Designing a sustainable closed-loop supply chain network considering lateral resupply and backup suppliers using fuzzy inference system

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Abstract
Sustainability is key factor for transforming traditional supply chain networks into modern ones. This study, for the first time, considers the impacts of the backup suppliers and lateral transshipment/resupply simultaneously on designing a Sustainable Closed-Loop Supply Chain Network (SCLSCN) to decrease the shortage that may occur during the transmission of produced goods in the network. In this manner, the fuzzy multi-objective mixed-integer linear programming model is proposed to design an efficient SCLSCN resiliently. Moreover, the concept of circular economy has been studied in this paper to reduce environmental effects. This study aims to optimize total and environmental costs, including energy consumption and pollution emissions, while increasing job opportunities. A demand uncertainty component is considered to represent reality more closely. Due to the importance of demand, this parameter is estimated using the Fuzzy Inference System (FIS) as an input into the proposed mathematical model. Then, the fuzzy robust optimization approach is applied in a fuzzy set’s environment. The model is tackled by a Multi-Choice Goal Programming Approach with Utility Function (MCGP-UF) to be solved in a timely manner, and the equivalent auxiliary crisp model is employed to convert the multi-objective function to a single objective. The proposed model is tested on the case study of the tire industry in terms of costs, environmental impacts, and social effects. The result confirmed that considering the concept of lateral resupply and backup supplier could considerably decrease the total costs and reduce shortages on the designed SCLSCN. Finally, sensitivity analysis on some crucial parameters is conducted, and future research directions are discussed.

Keywords Sustainable closed-loop supply chain network · Fuzzy robust optimization · Lateral transshipment/resupply · Backup suppliers · Fuzzy inference system · Circular economy

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1 Introduction

During the last two decades, the concept of Sustainability in Closed-Loop Supply Chain Network (CLSCN) has been widely expanded by multi-national corporations that have committed to reducing the undesirable effects of industrialization (Ahmed et al., 2020; Ebrahimi & Momenitabar, 2017). Many businesses are still improving CLSCN by adopting sustainability factors into their network through considering real challenges, such as climate change, social legislation/regulation, environmental pollution, etc. Therefore, they must find ways to address these challenges that have unprecedented adverse effects on the entire network.

On the other hand, the concept of Circular Economy (CE) is increasingly considered in CLSCN, which empowers companies and organizations to collaborate, innovate in ways that assume resource scarcity and climate risk, and respond to consumer and community pressure to reduce waste. Indeed, CE aims to maintain components, products, and materials in CLSCN at the highest level of utility and its value always. This concept is a new approach for production and distribution companies to deal with sustainability challenges and resource consumption efficiency.

The uncertainty concept in designing a Sustainable Closed-Loop Supply Chain Network (SCLSCN) makes it a strategic necessity for companies to identify products’ future demand and market share. In this way, the Fuzzy Inference System (FIS) is one of the efficient and widely used approaches in demand estimation utilized in this study (Sridharan, 2021). The features of this approach not only make it possible to analyze and predict the state of complex markets but also lead to a comprehensive understanding of the fundamental market mechanism. Therefore, in this study, the criteria to forecast demand are identified using FIS to be imported into the mathematical model as a parameter discussed later in detail.

Our model was inspired by a real-world difficulty faced by manufacturing; however, because many businesses experience similar problems, the model was built to be general. The problem here is that customers order products based on their needs, and the manufacturers have to make the products customers want. On the other hand, manufacturers must obtain their raw material from primary or secondary suppliers, whichever opened/selected (output of proposed mathematical model). By obtaining raw materials, manufacturers build customers’ products based on the Bill of Material (BOM). The produced products are sent to the distribution center to be delivered to the customers. During this time, customers may be unsatisfied with their products, so they might want to return them to the manufacturers. In this way, the returned items will be gathered at collection centers, and they will be checked in terms of suitability. After inspection, if the returned items/goods are detected to be usable again, they will send to the manufacturing centers to be repaired for reusing. If they are seen as not functional, they will send to the disposal center to be disposed. Based on that, in order to address this problem, in reality, we selected the tire industry in Iran as the case study of this research. The tire industry is a growing industry with recyclable goods that are expected to increase at a rate of 3.8 percent each year through 2025, according to predictions (Markets, 2025). This growth in demand shows how the tire industry’s actions can have an impact on a country’s economy, environment, and society.

Figure 1 shows a framework of this study for designing an efficient SCLSCN under uncertainty. This framework intends first to estimate demand using FIS and then optimize SCLSCN by minimizing the total costs of the network, the total environmental effects, and maximizing the social effects through applying the Fuzzy Robust Optimization (FRO) approach. Moreover, we consider both planning decisions, including
the inventory level of products at manufacturing centers and distribution centers, the number of the finished product at manufacturing centers, and the number of product transferred between different centers of the network and strategic decisions, including the selection of primary and secondary suppliers and facility locations into the model. Indeed, this study considered the secondary suppliers as a backup supplier to support primary suppliers in the first level and concept of lateral transshipment/resupply through substituting products between manufacturing centers as well as distribution centers to avoid shortage during the transmission of produced goods in the network.

We develop a novel fuzzy multi-objective mixed-integer linear programming (FMO-MILP) model to design an efficient SCLSCN by minimizing the total costs of the network, the total environmental effects, and the social effects. This study, for the first time, considered the backup suppliers and lateral transshipment/resupply simultaneously to decrease the shortage that may occur during the transmission of produced goods in the network. Because of the essence of demand parameters, we estimate this parameter using FIS that will be used as input into the proposed mathematical model. Then, we utilized the FRO approach to present the mathematical model in a fuzzy sets environment and tackled it by Multi-Choice Goal Programming Approach with Utility Function (MCGP-UF) approach in a timely manner. Furthermore, before solving the proposed model, we employed the Equivalent Auxiliary Crisp (EAC) model to convert the multi-objective function to a single objective. The model’s computational requirements are analyzed as well. Regarding this, we are looking for answers to the following questions as follows:
• Which centers of the SCLSCN should be opened to transfer the finished products to the customer and return it to the collection centers?
• How many products should be transformed to avoid shortages that may occur at manufacturing centers and distribution centers?
• What would be the total costs, total environmental effects, and social effects of various centers when they are opened?

The remaining parts of the paper are organized as follows. In Sect. 2, the literature review on SCLSCN are discussed. The main contribution of this work has been explained in Sect. 3. Also, the mathematical modeling and solution methodology are proposed and discussed in Sects. 4 and 5. The tire case study, results, and the sensitivity of the model are investigated in Sect. 6. Finally, Sect. 7 provides concluding remarks and future research directions of this study.

2 Literature review

In this section, we briefly present some works done in the past by authors and some literature reviews on SCLSCN design. Some comprehensive literature reviews have been conducted in recent years (Battini et al., 2017; Govindan et al., 2015; ildizbaşı, 2021; Khalili Nasr et al., 2020; Mehrjerdi & Shafiee, 2020; Rajak, 2021; Souza, 2013; Zhalechian et al., 2016). In the following paragraphs, we will discuss different aspects of SCLSCN comprehensively.

2.1 Sustainability scale of closed-loop supply chain network

The SCLSCN consists of two parts, including forward and reverse flow (Cilacı Tombuş et al., 2017). A lack of concern for uncertainty in the real world can prevent companies from meeting the needs of their customers. Uncertainty in today’s world is an essential part of every SCLSCN. Many researchers have considered the concept of uncertainty in both demand and supply when designing a SCLSCN (Ahmed et al., 2020; Arani et al., 2021; Zhalechian et al., 2016). Zhalechian et al. (2016) formulated a stochastic-possibilistic programming model to handle the uncertainty of SCLSCN for large-sized problems by using a hybrid meta-heuristic algorithm and lower bounds. Mehrjerdi et al. (2020) included the interaction of sustainability and resilience simultaneously to design a SCLSCN. They used the fuzzy TOPSIS method to rank supply chain strategies, such as holding additional inventory, backup capacity, multiple sourcing, and so on (ildizbaşı, 2021). Khalili Nasr et al. (2020) utilized the fuzzy best-worst method to select the best suppliers. By proposing a multi-objective mixed-integer linear programming model, they could design a multi-product, multi-period, SCLSCN. Uncertain parameters such as demand and return products were considered by Amin and Zhang (2013). They employed a scenario-based analysis to face uncertainty in their proposed model by using stochastic programming formulation and applying the weighted sums method as well as the Epsilon constraint method to solve their proposed model. Burton et al. (2005) analyzed the cost effects of two lateral (intra-echelon) transshipment approaches in a two-echelon supply chain network, with a single supply source at the higher echelon and multiple retail locations at the lower, using a series of simulation experiments under different operating conditions. Ghomi-Avili et al. (2019) proposed a multi-objective model for designing the CLSCN with a price-dependent
demand while considering random disruptions and shortage. They have considered various resilience strategies, including lateral transhipment among production centers and multi-source allocation to model the resilient supply chain network design problem.

Ahmed et al. (2020) designed a new green supply chain design approach for maintaining the financial virtue accompanying the environmental factors, proposing a multi-objective mathematical model to minimize the total costs and CO_2 emissions. They solved the model by applying two optimization models, ε-constraint method, and genetic algorithm (GA). Goodarzian et al. (2021) used a production-distribution-inventory-allocation-location problem to design a sustainable medical supply chain network by considering three hybrid meta-heuristic algorithms, including ant colony optimization, fish swarm algorithm, and firefly algorithm to solve their model. Soleimani et al. (2017) studied a SCLSCN with multiple levels, multiple products, and multiple periods by applying the GA to solve their model. Rezaei and Kheirkhah (2018) proposed a mathematical model for designing the SCLSCN based on economic, environmental, and social requirements by applying cross-docking operations. Indeed, they utilized a cuckoo optimization algorithm for the first time to tackle their model.

According to Hillier and Lieberman (2012), the lateral transshipment concept is a variant of the minimum cost flow problem in which products move through intermediary transfer locations on their way from one source to another. Reduced total network costs, increased service levels (Tracht et al., 2011), and reduced interruption risk are all advantages of transshipment (Jabbarzadeh et al., 2018). Only a few scholars have incorporated transshipment into their models, despite the fact that it delivers the aforesaid benefits and simplifies CLSC design. Arani et al., (2021) presented a mixed-integer mathematical programming model to design a sustainable supply chain network design under uncertainties through considering the concept of lateral transshipment. They showed that considering this concept could allow hospitals to satisfy their demand from more than one source. Jabbarzadeh et al. (2018) considered an SCLSCN subject to random disruption risks. They found that including lateral transshipment was useful to overcome disruption risks. Another study by Samuel et al. (2021) integrated a model to design a multi-component multi-product SCLSCN with economic scale to locate the processing centers, transshipment of inspected products between centers, and reliability of returned products. Lastly, Tracht et al. (2011) applied a simulation model to design a multi-echelon spare-part closed-loop supply chain, in which spare parts are repaired and led back to stock after removal from a broken machine. Also, they found that utilizing the concept of lateral transshipments leads to reducing the total cost of the model. It was also found that higher loan costs resulted in longer stock-outs. For more information, readers are referred to Ahmed et al. (2020), Ebrahimi & Momenitabar (2017), Safaei et al. (2022), Momenitabar et al. (2013).

2.2 Circular economy and demand forecasting aspects of SCLSCN

Some studies considered the concept of CE in SCLSCN (Genovese et al., 2017; Nasir et al., 2017). Abdul Nasir et al. (2017) applied a case study in the construction industry to show how the environmental effects by including carbon emissions can be achieved by CE principles. They could benefit from integrating the concept of CE into a sustainable supply chain network in terms of environmental gains. Genovese et al. (2017) considered two studies to
compare the performance of traditional and circular production systems. They concluded that the integration of CE with SCLSCN provided clear advantages in terms of environmental effects. Rashedul Kabir et al. (2021) proposed an improved network design of an open-loop reverse supply chain of a water treatment plant using circular economy that had benefits such as reducing environmental burdens, enhancing the protection of raw material supply, increasing competition, promoting productivity, boosting sustainable economic growth, and creating employment. Computational experiments showed that when the number of the returned product increases, the total profit increases, which leads to achieving the circular economy with the most efficiency.

Some studies designed a decision support system to predict the demand for medical equipment in the event of a COVID-19 outbreak pandemic (Govindan et al., 2019). A FIS is used to predict the amount of demand. Criteria for predicting demand include patient age, fatigue, number of coughing hours, fever, and fatigue. The results indicated the proper performance of the proposed system (Govindan et al., 2019). Nabavi et al. (2019) predicted white rice demand by considering some criteria, including transportation, machinery, electricity, and human labor. The neural network approach has been used to calculate the weight of the criteria. The results showed an accurate prediction of the proposed model. Souza et al. (2020) predicted the demand of the beauty industry by four FIS-based methods. The result indicated that the proposed predicting models for short-term and long-term performance had performed well.

3 Summary of literature review and motivation

To the authors’ knowledge, a few studies considered the concept of lateral transshipment/resupply by substituting the final products at manufacturing and distribution centers to prevent shortage as well as concepts of the backup supplier in their studies. Indeed, lateral transshipment/resupply is a type of inventory system that permits manufacturing center to satisfy its demand by other manufacturing inventories in the absence of other required products. Also, considering backup suppliers help the manufacturing centers to meet their needs. More interestingly, demand estimation is an essential task for reaching more accurate results which plays as an input to the model by solving the mathematical model of this study. Regarding this, the main contribution of this study that makes a sharp distinction between this study and related studies are as follows:

- Proposing a new formulation of designing a SCLSCN by applying Fuzzy Robust Optimization model in the fuzzy set environment,
- Utilizing the Multi-Choice Goal Programming with Utility Function (MCGP-UF) to solve the proposed mathematical model in a deterministic environment,
- Considering the backup supplier as supporter role for a primary supplier in the first level of the network as well as the concept of lateral transshipment/resupply in manufacturing and distribution centers to prevent shortages, and
- Utilizing the customized Fuzzy Inference Systems method to estimate the required demands as an input to the designed network.
4 Mathematical modeling

This section firstly plans to propose the problem statement and then presents the mathematical model of this study. Before proposing the mathematical model, we will explain how we estimate the demand parameter using FIS as an input to the mathematical model (Momenitabar et al., 2020).

4.1 Problem statement

This paper addresses the design of multi-echelon, multi-products, and multi-periods SCLSCN, which comprises various layers, including primary suppliers and secondary suppliers at the first level, manufacturing centers at the second level, distribution centers at the third level, customers at the fourth level, and collection and disposal centers at the fifth and sixth levels, respectively.

The SCLSCN studied in this paper is constituted by forward and reverse flows. Primary suppliers, secondary suppliers, manufacturing centers, distribution centers, and customers are placed in forwarding flow, while collectors and disposal centers are placed in reverse flows of the proposed network. In the first level, primary suppliers and secondary suppliers are responsible for preparing the raw material for manufacturing centers at the second level by sending them to the manufacturing centers to produce the products according to BOM at manufacturing centers. Then, the made products are shipped to the customers through distribution centers. In the reverse flow, the returned products are gathered by collection centers. The purpose of collecting the returned products by customers is to fulfill the needs of customers through recovering or repairing the returned products. The returned products are sent to the collection centers to check if they can be used again or not. After careful inspection, the returned products are either returned to the manufacturing centers or sent to the disposal centers as scrapped products.

The demand for products happens in the fourth layer, where the customer is located. As we can see from Fig. 2, the demand can be fulfilled by sending generated products from the distribution centers to the customers. On the other hand, due to the nature of the case study discussed in Sect. 6, the demand for this study is considered as an uncertain parameter as estimated using FIS that will be addressed in the following sub-section.

4.2 Fuzzy inference system (FIS)

The FIS procedure applied in this research is shown in Fig. 3. First, the criteria for determining the amount of demand are selected by experts and converted to a fuzzy number. Then, fuzzified criteria are entered into the fuzzy inference engine. In this process, linguistic membership functions are first defined, and then the desired operators are customized. In the next step, the rules set by the experts are evaluated and aggregated by the relevant operators. In the last step, the required amount of demand is estimated.

Mamdani Inference System was first introduced by Mamdani et al. (1975). Due to its visual nature, this system can be widely used in decision support systems. The steps of Mamdani FIS are described in the following sections.
4.2.1 Identifying demand criteria

In this study, an expert is a person who has at least five years of experience in relevant work and at least a bachelor’s degree. According to the statistical population, 30 people have the conditions as an expert to be selected. Based on experts’ opinions, five criteria have been chosen by using the Fuzzy Delphi Approach to predict demand. Selected criteria include the product price, product quality, environmental impact, advertising, and product availability. In Fig. 4, we have shown these criteria selected by the experts.
The terms Moderate Importance (MI), Weak Importance (WI), and Strong Importance (SI) have also been used to weight the selected criteria. Table 1 shows how these three criteria are weighted.

### 4.2.2 Fuzzification and generating membership functions

In this step, the membership function, inputs, and outputs (demand) are determined. The numbers considered in this function are fuzzy triangular. Also, the linguistic terms considered in this research include High (H), Medium (M), and Low (L). Figure 5 shows the fuzzy structure that has been considered in this study.

### 4.2.3 Apply fuzzy operators

Mamdani Inference System has been used as fuzzy operators. Therefore, the operator’s min and multiplication are used to process each rule. Equations (1) and (2) show how these operators are used in this study.

\[
R(U, V) = \min [\mu_A(u), \mu_B(u)]
\]  

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**Table 1** The linguistic weighting terms for criteria

| Linguistic terms               | Fuzzy set          |
|-------------------------------|--------------------|
| Weak importance (WI)          | (0, 0.2, 0.4)      |
| Moderate importance (MI)      | (0.2, 0.4, 0.6)    |
| Strong importance (SI)        | (0.6, 0.8, 1)      |
4.2.4 Rule evaluation

Rules evaluation is the central part of the FIS, and it is determined as “if–then” based on expert opinion. A fuzzy rule can be “if $x_1$ is $a_1$ AND $x_2$ is $b_1$ THEN $y$ is $c_1$” so $x_1$, $x_2$, $y$ are considered variables, and $a$, $b$, $c$ are the linguistic variables. As an example, Table 2 shows the rules produced by Decision Maker 1. Rule 1, for example, states that demand is high

\[
R(U, V) = \mu_A(u) \cdot \mu_B(u)
\]  

(2)

### Table 2 Proposed rules of the decision-mer 1

| Rules | Criteria          | Price | Quality | Environmental impact | Advertisement | Availability | Demand |
|-------|-------------------|-------|---------|----------------------|---------------|--------------|--------|
| Rule 1 |                   | L     | M       | L                    | M             | H            | H      |
| Rule 2 |                   | L     | H       | M                    | H             | M            | H      |
| Rule 3 |                   | M     | H       | L                    | M             | M            | H      |
| Rule 4 |                   | M     | H       | M                    | H             | H            | H      |
| Rule 5 |                   | M     | L       | M                    | M             | L            | M      |
| Rule 6 |                   | M     | L       | M                    | M             | M            | M      |
| Rule 7 |                   | M     | M       | M                    | M             | M            | M      |
| Rule 8 |                   | L     | M       | L                    | H             | H            | M      |
| Rule 9 |                   | M     | M       | L                    | H             | H            | M      |
| Rule 10|                   | M     | M       | L                    | H             | M            | M      |
| Rule 11|                   | H     | L       | H                    | L             | M            | L      |
| Rule 12|                   | H     | M       | M                    | M             | L            | L      |
| Rule 13|                   | M     | L       | H                    | L             | M            | L      |
| Rule 14|                   | H     | L       | M                    | M             | L            | L      |
| Rule 15|                   | H     | M       | M                    | M             | M            | L      |
| Rule 16|                   | M     | L       | H                    | L             | L            | L      |
if price, quality, environmental impact, advertising, and availability are low, medium, low, medium, and high, respectively.

### 4.3 Mathematical model

This sub-section details the mathematical model of this study, as illustrated in Sect. 4.1. Also, before proposing the formulation of this study, we need to define some assumptions to build the model in a proper way. The assumptions include but are not limited to:

- The concept of “Lateral Resupply” is considered to avoid the shortage that may occur at manufacturing centers and distribution centers.
- The length of each period is one day.
- The candidate locations of primary and secondary suppliers are fixed.
- Manufacturing centers are fed by both primary and secondary suppliers. Indeed, the secondary suppliers play a role as a supporter for primary suppliers to avoid shortages in different periods.
- Capacity is limited at each level of the proposed SCLSCN.
- The demand and supply are considered uncertain. Also, the demand parameter is estimated by the FIS procedure, as is discussed in Sect. 4.2 in detail.

Figure 6 displays the framework of the proposed model, considering main inputs or parameters, objective functions that include two minimizing objective functions and one maximizing objective function, constraints that build the feasible solution of the proposed model, and main outputs that state the number of decisions variables in a deterministic space as they will be reported in Sect. 6.

The sets, parameters, and variables of this study are presented in detail in Tables 3, 4, 5, 6, and 7.

![Fig. 6 The framework of the proposed model](image-url)
After defining sets, parameters, and variables, the mathematical model of this study is presented as follows:

\[ Z_{\text{FixedCost}} = \left( \sum_{m} FC_{m}^{1} \cdot OE_{m}^{1} + \sum_{d} FC_{d}^{2} \cdot OE_{d}^{2} + \sum_{o} FC_{o}^{3} \cdot OE_{o}^{3} + \sum_{r} FC_{r}^{4} \cdot OE_{r}^{4} \right) \]

\[ + \left( \sum_{p} CPS_{p}^{1} \cdot PS_{p} + \sum_{b} CPS_{b}^{2} \cdot SS_{b} \right) \]

\[ + \left( \sum_{a} \sum_{p} PPS_{ap}^{1} \cdot PS_{p} + \sum_{a} \sum_{b} PPS_{ab}^{2} \cdot SS_{b} \right) \]

(3)

\[ Z_{\text{TransportationCost}} = \left( \sum_{o} \sum_{m} \sum_{i} TR_{i}^{1} \cdot R_{i}^{1} + \sum_{a} \sum_{b} \sum_{l} TR_{l}^{2} \cdot R_{l}^{2} + \sum_{e} \sum_{d} \sum_{t} TR_{t}^{3} \cdot R_{t}^{3} \right) \]

\[ + \sum_{e} \sum_{d} \sum_{t} TR_{t}^{4} \cdot R_{t}^{4} + \sum_{e} \sum_{t} \sum_{r} TR_{r}^{5} \cdot R_{r}^{5} \]

\[ + \sum_{e} \sum_{o} \sum_{c} TR_{c}^{6} \cdot R_{c}^{6} \]

(4)

\[ Z_{\text{PurchaseCost}} = \sum_{e} \sum_{m} \sum_{l} PC_{l} \cdot Q_{l} + \sum_{e} \sum_{d} \sum_{t} PP_{t}^{3} \cdot R_{t}^{3} + \sum_{e} \sum_{o} \sum_{c} PP_{c}^{4} \cdot R_{c}^{4} \]

(5)

\[ Z_{\text{Holding - ShortageCost}} = \sum_{e} \sum_{m} \sum_{l} HC_{l}^{1} \cdot I_{l}^{1} + \sum_{e} \sum_{d} \sum_{t} HC_{t}^{2} \cdot I_{t}^{2} + \sum_{e} \sum_{o} \sum_{t} HC_{t}^{3} \cdot I_{t}^{3} \]

(6)

\[ Z_{\text{DisposalCost}} = \sum_{e} \sum_{o} \sum_{r} \sum_{t} DC_{t} \cdot \eta_{r}^{2} \cdot R_{r}^{7} \]

(7)
The first objective function, which is shown by Eq. (8) consists of five sub-functions that aim to minimize the total costs of the network. The first term is Eq. (3) that minimizes the total fixed costs of SCLSCN, while Eq. (4) aims at minimizing the total transportation.
### Table 5  Certain parameters

| Parameters | Name of parameters |
|------------|--------------------|
| $TR^1_{apmt}$ | Transportation cost of transferring raw material $a$ from primary suppliers $p$ to manufacturing center $m$ in period $t$ |
| $TR^2_{bmt}$ | Transportation cost of transferring raw material $a$ from secondary suppliers $b$ to manufacturing center $m$ in period $t$ |
| $TR^3_{edm}$ | Transportation cost of transferring product type $e$ from manufacturing center $m$ to distribution center $d$ in period $t$ |
| $TR^4_{edct}$ | Transportation cost of transferring product type $e$ from distribution center $d$ to customer $c$ in period $t$ |
| $TR^5_{ecot}$ | Transportation cost of transferring product type $e$ from customer $c$ to collection center $o$ in period $t$ |
| $TR^6_{eom}$ | Transportation cost of transferring product type $e$ from collection center $o$ to manufacturing center $m$ in period $t$ |
| $TR^7_{eort}$ | Transportation cost of transferring product type $e$ from collection center $o$ to disposal center $r$ in period $t$ |
| $PP^1_{emt}$ | The price of purchasing product type $e$ from manufacturing center $m$ in period $t$ |
| $PP^2_{edt}$ | The price of purchasing product type $e$ from distribution center $d$ in period $t$ |
| $PP^3_{ect}$ | The price of purchasing product type $e$ from customer $c$ in period $t$ |
| $PP^4_{cot}$ | The price of purchasing product type $e$ from collection center $o$ in period $t$ |
| $PC^1_{emt}$ | The production cost of product $e$ in manufacturing center $m$ in period $t$ |
| $EP^1_{pmt}$ | The amount of pollution emission through transportation between primary supplier $p$ and manufacturing center $m$ in period $t$ |
| $EP^2_{bmt}$ | The amount of pollution emission through transportation between secondary supplier $b$ and manufacturing center $m$ in period $t$ |
| $EP^3_{mdt}$ | The amount of pollution emission through transportation between manufacturing center $m$ and distribution center $d$ in period $t$ |
| $EP^4_{dct}$ | The amount of pollution emission through transportation between distribution center $d$ and customer $c$ in period $t$ |
| $EP^5_{cot}$ | The amount of pollution emission through transportation between customer $c$ and collection center $o$ in period $t$ |
| $EP^6_{omt}$ | The amount of pollution emission through transportation between collection center $o$ and manufacturing center $m$ in period $t$ |
| $EP^7_{ort}$ | The amount of pollution emission through transportation between collection center $o$ and disposal center $r$ in period $t$ |
| $CW^1_{mt}$ | The amount of water consumed at manufacturing center $m$ in period $t$ |
| $CW^2_{dt}$ | The amount of water consumed at distribution center $d$ in period $t$ |
| $CW^3_{ot}$ | The amount of water consumed at the collection center $o$ in period $t$ |
| $CW^4_{rt}$ | The amount of water consumed at the disposal center $r$ in period $t$ |
| $CE^1_{mt}$ | The amount of energy consumed at manufacturing center $m$ in period $t$ |
| $CE^2_{dt}$ | The amount of energy consumed at distribution center $d$ in period $t$ |
| $CE^3_{ot}$ | The amount of energy consumed at collection center $o$ in period $t$ |
| $CE^4_{rt}$ | The amount of energy consumed at disposal center $r$ in period $t$ |
| $PE^1_{mrt}$ | The amount of emitted pollution at manufacturing center $m$ in period $t$ |
| $PE^2_{drt}$ | The amount of emitted pollution at distribution center $d$ in period $t$ |
| $PE^3_{ort}$ | The amount of emitted pollution at collection center $o$ in period $t$ |
| $PE^4_{rtr}$ | The amount of emitted pollution at disposal center $r$ in period $t$ |
| $HC^1_{emt}$ | Holding cost of product type $e$ in manufacturing center $m$ in period $t$ |
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Table 5 (continued)

| Parameters | Name of parameters |
|------------|--------------------|
| $HC_{edt}^2$ | Holding cost of product type $e$ in distribution center $d$ in period $t$ |
| $HC_{eot}^3$ | Holding cost of product type $e$ in collection center $o$ in period $t$ |
| $DC_{ert}^4$ | Disposal cost of product type $e$ in disposal center $r$ in period $t$ |
| $a_m$ | The quantity of raw material $a$ to produce one finished product |
| $n_{iec}^1$ | The percentage of scrapped products type $e$ returned from customer zone $c$ |
| $n_{iec}^2$ | The percentage of products type $e$ scrapped from collection center $o$ |

Table 6 Binary variables

| Binary variables | Name of binary variables |
|------------------|--------------------------|
| $OE_{mt}^1$ | If manufacturing center $m$ is opened 1, otherwise 0 |
| $OE_{dt}^2$ | If distribution center $d$ is opened 1, otherwise 0 |
| $OE_{o}^3$ | If collection center $o$ is opened 1, otherwise 0 |
| $OE_{r}^4$ | If disposal center $r$ is opened 1, otherwise 0 |
| $PS_p^1$ | If primary supplier $p$ is selected 1, otherwise 0 |
| $SS_b^2$ | If secondary supplier $b$ is selected 1, otherwise 0 |
| $Y_{1pmt}^1$ | If primary supplier $p$ is assigned to manufacturing center $m$ in period $t$ is 1, otherwise 0 |
| $Y_{2bmt}^2$ | If secondary supplier $b$ is assigned to manufacturing center $m$ in period $t$ is 1, otherwise 0 |
| $Y_{3mdt}^3$ | If manufacturing center $m$ is assigned to distribution center $d$ in period $t$ is 1, otherwise 0 |
| $Y_{4dct}^4$ | If distribution center $d$ is assigned to customer $c$ in period $t$ is 1, otherwise 0 |
| $Y_{5cot}^5$ | If customer $c$ is assigned to collection center $o$ in period $t$ is 1, otherwise 0 |
| $Y_{6omt}^6$ | If collection center $o$ is assigned to manufacturing center $m$ in period $t$ is 1, otherwise 0 |
| $Y_{7ort}^7$ | If collection center $o$ is assigned to disposal center $r$ in period $t$ is 1, otherwise 0 |

The costs of the network. Equation (5) minimizes the total production cost at manufacturing centers as well as purchasing prices of products at all the centers except primary suppliers, secondary suppliers, and customer’s centers. Equation (6) is designed to minimize the number of inventories at manufacturing centers and distribution centers, while Eq. (7) minimizes the disposal costs of disposal centers for scrapped products returned from the collection centers after inspection.

$$Z_{\text{consumption}} = \left( \sum_{m} \sum_{t} CW_{mt}^{1} \cdot OE_{mt}^{1} + \sum_{d} \sum_{t} CW_{dt}^{2} \cdot OE_{dt}^{2} + \sum_{o} \sum_{t} CW_{o}^{3} \cdot OE_{o}^{3} + \sum_{r} \sum_{t} CW_{r}^{4} \cdot OE_{r}^{4} \right)$$

$$+ \left( \sum_{m} \sum_{t} CE_{mt}^{1} \cdot OE_{mt}^{1} + \sum_{d} \sum_{t} CE_{dt}^{2} \cdot OE_{dt}^{2} + \sum_{o} \sum_{t} CE_{o}^{3} \cdot OE_{o}^{3} + \sum_{r} \sum_{t} CE_{r}^{4} \cdot OE_{r}^{4} \right)$$

$$+ \left( \sum_{m} \sum_{t} PE_{mt}^{1} \cdot OE_{mt}^{1} + \sum_{d} \sum_{t} PE_{dt}^{2} \cdot OE_{dt}^{2} + \sum_{o} \sum_{t} PE_{o}^{3} \cdot OE_{o}^{3} + \sum_{r} \sum_{t} PE_{r}^{4} \cdot OE_{r}^{4} \right)$$

(9)
The second objective function, shown by Eq. (11), plans to minimize total emissions and resource consumption of the network, which is embodied by two parts. The first part is related to the water consumption, electricity consumption, and pollution created by these utilities, which is shown by Eq. (9). While, the second part, Eq. (10), tries to minimize the emissions created by transporting finished products and raw materials between different centers of the network.

\[
Z_{\text{Environmental}} = Z_{\text{consumption}} + Z_{\text{Emission}}
\]

\[
\text{Min } Z_{\text{Environmental}}^2 = Z_{\text{consumption}} + Z_{\text{Emission}}^2
\]  

Table 7 Non-negative variables

| Variables | Name of variables |
|-----------|-------------------|
| \( R_{\text{apmt}}^{1}\) | The amount of transferring raw material \( a \) from primary suppliers \( p \) to manufacturing center \( m \) in period \( t \) |
| \( R_{\text{abmt}}^{2}\) | The amount of transferring raw material \( a \) from secondary suppliers \( b \) to manufacturing center \( m \) in period \( t \) |
| \( R_{\text{emdt}}^{3}\) | The amount of transferring product type \( e \) from manufacturing center \( m \) to distribution center \( d \) in period \( t \) |
| \( R_{\text{edct}}^{4}\) | The amount of transferring product type \( e \) from distribution center \( d \) to customer \( c \) in period \( t \) |
| \( R_{\text{ecot}}^{5}\) | The amount of returned product type \( e \) from customer \( c \) to collection center \( o \) in period \( t \) |
| \( R_{\text{ecomt}}^{6}\) | The amount of returned product type \( e \) from collection center \( o \) to manufacturing center \( m \) in period \( t \) |
| \( R_{\text{eort}}^{7}\) | The amount of returned product type \( e \) from collection center \( o \) to disposal center \( r \) in period \( t \) |
| \( I_{\text{emt}}^{1}\) | The inventory level of product type \( e \) in manufacturing center \( m \) in period \( t \) |
| \( I_{\text{edt}}^{2}\) | The inventory level of product type \( e \) in distribution center \( d \) in period \( t \) |
| \( I_{\text{eot}}^{3}\) | The inventory level of product type \( e \) in collection center \( o \) in period \( t \) |
| \( X_{\text{emm}}^{4}\) | The number of product type \( e \) that is transshipped from manufacturing center \( m \) to manufacturing center \( m' \) in period \( t \) |
| \( X_{\text{edd}}^{5}\) | The number of product type \( e \) that is transshipped from distribution center \( d \) to distribution center \( d' \) in period \( t \) |
| \( Q_{\text{emt}}^{6}\) | The production quantity of product \( e \) at manufacturing center \( m \) in period \( t \) |
The third objective function proposed by Eq. (14) aims to maximize the social effects comprised of the total number of workers employed when some centers are opened. This objective function is structured into two parts, including fixed- and variable-job opportunities which are shown by Eqs. (12) and (13).

After proposing the three objective functions above, we need to build a feasible solution by providing some constraints.

Assignment constraints:

$$\sum_p Y^1_{pmt} + \sum_b Y^2_{bmt} = 1, \forall m, t$$

$$\sum_p Y^1_{pmt} \leq OE^1_{m}, \forall m, t$$

$$\sum_b Y^2_{bmt} \leq OE^1_{m}, \forall m, t$$

$$\sum_m Y^3_{mdt} \leq OE^2_{d}, \forall d, t$$

The first group of constraints is assignment constraints which are stated by Eq. (15)–(18). Indeed, the aims of constructing these equations are to set up some centers in the proposed network.

Capacity constraints:

$$R^1_{apmt} \leq \tilde{C}^1_{apt} \cdot Y^1_{pmt}, \quad \forall a, p, m, t$$

$$R^2_{abmt} \leq \tilde{C}^2_{abt} \cdot Y^2_{bmt}, \quad \forall a, b, m, t$$

$$R^3_{emdt} \leq \tilde{C}^3_{emt} \cdot Y^3_{mdt}, \quad \forall e, m, d, t$$

$$R^4_{edct} \leq \tilde{C}^4_{edt} \cdot Y^4_{dct}, \quad \forall e, d, c, t$$

$$R^6_{eomt} \leq \tilde{C}^5_{eot} \cdot Y^6_{omt}, \quad \forall e, o, m, t$$
Equations (19)–(24) ensure that the number of products or raw materials that have been transferred from one center to another center should not exceed the capacity of the original center. This statement is written mathematically by Eqs. (19)–(24) for different layers of the network. Additionally, two Eqs. (25) and (26) are written for the amount of supply from first layers that primary and secondary suppliers are located to second layers (manufacturing centers) that should be at least a specific number to be used by manufacturing centers to produce goods.

Supply constraints:

\[
R_{apmt}^1 \geq SU_{apt}^1 \cdot Y_{pmt}^1, \quad \forall a, p, m, t
\]  

(25)

\[
R_{abmt}^2 \geq SU_{abt}^2 \cdot Y_{bmt}^2, \quad \forall a, b, m, t
\]  

(26)

Equations (27)–(32) are related to balanced constraints that show the flows of products between different layers of the network. For instance, Eq. (27) indicates that the number of raw materials sent from primary and secondary suppliers to manufacturing centers should be equal to the number of products produced in manufacturing centers. These statements are acceptable for other constraints such as Eq. (32) as well.

Balanced constraints:

\[
\sum_a \sum_p R_{apmt}^1 + \sum_a \sum_b R_{abmt}^2 = \sum_e \sum_a y_a \cdot Q_{emt}, \quad \forall m, t
\]  

(27)

\[
\sum_m R_{emdt}^3 = \sum_c R_{edct}^4, \quad \forall e, d, t
\]  

(28)

\[
\sum_d R_{emdt}^3 = Q_{emt}, \quad \forall e, m, t
\]  

(29)

\[
\sum_d R_{edct}^4 \leq \tilde{D}_{ect}, \quad \forall e, c, t
\]  

(30)

\[
\sum_d R_{edct}^4 \geq \sum_o \eta_o^1 \cdot R_{ecot}^5, \quad \forall e, c, t
\]  

(31)

\[
\sum_c R_{ecot}^7 \cdot \eta_{ec}^1 = \sum_m R_{emt}^6 \cdot (1 - \eta_{eo}^2) + \sum_r \eta_{eo}^2 \cdot R_{ecot}^7, \quad \forall e, o, t
\]  

(32)

The inventory equations are written by Eqs. (33)–(35), which display the amount of inventory in each period in manufacturing centers, distribution centers, and collection centers as well. For each center, including manufacturing centers, distribution centers, and collection centers, we have written the inventory equations. For example, Eq. (33) indicates that inventory level for manufacturing center should come up with inventory level of each product in the previous period, number of produced products in the manufacturing center, number of returned products from collection center, number of products sent out from the
manufacturing center and number of substituted products between manufacturing centers (whichever have inventory level to meet other centers to avoid shortage).

Inventory constraints:

\[ I_{emt} = I_{em(t-1)} + Q_{emt} + \sum_{o} R_{emt}^6 - \sum_{d} R_{emdt}^3 + \sum_{m \in M/\{m\}} X_{emt}^1 - \sum_{m' \in M/\{m\}} X_{emt}^1, \quad \forall e, m, t \tag{33} \]

\[ I_{edt} = I_{ed(t-1)} + \sum_{m} R_{edm}^3 - \sum_{c} R_{edct}^4 + \sum_{d' \in D/\{d\}} X_{eddt}^2 - \sum_{d' \in D/\{d\}} X_{eddt}^2, \quad \forall e, d, t \tag{34} \]

\[ I_{eot} = I_{eot(t-1)} + \sum_{c} \eta_{ec}^1 \cdot R_{ecot}^5 - \sum_{m} (1 - \eta_{eo}^2) \cdot R_{emot}^6 - \sum_{r} \eta_{eo}^2 \cdot R_{eort}^7, \quad \forall e, o, t \tag{35} \]

Finally, the nature of each defined variable is shown by Eqs. (36) and (37).

\[ OE_{m}^1, OE_{d}^2, OE_{o}^3, OE_{r}^4, PS_{p}, SS_{b}, Y_{pmt}^1, Y_{bmt}^2, Y_{mdt}^3, Y_{dct}^4, Y_{cot}^5, Y_{smt}^6, Y_{ort}^7 \in \{0, 1\}, \quad \forall m, d, o, r, p, b \tag{36} \]

\[ R_{apmt}^1, R_{abmt}^2, R_{emdt}^3, R_{edct}^4, R_{ecot}^5, R_{eomt}^6, R_{eort}^7, I_{emt}^1, I_{edt}^2, I_{eot}^3, Q_{emt} \geq 0, \quad \forall e, a, p, b, m, d, c, o, r, t \tag{37} \]

5 Solution methodology

This section presents the solution methodology to solve the proposed mathematical model in the previous section. Also, the flowchart of the proposed solution procedure is depicted in Fig. 7.

What is clear from Fig. 7 is that firstly, the demand was estimated using FIS, and then it was used as a parameter to be imported to a mathematical model. After that, the FMO-MILP model is proposed in Sect. 3.3 in a fuzzy environment. Then, it is converted to a deterministic environment by using an Equivalent Auxiliary Crisp (EAC) model (Jiménez et al., 2007). Finally, the Deterministic Multi-objective Mixed-Integer Linear Programming (DMO-MILP) model is solved by utilizing the Multi-Choice Goal Programming Approach with Utility Function (MCGP-UF) to obtain the results of the proposed model.

As we discussed in the previous section, some parameters in the proposed model were uncertain. Uncertainty can be classified into different types, including randomness, epistemic, and deep uncertainty. Figure 8 shows the classification of uncertain data based on the essence of data availability. Because of the nature of our research problem, the type of uncertainty that we use is epistemic (Bairamzadeh et al., 2018).

5.1 Equivalent auxiliary crisp (EAC)

The Equivalent Auxiliary Crisp (EAC) model was first introduced by Jiménez et al. (2007). The EAC converts optimization problems that have triangular/trapezoidal fuzzy numbers
to deterministic problems. The first term of the first objective function, which is shown by Eqs. (3), (12), and (13), are converted to Eqs. (38), (39), and (40) as follows:

\[
Z_{\text{FixedCost}} = \sum_m \left( \frac{FC_1^{\text{pes}} + 2FC_1^{\text{mos}} + FC_1^{\text{opt}}}{4} \right) \cdot OE_m + \sum_d \left( \frac{FC_2^{\text{pes}} + 2FC_2^{\text{mos}} + FC_2^{\text{opt}}}{4} \right) \cdot OE_d + \sum_o \left( \frac{FC_3^{\text{pes}} + 2FC_3^{\text{mos}} + FC_3^{\text{opt}}}{4} \right) \cdot OE_o + \sum_r \left( \frac{FC_4^{\text{pes}} + 2FC_4^{\text{mos}} + FC_4^{\text{opt}}}{4} \right) \cdot OE_r
\]

\[
Z_{\text{FixedJob}} = \sum_p \left( \frac{PPS_{1p}^{\text{pes}} + 2PPS_{1p}^{\text{mos}} + PPS_{1p}^{\text{opt}}}{4} \right) \cdot PS_p + \sum_b \left( \frac{PPS_{1b}^{\text{pes}} + 2PPS_{1b}^{\text{mos}} + PPS_{1b}^{\text{opt}}}{4} \right) \cdot SS_b
\]

(38)

(39)
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Also, constrains (19)–(24) and (30) are fuzzy constrains that need to be converted to deterministic constraints. Then, we have:

\[ R_{apmt}^1 \leq \left[ \alpha \cdot \left( \frac{C_{apmt}^{pes}}{2} + \frac{C_{apmt}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{C_{apmt}^{mos}}{2} + \frac{C_{apmt}^{opt}}{2} \right) \right] \cdot Y_{pmt}^1, \quad \forall a, p, m, t \]  

\[ R_{abmt}^2 \leq \left[ \alpha \cdot \left( \frac{C_{abmt}^{pes}}{2} + \frac{C_{abmt}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{C_{abmt}^{mos}}{2} + \frac{C_{abmt}^{opt}}{2} \right) \right] \cdot Y_{bmt}^2, \quad \forall a, b, m, t \]  

\[ R_{emdt}^3 \leq \left[ \alpha \cdot \left( \frac{C_{emdt}^{pes}}{2} + \frac{C_{emdt}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{C_{emdt}^{mos}}{2} + \frac{C_{emdt}^{opt}}{2} \right) \right] \cdot Y_{mdt}^3, \quad \forall e, m, d, t \]  

\[ R_{edct}^4 \leq \left[ \alpha \cdot \left( \frac{C_{edct}^{pes}}{2} + \frac{C_{edct}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{C_{edct}^{mos}}{2} + \frac{C_{edct}^{opt}}{2} \right) \right] \cdot Y_{dct}^4, \quad \forall e, d, c, t \]  

\[ R_{eomt}^6 \leq \left[ \alpha \cdot \left( \frac{C_{eomt}^{pes}}{2} + \frac{C_{eomt}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{C_{eomt}^{mos}}{2} + \frac{C_{eomt}^{opt}}{2} \right) \right] \cdot Y_{omt}^6, \quad \forall e, o, t \]  

\[ R_{eort}^7 \leq \left[ \alpha \cdot \left( \frac{C_{eort}^{pes}}{2} + \frac{C_{eort}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{C_{eort}^{mos}}{2} + \frac{C_{eort}^{opt}}{2} \right) \right] \cdot Y_{ort}^7, \quad \forall e, o, r, t \]  

\[ \sum_{d} R_{edct}^4 \leq \left[ \alpha \cdot \left( \frac{D_{edct}^{pes}}{2} + \frac{D_{edct}^{mos}}{2} \right) + (1 - \alpha) \cdot \left( \frac{D_{edct}^{mos}}{2} + \frac{D_{edct}^{opt}}{2} \right) \right], \quad \forall e, c, t \]
and constraint (15)–(18), (25)–(29), and (31)–(37).

### 5.2 Multi-choice goal programming approach with utility function

In this sub-section, an efficient solution methodology called Multi-Choice Goal Programming Approach with Utility Function (MCGP-UF) is proposed to solve the deterministic multi-objective MILP model in Sect. 5.1. Since the proposed FMO-MILP model has multiple decision variables, it needs to be solved within a feasible solution space in a faster time. While considering a case study, the proposed model is coded on a computer with an intel CPU @2.9 GHz processor and 64 GB of RAM using CPLEX solver.

The Goal Programming (GP) method is an efficient tool that is still widely used to solve multi-objective and multi-criteria decision-making problems. In the goal programming method, an aspiration level is defined for each objective function and is calculated based on an expert’s opinion. This paper applies the MCGP-UF approach proposed by Chang (2011). Chang (2011) presented a methodology to solve the model by substituting the aspiration level with the scalar value for multiple objective problems, including classic GP and MCGP in terms of the level achieved for the Utility Function (UF). Indeed, the reasons for utilizing this technique are to aid decision-makers in developing the best strategy for their goals and to achieve the highest level of usefulness (Arani et al., 2021; Nayeri et al., 2018).

The MCGP with UF applied in this study is defined as follows:

Min \[ \sum_k \left[ w_k^d (d_k^+ + d_k^-) + w_k^e (\xi_k^-) \right] \]

s.t.
\[ \lambda_k \leq \frac{U_{k,\text{max}} - y_k}{U_{k,\text{max}} - U_{k,\text{min}}} \quad \forall k \]
\[ f_k(X) + d_k^- - d_k^+ = y_k \quad \forall k \]
\[ \lambda_k + \xi_k^- = 1 \quad \forall k \]
\[ U_{k,\text{min}} \leq y_k \leq U_{k,\text{max}} \quad \forall k \]
\[ d_k^-, d_k^+, y_k, \lambda_k, \xi_k^- \geq 0 \quad \forall k \]

\( y_k \): continuous variable, \( U_k, \text{max} \), \( \text{max}_{k,\text{min}} \): rank of \( k \)th aspiration level. \( d_k^+, d_k^- \): negative and positive deviations, \( \xi_k^- \): normalized deviation of \( y_k \) from \( U_{k,\text{min}} \), \( w_k^d, w_k^e \): weight of \( \xi_k^- \), \( \lambda_k \): utility value.

According to Change (2011), the normalized MCGP with UF can be shown as follows:

Min \[ \sum_k \left[ w_k^d \cdot \left( \frac{d_k^+ + d_k^-}{\xi_k^- - f_k^-} \right) + w_k^e \left( \xi_k^- \right) \right] \]

Fig. 8 Classification of uncertainty (Bairamzadeh et al., 2018)
does not need to be normalized because it is between 0 and 1. On the other hand, 
\( f_k^+ = \min f_k(X) \) and \( f_k^- = \max f_k(X) \). To calculate the upper and lower level of each objecti

tion (aspiration level), we need to calculate \( U_k, \max_k, \min_k \).

6 Case study results

In this section, we considered the tire industry as a case study of this study to validate the

proposed mathematical model in Sect. 4. Then, we report the result of the proposed model

by running the model using the CPLEX solver.

6.1 Description of case study

The tire industry in Iran is interdisciplinary. Figure 9 shows the share of different tire

factories production in Iran. As we can see, the Barez factory is located at the top with

36.40%, and the Kian factory and Pars factory are among the lowest level with 4.90%.

In this study, the Barez Tire factory was used to validate the proposed model (Shabani,

2018). The Barez tire factory was established in Kerman/Iran, and the construction of

the factory began with a nominal capacity of 25,500 tons (Shabani, 2018). The company’s operating capacity is currently 27,900 tons of all kinds of tires and rims (flaps) per year. The factory also provides direct and full-time employment for 1200 people and indirect employment for 2000 people. The main goal of this factory is to minimize supply chain costs, minimize pollution emissions and resource consumption, and maximize social impacts. The considered period includes three periods. In this research, two products, Truck Tire (product-type 1) and Bus Tire (product-type 2), have been considered for planning. Table 8 shows the amount of demand estimated by the FIS in each period. For example, the demand for product 1 and first customer in period 1 is equal to (1000, 1200, 1400). Also, Tables 9, 10, and 11 have shown the number of input parameters for the proposed model. As discussed in Sect. 4.3, some parameters are certain numbers, and others are fuzzy numbers. So, these parameters are defined and numbered through uniform distribution and fuzzy triangular numbers, as shown in Tables 9, 10, and 11.

As discussed in Sect. 3.4, some parameters are certain, and others are fuzzy numbers. So, these defined parameters are numbered through uniform distribution and fuzzy triangular numbers, as shown in Tables 10 and 11.

6.2 Objective functions

This section provides the results of the proposed mathematical model in the tire industry by applying the MCGP-UF approach. Firstly, the weight of each objective function is consi-

dered 0.3, 0.4, 0.3, and the parameters of MCGP-UF are given in Table 12. Secondly, the deterministic model is solved under six scenarios—two optimum values are sought for each objective function—to obtain the required results discussed in Table 13.
6.3 Strategic decisions

As we stated previously, the strategic decisions of the proposed model are pertinent to the selection of primary and secondary suppliers and facilities’ locations. The result of the proposed model is shown in Table 14. Table 14 displays which suppliers and facility centers are opened in the network for all periods. As we can see, secondary supplier number 1 is selected as the supportive supplier to help primary suppliers to avoid any interruptions between levels 1 and 2 of the networks. Two manufacturing centers, as well as two distribution centers, are selected to produce the products and deliver them to the customers. Additionally, one collection center and one disposal center are opened to collect the returned products from customers and for scrapped items that are not able to be reused.
| Primary Suppliers (p) | Secondary Suppliers (b) | Manufacturing Centers (m) | Distribution Centers (d) | Customer Zone (c) | Collection Centers (o) | Disposal Centers (r) | Raw Material (a) | Finished Product (e) | Time period (t) |
|----------------------|-------------------------|---------------------------|--------------------------|------------------|------------------------|---------------------|-----------------|---------------------|----------------|
| 3                    | 3                       | 3                         | 3                        | 5                | 3                      | 3                   | 3               | 3                   | 2              | 5              |
### Table 10 Values of certain parameters

| Parameters | Random distribution |
|------------|---------------------|
| $TR_{apmt}$, $TR_{abmt}$, $TR_{emdt}$, $TR_{edct}$, $TR_{emt}$, $TR_{eort}$ | Uniform [0.05 0.15] per kilometer |
| $PP_{emt}$, $PP_{edt}$, $PP_{emt}$, $PP_{eort}$ | Uniform [120 300] |
| $PC_{emt}$ | Uniform [10 50] |
| $EP_{omt}$, $EP_{omt}$, $EP_{enmt}$, $EP_{enmt}$, $EP_{enmt}$, $EP_{enmt}$ | Uniform [0.55 0.95] kilograms per kilometer |
| $CW_{mt}$, $CW_{mt}$, $CW_{edt}$, $CW_{edt}$, $CW_{edt}$, $CW_{edt}$ | Uniform [50 100] liter per hour |
| $CE_{omt}$, $CE_{omt}$, $CE_{edt}$, $CE_{edt}$, $CE_{edt}$, $CE_{edt}$ | Uniform [11 25] megawatt per hour |
| $HC_{emt}$, $HC_{emt}$, $HC_{edt}$, $HC_{edt}$ | Uniform [5,000 8,000] cubic meters per hour |
| $\gamma_{a}$ | Uniform [1.05 1.25] |
| $\eta_{sc}$, $\eta_{so}$ | Uniform [0.20 0.40] |
| $\alpha$ | 0.10 |

### Table 11 Values of triangular fuzzy parameters

| Parameters | Triangular fuzzy number |
|------------|------------------------|
| $FC_{mt}$, $FC_{dt}$, $FC_{o}$, $FC_{r}$ | (50,000 100,000 150,000) in dollar |
| $CPS_{a}$, $CPS_{b}$ | (50,000 100,000 150,000) in dollar |
| $PPS_{ap}$, $PPS_{ab}$ | (50 100 200) |
| $CFJ_{pt}$, $CFJ_{bt}$, $CFJ_{mt}$, $CFJ_{dt}$, $CFJ_{emt}$, $CFJ_{eort}$ | (500 1000 1500) |
| $CVJ_{pt}$, $CVJ_{bt}$, $CVJ_{mt}$, $CVJ_{dt}$, $CVJ_{emt}$, $CVJ_{eort}$ | (100 200 300) |
| $\tilde{C}_{apmt}$, $\tilde{C}_{abmt}$, $\tilde{C}_{emdt}$, $\tilde{C}_{edct}$, $\tilde{C}_{emt}$, $\tilde{C}_{eort}$ | (2000 4000 6000) |
| $SU_{ap}$, $SU_{ab}$ | (2000 4000 6000) |

### Table 12 Parameters of MCGP-UF solution methodology

| | $U_{min}$ | $U_{max}$ | $f^+$ | $f^-$ |
|----------------|-----------|-----------|-------|-------|
| First objective function | 1,399,289 | 1,986,213 | 1,399,289 | 1,986,213 |
| Second objective function | 58,232 | 96,814 | 58,232 | 96,814 |
| Third objective function | 2016 | 3547 | 3547 | 2016 |

### Table 13 Result of the objective function

| | Minimizing total costs | Minimizing environmental effects | Maximizing social effects |
|----------------|------------------------|-------------------------------|--------------------------|
| Value | 1,428,216 | 62,407 | 3134 |
6.4 Planning decisions

This sub-section shows the value of planning variables such as the number of finished products transferred from distribution centers to customers and the substitution between distribution centers. For instance, Table 15 shows that in period one, 648 units of product type 1 are transferred from distribution center 2 to customer 1.

Moreover, Table 16 shows the number of finished products substituted between distribution centers. For instance, in the third period, 1139 units of products type 1 are replaced between distribution centers.

6.5 Sensitivity analysis

In this sub-section, sensitivity analyses on demand and lateral resupply are presented. By doing the sensitivity analysis, we aim to understand the variations on demand as well as supply how much can impact the first, second, and third objective functions.

### Table 14 Result of facility location

| Name of centers | Primary suppliers (p) | Secondary suppliers (b) | Manufacturing centers (m) | Distribution centers (d) | Collection centers (o) | Disposal centers (r) |
|----------------|----------------------|-------------------------|---------------------------|-------------------------|------------------------|----------------------|
| Number of facilities | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Selected centers | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

### Table 15 Transferring number of finished products between distribution centers and customers

| Period 1 | Period 2 | Period 3 |
|----------|----------|----------|
| d1 | d2 | d1 | d2 | d1 | d2 |
| c1.e1 | 703 | 648 | 446 | 512 | 824 | 1251 |
| c1.e2 | – | – | 801 | 1282 | 719 | 917 |
| c2.e1 | 1604 | 1738 | 2238 | 2454 | 1146 | 3051 |
| c2.e2 | 1456 | 4875 | 2356 | 6202 | 3468 | 5732 |
| c3.e1 | – | – | – | – | – | – |
| c3.e2 | 1271 | 4606 | 2,158 | 4887 | 2378 | 4295 |
| c4.e1 | 347 | 542 | 551 | 493 | 617 | 679 |
| c4.e2 | – | – | – | – | – | – |
| c5.e1 | 915 | 1312 | 1256 | 1116 | 1178 | 1250 |
| c5.e2 | 1109 | 2930 | 1109 | 2348 | 934 | 1805 |

6.5.1 Sensitivity analysis on demand

The model was solved considering different levels of demand (Base case, − 10%, − 20%, + 10%, and + 20%). Results are shown in Figs. 10, 11, and 12. Figure 10 shows that as
demand increases from $-20$ to $+20\%$, the value of the first objective function, which is total costs, increases from approximately $1,200,000$ to $1,700,000$. More interestingly, a positive relationship is also found between demand and the value of the second objective function where demand is increased (see Fig. 11). Lastly, Fig. 12 shows that by increasing demand, the value of the third objective function, which is related to the maximization of social effects, also increases. In other words, when the demand increased, the number of direct and indirect employees also increased.

6.5.2 Sensitivity analysis on supply

Another critical parameter for SCLSCN is to consider the supply amount. Sensitivity analysis was also conducted for the impacts of supply variations on the three objective functions (see Figs. 13, 14, and 15).

The sensitivity analysis of supply variations is periodic for the second objective function (both sides of Fig. 14) and the right sides of Fig. 13 and 15. As we can see, these figures are repeated intermittently by changing the supply amount in each period. On the other hand, the decreasing orientation occurs for the left side of Fig. 13. The same happens for the left side of Fig. 15, except for a 20% increase in demand causes the third objective function to increase.

![Table 16 Substituting finished products between distribution centers](image)

| $X^2_{edd}$ | Period 1 | Period 2 | Period 3 |
|-------------|----------|----------|----------|
|             | $d'1$    | $d'2$    | $d'1$    | $d'2$    | $d'1$    | $d'2$    |
| d1 (e1)     | –        | 368      | –        | –        | –        | 1139      |
| d2 (e1)     | –        | –        | –        | –        | –        | –         |
| d1 (e2)     | –        | 3956     | –        | 3,652    | –        | 1543      |
| d2 (e2)     | –        | –        | –        | –        | –        | –         |

![Fig. 10 Demand variation with the first objective function](image)
6.5.3 Sensitivity analysis on lateral transshipment/resupply

This sub-section is dedicated to the examination of how lateral resupply could have effects on the total costs of the SCLSCN. The analysis first considers the network without lateral resupply and then analyzes the same network while allowing for lateral resupply. Results are shown in Fig. 16.

Results show that lateral resupply could considerably decrease the total cost of the SCLSCN. In other words, this strategy could remarkably help managers to lower the total costs of the network. The lateral resupply is considered in Eqs. (33) and (34) in Sect. 4.3. Transferring goods between manufacturing centers and distribution centers could alleviate...
Fig. 13  Supply variation of primary and secondary suppliers with the first objective function

Fig. 14  Supply variation of primary and secondary suppliers with the second objective function

Fig. 15  Capacity variation of primary and secondary suppliers with the third objective function
the shortage that may occur in the network by substituting the products between manufacturing centers at the second level and distribution centers at the third level.

7 Conclusion

This study addressed the design of multi-echelon, multi-products, and multi-periods SCLSCN, which comprises primary suppliers, secondary suppliers, manufacturing centers, distribution centers, customers, collection centers, and disposal centers. The proposed mathematical model aimed at minimizing the total costs of the network, minimizing the environmental effects, and maximizing social outcomes. This study, for the first time, considered the backup suppliers and lateral transshipment/resupply simultaneously to decrease the shortage that may occur during the transmission of produced goods in the network by proposing an FMO-MILP model. Also, the concept of circular economy is included in this study to reduce environmental effects. Given the importance of the demand, this parameter was estimated by the FIS procedure. After screening, the criteria including price, quality, environmental impact, advertising, and availability were selected as the final criteria. After fuzzification and determining the membership functions, the criteria are weighted, and then the chosen criteria and rules enter the FIS procedure. Finally, the output of the proposed FIS was the amount of product demand that was imported to the mathematical model as a parameter (Momenitabar et al., 2021).

This study utilizes the MCGP-UF approach to solve the FMO-MILP in Sect. 4. Before using this approach, we employed the EAC model to convert the multi-objective function to a single objective one. Location and allocation of centers, along with the study of the flow of raw materials and products, have been among the decisions made in this study. In addition, in this research, the level of inventory of the collection, production, and distribution centers and the amount of production of products in each period has been determined. The solution confirmed that the proposed model could reach the target level as the decision-makers defined. Also, we examined each objective function’s response using sensitivity analysis based on demand variations.

![Fig. 16 Analyzing two conditions for CLSCN based on demand variations](image)
By conducting this study, we found that increasing demand led to an increase in social-economic impacts such as creating direct jobs and indirect jobs at the tire manufacturing companies while leading to a decrease in pollution emission and energy consumption (see Figs. 10, 11, and 12). Also, by conducting sensitivity analysis on supply variation, we understood that the supply variations are periodic from one period to another period. (see Figs. 13, 14, and 15). By considering the concept of lateral resupply and secondary suppliers in the designed SCLSCN, we have shown in Fig. 16 that the proposed methodology could decrease the total costs as considered in the first objective function.

The limitation of this research should be addressed as well. Disruption can be considered in various centers of designed SCLSCN, including primary suppliers, secondary suppliers, manufacturing centers, disposal centers, and distribution centers (Arani et al., 2020). Indeed, disruption can have negative impacts on the whole network as it disturbs the supply chain of transporting goods. Considering other decision variables such as vehicle routing and scheduling can be other ideas for future research as well. Also, another study can be prioritizing backup suppliers on sustainable criteria. There are many approaches for handling uncertainty for various types of data availability (Fig. 8), such as two-stage stochastic programming, fuzzy robust programming, and robust convex programming. Lastly, the proposed model can be solved in large size by considering several metaheuristic algorithms and using criteria reported in Zhang and Gen (2014) to compare the algorithms.

References

Ahmed, M. M., SalauddinIqbal, S. M., Priyanka, T. J., Arani, M., Momenitabar, M., Billal, M. M. (2020). An environmentally sustainable closed-loop supply chain network design under uncertainty: Application of optimization. In Progress in intelligent decision science. IDS 2020, (Vol. 1301, pp. 343-358). Springer, Cham
Amin, S. H., & Zhang, G. (2013). A multi-objective facility location model for closed-loop supply chain network under uncertain demand and return. Applied Mathematical Modelling, 37, 4165–4176.
Arani, M., Dastmard, M., Ebrahimi, Z. D., Momenitabar, M., Liu, X. (2020). Optimizing the total production and maintenance cost of an integrated multi-product process and maintenance planning (IPPMP) model. In IEEE international symposium on systems engineering (ISSE). Vienna, Austria.
Arani, M., Chan, Y., Liu, X., & Momenitabar, M. (2021). A lateral resupply blood supply chain network design under uncertainties. Applied Mathematical Modeling, 93, 165–187.
Bairamzadeh, S., Saidi-Mehrabad, M., & Pishvae, M. S. (2018). Modelling different types of uncertainty in biofuel supply network design and planning: A robust optimization approach. Renewable Energy, 116, 500–517.
Battini, D., Bogataj, M., & Choudhary, A. (2017). Closed loop supply chain (CLSC): Economics, modeling, management and control. International Journal of Production Economics, 183, 319–321.
Burton, J., & Banerjee, A. (2005). Cost-parametric analysis of lateral transshipment policies in two-echelon supply chains. International Journal of Production Economics, 93–94, 169–178.
Chang, C.-T. (2011). Multi-choice goal programming with utility functions. European Journal of Operational Research, 215, 439–445.
Cilacı Tombuş, A., Aras, N., & Verter, V. (2017). Designing distribution systems with reverse flows. Journal of Remanufacturing, 7, 113–137.
Ebrahimi, Z. D., & Momenitabar, M. (2017). Design of mathematical modeling in a green supply chain network by collection centers in the environment. Environmental Energy and Economic Research, 1(2), 153–162.
Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. Omega, 66, 344–357.
Ghomi-Avili, M., Khosrojerdi, A., & Tavakkoli-moghaddam, R. (2019). A multi-objective model for the closed-loop supply chain network design with a price-dependent demand, shortage and disruption. Journal of Intelligent & Fuzzy Systems, 36(6), 5261–5272.
Goodarzian, F., Taleizadeh, A. A., Ghasemi, P., & Abraham, A. (2021). An integrated sustainable medical supply chain network during COVID-19. *Engineering Applications of Artificial Intelligence*, 100, 104188.

Govindan, K., Mina, H., & Alavi, B. (2020). A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19). *Transportation Research Part E: Logistics and Transportation Review*, 138, 101967.

Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, 240, 603–626.

Hillier, F. S., & Lieberman, G. J. (2012). *Introduction to operations research*. Tata McGraw-Hill Education.

Jabbarzadeh, A., Haughton, M., & Khosrojerdi, A. (2018). Closed-loop supply chain network design under disruption risks: A robust approach with real world application. *Computers & Industrial Engineering*, 116, 178–191.

Jiménez, M., Arenas, M., Bilbao, A., & Rodríguez, M. V. (2007). Linear programming with fuzzy parameters: An interactive method and information resolution. *European Journal of Operational Research*, 177, 1599–1609.

KhaliliNasr, A., Tavana, M., Alavi, B., & Mina, H. (2020). A novel fuzzy multi-objective circular supplier selection and order allocation model for sustainable closed-loop supply chains. *Journal of Cleaner Production*, 287, 124994.

Mamdani, E., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies*, 7(1), 1–13.

Markets, R. A. (2021) Automotive tire market to 2025 - global analysis and forecasts by tire type; vehicle type; and distribution channel. 08 December 2021. [Online]. Available: https://www.researchandmarkets.com/research/5lv58g/global_automotive

Mehrjerdi, Y. Z., & Shafiee, M. (2020). A resilient and sustainable closed-loop supply chain using multi-pleursourcing and information sharing strategies. *Journal of Cleaner Production*, 289, 125141.

Momenitabar, M., Ebrahimi, Z. D., Hoseini, S. H., Arani, M. (2020). A proposed lean distribution system for solar power plants using mathematical modeling and simulation technique. In *2020 international conference on decision aid sciences and application (DASA)*. Sakheer, Bahrain.

Momenitabar, M., Akar, N., Zaghi, D., & Feili, H. (2013). Fuzzy Mathematical modeling of distribution network through location allocation model in a three-level supply chain design. *Journal of Mathematics and Computer Science*, 9(3), 165–174.

Momenitabar, M., Bridgelall, R., DehdariEbrahimi, Z., & Arani, M. (2021). Literature review of socio-economic and environmental impacts of high-speed rail in the world. *Sustainability*, 13, 12231.

Nabavi-Pelesareai, A., Rafiee, S., Mohtasebi, S. S., Hosseinzadeh-Bandbafha, H., & Chau, K.-W. (2019). Comprehensive model of energy, environmental impacts and economic in rice milling factories by coupling adaptive neuro-fuzzy inference system and life cycle assessment. *Journal of Cleaner Production*, 217, 742–756.

Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, 183, 443–457.

Nayeri, S., Asadigangraj, E., & Emami, S. (2018). Goal programming-based post-disaster decision making for allocation and scheduling the rescue units in natural disaster with time-window. *International Journal of Industrial Engineering & Production Research*, 29, 65–78.

Rezaei, S., & Kheirkhah, A. (2018). A comprehensive approach in designing a sustainable closed-loop supply chain network using cross-docking operations. *Computational and Mathematical Organization Theory*, 24, 51–98.

Rajak, S., Vimal, K. E. K., Arumugam, S., Parthiban, J., Sivaraman, S. K., Kandasamy, J., & Duque, A. (A. 2021). Multi-objective mixed-integer linear optimization model for sustainable closed-loop supply chain network: a case study on remanufacturing steering column. *Environment, Development, and Sustainability*.

Sridharan, M. (2021) Application of mamdani fuzzy inference system in predicting the termal performance of solar distillation still. *Journal of Ambient Intelligence and Humanized Computing*, 1–15.

Safaei, S., Ghasemi, P., Goodarzian, F., Momenitabar, M. (2022). Designing a new multi-echelon multi-period closed-loop supply chain network by forecasting demand using time series model: A genetic algorithm. *Environmental Science and Pollution Research*.

Sahebjamnia, N., Fathollahi-Fard, A. M., & Hajiaigaei-Keshetl, M. (2018). Sustainable tire closed-loop supply chain network design: Hybrid metaheuristic algorithms for large-scale networks. *Journal of Cleaner Production*, 196, 273–296.

Samuel, C. N., Diallo, C., Venkatadri, U., & Ghayebloo, S. (2021). Multicomponent multiproduct closed-loop supply chain design with transshipment and economies of scale considerations. *Computers & Industrial Engineering*, 153, 107073.
Shabani, S. (2018). Tire industry analysis in Iran. 26 August 2018. [Online]. Available: https://old.babc.ir/my_doc/tbct/tahilhatahlil%20sanat%20lastik.pdf

Soleimani, H., Govindan, K., Saghaei, H., & Jafari, H. (2017). Fuzzy multi-objective sustainable and green closed-loop supply chain network design. Computers & Industrial Engineering, 109, 191–203.

Souza, G. C. (2013). Closed-loop supply chains: A critical review, and future research. Decision Sciences, 44, 7–38.

Souza, R., Wanke, P., & Correa, H. (2020). Demand forecasting in the beauty industry using fuzzy inference systems. Journal of Modelling in Management, 15(4), 1389–1417.

Tracht, K., Mederer, M., & Schneider, D. (2011). Effects of lateral transshipments in multi-echelon closed-loop supply chains. Glocalized solutions for sustainability in manufacturing. Springer.

Yıldızbaşi, A., Öztürk, C., Efendioğlu, D., & Bulkan, S. (2021). Assessing the social sustainable supply chain indicators using an integrated fuzzy multi-criteria decision-making methods: A case study of Turkey. Environment, Development and Sustainability, 23, 4285–4320.

Yu, D., & Sheng, L. (2021). Exploring the knowledge base and trajectories of knowledge dissemination in closed loop supply chain. Journal of Cleaner Production, 316, 128231.

Zhalechian, M., Tavakkoli-Moghaddam, R., Zahirí, B., & Mohammadi, M. (2016). Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty. Transportation Research Part e: Logistics and Transportation Review, 89, 182–214.

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