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Research Article

A Multiobjective Model for Optimizing Green Closed-Loop Supply Chain Network under Uncertain Environment by NSGA-II Metaheuristic Algorithm

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Nowadays, due to growing development and competitiveness in global markets of products, companies are forced to make significant efforts for supply procurement, production, and goods distribution in order to survive in the market and be able to respond to their customers' needs as quickly and cost-efficiently as possible. In this regard, supply chain management is considered a crucial indicator. This study presents a multiobjective, multifacility, closed-loop supply chain under uncertain environments considering green supply chain aspects. The model is designed with multiple products, periods, plants, customer markets, collection centers, recycle centers, distribution centers, return facilities, product recovery facilities, and suppliers. After modeling the study, the model is solved by the Nondominated Sorting Genetic Algorithms (NSGA-II) in order to rank the optimum solutions. The efficiency of the research model is indicated by the results and depicted graphs in the present study. Results show that the exact value of the triple objective functions is calculated. Also, the problem is solved in small, medium, and large dimensions. Then, the accuracy of the proposed model compared to the metaheuristic method is shown. Finally, by performing sensitivity analysis, we showed that target functions are less sensitive to reducing the capacity of centers.

1. Introduction

In the present global competition, diverse products should be made available to customers according to their demands. Customer demand for high-quality and prompt services has imposed some unprecedented pressures. Therefore, companies are incapable of handling all the tasks on their own. In this regard, supply chain management is presently considered a simplifying and economical approach to stabilizing a business. It is worth noting that capturing a higher market share is one of the goals in the supply chain. Accordingly, activities such as supply and demand planning, sourcing raw materials, product manufacturing and planning, product storage services, inventory management, distribution, delivery, and customer services are included in the supply chain in which the coordinated control and management of all these activities is the key point [1].

Supply chain management is responsible for integrating all the functions related to financial, information, and material flow in order to turn goods from the raw material into the finished product. Location-allocation decision is one of the crucial decisions in the supply chain. When the suitable number and location of facilities are selected and a proper distribution network is designed, these problems contribute much to cost reduction and access to competitive advantages in supply chain. Since in the real world, supply chains do not deal with precise and certain data regarding customer demand and prime cost in the supply chain, it is more desirable to use fuzzy sets in order to identify customer demands and prime cost in the supply chain [2]. Today, supply chain network design has been a demanding question and attracted great interest in a wide range of fields [3]. In general, open-loop supply chains include materials that are recovered by components other than the major manufacturers that have the ability to reuse these materials or products. Ring supply chains, on the other hand, depend on the concept of reusing products from customers and returning them to the original manufacturer to recover added value by reusing the entire product or part of it. Closed-loop supply chains that extend into the reverse supply chain include reproduction, reuse, repair, renovation, and recycling. They need a significant investment in resources and then the development of a collection system that takes the product back at the end of its life. Open-loop chains consist of different materials from manufacturers, and closed-loop chains focus on a specific manufacturer [4].

As mentioned above, the novelties and main contributions of the present research are as follows:

(i) Developing a mathematical model with consideration of multiple periods for the network, diversity in products, and number of facilities

(ii) Using the fuzzy approach to develop the multi-objective mathematical model

(iii) Using the NSGA-II algorithm to solve the developed model and applying the paired *t*-test and Mann–Whitney test for statistical analysis

The rest of the study is organized as follows: Section 2 presented a literature review. In Section 3, we provided a research methodology that includes mathematical model description and research solution approaches. In Section 4, we provided results that consist of main results, model validation, and sensitive analysis. In Section 5, we presented research managerial insights and finally in Section 6 conclusion and future studies are presented.

2. Literature Review

In recent years, a variety of research has been conducted on the supply chain. Ekhtiari [5] presented a three-echelon, single-product supply chain including manufacturers, distribution centers, and customers. In this supply chain, customer demands, returned products, and shipping time from distribution centers to customers are considered fuzzy variables. It is under uncertain conditions that distributors and suppliers are selected and customers are determined. Amin and Zhang [6] presented a multiobjective facility location model for a closed-loop supply chain network under uncertain demand and return. This closed-loop supply chain network includes both forward and reverses supply chains. In their study, they investigated a supply chain network consisting of multiple plants, collection centers, demand markets, and products. In addition, a mixed-integer linear programming model is used to minimize the total cost. Latha Shankar et al. [7] presented the location and allocation decisions for a four-echelon supply chain network consisting of suppliers, plants, distribution centers, and customers. Using a multiobjective swarm particle optimization algorithm, this model minimizes the total cost of production, setup, and shipment in the supply chain network and maximizes the fill rate. Mousavi and Niaki [8] presented a capacitated location-allocation problem with uncertain customer locations and demands. The customer demands were assumed fuzzy, customer locations followed a normal probability distribution, and the genetic algorithm was applied to solve the model. Zareian Jahromi et al. [9] designed a sustainable multiproduct closed-loop logistic network in four echelons of supply, production, distribution, and customer under uncertain conditions of customer demands, interfaculty transportation costs, and facility-related operational costs. They developed a model in order to maximize social impacts and profit based on two criteria, i.e., the number of job opportunities created and the number of lost days, and to minimize environmental impacts based on the carbon emission index. Jahani et al. [10] aimed to maximize total profit, taking into consideration the demand and price uncertainty and their correlation as two major risk factors. Mazaheri et al. [11] aimed to maximize the supply chain profit, minimize the suppliers' shortages, minimize the financial risk, and finally, maximize the customer satisfaction. The mathematical model is formulated and solved using the LINGO software. The results indicate that the supply chain network can expand and gain significantly increased profit. Anand and Sudhakara Pandian [12] presented a new algorithm for customer-to-customer supply chain management considering cost reductions in quantity rebates for inbound and outbound logistics transportation. In their article, a unique, six-phase approximation procedure is applied to simplify distance calculation details and to develop an algorithm in order to solve the supply chain management problems using a nonlinear optimization technique. Fathi et al. [13] considered uncertainty in the quality of returned products. The main objective of this study was to apply the stochastic planning model and maximize the expected profit for all the scenarios of quality status. Zare Mehrjerdi and Lotfi [14]; presented a two-stage, mixed-integer linear programming is used for modeling and a robust counterpart model is utilized to encounter the demand uncertainties. The Conditional Value-at-Risk criterion is considered to model risk and compared with Value-at-Risk and average absolute deviation. Sabouhi et al. [15] presented an optimization approach for a sustainable and resilient supply chain design with regional considerations. They applied a metaheuristic method to solve the developed model. In the study by Lotfi et al. [16],, for the first time, the aspects of stability, flexibility, robustness, and transient risk in the closed-loop supply chain are considered. For this purpose, a complex integer linear programming model is presented. In addition, a robust model of this problem is presented to consider the uncertainty in the problem. In Gerdrodbari et al. [17], a bi-objective mixed-integer linear programming (MILP) model is proposed to design a multi-level, multi-period, multiproduct closed-loop supply chain (CLSC) for timely production and distribution of perishable products, taking into account the uncertainty of demand. To face the model uncertainty, the robust optimization (RO) method is utilized. Moreover, to solve and validate the bi-objective model in small-size problems, the epsilon-constraint method (EC) is presented. On the other hand, a Nondominated Sorting Genetic Algorithm (NSGA-II) is developed for solving large-size problems. In Zadeh et al. [18], a multiobjective mixed-integer linear programming model is developed for a green multi-echelon closed-loop supply chain network design under uncertainty. Moreover, a partial disruption is considered for distribution centers that have not been studied enough in previous works. The fuzzy credibility constraint approach is applied to cover uncertainty. In the following, the epsilon-constraint method is presented to solve and validate the model in small-sized instances. Moreover, a Nondominated Sorting Genetic Algorithm is developed for solving large-sized problems. Safaei et al. [19] addressed a new multi-echelon multi-period closed-loop supply chain network to minimize the total costs of the network. The echelons include suppliers, manufacturers, distribution centers, customers, and recycling and recovery units of components in the proposed network. Also, a Mixed-Integer Linear Programming (MILP) model considering factories' vehicles and rental cars of transportation companies is formulated for the proposed problem. Momenitabar et al. [20] considered 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 multiobjective mixed-integer linear programming model is proposed to design an efficient SCLSCN resiliently.

2.1. Research Gap. According to studies, there is a lack of development of a mathematical model by considering multiple courses for the network, variety of products, and the number of available facilities that will be able to consider the uncertainty parameters in a chain. For this purpose, in this research, a fuzzy approach is used to develop a multiobjective mathematical model. Also, the NSGA-II algorithm is used to solve the developed model, and paired *t*-test and Mann–Whitney test are used for statistical analysis. Table 1 categorizes previous studies.

3. Research Methodology

3.1. Problem Statement. Considering uncertain prices and using a transportation model to reduce transportation costs, the present study introduces a green closed-loop supply chain (CLSC) problem. In the CLSC network of the present study, the forward chain contains three levels, and there are three echelons in the reverse chain as well. The forward supply chain includes the procurement of the materials and components (supply phase), production of new products (production phase), and distribution of the new products (distribution phase). On the other hand, the reverse supply chain includes collection of end-of-life products (collection phase), inspection and recovery of returned products (recovery phase), and distribution of recovered products (redistribution phase). Figure 1 illustrates these levels.

In the first level of this chain, raw materials and components required for plants are supplied by reverse centers and suppliers. According to the allowed returned product rate, the components of end-of-life products (EOLPs) are served to supply plants. In the event of any shortage in supplying the required components from reverse centers, plants can procure their required components from suppliers. The recovered components must satisfy the minimum specifications for reuse in plants. In the second level, plants manufacture new products and deliver them to distribution centers where products are delivered to customers based on their demand variety. The reverse supply chain process starts with customer returns. In the first step of the reverse chain, the end-of-life products are collected in collection centers and sent to reverse centers for sorting, inspection, and decision making. In the second step, the best decisions are made for the inspected products (the decisions on whether to recover the products or dismount the parts). Product recovery includes refurbishing and minor repairing of products while dismounting the parts includes disassembling a product to its components in order to reuse it in certain facilities. Reverse centers send the components from disassembled products to plants in order to satisfy their demands. On the other hand, based on their quality level, some components can be decomposed into their materials and sold to external suppliers to gain profit for the supply chain, although less significantly. In the final step of the reverse chain, recovery facilities run the repairing and refurbishing operations and send the recovered products to distribution centers after quality control and packaging.

In the present study, the closed-loop supply chain (CLSC) model is applied to manufacture and recover a number of products under various demands and return rates. Each product is made of different numbers and kinds of components, and each component is made of different numbers and quantities of materials. Considering the relationship between retrieve price and return rate leads us to a multi-objective guideline for maximizing the level of satisfaction and profitability. In the present study, the level of satisfaction is defined as adjusting the retrieved price and desirable return rate, in a way that the price for returned products provides satisfaction. The corresponding CLSC network is illustrated in Figure 1.

3.2. Picture of Problem Statement. The uncertainty related to the selling price and purchase price of a product is investigated in this section. We assume that there are acceptable upper and lower bounds of prices for sellers and buyers. Here, we have two different perspectives about the satisfaction of both parties in a trade: first, customers and buyers who purchase a (new and/or recovered) product, and second, customers who are sellers of EOLPs to reverse centers through collection centers. Therefore, two different roles, buyer and seller, are to be investigated for customers in a closed-loop supply chain. A summary of the corresponding conditions in our model is given as follows:

Customers are buyers of recovered or new products and distribution centers play the role of sellers. The agreed price

Table 1: Literature review.

Authors	Year of publication	Elements			
		Multiproduct	Multistage	Uncertainty	Multiobjective
Ekhtiari	2010	*	*	*	—
Zhang and Amin	2013	—	—	*	*
Shankar et al.	2013	—	*	—	*
Mousavi and Niaki	2013	—	—	*	—
Zareian et al.	2014	*	*	—	*
Mazaher et al.	2019	—	—	—	*
Mehrjerdi and Lotfi	2019	—	*	*	—
Gerdrodbari et al.	2021	*	*	—	*
Keshmiry Zadeh et al.	2022	—	*	*	*

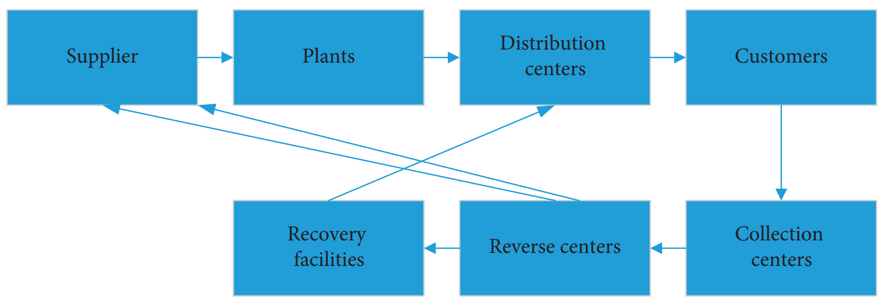

Figure 1: Levels of the corresponding supply chain in the present study.

of recovered products can be within the range of minimum selling price and ideal selling price for distribution centers, and a membership function can represent the degree of satisfaction for distribution centers. Similarly, the agreed price of the recovered product can be limited within the range of ideal purchase price and maximum purchase price, and a membership function can represent the degree of satisfaction for customers.

A number of parameters for pricing recovered products are as follows:

P^r is the agreed price of recovered products

$P^{r\min}$ is the minimum selling price for distribution centers

P^{rdid} is the ideal selling price for distribution centers

P^{rcid} is the ideal purchase price for customers

$P^{r\max}$ is the maximum purchase price for customers

We assume that the membership function is linear within the value range of minimum selling price and ideal selling price for distribution centers. Similarly, a linear pattern is assumed to exist between ideal and maximum purchase prices for customers. Here, we have two different conditions for product i:

(1) $P^{rdid} < P^{rcid}$ condition: this represents the condition in which the ideal price for distribution centers is higher than the ideal purchase price for customers. In this situation, it is hard to satisfy both parties in terms of product price. Here, there is a single acceptable price that can meet the expectations of both parties. The intersection point of membership function shows the best choice with the highest degree of satisfaction. We assumed that there is at least one intersection point in which the expected price of customers and distribution centers is satisfied.

(2) $P^{rdid} \geq P^{rcid}$ condition: this represents the condition in which the ideal selling price of contribution centers is lower than the ideal purchase price of customers. In this case, it is an easy job to satisfy both parties in the trade.

Equation (1) shows the membership function of recovered products for the degree of satisfaction among distribution centers and customers.

$$\mu^r = \begin{cases} 0, & p^r < p^{r_{\min}}, \\ \dfrac{p^r - p^{r_{\min}}}{p^{r_{\text{did}}} - p^{r_{\min}}}, & p^{r_{\min}} \leq p^r \leq p^{r_{\text{did}}}, \\ 1, & p^{r_{\text{did}}} \leq p^r \leq p^{r_{\text{cid}}}, \\ \dfrac{p^{r_{\max}} - p^r}{p^{r_{\max}} - p^{r_{\text{cid}}}}, & p^{r_{\text{cid}}} \leq p^r \leq p^{r_{\max}}, \\ 0, & p^r \geq p^{r_{\max}}. \end{cases} \tag{1}$$

Similar mathematical relations are valid for the condition in which customers are buyers of a new product and distribution centers are sellers. The agreed price for a new product can be within the range of minimum selling price and ideal purchase price for distribution centers, and a membership function can represent this price in order to express the degree of satisfaction for distribution centers. Similarly, the agreed price of a new product can be within the value range of the ideal purchase price and maximum purchase price for customers, and a membership function can represent the degree of satisfaction among customers.

A number of parameters for pricing new products are as follows:

P^n agreed price of new products
$P^{n\min}$ minimum selling price for distribution centers
P^{ndid} ideal selling price for distribution centers
P^{ncid} ideal purchase price for customers
$P^{n\max}$ maximum purchase price for customers

Equation (2) represents the membership function for distribution centers and customers' degree of satisfaction from new products.

$$\mu^n = \begin{cases} 0, & p^n < p^{n_{\min}}, \\ \dfrac{p^n - p^{n_{\min}}}{p^{n_{\mathrm{did}}} - p^{n_{\min}}}, & p^{n_{\min}} \le p^n \le p^{n_{\mathrm{did}}}, \\ 1, & p^{n_{\mathrm{did}}} \le p^n \le p^{n_{\mathrm{cid}}}, \\ \dfrac{p^{n_{\max}} - p^n}{p^{n_{\max}} - p^{n_{\mathrm{cid}}}}, & p^{n_{\mathrm{cid}}} \le p^n \le p^{n_{\max}}, \\ 0, & p^n \ge p^{n_{\max}}. \end{cases} \quad (2)$$

In the reverse supply chain, customers are sellers of returned products while reverse centers are buyers of these products. It is clear that both customers and reverse centers consider an acceptable limit for the price of returned products. On one hand, the higher the selling price of a product, the more satisfied the customers. For reverse centers on the other hand, it is more desirable that the purchase price of returned products is as low as possible. The symbols for membership function are as follows:

P^e agreed price of returned products
P^{erid} ideal purchase price for reverse centers
$P^{e\max}$ maximum purchase price of returned products for reverse centers
P^{ecid} ideal selling price of returned products for customers
$P^{e\min}$ minimum selling price of returned products for customers

Equation (3) shows the satisfaction behavior of customers and reverse centers.

$$\mu^e = \begin{cases} 0, & p^e < p^{e_{\min}}, \\ \dfrac{p^e - p^{e_{\min}}}{p^{e_{\mathrm{cid}}} - p^{e_{\min}}}, & p^{e_{\min}} \le p^e \le p^{e_{\mathrm{did}}}, \\ 1, & p^{e_{\mathrm{cid}}} \le p^e \le p^{e_{\mathrm{rid}}}, \\ \dfrac{p^{e_{\max}} - p^e}{p^{e_{\max}} - p^{e_{\mathrm{rid}}}}, & p^{e_{\mathrm{rid}}} \le p^e \le p^{e_{\max}}, \\ 0, & p^e \ge p^{e_{\max}}. \end{cases} \quad (3)$$

3.3. Fuzzy Multi-Objective CLSC Model. The main purpose of the presented model is to describe a designed CLSC including customers, collection centers, reverse centers, plants, distribution centers, and recovery facilities. In the present study, we formulate a multi-period, multi-echelon, and multiproduct CLSC model which involves all activities from suppliers to recovery facilities. The model aims to achieve the maximum level of satisfaction and profitability in the network.

(i) Notation

Sets and indices are as follows:

P: set of possible locations for plants
D: set of possible locations for distribution centers
R: set of possible locations for reverse centers
J: set of possible locations for collection centers
C: set of possible locations for customers
T: periods
I: set of product types
N: set of component types
M: set of material types
G: set of transportation vehicles

Decision variables are as follows:

Y_{cjt} = index for assigning customer c to collection center j in period t
Y_{jrt} = index for assigning collection center j to reverse center r in period t
Y_{rft} = index for assigning reverse center r to recovery facility f in period t
Y_{rpt} = index for assigning reverse center r to plant p in period t
Y_{fdt} = index for assigning recovery facility f to distribution center d in period t
Y_{pdt} = index for assigning plant p to distribution center d in period t
Y_{dct} = index for assigning distribution center d to customer c in period t
Z_{jt} = index for opening collection center j in period t
Z_{rt} = index for opening reverse center r in period t
Z_{ft} = index for opening recovery facility f in period t
Z_{pt} = index for opening plant p in period t
Z_{dt} = index for opening distribution center d in period t

X_{ridct} = quantity of recovered products sent from distribution center d to customer c in period t
X_{nidct} = quantity of new products sent from distribution center d to customer c in period t
X_{icjt} = quantity of returned products from customer c to collection center j in period t
X_{ijrt} = quantity of returned products from collection center j to reverse center r in period t
X_{irft} = quantity of returned products from reverse center r to recovery facility f in period t
X_{irpt} = quantity of components and compounds from reverse center r to plant p in period t
X_{ifdt} = quantity of recovered products from recovery facility f to distribution center d in period t
X_{ipdt} = quantity of new products from plant p to distribution center d in period t
X_{mrt} = quantity of materials prepared in reverse center r in period t
X_{npt} = quantity of outsourced components and compounds for plant p in period t
XV_{icjt} = number of vehicles to transport product i from customer c to collection center j in period t
XV_{ijrt} = number of vehicles to transport product i from collection center j to reverse center r in period t
XV_{irft} = number of vehicles to transport product i from reverse center r to recovery facility f in period t
XV_{ifdt} = number of vehicles to transport product i from recovery facility f to distribution center d in period t
XV_{ipdt} = number of vehicles to transport product i from plant p to distribution center d in period t
XV_{nrpt} = number of vehicles to transport component n from reverse center r to plant p in period t
XV^{n}_{idct} = number of vehicles to transport new product i from distribution center d to customer c in period t
XV^{T}_{idct} = number of vehicles to transport returned product i from distribution center d to customer c in period t

Parameters are as follows:

TF_g = fixed transportation cost when vehicle g is selected for transportation
TV_g = variable transportation cost when vehicle g is selected for transportation
GHG_g = quantity of CO_2 generated by vehicle g per unit of distance
GHL = acceptable greenhouse gas emission limit
WT = permitted amount of waste disposal by each facility
WP = percentage of waste production in each facility
Θ = maximum number of periods
W^{dm} = waste production rate for remanufacturing
W^{di} = waste production rate for disassembling the components
W^{rr} = waste production rate for refurbishing/renovating the products
d_{cj} = distance between customer c and collection center j
d_{jr} = distance between collection center j and reverse center r
d_{rf} = distance between reverse center r and recovery facility f
d_{rp} = distance between reverse center r and plant p
d_{pd} = distance between plant p and distribution center d
d_{fd} = distance between recovery facility f and distribution center d
d_{dc} = distance between distribution center d and customer c
C^{sc}_{irt} = cost of each sorting and classifying unit
C^{di}_{irt} = cost of each dissembling unit
C^{dm}_{irt} = cost of each remanufacturing unit
C^{rr}_{ift} = cost of each refurbishing/renovating unit
C^{dp}_{irt} = cost of each waste disposal unit in reverse center r
C^{df}_{ift} = cost of each waste disposal unit in recovery facility f
C^{pr}_{ipt} = cost of each production unit
C^{h}_{idt} = cost of each handling unit for products in distribution center d
v_i = volume of each unit of product i (m^3)
b_j = maximum capacity of collection center j
b_r = maximum capacity of reverse center r
b_d = maximum capacity of distribution center d
b_p = maximum capacity of plant p
b_f = maximum capacity of recovery facility f
c^s_j = cost of setting up collection center j
c^s_r = cost of setting up reverse center r
c^s_d = cost of setting u distribution center d
c^s_p = cost of setting up plant p
c^s_j = cost of setting up recovery facility f
c^f_j = fixed cost of opened collection center j
c^f_r = fixed cost of opened reverse center r
c^f_d = fixed cost of opened distribution center d
c^f_p = fixed cost of opened plant p
c^f_f = fixed cost of opened recovery facility f
c^p_i = penalty for each unit of unsatisfied demand
r^{di}_t = percentage of used products suitable for disassembling and demounting
r^{dm}_t = percentage of used products suitable for remanufacturing
r^{rr}_t = percentage of used products suitable for refurbishing/renovating
p^o_n = price of purchasing each unit of component n from market
p^e_i = purchase price for each unit of returned products
p^m_m = selling price for each unit of material m
p^n_i = selling price for each unit of new products

p_i^r = selling price for each unit of recovered products
q_{in}^c = quantity of component n in product i
q_{nm}^m = quantity of material m and component n
D_{ict}^n = quantity of customer demands for new products
D_{ict}^r = quantity of customer demands for returned products

The essential abbreviations are as follows:

TREV = total revenue of the supply chain
TSC = total setup cost
TFC = total fixed cost
TPC = total process cost
TPUC = total purchase cost
TTC = total transportation cost
THC = total handling cost
TPEC = total penalty cost

(ii) Mathematical Modeling

Here, we consider two conflicting objectives presented as follows: the first objective is to maximize the degree of satisfaction for both parties regarding CLSC. This degree of satisfaction is obtained based on the selling and purchase prices of products. TS represents the total degree of satisfaction for customers, distribution centers, and reverse centers:

$$TS = \sum_{i\in I}\mu_i^r + \sum_{i\in I}\mu_i^n + \sum_{i\in I}\mu_i^e. \tag{4}$$

The second objective is to maximize the total profit of the whole chain.

$$\begin{aligned}\text{PROFIT} = {} & \text{TREV} - \text{TSC} - \text{TFC} - \text{TPC} - \text{TPUC} \\ & - \text{TTC} - \text{THC} - \text{TPEC}.\end{aligned} \tag{5}$$

Equation (5) represents the total profit of the whole chain. This equation is obtained by subtracting the revenue and expenses of the chain. Each part of the above objective function is presented in detail as follows:

$$\begin{aligned}\text{TREV} = {} & \sum_{d\in D}\sum_{i\in I}\sum_{t\in T}\sum_{c\in C} P_i^n X_{\text{idct}}^n + \sum_{d\in D}\sum_{i\in I}\sum_{t\in T}\sum_{c\in C} P_i^r X_{\text{idct}}^r \\ & + \sum_{d\in D}\sum_{i\in I}\sum_{t\in T}\sum_{c\in C} P_m^m X_{\text{mrt}}^m.\end{aligned} \tag{6}$$

Equation (6) represents the total revenue of the whole chain. This revenue can be obtained from three sections including selling new products to customers, selling returned products to customers, and selling product materials by reverse centers, respectively.

$$\begin{aligned}TSC = {} & \sum_{t\in T}\sum_{j\in J} c_j^s\left(Z_{jT} - Z_{j(T-1)}\right) + \sum_{t\in T}\sum_{r\in R} c_r^s\left(Z_{rT} - Z_{r(T-1)}\right) \\ & + \sum_{t\in T}\sum_{p\in P} c_p^s\left(Z_{pT} - Z_{p(T-1)}\right) \\ & + \sum_{t\in T}\sum_{f\in F} c_f^s\left(Z_{fT} - Z_{f(T-1)}\right) + \sum_{t\in T}\sum_{d\in D} c_d^s\left(Z_{dT} - Z_{d(T-1)}\right).\end{aligned} \tag{7}$$

Equation (7) shows the total setup cost for each facility in the chain.

$$\begin{aligned}\text{TFC} = {} & \sum_{j\in J} c_j^f \sum_{t\in T} Z_{jT} + \sum_{r\in R} c_r^f \sum_{t\in T} Z_{rT} + \sum_{p\in P} c_p^f \sum_{t\in T} Z_{pT} \\ & + \sum_{f\in F} c_f^f \sum_{t\in T} Z_{fT} + \sum_{d\in D} c_d^f \sum_{t\in T} Z_{dT}.\end{aligned} \tag{8}$$

Equation (8) represents the total fixed cost of the chain.

$$\begin{aligned}TPC = {} & \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} c_{\text{irt}}^{sc} X_{\text{ijrt}} + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} c_{\text{irt}}^{di} r_t^{di} X_{\text{ijrt}} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{f\in F} c_{\text{ift}}^{rr} X_{\text{irft}} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} c_{\text{irt}}^{dm} r_t^{di} r_t^{dm} X_{\text{ijrt}} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{p\in P}\sum_{d\in D} c_{\text{ipt}}^{pr} X_{\text{ipdt}} + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{f\in F} c_{\text{ift}}^{df} w^{rr} X_{\text{irf}t} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} c_{\text{irt}}^{dp} w^{dm} r_t^{di} X_{\text{ijrt}} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} c_{\text{irt}}^{dp} w^{di} r_t^{dm} r_t^{di} X_{\text{ijrt}}.\end{aligned} \tag{9}$$

Equation (9) represents the CLSC total process cost which includes the cost of sorting products in reverse centers, cost of each disassembling and dismounting unit, cost of each remanufacturing unit, cost of each refurbishing unit, cost of each production unit in plants, cost of each disposal unit in the stage of disassembling components in reverse centers, cost of each disposal unit in the stage of remanufacturing components, and cost of disposal in refurbishing and recovery centers.

$$\text{TPUC} = \sum_{t\in T}\sum_{n\in N}\sum_{d\in D}\sum_{c\in C} p_n^o X_{\text{npt}} + \sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{c\in C} p_i^e X_{\text{icjt}}. \tag{10}$$

Equation (10) represents the total purchase cost of the chain in a way that this cost includes purchasing components and returned products from customers.

$$\begin{aligned}\text{TTC} = {} & \sum_{t\in T}\sum_{i\in I}\sum_{j\in J}\sum_{r\in R}\sum_{c\in C}\sum_{f\in F}\sum_{d\in D}\sum_{p\in P}\sum_{n\in N} TF_g\left(XV_{\text{icjt}} + XV_{\text{ijrt}} + XV_{\text{irft}} + XV_{\text{ifdt}} + XV_{\text{ipdt}} + XV_{\text{nrpt}} + XV_{\text{idct}}^n + \text{XV}_{\text{idct}}^{\text{r}}\right) \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{j\in J}\sum_{c\in C}\sum_{r\in R}\sum_{f\in F}\sum_{d\in D}\sum_{p\in P}\sum_{n\in N} TV_g\left(d_{cj}XV_{\text{icjt}} + d_{jr}XV_{\text{ijrt}} + d_{rf}XV_{\text{irft}} + d_{fd}XV_{\text{ifdt}} + d_{pd}XV_{\text{ipdt}} + d_{rp}XV_{\text{nrpt}} + d_{dc}XV_{\text{idct}}^n + d_{dc}XV_{\text{idct}}^r\right).\end{aligned} \tag{11}$$

Equation (11) represents the total transportation cost in the chain. This cost is obtained from two fixed and variable costs.

$$\text{THC} = \sum_{t\in T}\sum_{i\in I}\sum_{d\in D} c^{h}_{\text{idt}}\left(\sum_{f\in F} X_{\text{ifdt}} + \sum_{p\in P} X_{\text{ipdt}} - \sum_{c\in C} X^{n}_{\text{idct}} - \sum_{c\in C} X^{r}_{\text{idct}}\right). \tag{12}$$

Equation (12) shows the handling cost which is provided in distribution centers by plants and recovery facilities.

$$\text{TPEC} = \sum_{t\in T}\sum_{i\in I}\sum_{c\in C} c^{p}_{i}\left(D^{n}_{\text{ict}} - \sum_{d\in D} X^{n}_{\text{idct}} + D^{r}_{\text{ict}} - \sum_{d\in D} X^{r}_{\text{idct}}\right). \tag{13}$$

Equation (13) represents the penalties of the chain.

In addition, the constraints of the model are as follows:

$$\sum_{t\in T} z_{jt}, \quad \leq \forall j \in J, \tag{14}$$

$$\sum_{\text{t}\in\text{T}} z_{rt}, \quad \leq \forall \text{r} \in \text{R}, \tag{15}$$

$$\sum_{t\in T} z_{pt}, \quad \leq \forall p \in P, \tag{16}$$

$$\sum_{t\in T} z_{dt}, \quad \leq \forall d \in D, \tag{17}$$

$$\sum_{t\in T} z_{ft}, \quad \leq \forall f \in F. \tag{18}$$

In equations (14) to (18), a maximum period is set for each facility.

$$\sum_{j\in J} z_{jt} \geq 1, \quad \forall t \in T, \tag{19}$$

$$\sum_{r\in R} z_{rt} \geq 1 \forall t \in T, \tag{20}$$

$$\sum_{p\in P} z_{pt} \geq 1, \quad \forall t \in T, \tag{21}$$

$$\sum_{d\in D} z_{dt} \geq 1, \quad \forall t \in T, \tag{22}$$

$$\sum_{f\in F} z_{ft} \geq 1, \quad \forall t \in T. \tag{23}$$

In equations (19) to (23), we assumed that there is at least one facility of each type in every period.

$$Z_{j(t+1)} - Z_{jt} \geq 0 \quad \forall t \in T, \forall j \in J, \tag{24}$$

$$Z_{r(t+1)} - Z_{rt} \geq 0 \quad \forall t \in T, \forall r \in R, \tag{25}$$

$$Z_{p(t+1)} - Z_{pt} \geq 0 \quad \forall t \in T, \forall p \in P, \tag{26}$$

$$Z_{f(t+1)} - Z_{ft} \geq 0 \quad \forall t \in T, \forall f \in F, \tag{27}$$

$$Z_{d(t+1)} - Z_{dt} \geq 0 \quad \forall t \in T, \forall d \in D. \tag{28}$$

In equations (24) to (28), we provided the final constraints for facilities. If the model decides to open a facility in a certain period, the model will continue with the same facility. The second class of constraints is allocation constraints presented as follows:

$$\sum_{j\in J} Y_{cjt} \geq 1 \quad \forall c \in C, \forall t \in T, \tag{29}$$

$$\sum_{d\in D} Y_{dct} \geq 1 \quad \forall c \in C, \forall t \in T. \tag{30}$$

Equation (29) expresses that in each period, the products collected from customers must be retransferred to a collection center. Similarly, equation (30) expresses that in each period, only one distribution center should be allocated to each customer.

$$Y_{\text{jrt}} \leq Z_{jt} \quad \forall j \in J, \forall r \in R, \forall t \in T, \tag{31}$$

$$Y_{\text{jrt}} \leq Z_{rt} \quad \forall j \in J, \forall r \in R, \forall t \in T, \tag{32}$$

$$Y_{\text{rpt}} \leq Z_{pt} \quad \forall p \in P, \forall r \in R, \forall t \in T, \tag{33}$$

$$\text{Y}_{\text{rpt}} \leq \text{Z}_{\text{rt}} \quad \forall p \in P, \forall r \in R, \forall t \in T, \tag{34}$$

$$Y_{\text{pdt}} \leq Z_{pt} \quad \forall p \in P, \forall d \in D, \forall t \in T, \tag{35}$$

$$Y_{\text{pdt}} \leq Z_{dt} \quad \forall p \in P, \forall d \in D, \forall t \in T, \tag{36}$$

$$Y_{\text{fdt}} \leq Z_{dt} \quad \forall f \in F, \forall d \in D, \forall t \in T, \tag{37}$$

$$Y_{\text{fdt}} \leq Z_{ft} \quad \forall f \in F, \forall d \in D, \forall t \in T, \tag{38}$$

$$Y_{\text{rft}} \leq Z_{rt} \quad \forall f \in F, \forall r \in R, \forall t \in T, \tag{39}$$

$$Y_{\text{rft}} \leq Z_{ft} \quad \forall f \in F, \forall r \in R, \forall t \in T. \tag{40}$$

In equations (31) to (40), we defined that each facility can be only allocated to a single type of other facilities. Another group of constraints is capacity constraints described as follows:

$$\sum_{\text{i}\in\text{I}}\sum_{c\in C} X_{\text{icjt}}\vartheta_i \leq b_j Z_{jt} \quad \forall j \in J, \forall t \in T, \tag{41}$$

$$\sum_{i\varepsilon I}\sum_{j\varepsilon J} X_{\text{ijrt}}\vartheta_i \leq b_r Z_{rt} \quad \forall r \in R, \forall t \in T, \tag{42}$$

$$\sum_{i\varepsilon I}\sum_{d\varepsilon D} X_{\text{ipdt}}\vartheta_i \leq b_p Z_{pt} \quad \forall p \in P, \forall t \in T, \tag{43}$$

$$\sum_{i\varepsilon I}\sum_{r\varepsilon R} X_{\text{irft}}\vartheta_i \leq b_f Z_{ft} \quad \forall f \in F, \forall t \in T, \tag{44}$$

$$\sum_{i\in I}\left[\sum_{f\in F}X_{\text{ifdt}}+\sum_{p\in P}X_{\text{ipdt}}\right],\quad \vartheta_i\le b_d Z_{dt}\ \forall d\in D,\ \forall t\in T. \tag{45}$$

Constraints (41) to (45) are capacity constraints that show the limited capacity of each facility. Every product has its own specific capacity which is of great importance for the capacity of each facility. Another group of constraints is green constraints which are presented as follows:

$$\sum_{i\in I}\sum_{g\in G}XV_{\text{icjtg}}\text{GHG}_g d_{cj}\le \text{GHL}_{jt}\quad \forall j\in J,\ \forall t\in T,\ \forall c\in C, \tag{46}$$

$$\sum_{j\in J}\sum_{g\in G}XV_{\text{ijrtg}}\text{GHG}_g d_{jr}\le \text{GHL}_{rt}\quad \forall r\in R,\ \forall t\in T,\ \forall i\in I, \tag{47}$$

$$\sum_{f\in F}\sum_{g\in G}XV_{\text{irftg}}\text{GHG}_g d_{rf}\le \text{GHL}_{ft}\quad \forall i\in I,\ \forall t\in T,\ \forall r\in R, \tag{48}$$

$$\sum_{d\in D}\sum_{g\in G}XV_{\text{ifdtg}}\text{GHG}_g d_{fd}\le \text{GHL}_{dt}\quad \forall i\in I,\ \forall t\in T,\ \forall f\in F, \tag{49}$$

$$\sum_{d\in D}\sum_{g\in G}XV_{\text{ipdtg}}\text{GHG}_g d_{cj}\le \text{GHL}_{dt}\quad \forall j\in J,\ \forall t\in T,\ \forall p\in P, \tag{50}$$

$$\sum_{p\in P}\sum_{g\in G}XV_{\text{nrptg}}\text{GHG}_g d_{cj}\le \text{GHL}_{pt}\quad \forall n\in N,\ \forall t\in T,\ \forall r\in R, \tag{51}$$

$$\sum_{c\in C}\sum_{g\in G}\left(XV^{n}_{\text{idctg}}+XV^{r}_{\text{idctg}}\right)\text{GHG}_g d_{pd}\le \text{GHL}_{ct}\quad \forall c\in C,\ \forall t\in T. \tag{52}$$

Constraints (46) to (52) express that transportation vehicles for each type of facility are permitted to generate a certain amount of greenhouse gases.

$$\sum_{c\in C}\sum_{i\in I}\sum_{t\in T}X_{\text{icjt}}WP_{ij}\le WT_j\quad \forall j\in J, \tag{53}$$

$$\sum_{j\in J}\sum_{i\in I}\sum_{t\in T}X_{\text{ijrt}}WP_{ir}\le WT_r\quad \forall r\in R, \tag{54}$$

$$\sum_{r\in R}\sum_{i\in I}\sum_{t\in T}X_{\text{irft}}WP_{if}\le WT_f\quad \forall f\in F, \tag{55}$$

$$\sum_{r\in R}\sum_{i\in I}\sum_{t\in T}X_{\text{irpt}}WP_{ip}\le WT_p\quad \forall p\in P, \tag{56}$$

$$\sum_{i\in I}\sum_{t\in T}\left(X_{\text{ifdt}}+X_{\text{ipdt}}\right)WP_{ip}\le WT_d\quad \forall d\in D,\ \forall f\in F,\ \forall p\in P, \tag{57}$$

$$\sum_{d\in D}\sum_{i\in I}\sum_{t\in T}(X^{n}_{\text{idct}}+X^{r}_{\text{idct}})WP_{ic}\le WT_c\quad \forall c\in C, \tag{58}$$

$$\sum_{n\in N}\sum_{t\in T}X_{\text{npt}}WP_{np}\le WT_p\quad \forall p\in P. \tag{59}$$

Constraints (53) to (59) express that each facility is permitted to produce a certain amount of waste.

The other group of constraints is balanced constraints presented as follows:

$$\sum_{c\in C} X_{icjt} \geq \sum_{r\in R} X_{ijrt} \quad \forall i \in I, \forall j \in J, \forall t \in T, \tag{60}$$

$$\sum_{f\in F} X_{irft} \leq r_t^{rr} \sum_{j\in J} X_{irjt} \quad \forall i \in I, \forall r \in R, \forall t \in, \tag{61}$$

$$\sum_{p\in P} X_{nrpt} \leq r_t^{di} \sum_{j\in J} \sum_{i\in I} X_{irjt} q_{in}^{c} \quad \forall n \in N, \forall r \in R, \forall t \in, \tag{62}$$

$$\sum_{p\in P} X_{nrpt} + X_{npt} = \sum_{d\in D} \sum_{i\in I} X_{ipdt} q_{in}^{c} \quad \forall n \in N, \forall d \in D, \forall t \in, \tag{63}$$

$$\sum_{f\in F} X_{ifdt} \geq \sum_{c\in C} X_{idct}^{r} \quad \forall i \in I, \forall d \in D, \forall t \in, \tag{64}$$

$$X_{mrt} = r_t^{dm} r_t^{di} \sum_{j\in J} \sum_{i\in I} X_{ijrt} \sum_{n\in N} q_{in}^{c} q_{nm}^{c} \quad \forall m \in M, \forall r \in R, \forall t \in . \tag{65}$$

Constraints (60) to (65) are balance constraints. For example, Constraint (67) expresses that the quantity of products sent from customers to collection centers is equal to or greater than the number of products sent from collection centers to reverse centers.

In Constraints (66) to (67), we have presented some equations to satisfy the demands for recovered and new products.

$$\sum_{d\in D} X_{idct}^{r} \leq D_{ict}^{r} \quad \forall i \in I, \forall c \in C, \forall t \in, \tag{66}$$

$$\sum_{d\in D} X_{idct}^{n} \leq D_{ict}^{n} \quad \forall i \in I, \forall c \in C, \forall t \in . \tag{67}$$

Another group of constraints are transportation constraints presented as follows:

$$\left(XV_{icjtg} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{icjt} \leq XV_{icjtg} V_g \quad \forall i \in I, \forall c \in C, \forall j \in J, \forall t \in T, \forall g \in \otimes, \tag{68}$$

$$\left(XV_{irjtg} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{ijrt} \leq XV_{ijrtg} V_g \quad \forall i \in I, \forall r \in R, \forall j \in J, \forall t \in T, \forall g \in, \tag{69}$$

$$\left(XV_{irftg} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{irft} \leq XV_{irftg} V_g \quad \forall i \in I, \forall r \in R, \forall f \in F, \forall t \in T, \forall g \in, \tag{70}$$

$$\left(XV_{ifdtg} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{ifdt} \leq XV_{ifdtg} V_g \quad \forall i \in I, \forall f \in F, \forall d \in D, \forall t \in T, \forall g \in, \tag{71}$$

$$\left(XV_{ipdtg} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{ipdt} \leq XV_{ipdtg} V_g \quad \forall i \in I, \forall p \in P, \forall d \in D, \forall t \in T, \forall g \in, \tag{72}$$

$$\left(XV_{nrptg} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{nrpt} \leq XV_{nrptg} V_g \quad \forall n \in N, \forall r \in R, \forall p \in P, \forall t \in T, \forall \in, \tag{73}$$

$$\left(XV_{idctg}^{n} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{idct}^{n} \leq XV_{idctg}^{n} V_g \quad \forall i \in I, \forall c \in C, \forall d \in D, \forall t \in T, \forall g \in, \tag{74}$$

$$\left(XV_{idctg}^{r} - 1\right) V_g \leq \sum_{i\in I} \vartheta_i X_{idct}^{r} \leq XV_{idctg}^{r} V_g \quad \forall i \in I, \forall c \in C, \forall d \in D, \forall t \in T, \forall g \in . \tag{75}$$

Constraints (68) to (75) express that the volume of products to be transferred should be within the range of a vehicle's capacity between n and $n-1$. Another constraint is price constraint described as follows:

$$p_i^n \leq p_i^r \quad \forall i \in I. \tag{76}$$

Constraint (76) expresses that price of recovered products is equal to or higher than the price of new products. Constraints (77) to (82) represent the degree of satisfaction in different facilities:

$$\frac{p^r - p^{r_{\min}}}{p_i^{r_{\text{did}}} - p^{r_{\min}}} \geq \mu_i^r \quad \forall i \in I, \tag{77}$$

$$\frac{p_i^{R_{\max}} - p^R}{p_i^{R_{\max}} - p_i^{R_{\text{cid}}}} \geq \mu_i^r \quad \forall i \in I, \tag{78}$$

$$\frac{p_i^n - p_i^{n_{\min}}}{p_i^{n_{\text{did}}} - p_i^{n_{\min}}} \geq \mu_i^n \quad \forall i \in I, \tag{79}$$

$$\frac{p_i^{n_{\max}} - p_i^n}{p_i^{n_{\max}} - p_i^{n_{\text{cid}}}} \geq \mu_i^n \quad \forall i \in I, \tag{80}$$

$$\frac{p_i^e - p_i^{e_{\min}}}{p_i^{e_{\text{cid}}} - p_i^{e_{\min}}} \geq \mu_i^e \quad \forall i \in I, \tag{81}$$

$$\frac{p_i^{e_{\max}} - p_i^e}{p_i^{e_{\max}} - p_i^{e_{\text{rid}}}} \geq \mu_i^e \quad \forall i \in I. \tag{82}$$

The last group of constraints is non-negativity and binary constraints (Figure 2):

$$\begin{aligned} &\forall j \in J; \forall r \in R; \forall f \in F; \forall p \in P; \forall d \in D; \forall c \in C; \\ &\forall i \in I; \forall t \in T; Z_{jt}; Z_{rt}, Z_{ft}, \\ &Z_{pt}; Z_{dt} \in \{0,1\}, \\ &Y_{\text{cjt}}, Y_{\text{jrt}}, Y_{\text{rft}}, Y_{\text{rpt}}, Y_{\text{fdt}}, Y_{\text{pdt}}, Y_{\text{dct}} \in \{0,1\}, \\ &X_{cj}, X_{jr}, X_{rf}, X_{rp}, X_{fd}, X_{pd}, X_{\text{mrt}}, X_{\text{npt}}, X_{dc}^r, X_{dc}^n \geq 0. \end{aligned} \tag{83}$$

First child	1	1	0	1	1	0
Second child	1	0	0	1	0	1

Figure 2: How crossover operator works.

3.4. Solution Approach

(i) Epsilon constraint: the Epsilon-constraint method was used to solve multi-objective problems. The–constraint method in this study was considered according to the stance of Pirouz and Khorram [21] and recommended by Abolghasemian et al. [22] recently. Epsilon-constraint method has two main advantages. One of the advantages of the method is its reduction of the search space to find the nondominated points. Another advantage of the method is shorter run time in comparison with other methods. According to the method, we first solve the single-objective optimization problem for each goal. Next, we determine the step length. Then, we generate the suitable sets of the points, and finally, we will solve the single-objective optimization and estimate the Pareto frontier [23].

(ii) Nondominated sorting genetic algorithm (NSGA-II): in the present study, we applied the sorting and searching methods based on Pareto analysis in order to develop the NSGA-II algorithms. In the following section, the details of this method are described. In the searching method, a variety of solutions are first obtained. Then, the decision maker selects the most suitable solutions which should be in balance with various objectives. Nondominated sorting genetic algorithm (NSGA-II) is one of the most efficient and popular optimization algorithms. Single-objective optimization algorithms find the optimal solution according to a single objective, while no single optimal solution can be found in multi-objective problems. Therefore, we normally deal with a set of solutions named nondominated solutions. From this finite set of solutions, the suitable solutions are those with acceptable performance regarding all objectives. The stages of the developed algorithm are as follows:

(iii) Initialization and structure of chromosome: the preliminary information to initiate the proposed NSGA-II algorithm contains an initial population size, crossover possibility, and mutation possibility along with the number of iterations. The structure of the chromosome is one of the most influential parts of multi-objective optimization algorithms. Each solution set contains a set of decision variables in the problem's model. In other words, a chromosome consists of several parts, the first of which represents the Z variable which shows opened distribution centers, collection points, recovery facilities, etc. The second part of the chromosome is allocated to Y variables which show assigning customers to collection points, collection points to recovery facilities, etc. the third part of the solution shows the quantity of product transferred within X levels. The next part shows the amount of inventory transferred by each vehicle within corresponding XV levels. The final part refers to the price of new and recovered products.

(iv) Evaluation of chromosome: in this stage, various criteria are introduced in order to evaluate the solutions among the population. Fitness evaluation is to check the value of objective function while the problem's constraints are considered.

(v) Fast nondominated sorting and crowd distance: in this section, ranking based on non-dominants is compared using the concepts of dominance, dominated, and crowd distance. In fast nondominated sorting, population is ranked using the concept of dominance. Generally, in order to sort a population with size n based on nondominated levels, each solution is compared to all the other solutions in the population so the dominated or nondominated nature of that solution is determined.

(vi) Parents: since parents are necessary to produce new offspring (for each child, two parents are required in crossover operator, and a single parent is required in mutation operator, in a way that parents must be prioritized over the rest of solutions in terms of fitness), the same happens in the NSGA-II algorithm. Here, parents who go under nondominated sorting and crowd distance operations are kept, and they will go under crossover and mutation operations in the next stage according to the corresponding selection strategy.

(vii) Selection strategy: crowded tournament selection operator is used in order to select parents for crossover and mutation operators to produce new offspring. This operator compares two solutions and finally selects the best one. Two criteria are applied to evaluate these two solutions:

(1) Having the higher rank and degree of nondominance in which rank is shown as r_i
(2) Having the greater crowd distance is shown as d_i

(viii) Crossover operator: this operator is applied on Z variable. How this operator works is described in the following. First, one of Z variables is randomly selected. Then, a uniform crossover is applied to determine the value of that variable for children, in a way that a varying length string that can take binary values is generated. Then, in order to produce children, for each gene in the string, the first child takes the value assigned to the first parent in case the gene value is zero, and the child takes the value assigned to the second parent if the value is one. The case is the opposite for the second child. Finally, some solutions are generated as offspring according to parents.

The same operation happens for all the defined strings. Of course, it happens randomly for only one string every time.

(ix) Mutation operator: mutation operator is generated to change the arrangement of the genes and make slight modifications in one point of the chromosome code. When this operator is applied, a new chromosome is generated by slight modifications in the gene sequence. The main objective of using a mutation operator is to avoid putting the algorithm within the local optimum and to increase the diversity of searching solution space. In fact, the mutation operator is a simple form of local searching. The following figure is an example to show how this operator works. The initial string is associated with the first parent, and the selected genes are the second and sixth genes, respectively. As shown in Figure 3, this operator is applied to the parent string, and offspring are produced.

This operation happens to all the defined strings. Of course, it happens randomly for only one string every time.

(x) Offspring evaluation and merging with previous solutions: in the next stage, we evaluate the set of offspring produced by crossover and mutation operators. Since a certain fitness value is allocated to each child, the whole population including children and parents is merged and a population larger than the initial population (almost twice in size) is generated. When solutions are merged, better solutions among the population of parents and offspring are not lost. Needless to say, the newly generated solutions must address all the problem's constraints.

(xi) Sorting the population and selecting N chromosomes: in this section, the population members of each boundary are ranked based on crowded distance and then according to nondominated sorting. Figure 4 illustrates the mechanism of NSGA-II evolution.

After the new population is sorted and ranked, the considered stop conditions need to be checked.

4. Simulation Results

The mathematical model in Gams software was transformed into a single-objective model using the Epsilon constraint, and in a personal system with Intel Core i5 CPU and 4 GB RAM is solved using the Baron tool. Table 2 shows the results obtained from the implementation and solution of the model. In order to compare the efficiency of NSGA-II, various examples are designed in different categories and sizes to evaluate the algorithm. Table 3 shows the descriptions of each category of problems.

Since this problem has two objective functions which are in conflict, there will be a two-dimensional (2D) Pareto solution set. Figure 5 shows the 2D Pareto front plot.

In this section, the results obtained by solving certain problems are expressed in form of evaluation criteria for metaheuristic algorithms. Table 4 shows the information obtained from the NSGA-II algorithm, respectively.

The data needs to be evaluated in terms of normality in order to conduct the statistical analysis of the results of solving problems by the metaheuristic algorithm. In this test, if the P value is greater than 0.05, it indicates that the data

1	3	5	2	5	8	1	4
1	8	5	2	5	3	1	4

Figure 3: How mutation operator works.

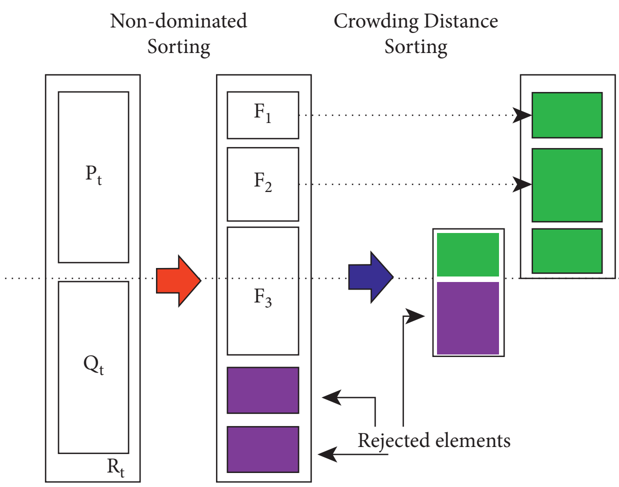

Figure 4: The process of NSGA-II evolution.

Table 2: Value of objective function.

Objective function	Customer satisfaction	Total profit	Total cost
Value	0.75	522000000	15200000

Table 3: Details of the designed problems.

Type of category	Number of problems	P, d, r, j, f	C
Small	5	[1, 3]	[4, 6]
Medium	5	[4, 5]	[6, 8]
Large	5	[5, 7]	[9, 10]

have no significant difference. Since the data obtained from the evaluation criteria have different scales, the normality test is conducted for each set of data. The results are shown in Table 5. The statistical analysis of the results is performed in the Minitab 16 Software. In this regard, the paired t-test and the Mann–Whitney test are used for statistical analysis using the results of the normality test. A confidence level (CL) of 95% is considered for the null hypothesis of zero difference between means. The results indicate the normality of data (CL = 0.05).

4.1. Model Validation. Validation step shows how the model can reflect the behavior of the real system. Model validity is accomplished through many methods that compare two outputs. In this study, absolute relative error (ARE) method was used to evaluate between the mathematical model and metaheuristic model. When ARE value is lower than 0.05 it means that the model can predict each other. Table 6 indicates the validation results. ARE value for each comparison is lower than 0.05. Therefore, both model gap is negligible.

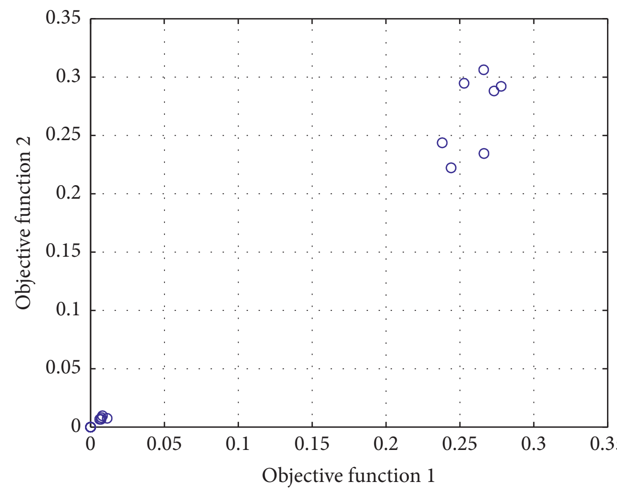

Figure 5: The Pareto set is based on two objective functions.

Table 4: Results of solution by the NSGA-II algorithm.

Problem	NPS	MID	S	D	T
1	5	0.6877	0.9856	238.06	110.35
2	6	0.620389	1.4557	244.12	150.24
3	7	0.691285	1.2589	244.42	155.04
4	7	0.630859	1.0002	243.6	174.08
5	5	0.726145	1.4678	237.8	179.91
6	9	0.612547	1.9909	359.1	255.99
7	8	0.642926	1.2774	380.36	353.88
8	8	0.720907	2.0472	369.14	394.29
9	10	0.739417	1.3449	378.11	386.12
10	7	0.6877	2.9399	385.33	376.03
11	11	0.620389	1.3593	457.6	419.21
12	13	0.691285	3.6333	455.8	483.66
13	12	0.630859	4.8656	486.1	491.14
14	14	0.726145	1.9881	492.11	479.11
15	10	0.612547	1.3486	428.62	504.83

Table 5: The results of normality test for evaluation criteria.

Criteria	P value	Result	Test
NPS	0.048	Nonparametric test	Mann–Whitney test
MID	0.01	Nonparametric test	Mann–Whitney test
S	0.15	Parametric test	Pair t-test
D	0.023	Nonparametric test	Mann–Whitney test
T	0.109	Parametric test	Pair t-test

4.2. Sensitivity Analysis. In this section, we have performed a sensitivity analysis on some important parameters such as the maximum capacity of collection, reverse, and distribution centers. For this purpose, by creating chaos in the existing value of the capacity of the considered centers, we examine the number of changes in the objective function.

Table 6: Validation.

Objective function	Output		ARE |mathematical model − NSGA|/NSGA
	Mathematical model	NSGA-II	
Customer satisfaction	0.75	0.76	0.01
Total profit	522000000	523000000	0.001
Total cost	15200000	15000000	0.01

Table 7: Sensitivity analysis.

Parameters	Current capacity			Increasing capacity (+10000)			Decreasing capacity (−10000)		
Collection center	25000			35000			15000		
Reverse center	20000			30000			10000		
Distribution center	35000			45000			25000		
Objective value	f_1^*	f_2^*	f_3^*	f_1^*	f_2^*	f_3^*	f_1^*	f_2^*	f_3^*
	0.75	522000000	15200000	0.85	545000000	160000	0.72	521000000	15100000

For this purpose, we increase and decrease the existing capacity of 10000 centers. Table 7 indicates pre-parameters for sensitivity analysis.

According to Table 7, in case of an increase of 10,000 units in the number of capacities, a significant impact on the target functions will be set. But if a reduction of 10,000 units is made, minor changes will be observed in the target functions.

5. Managerial Insights

Most organizational architectures are linear and consider the value chain model, producing and destroying the product, as a result of which the natural resources available on the planet are consumed. Hence, sustainable development guidelines are increasingly calling for the change of supply chains from linear to closed-loop models, in which circular ideals such as reuse, reconstruction and recycling are considered new. Therefore, the inclusion of existing links in supply chains has been considered by many researchers, physicians, and policymakers as an approach to improve the results of sustainability in jobs. A number of companies are looking for ways to speed up large-scale operations and move to a more closed-loop supply chain. This change requires not only innovation in product, process, and technology, but also innovation in the business model, which must consider new recycling systems to return used products. Also, it is not possible to create a supply chain link by a particular company, as this requires cooperation between different supply chain organizations and other stakeholders from similar or diverse sectors. In general, a change in an organization's business model affects the business activities of other organizations involved in their supply chain. Therefore, a systemic approach to managing the better use of materials, energy, and other valuable resources through higher recycling, reuse, and recycling rates is essential for success. However, there is limited theoretical and empirical knowledge about this phenomenon of interest. The need to meet global demand in a sustainable way that is constantly growing indicates adequate and efficient management of supply chain operations. Sustainability has been the subject of much debate in the academic literature, including the supply chain management (SCM) literature. However, global patterns of production, consumption, and trade remain dangerously unstable. If there is no change in the way supply, production, delivery, recovery, and reconstruction of products, the world will consume a lot of natural resources at its current level of consumption. An important philosophy that may help shape change is the closed-loop supply chain. This theory is increasingly recognized as a viable alternative to the economic model. Closed-loop supply chain theory is becoming an influential driving force for sustainability, both in practice and as an important potential to help organizations achieve sustainable performance success. The closed-loop supply chain has become a strategic variable for organizations even beyond the environmental aspects. There is also an important direction that increases the focus of the study in this regard and given the social and economic scenarios that affect different stakeholders, in a broader sense, as research on the method. Has shifted towards a more sustainable production system. Defining a new range of specific measures necessary for the adequate implementation of the principles of rotational economics for supply chains is the adoption of systemic innovations for them.

6. Conclusion and Future Work

This study presents the problem of supply chain planning considering product recovery processes under uncertainty in prices and using the mixed-integer nonlinear programming. In this problem, the supply chain includes customers, collection centers, return facilities, plants, recovery facilities, and distribution centers. The problem has two objective functions, the first of which seeks to maximize transaction-level satisfaction. In addition, the second objective function maximizes the profit from the supply chain. The constraints associated with the green supply chain are also considered in the problem.

The NSGA-II metaheuristic algorithm is used to solve the model. Finally, a set of small, medium, and large-scale problems are used to evaluate the performance efficiency of the algorithms. Being evaluated using the statistical methods, the results of this study indicate that in the NSGA-II algorithm, the developed model shows a good performance in terms of maximum expansion and distancing. However, no significant difference was observed in other criteria. Due to a large number of model limitations of this research, Gomez software could hardly solve the problem completely in a long time. This factor took a long time to calculate some examples. The main results of the study are as follows:

(i) The exact value of the triple objective functions is calculated

(ii) The problem is solved in small, medium, and large dimensions

(iii) The accuracy of the proposed model compared to the metaheuristic method is shown

(iv) By performing sensitivity analysis, we showed that target functions are less sensitive to reducing the capacity of centers

For further research, it is suggested to consider an appropriate robust model to deal with the uncertainty in this research and compare the results with the existing model.

Data Availability

The data are included in the article and are available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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