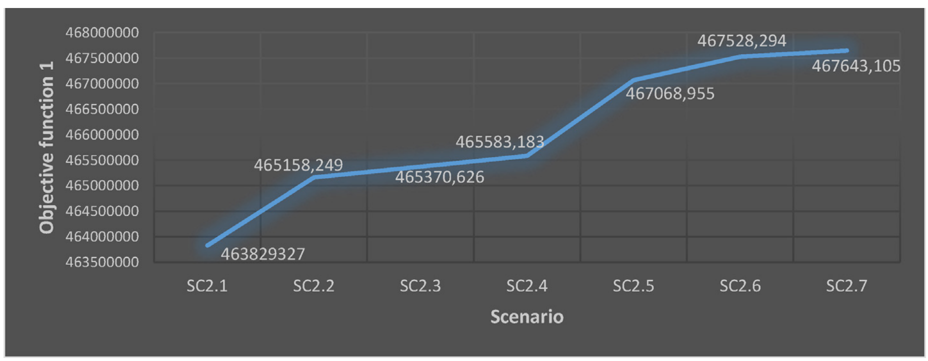

Fig. 5. The sensitivity analysis of objective function 1 regarding the changes in coefficients of objective functions 1 and 3.

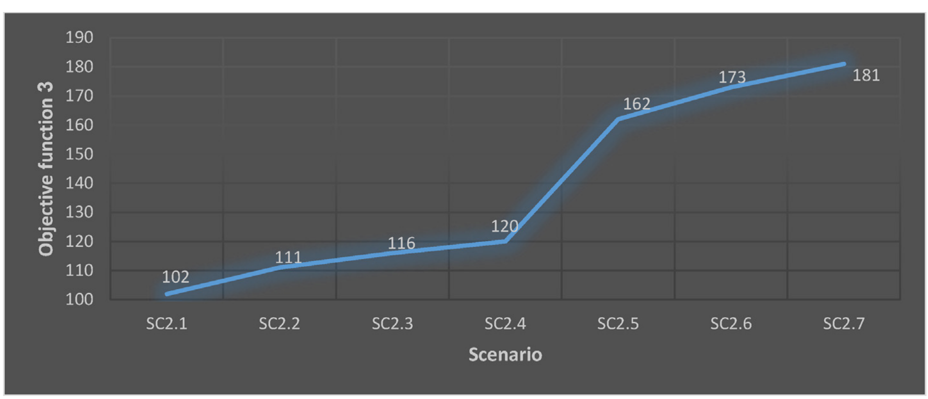

Fig. 6. The sensitivity analysis of objective function 3 regarding the changes in coefficients of objective functions 1 and 2.

function coefficient 1 and decreasing the objective function coefficient 4, simultaneously, the costs and the amount of lost sales are increased and decreased, respectively. Moreover, by decreasing the coefficient of objective function 1 and increasing that of objective function 4 simultaneously, the optimal amount of objective functions 1 and 4 are increased and decreased respectively, which shows the correct behavior of the proposed model. As shown in Fig. 7, there is a significant jump in the costs scenario SC3.5 compared to the SC3.4 scenario because in SC3.4, production center 3 is established, but the model in scenario SC3.5 suggests use production center 2. It is because the production cost and production capacity of production center 3 are lower than production center 2. Also, in Fig. 7, a significant jump in costs occurred in scenario SC3.8 compared to scenario SC3.7 due to a change in production centers establishment. In scenario SC3.8, the model decides to establish production center 1, which has higher capacity and establishment cost compared to production center 2. So this increase in cost has led to a decrease in lost sales.

- **The scenario set 4:** This part addresses the generation of scenarios according to the changes in the coefficients of objective functions 1 and 5, and those of the other objective functions are kept constant, and the proposed model is implemented for each scenario. It is expected that with an increase in the coefficient of the cost objective function, the objective function value will not deteriorate, and with a reduction in the coefficient, it will not improve. It is also predicted that with the increase and decrease of the coefficient of objective function 5, its value will not get

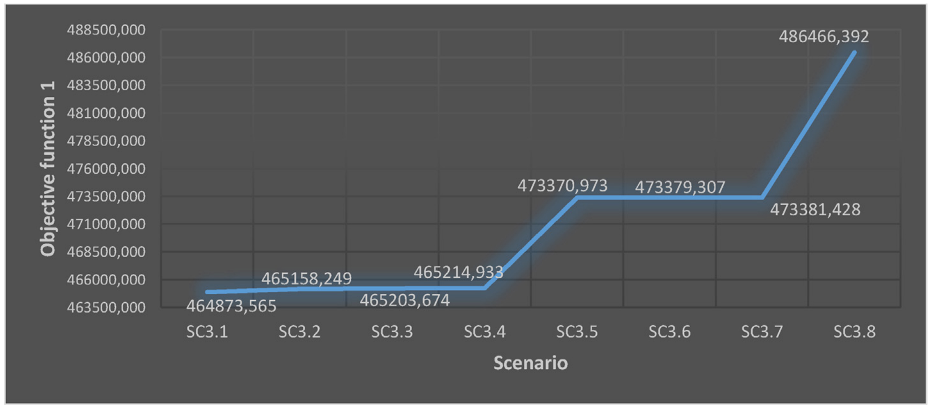

Fig. 7. The sensitivity analysis of objective function 1 regarding the changes in coefficients of objective functions 1 and 4.

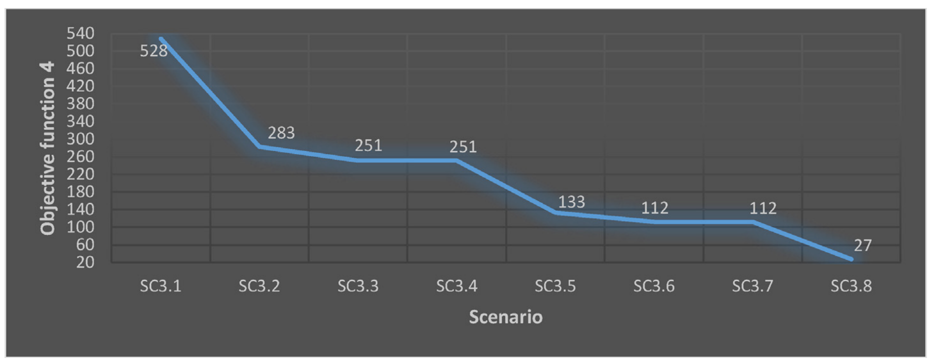

Fig. 8. The sensitivity analysis of objective function 4 regarding the changes in coefficients of objective functions 1 and 4.

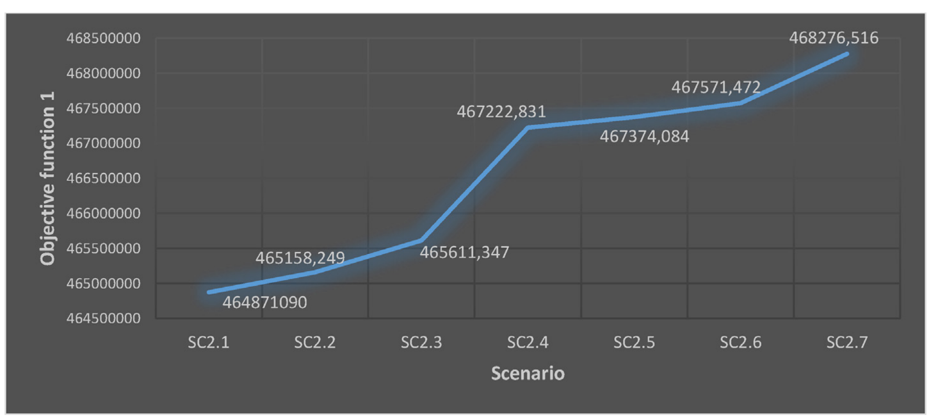

Fig. 9. The sensitivity analysis of objective function 1 regarding the changes in coefficients of objective functions 1 and 5.

worse and better, respectively. In Table 21, the above scenarios and the optimal values of objective functions 1 and 5 are given for each scenario. Also, the trend of changes in the objective functions 1 and 5 for the sensitivity analysis of their coefficients is illustrated in Figs. 9 and 10, respectively.

As expected, by increasing coefficient of objective function 1 and decreasing coefficient of the objective function 5, the optimal values of these two objective functions are decreased and also by decreasing coefficient of objective function 1 and increasing coefficient of objective function 5, the optimal values of both objective functions are increased. This indicates that the increased coefficient of objective function 5 leads to an increase in raw material purchases from suppliers 3 and 5 so that in SC4.7 scenario, raw materials are purchased just from two suppliers 3 and 5 since these two suppliers have a higher sustainability index. Therefore, the results obtained in this sensitivity analysis: (1) supports the acceptable behavior of the proposed model and (2) confirms the efficiency and effectiveness of the proposed model and the solution approach.

6. Managerial implications

As stated in the case study section, the input data are derived

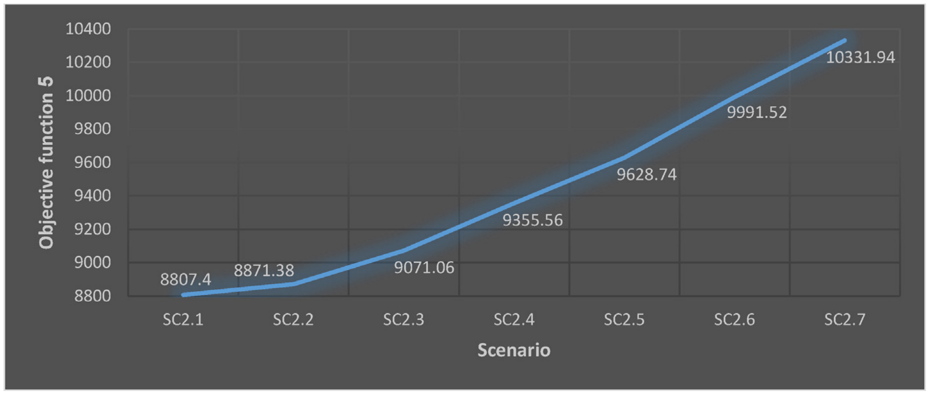

Fig. 10. The sensitivity analysis of objective function 5 regarding the changes in coefficients of objective functions 1 and 5.

from the historical documents of the studied company and simulated according to the experts' knowledge. Much of this data is related to the forward network, and a significant portion of the reverse network data is simulated. So the focus of managerial insights is on the forward chain. The studied network currently operates with production center 3, distribution centers 2, 3 and 4, and cross-docking center 1 and 3, and its overall strategy is to avoid shortages while the obtained results highlight that a network with production center 3, distribution center 2 and 3, and cross-docking center 3 is the optimal design. Although the proposed model results in 283 units of shortages, it does not establish distribution center 4 and cross-docking center 1, which would save $119,500 in establishment fixed costs.

Moreover, the network is currently operating with 8 vehicles, while the proposed model proposes to remove vehicles 3 and 5, which leads to a significant reduction ($18,700) in costs, and it has an effect on reducing pollution. It is worth mentioning that the practitioners and DMs of the network prefer to collaborate with suppliers 1, 3, and 4, rather than supplier 5. It is because this supplier has a branding issue. The proposed model proves that although supplier 5 does not have high branding credentials, he has a higher sustainability ranking and less procurement cost rather than supplier 4. Therefore, it is recommended to replace supplier 4 with supplier 5. It should be noted that both the proposed model and the DMs agree on excluding supplier 2.

7. Conclusion

To the best of our knowledge, the integrated MCDM-MOMILP approach proposed in this study is the first model to consider a sustainable CLSC network with inventory-location-routing and cross-dock scheduling components, and uncertain demand, CSS, order allocation, a quantity discount, lost sales, time window, and alternative transportation modes. The supplier evaluation criteria were obtained from the related literature and based on expert opinion from four economic, environmental, circular, and social aspects and weighted using the fuzzy BWM method. Finally, the suppliers' sustainability scores are calculated. The supply chain network is then structured using a MOMILP model and transformed into an equivalent single-objective model using a new fuzzy goal programming approach. Finally, based on expert knowledge and data from a suit production and distribution network, the proposed approach's performance is evaluated in the garment industry. The proposed model's behavior is analyzed using four categories of scenarios based on objective function coefficients. The network studied here could be extended for perishable products with disruption considerations. Since the studied problem is NP-hard, it is further recommended to solve large-scale instances with exact methods such as Lagrangian relaxation, Benders decomposition algorithms.

CRediT authorship contribution statement

Arash Khalili Nasr: Methodology, Project administration, Validation, Data curation. **Madjid Tavana:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision. **Behrouz Alavi:** Investigation, Resources, Software. **Hassan Mina:** Conceptualization, Methodology, Formal analysis, Methodology, Validation.

Declaration of Competing Interest

The above authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Indices

r	Raw material	$r\in\{1,2,...,R\}$
c	Product component	$c\in\{1,2,...,C\}$
p	Product	$p\in\{1,2,...,P\}$
s	Supplier	$s\in\{1,2,...,S\}$
m	Potential manufacturing center	$m\in\{1,2,...,M\}$
d,d'	Potential distribution center	$d,d'\in\{1,2,...,D\}$
q	Potential cross-docking center	$q\in\{1,2,...,Q\}$
k,k'	Customer	$k,k'\in\{1,2,...,K\}$
g	Potential collection center	$g\in\{1,2,...,G\}$
a	Potential remanufacturing center	$a\in\{1,2,...,A\}$
b	Potential disposal center	$b\in\{1,2,...,B\}$
e	Price level	$e\in\{1,2,...,E\}$
f	Transportation mode	$f\in\{1,2,...,F\}$
v,u	Vehicle type	$v,u\in\{1,2,...,V\}$
t	Time period	$t\in\{1,2,...,T\}$

Appendix 2. Parameters

ϑ_{st}^{SPLR}	Cost of order to supplier s in period t
ϑ_{m}^{MNF}	Fix cost of establishing manufacturing center m
ϑ_{d}^{DSTB}	Fix cost of establishing distribution center d
ϑ_{q}^{CRS}	Fix cost of establishing cross-docking center q
ϑ_{g}^{CLCT}	Fix cost of establishing collection center g
ϑ_{a}^{RMNF}	Fix cost of establishing remanufacturing center a
ϑ_{b}^{DSP}	Fix cost of establishing disposal center b
ϑ_{v}^{VH}	Cost of supplying vehicle v
ϕ_{rest}^{SPLR}	Purchase price of one unit raw material r from the supplier s at price level e in period t
ϕ_{pmt}^{MNF}	Cost of producing one unit of product p at the manufacturing center m in period t
ϕ_{pdt}^{DSTB}	Cost of processing one unit of product p at distribution center d in period t
ϕ_{pqt}^{CRS}	Cost of processing one unit of product p at cross-docking center q in period t
ϕ_{pgt}^{CLCT}	Inspection and separation cost of one unit of product p at the collection center g in period t
ϕ_{pat}^{RMNF}	Remanufacturing cost of one unit of product p at the remanufacturing center a in period t
ϕ_{pbt}^{DSP}	Cost of disposing one unit of product p at disposal center b in period t
$\eta_{rsmft}^{SPLR-MNF}$	Cost of shipping one unit of raw material r from the supplier s to manufacturing center m using transportation mode f in period t
$\eta_{pmdt}^{MNF-DSTB}$	The shipping cost of one unit of product p from manufacturing center m to distribution center d in period t
$\eta_{pkgt}^{RT-CLCT}$	The shipping cost of one unit of returned product p from customer k to collection center g in period t
$\eta_{pgat}^{CLCT-RMNF}$	The shipping cost of one unit of product p from the collection center g to remanufacturing center a in period t
$\eta_{pgbt}^{CLCT-DSP}$	The shipping cost of one unit of product p from the collection center g to disposal center b in period t
$\eta_{padt}^{RMNF-DSTB}$	The cost of shipping one unit of product p from remanufacturing center a to distribution center d in period t
$\eta_{camt}^{RMNF-MNF}$	The cost of shipping one unit of product component c from remanufacturing center a to manufacturing center m in period t
$\eta_{pabt}^{RMNF-DSP}$	The cost of shipping one unit of product p from remanufacturing center a to disposal center b in period t
ψ_{pt}^{PST}	The holding cost of one unit of product p at the warehouse of customers in period t
ψ_{pt}^{NGT}	The shortage cost of one unit of product p in period t
$\tau_{d'd}^{DSTB}$	The distance of distribution center d' from distribution center d
$\tau_{dq}^{DSTB-CRS}$	The distance between distribution center d and cross-docking center q
$\tau_{k'k}^{RT}$	The distance of the customer k' from customer k
τ_{kq}^{RT-CRS}	The distance of customer k from cross-docking center q
$\tau_{vk'k}$	The time distance between customer k' and customer k by vehicle v
$\widehat{\tau}_{vkq}$	The time distance between customer k and cross-docking center q by vehicle v
UL_k	The average unloading time at the site of customer k
φ	Time window
UP_{pest}	The upper limit of the volume of raw material r purchased from the supplier s at price level e in period t
LW_{pest}	The lower limit of the volume of raw material r purchased from the supplier s at price level e in period t
ω_{rst}^{SPLR}	The capacity of supplier s for supplying raw material r in period t
ω_{pmt}^{MNF}	The capacity of manufacturing center m for producing product p in period t
ω_{pdt}^{DSTB}	The capacity of distribution center d for product p in period t
ω_{pqt}^{CRS}	The capacity of cross-docking center q for product p in period t
ω_{pgt}^{CLCT}	The capacity of collection center g for product p in period t
ω_{pat}^{RMNF}	The capacity of remanufacturing center a for product p in period t
ω_{pbt}^{DSP}	The capacity of disposal center b for product p in period t
ω_{v}^{VH}	The capacity of vehicle v
ω_{pkt}	The demand of customer k for product p in period t
κ_{rc}^{RW-CM}	Amount of raw material r required to produce one unit of product component c
κ_{cp}^{CM-PR}	Number of product component c used in product p
κ_{pkt}^{RT}	Rate of returned product p from customer k in period t
κ_{pgt}^{CLCT}	Percentage of manufacturable product p transferred from collection center g to remanufacturing center(s) in period t
$\kappa_{pat}^{RMNF-DSTB}$	Percentage of product p transferred from remanufacturing center a to distribution center(s) in period t
$\kappa_{pat}^{RMNF-DSP}$	Percentage of product p transferred from remanufacturing center a to disposal center(s) in period t
δ_{m}^{MNF}	The amount of environmental damage for establishing manufacturing center m
δ_{d}^{DSTB}	The amount of environmental damage for establishing distribution center d
δ_{q}^{CRS}	The amount of environmental damage for establishing cross-docking center q
δ_{g}^{CLCT}	The amount of environmental damage for establishing collection center g
δ_{a}^{RMNF}	The amount of environmental damage for establishing remanufacturing center a
δ_{b}^{DSP}	The amount of environmental damage for establishing disposal center b
$\delta_{rsmft}^{SPLR-MNF}$	The amount of environmental damage for shipping each unit raw material r from supplier s to manufacturing center m by transportation mode f in period t

(*continued*)

ξ_m^{MNF}	Number of created job opportunities by opening the manufacturing center m
ξ_d^{DSTB}	Number of created job opportunities by opening the distribution center d
ξ_q^{CRS}	Number of created job opportunities by opening the cross-docking center q
ξ_g^{CLCT}	Number of created job opportunities by opening the collection center g
ξ_a^{RMNF}	Number of created job opportunities by opening the remanufacturing center a
ξ_b^{DSP}	Number of created job opportunities by opening the disposal center b
SSR_s	Sustainability score of supplier s
γ_v	Consumption of fuel by vehicle v per distance unit
σ	The cost of one unit of fuel
M	A big number

Appendix 3. Variables

$\theta_{rest}^{SPLR}\begin{cases}1\\0\end{cases}$	Binary	If supplier s is chosen for the purchase of raw material r at price level e in period t Otherwise
$\theta_m^{MNF}\begin{cases}1\\0\end{cases}$	Binary	If manufacturing center m is opened Otherwise
$\theta_d^{DSTB}\begin{cases}1\\0\end{cases}$	Binary	If distribution center d is opened Otherwise
$\theta_q^{CRS}\begin{cases}1\\0\end{cases}$	Binary	If cross-docking center q is opened Otherwise
$\theta_g^{CLCT}\begin{cases}1\\0\end{cases}$	Binary	If the collection center g is opened Otherwise
$\theta_a^{RMNF}\begin{cases}1\\0\end{cases}$	Binary	If remanufacturing center a is opened Otherwise
$\theta_b^{DSP}\begin{cases}1\\0\end{cases}$	Binary	If disposal center b is opened Otherwise
$\theta_v^{VH}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v is supplied Otherwise
$\theta_{vqt}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v is allocated to cross-docking center q for receiving products from the distribution center(s) in period t Otherwise
$\theta'_{vqt}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v is allocated to cross-docking center q for delivering products to the customer(s) in period t Otherwise
$\alpha_{vd'dt}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v travels from distribution center $d'$to distribution center d in period t Otherwise
$\alpha'_{vk'kt}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v travels from customer $k'$to customer k in period t Otherwise
$\chi_{vukt}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v arrives at customer k before vehicle u in period t Otherwise
$\mu_{resmft}^{SPLR-MNF}$	Positive	Amount of raw material r purchased from supplier s by manufacturing center m at price level e using transportation mode f in period t
$\mu_{pmdt}^{MNF-DSTB}$	Positive	Amount of product p transferred from manufacturing center m to distribution center d in period t
$\mu_{pvdqt}^{DSTB-CRS}$	Positive	Amount of product p transferred from distribution center d to cross-docking center q by vehicle v in period t
μ_{pvqkt}^{CRS-RT}	Positive	Amount of product p transferred from cross-docking center q to customer k by vehicle v in period t
$\mu_{pkgt}^{RT-CLCT}$	Positive	Amount of product p returned from customer k to collection center g in period t
$\mu_{pgat}^{CLCT-RMNF}$	Positive	Amount of product p transferred from collection center g to remanufacturing center a in period t
$\mu_{pgbt}^{CLCT-DSP}$	Positive	Amount of product p transferred from collection center g to disposal center b in period t
$\mu_{pabt}^{RMNF-DSP}$	Positive	Amount of product p transferred from remanufacturing center a to disposal center b in period t
$\mu_{padt}^{RMNF-DSTB}$	Positive	Amount of product p transferred from the remanufacturing center a to distribution center d in period t
$\mu_{camt}^{RMNF-MNF}$	Positive	Amount of product component c transferred from remanufacturing center a to manufacturing center m in period t
μ_{pvdt}	Positive	Amount of product p carried by vehicle v after departing the customer k at period t
μ'_{vkt}	Positive	Arrival time of vehicle v to the location of customer k in period t
ϖ_{pkt}^{PST}	Positive	Amount of product p in the warehouse of customer k in period t
ϖ_{pkt}^{NGT}	Positive	Amount of lost sales from product p faced by customer k at period t

Appendix 4. The nonlinear model for calculating the local weights of criteria

$$Min\ \vartheta^*$$

s.t.

$$
\begin{aligned}
&l_1^w - 2.5 \times u_2^w \le \vartheta \times u_2^w; l_1^w - 2.5 \times u_2^w \ge -\vartheta \times u_2^w \\
&m_1^w - 3 \times m_2^w \le \vartheta \times m_2^w; m_1^w - 3 \times m_2^w \ge -\vartheta \times m_2^w \\
&u_1^w - 3.5 \times l_2^w \le \vartheta \times l_2^w; u_1^w - 3.5 \times l_2^w \ge -\vartheta \times l_2^w \\
&l_1^w - 1.5 \times u_3^w \le \vartheta \times u_3^w; l_1^w - 1.5 \times u_3^w \ge -\vartheta \times u_3^w \\
&m_1^w - 2 \times m_3^w \le \vartheta \times m_3^w; m_1^w - 2 \times m_3^w \ge -\vartheta \times m_3^w \\
&u_1^w - 2.5 \times l_3^w \le \vartheta \times l_3^w; u_1^w - 2.5 \times l_3^w \ge -\vartheta \times l_3^w \\
&l_1^w - 0.667 \times u_4^w \le \vartheta \times u_4^w; l_1^w - 0.667 \times u_4^w \ge -\vartheta \times u_4^w \\
&m_1^w - m_4^w \le \vartheta \times m_4^w; m_1^w - m_4^w \ge -\vartheta \times m_4^w \\
&u_1^w - 1.5 \times l_4^w \le \vartheta \times l_4^w; u_1^w - 1.5 \times l_4^w \ge -\vartheta \times l_4^w \\
&l_3^w - 0.667 \times u_2^w \le \vartheta \times u_2^w; l_3^w - 0.667 \times u_2^w \ge -\vartheta \times u_2^w \\
&m_3^w - m_2^w \le \vartheta \times m_2^w; m_3^w - m_2^w \ge -\vartheta \times m_2^w \\
&u_3^w - 1.5 \times l_2^w \le \vartheta \times l_2^w; u_3^w - 1.5 \times l_2^w \ge -\vartheta \times l_2^w \\
&l_4^w - 1.5 \times u_2^w \le \vartheta \times u_2^w; l_4^w - 1.5 \times u_2^w \ge -\vartheta \times u_2^w \\
&m_4^w - 2 \times m_2^w \le \vartheta \times m_2^w; m_4^w - 2 \times m_2^w \ge -\vartheta \times m_2^w \\
&u_4^w - 2.5 \times l_2^w \le \vartheta \times l_2^w; u_4^w - 2.5 \times l_2^w \ge -\vartheta \times l_2^w \\
&\frac{1}{6} \times (l_1^w + l_2^w + l_3^w + l_4^w) + \frac{2}{3} \times (m_1^w + m_2^w + m_3^w + m_4^w) + \\
&\frac{1}{6} \times (u_1^w + u_2^w + u_3^w + u_4^w) = 1 \\
&l_1^w \le m_1^w \le u_1^w; l_2^w \le m_2^w \le u_2^w; l_3^w \le m_3^w \le u_3^w; l_4^w \le m_4^w \le u_4^w \\
&l_1^w, l_2^w, l_3^w, l_4^w > 0 and \vartheta \ge 0
\end{aligned}
$$

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