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Research Article

Application of Circular Economy and Uncertainty Planning in Analyzing the Sustainable Closed-Loop Supply Chain Network Design

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Supply chain sustainability as a new and very effective approach has recently attracted the attention of researchers in the field of supply chain management. Also, a circular economy helps to reduce the waste materials and products in a supply chain. In order to include circular economy in supply chain network design, it is necessary to use the concept of closed-loop network design. Therefore, designing a sustainable closed-loop supply chain network that works well even by changing some parameters seems to be necessary. This paper presents a multiproduct, sustainable closed-loop supply chain network under uncertainty. First, a mathematical model is proposed to design a closed-loop network, and then a set of possible scenarios is used to deal with the uncertainty of the parameters. In order to show the validity and applicability of the proposed model, numerical examples are presented and analyzed. In this regard, numerical results show the appropriate performance of the proposed model. Finally, sensitivity analysis is performed to assess the role of customer demand in different aspects of sustainability. It is revealed that increasing customer demand will have a strong impact on economic and environmental objectives.

1. Introduction

The importance of significant changes in the current business environment and competitive market as well as transportation costs has led to the issue of designing a sustainable supply chain network. Supply chain management is not limited to product manufacturing companies. However, service businesses can benefit from this approach [1]. The supply chain examines material flows and financial information from beginning to end, so the success of a supply chain depends on the integration and coordination of all entities in that chain in the form of an efficient and effective network structure [2]. According to [3], network design is the first management decision in the supply chain that affects all subsequent decisions and has the most significant impact on overall performance and return on investment in the supply chain. In addition to all the issues related to material flow planning along the supply chain, these decisions also include location, allocation, distribution, inventory, and purchase policy.

In recent years, the necessity and importance of a sustainable supply chain have led managers and planners of organizations and companies to take particular emphasis on this issue in the perspectives and strategies of their organization and company. Critical aspects of sustainable supply chain management include the sustainability of the supply chain network and supply chain environment, the application of environmentally friendly strategies, and the acceptance of social responsibility, so considering supply chain sustainability can be considered in addition to profitability

[4]. Financial considerations also considered and minimized adverse environmental and social adverse effects [5].

Recently, due to government measures, environmental issues and pollution, social issues, and customer pressures, there has been a growing focus on circular economy (CE) as well as sustainability. CE has been introduced as a new and efficient tool in supply chain optimization [6].

Since supply chains are undeniable entities in the current markets, their importance is increasing day by day due to shorter product life cycle, technology development, globalization, and competitive markets and because uncertainty is a separate component. It is the impossibility of real systems that can turn an appropriate decision into a lousy guarantee in the future. Therefore, designing a sustainable supply chain network based on a CE that can be compatible with a variety of natural changes seems to be necessary.

In the following and in Section 2, a comprehensive review of the literature is given. In Section 3, the proposed mathematical model is presented, in Section 4, the validation of the mathematical model and numerical results are provided, and finally, in Section 5, conclusions and future studies are given.

2. Literature Review

Although more attention has recently been paid to the environmental impact of the supply chain, limited research has considered the concept of a circular supply chain.

Pishvaei et al. [7] proposed a multiobjective stochastic programming model for designing a sustainable drug supply chain under uncertain conditions. Since the model was NP-hard, an accelerator decomposition algorithm was designed to deal with the computational complexity of the predetermined model. The results indicated the validity of the model and its solution method. Ghaderi et al. [8] presented a multiobjective model for designing a sustainable biotechnical supply chain based on the sustainability of the chain under uncertainty of the input data and taking into account economic, environmental, and social goals. The life cycle assessment (LCA) method was applied to the proposed model to estimate environmental and social impacts, of which computational analysis using a real case study demonstrates the validity of the proposed model. Eskandari et al. [9] presented an optimization model for a multiobjective sustainable supply chain with uncertain data due to adverse conditions during and after a disaster. The echelons of the studied supply chain were donor groups, blood collection facilities, distribution centers, and hospitals as points of demand.

An important way to deal with uncertainty is to use a fuzzy programming approach. Soleimani et al. [10] used a fuzzy approach to solve a multilevel, multipurpose model that included almost all activities from suppliers to recycling centers and customers. Özkır and Başlıgil [11] used fuzzy programming to model the problem of mutual and customers' satisfaction in the supply chain. Su [12] conducted a study focusing on the relationship between new and recycled materials with respect to variable production costs, device efficiency, and energy consumption. In this research, a linear multifunctional fuzzy planning model was used to analyze the relationship between the factors involved in effective costs and CO2 emissions. Mohammadi et al. [13] optimized the environmental effects of industry and total cost to design and plan a multicycle closed-circuit supply chain network. Their model evaluated the exchanges between carbon emissions as the impact of the industrial environment and total cost. It was concluded that although multistage scenario-based stochastic approaches can provide robust solutions, optimal approaches must be developed to solve real cases.

In the field of closed-loop supply chain network design, Devika et al. [14] proposed a mixed-integer linear programming model for the closed-loop supply chain network design. To solve this NP-hard problem, they used imperialist competitive algorithms (ICA) and variable neighborhood search (VNS). To test the performance of these algorithms, they were compared not only with each other but also with other powerful algorithms. The results show that the proposed approach achieves better solutions compared to others. Zhang and Jiang [15] presented a comprehensive approach to designing a sustainable closed-loop supply chain network based on economic, environmental, and social requirements. The objectives of the model were (1) to minimize total costs, (2) to minimize environmental impacts, and (3) to maximize social benefits. In that study, a multiobjective linear programming model was developed, and simulated annealing (SA) algorithm was used to solve the NP-hard problem. The results of implementing these algorithms showed that SA is almost the most efficient method.

Amin et al. [16] have optimized the closed-loop supply chain based on rubber production options. Their model analyzes a real case study in Canada by calculating the net present value of the problem. Rezaei and Kheirkhah [17] formulated a mathematical model of the TBL-based supply chain network. The objectives were (1) to maximize total profits, (2) to minimize overall environmental impacts, and (3) to maximize social benefits. They used the improved particle swarm optimization (PSO) algorithm to solve the problem, which gave appropriate results. Soleimani et al. [18] examined a sustainable closed-loop supply chain network with multiple levels, multiple products, and multiple cycles and determination of all components and raw materials of products. Modeling was done with an emphasis on high profitability and customer satisfaction by responding to demand and at the same time adhering to environmental and social responsibilities. A genetic algorithm (GA) was proposed to investigate various cases in this field. Based on the results, the proposed algorithm was able to provide a solution with a large approximation at the right time.

The multiplicity of goals in supply chain design is an issue that has been highly regarded by researchers in this field. Li and Hu [19] developed a two-stage randomized mixed-integer linear programming model based on petroleum biodegradation of which parameters such as biomass access, technological progress, and biofuel price are considered under uncertainty. Montoya-Torres et al. [20] focused on the effects of carbon in a supply chain and showed how to determine and optimize carbon effects throughout the supply chain and life cycle. Ahn et al. [21] proposed a linear mixed-integer linear programming model for the design of microalgae in the biodiesel supply chain to help with the estimated cost per hectare, including costs. Gonela et al. [22] proposed a linear programming model of different uncertain types for the design of bioethanol production supply chains based on industrial coexistence. In their model, the total profit is maximized due to the total emission limit of greenhouse gases and other reasonable limits. In order to realize this issue, the economic, social, and environmental pressures resulting from the construction of the mentioned supply chain were studied and modeled with three-objective functions of increasing profit, increasing social responsibility, and reducing carbon emission, respectively.

Lahane et al. [23] described the concept of circular economy in the supply chain. This research, which is the result of reviewing articles in the last ten years, shows that multicriteria optimization and decision-making techniques can create new frameworks in this area. Del Giudice et al. [24] investigated the application of big data in circular supply chain management and provided a circular supply chain. For this purpose, 378 Italian companies have been studied. The results of this study show that a supply chain based on big data as a modulator of the relationship between human resource management and company performance can provide good performance for a circular supply chain. Hussain and Malik [25] combined the paradigm of sustainability and circular economy in supply chain management. In this regard, structural equation modeling has been used to test the hypotheses. The research results show that the circular supply chain can provide a high level of stability for the supply chain.

Mastos et al. [26] have introduced the application of industry 4.0 in circular supply chain management. In this research, it is pointed out that, in order to manage a circular supply chain, it is necessary to study and evaluate the principles of supply chain sustainability. An industry 4.0-based solution is also proposed to evaluate the performance of circular supply chain sustainability.

Rentizelas et al. [27] proposed a mathematical formulation for the multiechelon supply chain network design by considering the circular economy of the wind turbine in Europe. They investigated the feasibility of the circular economy pathway of mechanical recycling for the reuse of end-of-life blades at composite material manufacturing while optimizing the required reverse supply network design in Europe for 2020 and for 2050.

After reviewing past research items, the main contribution of this research can be summarized as follows:

(i) Designing a design of a closed-loop supply chain network in multiperiod and multiproduct conditions
(ii) Considering the role of circular economy in supply chain network design
(iii) Analyzing the effect of circular economy in achieving the optimal solution of the supply chain

3. Problem Statement

In this research, a closed-loop supply chain is assessed. In the forward flow of this supply chain, there are four echelons, including suppliers, manufacturing centers, distribution centers, and customers. In the reverse flow, there are six echelons, including collection and inspection centers, repair centers, disposal centers, recycling centers, redistribution centers, and second-category consumers. The network of this supply chain is depicted in Figure 1.

Suppliers are in charge of obtaining raw materials in the forward network. The items are manufactured at production facilities and then distributed to clients in the first market via forwarding flow networks. After collection and examination, returned items are separated into two categories: separable products and nonseparable products. Products that can be separated into components are sent to a separate facility and turned into different parts. Parts are separated into two groups, recoverable and nonrecoverable, and transported to inspection, cleaning, and sorting centers.

Next, these items are transferred to manufacturers after inspection, cleaning, and sorting in these facilities, where they are combined with other parts and changed into new goods before being returned to the distribution loop. The recyclable separated items are transported throughout the recycling process. Repairable items are gathered from the centers during the repair process and, following inspection, are sent to these centers based on the capacity of the repair centers. Faulty and defective components of returned products can be retrieved, fixed, or replaced with healthy ones in these centers.

Finally, the repaired items are subsequently transferred to redistribution centers, where they are sold on the secondary market.

In order to design the network of this supply chain, a multiobjective mathematical model is proposed, which is presented as follows.

3.1. Notations

The notations used in the mathematical model of the closed-loop network are presented as follows.

3.2. Objective Functions

3.2.1. Maximizing the Profit of the Whole Chain

The profit performance is as follows:

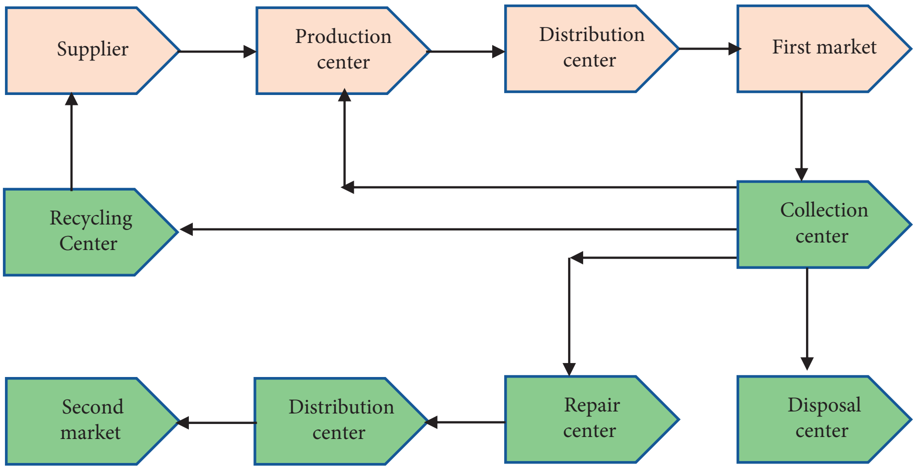

Figure 1: The proposed closed-loop supply chain.

$$
\begin{aligned}
MAX\, Z_1 = {} & \Bigg(\sum_s pb_s \Bigg[\sum_i \sum_c \sum_p QJC^s_{JCP}.\Pr^s_{cp} + \sum_s \sum_u \sum_p prr^s_{qpP}.Q\overline{D}Q^s_{uqp} \Bigg) \\
& - \Bigg(\sum_v \sum_{\check{m}} \sum_e QV\check{M}^s_{v\check{m}e}.TV\check{M}^s_{v\check{m}e} + \sum_{\check{m}} \sum_J \sum_p Q\check{M}J^s_{IJP}.T\check{M}J_{\check{m}jp} \\
& \quad + \sum_J \sum_C \sum_P QJC^s_{jcp}.TJC_{\check{m}jp} + \sum_C \sum_K \sum_p QCK^s_{ckp}.TCK_{ckp} \\
& \quad + \sum_J \sum_C \sum_P QK\check{M}^s_{k\check{m}p}.TK\check{M} + \sum_{\check{m}} \sum_J \sum_p QKD^s_{k\,dp}.TKD_{kdp} \\
& \quad + \sum_l \sum_{\bar{d}} \sum_p QL\overline{D}^s_{l\bar{d}p}.TL\overline{D} + \sum{}_{\bar{d}} \sum_q \sum_p Q\bar{D}Q^s_{\bar{d}qp}.T\bar{D}Q_{\bar{d}qp} \\
& \quad + \sum_r \sum_v \sum_e QRV^s_{rve}.TV_{rve} \Bigg) \\
& - \Bigg(\sum_v \sum_{\check{m}} \sum_e QV\check{M}^s_{c\check{m}p}.\overline{D}C_{ve} \\
& \quad + \sum_{\check{m}} \sum_j \sum_p Q\check{M}J^s_{j\check{m}p}.MC^s_{\check{m}p} + \sum_j \sum_c \sum_p QJC^s_{jcp}.DC_{jp} \\
& \quad + \sum_c \sum_k \sum_p QCK^s_{k\,dp}.CC_{kp} + \sum_k \sum_{\check{m}} \sum_p QK\check{M}^s_{jkp}.RMC^s_{\check{m}p} \\
& \quad + \sum_k \sum_d \sum_p QKD^s_{k\,dp}.DP\ C_{dp} + \sum_k \sum_l \sum_p QKL^s_{klp}.RPC_{lp} \\
& \quad + \sum_k \sum_r \sum_p QKD^s_{krp}.RC_{rp} + \sum_k \sum_r \sum_p QKD^s_{krp}.RC_{rp} \\
& \quad + \sum_l \sum_{\bar{d}} \sum_p QL\overline{D}^s_{l\bar{d}p}.R\ DC_{\bar{d}p} \Bigg] \Bigg) \\
& + \Bigg[\Bigg(\sum_{\check{m}} \sum_h FX_{\check{m}h}.X_{\check{m}h} \\
& \quad + \sum_j \sum_h FY_{jh}.Y_{jh} + \sum_k \sum_h FH_{kh}.T_{kh} + \sum_l \sum_h FW_{lh}.W_{lh} \\
& \quad + \sum_{\bar{d}} \sum_h FO_{\bar{d}h}.O_{\bar{d}h} + \sum_r \sum_h FN_{rh}.N_{rh} \Bigg) \\
& + \Bigg(\sum_s pb_s \Bigg[\sum_{i\in\widehat{M}\bigcup\widetilde{M}} \sum_{\overline{w}\in\overline{w}} \sum_{t\in T} \overline{f}_i.l_i^{\overline{w}t^s} + \sum_{i\in\widehat{M}\bigcup\widetilde{M}} \sum_{\overline{w}\in\overline{w}} \sum_{t\in T} h_i.T\text{ŋ}_i^{\overline{w}t^s-1} + \sum_{i\in\widehat{M}\bigcup\widetilde{M}} \sum_{p\in P} \sum_{t\in T} v_i^p. + \zeta_i^{pt^s} \\
& \quad + \sum_{i\in\widehat{D}\bigcup\widetilde{D}} \sum_{t\in T} \overline{h}_i.T\overline{\text{ŋ}}_i^{t^s} + \sum_{i\in\check{D}} \sum_{p\in P} \sum_{t\in T} \overline{v}_i^p. + \pi_i^{pt^s} \Bigg] \Bigg).
\end{aligned}
\tag{1}
$$

Equation (1) displays the profit maximization from the supply chain in the form of total revenue minus total chain expenses. The income from the sale of items in the first- and second-category markets is shown in the first parenthesis. The shipping charges of each facility are shown in the second parenthesis. The supply chain's operational expenses are included in the third parenthesis. The cost of raw materials, the cost of product production and reproduction in production centers, operating costs in distribution and redistribution centers, inspection costs for products returned to collection centers, disposal costs, repair costs, and costs related to recycling are all included in these costs.

The fixed costs of establishing, distribution and redistribution, collection, and recycling are shown in the fourth parenthesis. The cost of working each employee, the cost of employing connected to the factory, the cost of jobless labor, contracting costs, and inventory costs in the distribution centers are all represented in the fifth parenthesis, respectively.

3.2.2. Second Objective Function: Reduction of Environmental Effects.

$$
\begin{aligned}
\text{MAX}\, Z_2 = \Bigg(\sum_s pb_s \Bigg[& \sum_v \sum_{\check{m}} \sum_e QV\check{M}^s_{v\check{m}e}.\text{ETV}\check{M}^s_{v,\check{m},p} + \sum_{\check{m}} \sum_j \sum_p Q\check{M}J^s_{j\check{m}p} \left(ET\check{M}J^s_{\check{m},j,p} + EM^s_{\check{m},p} \right) \\
& + \sum_j \sum_c \sum_p QJC^s_{jcp}.ETJC^s_{j,c,p} + \sum_c \sum_k \sum_p QCK^s_{ckp}.ETCK^s_{c,k,p} + \sum_k \sum_{\check{m}} \sum_p QKI^s_{k\check{m}p} \left(ETK\check{M}^s_{k,\check{m},p} + ER\check{M}^s_{\check{m},p} \right) \\
& + \sum_k \sum_d \sum_p QKD^s_{k\,dp}.ETKD^s_{k,d,p} + \sum_r \sum_v \sum_e QRV^s_{rve}.ETRV^s_{r,v,e} + \sum_k \sum_l \sum_p QKL^s_{klp} \left(ETKL^s_{K,L,p} + ERP_{lp} \right) \\
& + \sum_k \sum_r \sum_p QKR^s_{krp} \left(ETKR^s_{K,r,p} + ERC_{rp} \right) + \sum_l \sum_{\bar{d}} \sum_p QL\overline{D}^s_{l\bar{d}p}.ETL\overline{D}^s_{l,\bar{d},p} + \sum_{\bar{d}} \sum_q \sum_p Q\overline{D}Q^s_{\bar{d}qp}.ET\overline{D}Q^s_{\bar{d}q,p} \Bigg] \Bigg).
\end{aligned}
\tag{2}
$$

The second objective function in (2) represents the minimization of environmental impacts based on the carbon emission index caused by the transportation of products between each of the centers as well as the carbon produced from the processes of production, reproduction, repair, and recycling.

3.2.3. Third Objective Function: Maximizing Social Effects.

$$
\begin{aligned}
\text{MAX}\, Z_3 = \Bigg(& \sum_s pb_s \left[\theta^s_{j,0} \left(\begin{array}{c} \sum_{\check{m}} \sum_h JOJ^s_{\check{m},h}.X_{\check{m}h} + \sum_j \sum_h JOJ^s_{j,h}.Y_{jh} + \sum_k \sum_h JOK^s_{k,h}.T_{kh} \\ + \sum_l \sum_h JOL^s_{l,h}.W_{lh} + \sum_{\bar{d}} \sum_h JO\overline{D}^s_{\bar{d},h}.O_{\bar{d}h} + \sum_r \sum_h JOR^s_{r,h}.\gamma_{rh} \end{array} \right) \right] \\
& - \sum_s pb_s \left[\theta^s_{ld} \left(\sum_{\check{m}} \sum_h L\; D\check{M}^s_{\check{m},h}.X_{\check{m}h} + \sum_l \sum_h L\; DL^s_{lh}.W_{lh} + \sum_r \sum_h L\; DR^s_{r,h}.\gamma_{rh} \right) \right] \\
& + \left(\sum_s pb_s \left[\begin{array}{l}
\left(\sum_{\left\{(i,\bar{j},\bar{r})\in\bar{A} | i\in V_{\bar{k}},\, j\in\widehat{M}_{\bar{k}},\, \bar{k}\in\bar{K},\, \bar{k}\neq\bar{K}\right\}} \sum_{e\in E} \sum_{t\in T} \widehat{H}^e_i.\widetilde{W}^{et^s}_{i\bar{j}\bar{r}} \right) \\
+ \left(\sum_{i\in\left\{\widehat{M}_{\bar{k}}\cup\widehat{M}_{\bar{k}} | \bar{k}\in\bar{k}^d\right\}} \sum_{\bar{w}\in\bar{W}} \sum_{t\in T} \widetilde{H}^{\bar{w}}_i.\delta^{\bar{w}t^s}_i + \sum_{i\in\left\{\overline{D}_{\bar{K}}\cup\overline{D}_{\bar{K}} | \bar{k}\in\bar{k}^d\right\}} \sum_{t\in T} \bar{\bar{H}}_i.\bar{\delta}^{-t^s}_i \right) \\
+ \left(\sum_{i\in\left\{\widehat{M}_{\bar{k}}\cup\widetilde{M}_{\bar{k}} | \bar{k}\in\bar{k}^d\right\}} \sum_{\bar{w}\in\bar{W}} \sum_{t\in T} T\eta^{\bar{w}t-1}_i.\delta^{\bar{w}t^s}_i + \sum_{i\in\left\{\bar{\widehat{D}}_{\bar{K}}\cup\widetilde{D}_{\bar{K}} | \bar{k}\in\bar{k}^d\right\}} \sum_{t\in T} T\eta^{-t^s}_i \right) \\
+ \left(\sum_{i\in\left\{\widehat{M}_{\bar{k}}\cup\widetilde{M}_{\bar{k}} | \bar{k}\in\bar{k}^u\right\}} \sum_{\bar{w}\in\bar{W}} \sum_{t\in T} L^{\bar{w}t-1}_i + \sum_{i\in\left\{\bar{\widehat{D}}_{\bar{K}}\cup\widetilde{D}_{\bar{K}} | \bar{k}\in\bar{k}^u\right\}} \sum_{t\in T} \bar{L}^{-t^s}_i \right) \\
+ \left(\sum_{i\in\left\{\overline{M}_{\bar{k}} | \bar{k}\in\bar{k}^d\right\}} \sum_{p\in P} \sum_{t\in T} \overline{H}^p_i.\zeta^{pt^s}_i + \sum_{i\in\left\{\bar{\check{D}}_{\bar{K}} | \bar{k}\in\bar{k}^d\right\}} \sum_{p\in P} \sum_{t\in T} \check{H}^p_i.\pi^{pt^s}_i \right)
\end{array} \right] \right)
\end{aligned}
\tag{3}
$$

The third objective function in (3) reflects the maximum of the supply chain network social impacts, which include maximizing new employment opportunities and limiting total days lost due to workplace injuries, acquiring raw materials from nonlocal suppliers, and growing the plant in the areas. Less developed, factory-owned distribution facilities in less developed areas are being closed down. All on contract factory employees are in more developed areas.

3.3. Constraints.

$$\sum_{J}\sum_{P} Q\check{M}J^{s}_{\check{m}JP} = \sum_{v}\sum_{e} QV\check{M}^{s}_{v\check{m}e} + \sum_{k}\sum_{p} QK\check{M}^{s}_{k\check{m}p}\ \forall_{\check{m}} \in \check{M}, s \in S, \tag{4}$$

$$\sum_{\check{m}} Q\check{M}j^{s}_{\check{m}jp} = \sum_{\check{m}} Qjc^{s}_{jcp}\ \forall j \in J, p \in P, s \in S. \tag{5}$$

Equation (4) states that, for any product, the sum of all inflows from all suppliers and collecting centers to each production center equals the outflows from that center. Equation (5) states that the sum of inflows from all production centers to each distribution center is equal to the sum of outflows from this distribution center for each product.

$$\sum_{j} Qjc^{s}_{jcp} \geq \mathrm{DE}_{cp}\ \forall c \in C, p \in P, s \in S. \tag{6}$$

Equation (6) indicates that it is necessary to meet the whole demand of all customers in the first market.

$$\sum_{\check{m}} QCK^{s}_{ckp} = \mathrm{DE}_{cp}.RT^{s}\forall c \in C, p \in P, s \in S. \tag{7}$$

Equation (7) depicts the link between consumer demand in the first market and items which are returned to all collection centers.

$$\sum_{d} QKD^{s}_{k\ dp} = \sum_{c} QcK^{s}_{ckp}.RD\ \forall k \in K, p \in P, s \in S. \tag{8}$$

Equation (8) indicates that, for each product, the number of products shipped from the collection centers to disposal centers is equal to the number of products shipped from customers in the first market to collection centers by considering the disposal ratio.

$$\sum_{l} QKl^{s}_{kLp} = \sum_{c} QcK^{s}_{ckp}.RR\ \forall k \in K, p \in P, s \in S. \tag{9}$$

Equation (9) states that the inflows to each collection center from all consumers in the first category market regions multiplied by the repair ratio equal the outflows from each collection center to all repair facilities for each product.

$$\sum_{r} QKR^{s}_{krp} = \sum_{c} QcK^{s}_{ckp}.RU\ \forall k \in K, p \in P, s \in S. \tag{10}$$

Equation (10) states that the inflows to each collection center from all consumers in the first category market regions multiplied by the recycling ratio equal the outflows from each collection center to all recycling centers for each product.

$$\sum_{\check{m}} QK\check{M}^{s}_{k\check{m}p} = \sum_{c} QcK^{s}_{ckp}.RM\ \forall k \in K, p \in P, s \in S. \tag{11}$$

Equation (11) shows that, for each product, the outflows from the collection centers to all production centers are equal to the inflows to each collection center from all customers in the first category market areas multiplied by the reproduction ratio.

$$\sum_{c} QcK^{s}_{ckp} = \sum_{d} QKD^{s}_{k\ dp} + \sum_{p} QKR^{s}_{kp} + \sum_{e} QK\check{M}^{s}_{kip} + \sum_{k} QKL^{s}_{k\check{m}p}\ \forall k \in K, p \in P, s \in S. \tag{12}$$

Equation (12) demonstrates the relation between the inflow and outflow in the collection center based on the products received from customers and sent to the repair centers or disposal centers.

$$\sum_{l} QKl^{s}_{klp} = \sum_{c} QL\overline{D}^{s}_{l\overline{d}p} \quad \forall l \in L, p \in P, s \in S. \tag{13}$$

Equation (13) states that the total of all inflows from all collection centers to each repair center is equal to the sum of all outflows from this repair facility for each product.

$$\sum_{l} QL\overline{D}^{s}_{l\overline{d}p} = \sum_{p} Q\overline{D}Q^{s}_{\overline{d}qp}\ \overline{\forall d} \in \overline{D}, p \in P, s \in S. \tag{14}$$

Equation (14) states that the total products received by redistribution centers from all repair centers should be equal to the total products shipped from redistribution centers

$$\sum_{l} Q\overline{D}Q^{s}_{\overline{d}qp} \geq DDE_{qp} \quad \forall q \in Q, p \in P, s \in S. \tag{15}$$

Equation (15) indicates that the demand of all customers in the second-category market areas is satisfied.

$$\sum_{k}\sum_{p} QKR^{s}_{krp} = \sum_{v}\sum_{e} QRV^{s}_{rve} \quad \forall r \in R, p \in P, s \in S. \tag{16}$$

Equation (16) states that the sum of inflows from all collecting centers to each recycling center is equal to the sum of outflows from these recycling centers for each raw material.

$$\sum_{e}\sum_{i} QV\check{M}^{s}_{v\check{m}e} \leq \mathrm{CAPV}_{v}\forall v \in V. \tag{17}$$

Equation (17) states that, for each supplier, the provided capacity should be of concern.

$$\sum_{j}\sum_{p} Q\check{M}J^{s}_{\check{m}jp} \leq \sum_{h} \mathrm{CAP}\check{M}_{\check{m}h}.X_{\check{m}h}\forall_{\check{m}} \in L. \tag{18}$$

Equation (18) shows the relation between the products sent from production centers and the products received by distribution centers as well as the shipment capacity.

$$\sum_{c}\sum_{p} QJC^{s}_{jcp} \leq \sum_{h} \mathrm{CAP}J_{\check{m}h}.Y_{\check{m}h}\forall j \in J. \tag{19}$$

Equation (19) states that all products sent from each distribution center should be less than the holding capacity in that distribution center.

$$\sum_{k}\sum_{p} QCK^{s}_{ckp} \le \sum_{h} \mathrm{CAP}K_{kh}.T_{kh} \forall k \in K. \tag{20}$$

Equation (20) states that all products received by the collection center should be less than the holding capacity of that collection center.

$$\sum_{k}\sum_{p} QKL^{s}_{klp} \le \sum_{h} \mathrm{CAP}K_{lh}.W_{lh} \forall l \in L. \tag{21}$$

Equation (21) states that the aggregate of all collecting centers inflows to repair centers for each product does not exceed the capacity.

$$\sum_{l}\sum_{p} QL\overline{D}^{s}_{l\overline{d}p} \le \sum_{h} \mathrm{CAP}\, L_{\overline{d}h}.O_{\overline{d}h} \forall_{\overline{d}} \in \overline{D}. \tag{22}$$

Equation (22) indicates that, for each product, the sum of the inflows to the redistribution centers by all collection centers does not exceed the capacity of the redistribution centers.

$$\sum_{k}\sum_{p} QKR^{s}_{krp} \le \sum_{h} \mathrm{CAP}R_{rh}.\gamma_{rh} \forall r \in R. \tag{23}$$

Equation (23) indicates that, for each product, the sum of the inflows to the recycling centers by the collection centers does not exceed the capacity of the recycling centers.

$$\sum_{h} X_{\check{m}h} \le 1 \forall_{\check{m}} \in I, \tag{24}$$

$$\sum_{h} Y_{\check{m}h} \le 1 \forall j \in J, \tag{25}$$

$$\sum_{h} T_{kh} \le 1 \forall k \in K, \tag{26}$$

$$\sum_{h} W_{lh} \le 1 \forall l \in L, \tag{27}$$

$$\sum_{h} O_{\overline{d}h} \le 1 \forall_{\overline{d}} \in \overline{D}, \tag{28}$$

$$\sum_{h} \overline{D}_{rh} \le 1 \forall r \in R. \tag{29}$$

Equations (24)–(29) ensure that production, distribution, collection, repair, redistribution, and recycling centers are built to a maximum capacity level, respectively.

$$\begin{gathered} T\overline{\text{ŋ}}_{i}^{t^{s}-1} + \overline{\text{ŋ}}_{i}^{t^{s}} - \overline{L}_{i}^{t^{s}} = T\overline{\text{ŋ}}_{i}^{t^{s}} \\ \forall i \in \widehat{D} \bigcup \widetilde{D}, t \in T, s \in S. \end{gathered} \tag{30}$$

The number of employees working each period and at each distribution center is expressed by (30).

$$\begin{gathered} T\overline{\text{ŋ}}_{i}^{t^{s}-1} \ge \overline{L}_{i}^{t^{s}} \\ \forall i \in \widehat{D} \bigcup \widetilde{D}, t \in T, s \in S. \end{gathered} \tag{31}$$

Equation (31) indicates that the number of fired workforces in each distribution center is fewer than the number of those who were previously employed.

$$\begin{gathered} T\text{ŋ}_{i}^{\overline{w}t^{s}-1} + \text{ŋ}_{i}^{\overline{w}t^{s}} - L_{i}^{\overline{w}t^{s}} = T\text{ŋ}_{i}^{\overline{w}t^{s}} \\ \forall i \in \widehat{M} \bigcup \widetilde{M}, t \in T, s \in S. \end{gathered} \tag{32}$$

Equation (32) expresses the number of employees working in each period and in each production center. These workforces include people in the previous period, plus those hired and minus those fired.

$$\begin{gathered} T\text{ŋ}_{i}^{\overline{w}t^{s}-1} \ge L_{i}^{\overline{w}t^{s}} \\ \forall i \in \widehat{M} \bigcup \widetilde{M}, t \in T, s \in S. \end{gathered} \tag{33}$$

Equation (33) states that in each distribution center, the number of those fired is less than the number of those who were previously employed.

$$\begin{gathered} \sum_{p} T\text{ŋ}_{i}^{\overline{w}t^{s}}.\left(\overline{H}_{i}^{p} + \overline{H}_{i}^{p}\right) \le \overset{=}{H} \\ \forall i \in \widehat{M} \bigcup \widetilde{M}, \overline{w} \in \overline{W}. \end{gathered} \tag{34}$$

Equation (34) refers to the fact that employees in the production centers must work as much as possible during shift work in order to expand and produce items.

$$\begin{gathered} T\text{ŋ}_{i}^{\overline{w}t^{s}}.\left(\overline{H}_{i}^{p}\right) \ge \sum_{j} Q\check{M}J_{i,j,p}^{s} \\ \forall i \in \widehat{M} \bigcup \widetilde{M}, \overline{w} \in \overline{W}, s \in S, p \in P. \end{gathered} \tag{35}$$

Equation (35) expresses the relationship between production and manpower. In this regard, the total amount of goods produced by the workforces in each production center should be more than the amount of goods shipped from that center.

$$\sum_{p} T\overline{\text{ŋ}}_{i}^{t^{s}}.\left(H_{i}^{''} + \widehat{H}_{i}^{p}\right) \le \overset{=}{H} \quad \forall i \in \widehat{D} \bigcup \widetilde{D}. \tag{36}$$

Equation (36) refers to the fact that individuals working in the distribution center are responsible for expanding and maintaining items and must work for the whole shift.

$$T\overline{\text{ŋ}}_{i}^{t^{s}}.\left(\widehat{H}_{i}^{p}\right) \ge \sum_{q} Q\overline{D}Q_{i,q,p}^{s} \forall i \in \widehat{D} \bigcup \widetilde{D}. \tag{37}$$

The connection between inventory and workforce planning is expressed in (37). The total quantity of goods sent by the workforces in each distribution center should be more than the total amount of products shipped from that center.

Table 1: Approximate parameters of the mathematical model.

Parameter	Low limit	Upper line	Parameter	Low limit	Upper line	Parameter	Low limit	Upper line
$\mathrm{Pr}^{\mathrm{s}}_{\mathrm{cp}}$	600	800	$\mathrm{RMC}^{\mathrm{s}}_{\check{\mathrm{m}},\mathrm{p}}$	0.2	0.3	$\mathrm{TKD}_{\mathrm{k,d,p}}$	2	3
$\mathrm{Pr}\, r^{s}_{qp}$	400	500	$DC_{j,p}$	0.3	0.4	$TKL_{k,l,p}$	2	3
DE^{s}_{cp}	50	60	$CC_{k,p}$	0.2	0.4	$TK\widehat{M}_{k},\check{m}_{p}$	2	3
$\mathrm{FX}_{\check{m},h}$	10	20	$RPC_{l,p}$	0.1	0.2	$TL\overline{D}_{l,\overline{d},p}$	2	3
$Fy_{j,h}$	15	20	$R\ DC_{\overline{d},p}$	0.3	0.4	$T\overline{D}Q_{\overline{d},q,p}$	1	3
$FH_{k,h}$	5	15	$RC_{r,p}$	0.1	0.3	$TRV_{r,v,e}$	1	3
$FO_{\overline{d},h}$	5	15	$TK\check{M}_{v},\check{m}_{e}$	2	3	$\overline{h}_{i}$	0.2	0.4
$FU_{r,h}$	10	15	$T\check{M}J\,\check{m}_{p}$	2	3	h_{i}	0.2	0.4
$\overline{v}^{p}_{i}$	0.1	0.3	$\widehat{M}\bigcup\widetilde{M}$	800	1000	$\mathrm{CAP}\,V_{u}$	500	800
$\mathrm{CAP}\,K_{l,h}$	700	1000	$\mathrm{CAP}\,J_{j,h}$	800	1000	$\mathrm{CAP}\,U_{\overline{d},h}$	800	1000
$CAP\,J_{j,h}$	900	1200						

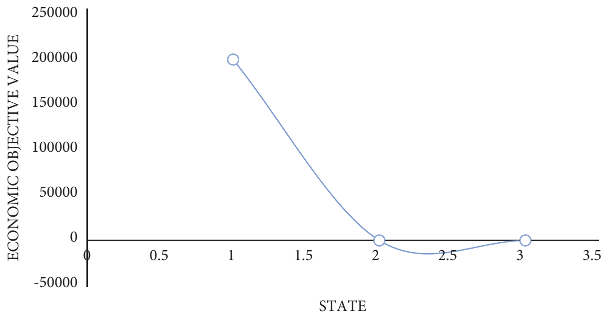

Figure 2: The value of the economic objective function under different scenarios.

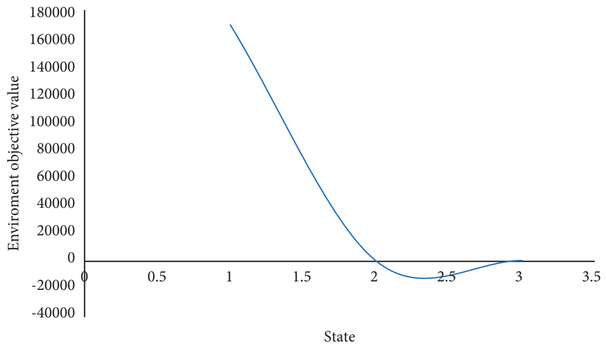

Figure 3: The value of the environment objective function under different scenarios.

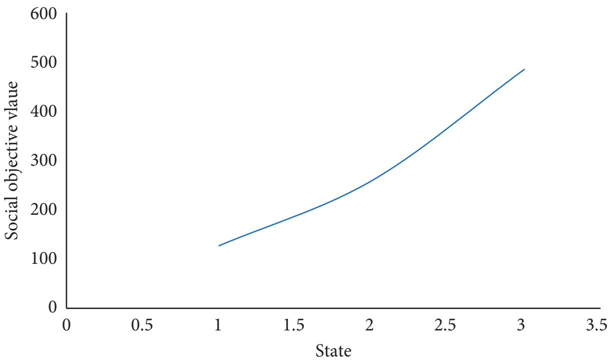

Figure 4: The value of social objective function under different scenarios.

$$X_{\check{m}h}, Y_{\check{m}h}, T_{kh}, W_{lh}, O_{\overline{d}h}, U_{rh} \in \{0, 1\},$$
$$QVI_{v\check{m}h}, QIJ_{\check{m}jp}, QJC_{jcp}, QCK_{ckp}, QKI_{k\check{m}p}, QKD_{k\ dp}, \tag{38}$$

$$QKL_{klp}, QKR_{krp}, QLU_{j\overline{d}p}, QRV_{rve} \geq 0. \tag{39}$$

Equations (38)-(39) show the kind of each decision variable.

4. Numerical Results

4.1. Validation of the Mathematical Model. The validity of the proposed multiobjective model developed in this study is evaluated using the GAMS software and a randomly generated test problem. The simulated data are used to create a numerical example, which is subsequently incorporated into the mathematical model. The following is the data in this numerical example.

The supply chain is thought to contain two raw material sources. There are five first markets and three second markets. There are three disposal centers, three possible distribution centers, two potential collecting centers, and two potential repair and recycling centers.

The goal is to produce and supply one specific product. There is only one production unit to produce this product. The repair rate in the repair centers is equal to 40%, the disposal rate in the disposal centers is equal to 30%, the recycling rate in the recycling centers is equal to 20%, and finally, the reproduction rate in the production center is equal to 10%. Other parameters of the mathematical model are generated based on a continuous uniform distribution. The upper limit and the lower limit are the values of each of the parameters according to Table 1.

Figure 2 shows that the maximum value of the objective function is obtained in the first case (maximizing the economic effect of the supply chain), and in no other case is the equivalent value obtained. Figure 3 also shows that the lowest value of the environmental impact objective function is obtained in the second case (supply chain environmental impact minimization mode), and in no other case is the equivalent value obtained. In a similar way, the trend of the third objective function in different scenarios is illustrated in Figure 4.

Table 2: Dimensions of designed examples.

Dimensions	Name	Number of suppliers	The number of the first market	Second market number	Number of disposal centers	Number of distribution centers	Number of collection centers	Number of repair centers	Number of recycling centers	Number of products	Number of scenarios
Small	P1	2	6	3	2	3	2	2	2	2	2
	P2	3	7	4	2	3	2	3	3	3	3
	P3	4	8	6	3	4	3	5	5	5	6
Medium	P4	7	9	8	5	5	5	5	6	6	7
	P5	7	12	10	5	6	4	7	6	6	10
	P6	8	11	10	6	8	5	8	8	8	10
	P7	10	14	10	6	8	6	9	8	8	13
Large	P8	11	17	15	6	10	11	11	11	11	16
	P9	13	21	17	8	13	11	14	14	17	19
	P10	15	29	21	9	15	12	14	15	22	21

Table 3: Results of solving different numerical examples.

	Optimal economic value	The optimal amount of social	Optimal environmental value	Solution time
P1	183712.6	234.6762	6863.064	33.02988
P2	245961.5	281.6311	13128.02	54.96419
P3	259506.8	421.6442	17239.34	115.0335
P4	410597.6	398.0413	23185.15	337.9464
P5	646575.7	414.8581	27424.11	455.4346
P6	1036983	692.0819	28936.21	534.6852
P7	1285350	1165.829	42623.64	1255.487
P8	1336998	1302.29	44986.48	2051.522
P9	2007278	1402.862	49408.82	3178.191
P10	1925290	1488.242	50817.1	3854.694

As a result, improving one of the three objectives will not bring all other ones to the optimal level, nor will optimizing two of the three objectives. Therefore, it may be argued that the objectives are in conflict. Because when the supply chain's economic effect is optimized, other objectives are not in their ideal value. As a result, the same is valid for social and environmental impact optimization.

4.2. CE Performance in Sustainability Supply Chain.

In order to evaluate the performance of CE in a sustainable supply chain, the mathematical model is solved using several numerical examples in various dimensions. In this regard, a total of ten numerical examples have been generated. Table 2 provides dimensional information for these test problems. Additional information is based on Table 1. The weighted sum technique is utilized to optimize the suggested three-objective problem. Three objectives with the same weight of 0.33 are combined, and their total objective is optimized.

These instances are then optimized in GAMS software using the optimization model. Table 3 summarizes the findings. The model information shown in Table 2 is given to the GAMS program in each of problems P1 through P10. After that, their weight distribution is optimized. Finally, the optimum value for each of the software's aims is shown. Table 3 summarizes the findings of this research.

According to Table 3, the proposed mathematical model can identify the best value for all three objectives in a variety of scenarios. This demonstrates the mathematical model's effectiveness. In Figures 5, 6, and 7, the method of determining the values of various functions is depicted in ten cases.

The ideal value of each of the objective functions grows as the dimensions of the issue expand from small to large, as seen in Figures 5, 6, and 7. These increases are not in a linear trend, and the rate of rising varies depending on the case. As the weight combination technique only offers the ideal value for each objective, it is not feasible to compare two objectives on the same problem, and only the trend of the values of each of the investigated goals is evaluated.

4.3. Sensitivity Analysis.

In this section, the effect of raising the demand parameter as one of the key parameters of the model on the values of each objective function is explored using sensitivity analysis in two ways. Because the demand parameter is important in supply chain concerns, the pattern of changes in the proposed model's objective functions with rising customer demand in the first and second markets has been investigated.

Figure 8 shows the trend of changes in the economic objective function against the increase in changes in customer demand in the first and second markets. As can be seen, the slope of the increase in the first objective function is nonlinear and nonparabolic. Therefore, with increasing changes in customer demand, the amount of the economic

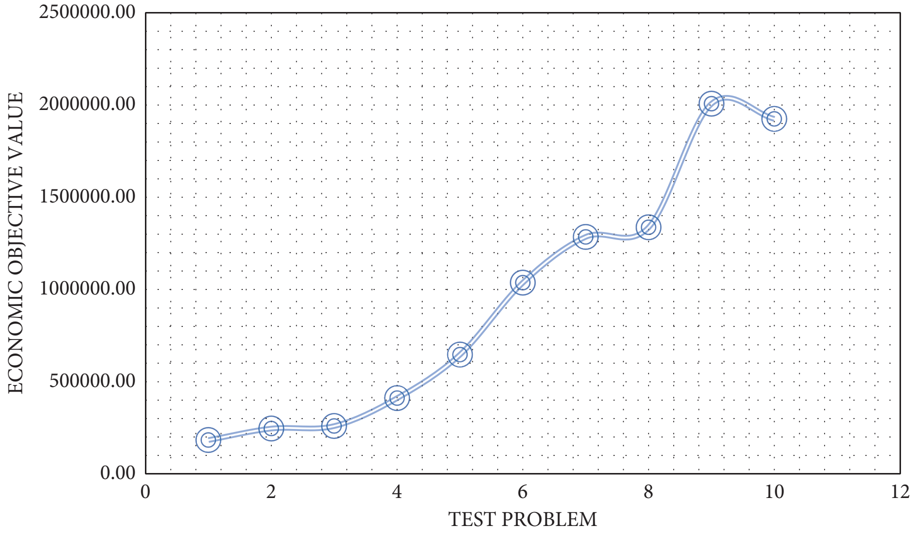

Figure 5: The trend of the first objective function on different numerical examples.

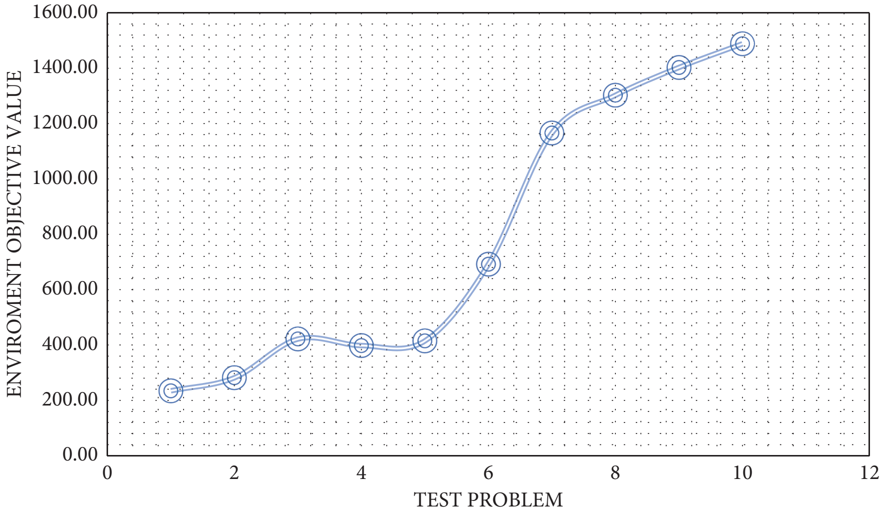

Figure 6: The trend of the second objective function on different numerical examples.

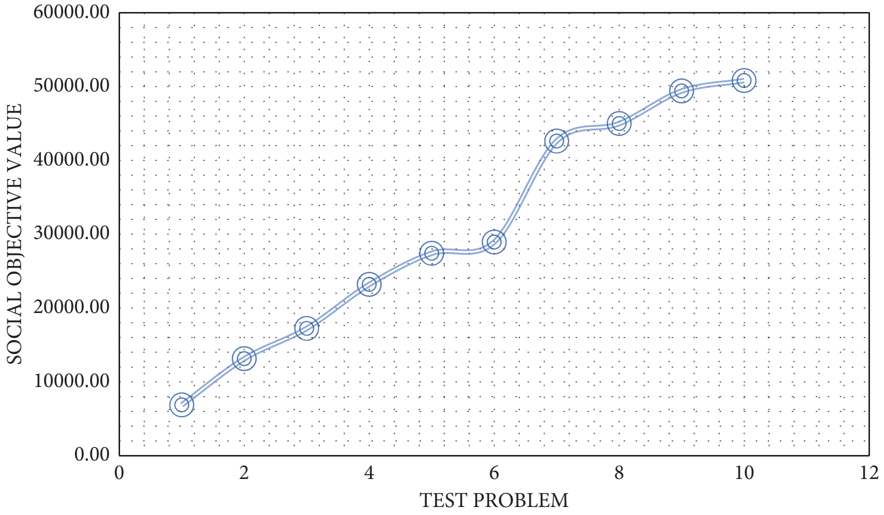

Figure 7: The trend of the third objective function on different numerical examples.

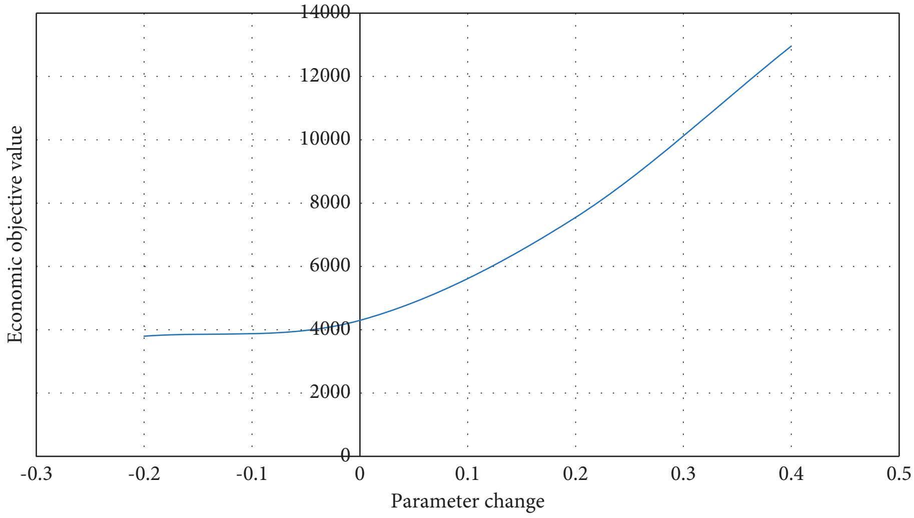

Figure 8: Sensitivity analysis of economic objective function.

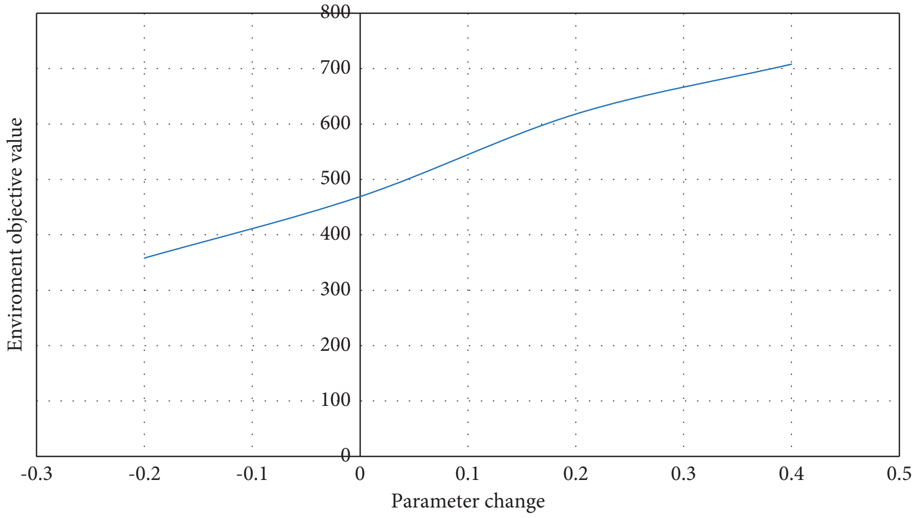

Figure 9: Sensitivity analysis of the environmental objective function.

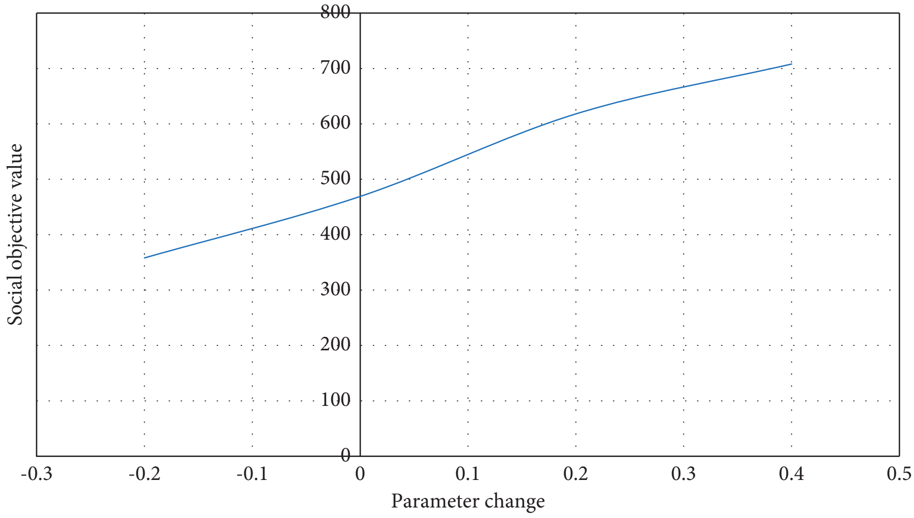

Figure 10: Sensitivity analysis of social objective function.

objective function has an increasing trend. Figures 9 and 10 show the trend of changes in the environmental and social objective function, respectively, against the increase in customer demand in the first and second markets, and in both cases, changes in both functions can have an increasing trend. The results obtained in this section indicate that the sharp increase in target functions with changes in demand indicates that it is essential that changes in demand can make optimal supply chain decisions, affecting whether in the economic, environmental, or social fields.

5. Conclusions and Future Directions

In this study, first, the previous related studies were reviewed. Next, inspired by the latest research items, a supply chain based on the circular economy was developed. This supply chain is closed-loop and consists of suppliers, manufacturers, distributors, customers, collection centers, repair centers, recycling centers, and disposal centers. Considering the multidimensional concept of sustainability, maximum profit according to the revenue and costs of the whole chain, minimizing environmental effects according to carbon emission index, and maximizing social effects according to the criteria of the number of job opportunities created and the number of lost days, is formulated in the proposed mathematical model. In this regard, purchasing raw materials from nonlocal suppliers, expanding the plant in less developed areas, firing employees from factory-owned distribution centers in less developed areas, location and allocation, and distribution are optimized through this model. To deal with the uncertainty of the parameters in the proposed closed-loop supply chain optimization model, the probabilistic method has been used. In the next step, the validation and the results of the model were examined. In the validation section, the results show that the individual optimization of each objective does not lead to the ideal level of other objectives, so the result is that economic, environmental, and social goals are in conflict with each other. Also, several examples were solved in small, medium, and large dimensions, which show that the designed mathematical model has the ability to find the ideal solution in different situations and conditions. At the end of the research, sensitivity on the customer demand parameter shows that increasing customer demand will have a substantial impact on all three objectives.

There was a key limitation in this study. Considering the circular economy for the supply chain requires a holistic view of all supply chains. In supply chain network design, however, only members of a chain are considered. Therefore, adding a circular economy to the supply chain network design problem is always a major constraint for real-world implementation. Because this requires the participation of a large number of supply chains, the complexity of the model makes it more challenging to optimize, and this is another limitation of the research. Some future suggestions for developing this study and presenting new research include using an improved GA or PSO algorithm to optimize a large-scale model and designing a hybrid metaheuristic algorithm.

Abbreviations

Indices

$v \in V$:	Set of fixed locations for suppliers
$c \in C$:	Set of fixed locations for the first market
$q \in Q$:	Set of fixed locations for the secondary market
$d \in D$:	Set of fixed locations for disposal centers
$k \in K$:	Set of potential locations for collection and inspection centers
$l \in L$:	Set of potential locations for repair centers
$r \in R$:	Set of potential locations for recycling centers
$p \in P$:	Set of products
$s \in S$:	Set of scenarios
$e \in E$:	Set of raw materials
$h \in H$:	Set of capacity levels for potential locations
$\widetilde{m} \in \widetilde{M}$:	Set of inventories owned by the factory
$\widehat{m} \in \widehat{M}$:	Set of new facilities owned by the factory
$\check{m} \in \check{M}$:	Set of possible factories
$\overline{w} \in \overline{W}$:	Set of types of departments owned by the factory
$\overline{d} \in \overline{D}$:	Set of potential locations for distribution centers
$\widetilde{d} \in \widetilde{D}$:	Set of existing distribution centers
$\widehat{d} \in \widehat{D}$:	Set of new redistribution centers
$\check{d} \in \check{D}$:	Set of conventional distribution centers
$\overline{A} = \{(i, \overline{j}, \overline{r})\}$:	Types of transportation whose origin is i and destination is j
$\overline{K} = \overline{k}^d \bigcup \overline{K}^u$:	A set of areas. d includes more developed areas, and u includes less developed areas.

Parameters

Pr_{cp}^s:	The selling price of product p in the first market c in scenario s
prr_{qp}^s:	The selling price of product p in the secondary market q in scenario s
DE_{cp}^s:	Demand for product p in the first market c in scenario s
$D\ D\ E_{qp}^s$:	Demand for product p in the secondary market q in scenario s
$\mathrm{FX}_{\check{m},h}$:	Fixed cost of construction of production center $\check{m}$ with capacity level h
$Fy_{j,h}$:	Fixed cost of constructing distribution center j with capacity level h
$FH_{k,h}$:	Fixed cost of constructing a collection and inspection center k with capacity level h
$FO_{\overline{d},h}$:	Fixed cost of construction of distribution center $\overline{d}$ with capacity level h
$FU_{r,h}$:	Fixed cost of constructing a recycling center r with capacity level h
$SC_{v,e}$:	Preparing cost of each unit of raw materials e with capacity level h
$MC_{\check{m},p}^s$:	Production cost per unit of product p in the production center $\check{m}$ in scenario s
$RMC_{\check{m},p}^s$:	Reproducing cost per unit of product p at the production center $\check{m}$ in scenario s

$\mathrm{DC}_{j,p}$:	Distribution and holding cost per unit of product p in the distribution center j
$\mathrm{CC}_{k,p}$:	Inspection and testing cost per unit of product p in the collection center k
DPC_{d,p^R}:	Disposal cost per unit of product p in the disposal center d
RPC_{l,p^R}:	Repairing cost per unit of product unit p in the repair center l
RDC_{d,p^R}:	Redistribution cost per unit of product p in the redistribution center $\overline{d}$
RC_{r,p^R}:	Redistribution cost per unit of product p in the recycling center r
$\mathrm{TVM}_{\check{m},v,e^R}$:	Transportation and purchasing cost per unit of raw materials e from the supplier v to the production center $\check{m}$
$\mathrm{TMJ}_{\check{m},j,p^R}$:	Transportation cost per unit of product p from the production center $\check{m}$ to the distribution center j
TJC_{j,c,p^R}:	Transportation cost per unit of product p from the distribution center j to the first market c
TCK_{k,c,p^R}:	Transportation cost per unit of used product p from the first market c to the collection center k
TKD_{k,d,p^R}:	Transportation cost per unit of used product p from the collection center k to the disposal center d for disposal
TKL_{k,l,p^R}:	Transportation cost per unit of used product p from the collection center k to the repair center l for repair
$\mathrm{TKM}_{k,\check{m},p^R}$:	Transportation cost per unit of used product p from the collection center k to the production center $\check{m}$ for reproduction
TKR_{k,r,p^R}:	Transportation cost per unit of used product p from the collection center k to the recycling center r for recycling
TLD_{d,l,p^R}:	Transportation cost per unit of repaired product p from the repair center l to the redistribution center $\overline{d}$
TDQ_{d,q,p^R}:	Transportation cost per unit of repaired product p from the redistribution center $\overline{d}$ to the secondary market q
TRV_{r,v,e^R}:	Transportation cost per unit of recycled raw materials e from the recycling center r to the supplier v
$\overline{h}_i$:	Hiring cost per unit for each employee with a distribution center belongs to $i \in \overline{d} \cup \mathrm{d}$
h_i:	The cost of hiring for each new hire related to the factory $i \in \check{m} \cup \tilde{m}$
$\overline{f}_i$:	The cost of dismissal of each dismissed employee belonging to the factory belongs to $i \in \check{m} \cup \tilde{m}$
v_i^p:	Subcontracts cost for each unit of the p family related to factory $i \in \check{m} \cup \tilde{m}$
$\overline{v}_i^p$:	Storage cost in each time period of the product family related to the distribution center belongs to $i \in \overline{d} \cup \mathrm{d}$

$\mathrm{CAP}V_{v^R}$:	Maximum supplier capacity v
$\mathrm{CAP}M_{\check{m}h^R}$:	Maximum production center capacity $\check{m}$ with capacity level h
$\mathrm{CAP}J_{jh^R}$:	Maximum capacity of distribution center j with capacity level h
$\mathrm{CAP}K_{kh^R}$:	Maximum capacity of collection center k with capacity level h
$\mathrm{CAP}L_{lh^R}$:	Maximum capacity of repair center l with capacity level h
$\mathrm{CAP}U_{\overline{d}h^R}$:	Maximum capacity of the redistribution center $\overline{d}$ with capacity level h
$\mathrm{CAP}R_{\mathrm{r}h^R}$:	Maximum capacity of recycling center r with capacity level h
RT^s:	Collection center usage rate in scenario s
RM:	Reproduction rates in production centers
RU:	Recycling rates at recycling centers
$R\ D$:	Disposal rates at disposal centers
RR:	Repair rates at repair centers
pb_s:	Probability of scenario s
$\theta_{j,0}^s$:	The normalized weighted for the total number of job opportunities created in the facility in scenario s
θ_{1,d^R}^s:	The normalized weighted for the total number of working days lost in the facility in scenario s
$\mathrm{JO}\check{m}_{\check{m},h^R}^s$:	The number of job opportunities created in case of construction of production center $\check{m}$ with capacity level h in scenario s
JOJ_{j,h^R}^s:	The number of job opportunities created in case of construction of distribution center j with capacity level h in scenario s
JOK_{k,h^R}^s:	The number of job opportunities created in case of construction of collection center k with capacity level h in scenario s
JOL_{l,h^R}^s:	The number of job opportunities created in case of construction of repair center l with capacity level h in scenario s
$\mathrm{JO}\overline{\mathrm{D}}_{\overline{d},h^R}^s$:	The number of job opportunities created in case of construction of redistribution center $\overline{d}$ with capacity level h in scenario s
JOR_{r,h^R}^s:	The number of job opportunities created in case of construction of recycling center r with capacity level h in scenario s
$J\ D\check{M}_{\check{m},h}^s$:	Average lost working days in case of construction of production center $\check{m}$ with capacity level h, which is sent to scenario s
$J\ DL_{l,h}^s$:	Average lost working days in case of construction of repair center l with capacity level h, which is sent to scenario s
$J\ DR_{r,h}^s$:	Average lost working days in case of construction of recycling center r with capacity level h, which is sent to scenario s
$\widehat{H}_i^e$:	The number of employees required to produce e raw materials by $i \in V$ supplier
$\widetilde{H}_i^{\overline{w}}$:	The number of employees required to expand a unit of capacity from the $\overline{w} \in w$ section of the factory belongs to $i \in \check{m} \cup \tilde{m}$

$\overline{H}_i^p$: The number of employee periods required to produce a unit of the product p is in the subcontract of factory $i \in \breve{m}$

$\overset{=}{H}$: The number of working time units an employee has available for each course

$H_i^{''}$: The number of employee courses required to expand a distribution center belongs to the $i \in \overline{d} \cup$d unit

$\widehat{H}_i^p$: The number of employee periods required to store one p product unit per time period in the $i \in \overline{d}$ subdistribution center

$ETV\breve{M}^s_{v,\breve{m},e}$: Carbon emission rate per shipment of raw materials e from supplier v to production center $\breve{m}$ in scenario s

$ET\breve{M}J^s_{\breve{m},j,p}$: Carbon emission rate per shipment of product p from the production center $\breve{m}$ to the distribution center j in scenario s

$ETJC^s_{j,c,p^R}$: The amount of carbon emissions per unit of product p transported from the distribution center j to the first market c in scenario s

$ETCK^s_{c,k,p^R}$: The amount of carbon emissions per shipment of used product p from the primary market c to the collection center k in scenario s

$ETK\breve{M}^s_{k,\breve{m},p^R}$: Carbon emission rate per shipment of used product p from the collection center k to the production center $\breve{m}$ for reproduction in scenario s

$ETKD^s_{k,d,p^R}$: Carbon emission rate per transport of product unit used p from collection center k to disposal center d for disposal in scenario s

$ETL\overline{D}^s_{l,\overline{d},p^R}$: Carbon emission rate per shipment of repaired product p from repair center l to redistribution $\overline{d}$ in scenario s

$ET\overline{D}Q^s_{\overline{d},q,p^R}$: Carbon emission rate per shipment of repaired product p from redistribution center $\overline{d}$ to secondary market q in scenario s

$ETRV^s_{r,v,e^R}$: Carbon emission rate per shipment of raw materials e from recycling center r to supplier v in scenario s

$EM^s_{\breve{m},p^R}$: The amount of carbon emissions per unit of product p produced at the production center $\breve{m}$ in scenario s

$ERM^s_{\breve{m},p^R}$: Carbon emission rate per reproduction per unit of product p at production center $\breve{m}$ in scenario s.

Decision variables

$QV\breve{M}^s_{v,\breve{m},e}$: The number of raw materials shipped e sent from supplier v to the production center $\breve{m}$ in scenario s

$Q\breve{M}J^s_{\breve{m},j,p}$: The number of products p shipped from supplier v to the production center $\breve{m}$ in scenario s

$QJC^s_{j,c,p}$: The number of products shipped p that is sent from distribution center j to the first market c to scenario s

$QCK^s_{c,k,p}$: The number of products shipped p that is sent from the first market c to the collection center k to scenario s

$QK\breve{M}^s_{k,\breve{m},p}$: The number of products transported p that is sent from the collection center k to the production center $\breve{m}$ for reproduction in scenario s

$QKD^s_{k,d,p}$: The number of products transported p that is sent from collection center k to disposal center d for disposal in scenario s

$QKR^s_{k,r,p}$: The number of products p shipped from collection center k to the recycle center r in scenario s

$QL\overline{D}^s_{l,\overline{d},p}$: The number of products shipped p that is sent from distribution center j to the first market c to scenario s

$QUQ^s_{\overline{d},q,p}$: The number of products shipped p that is sent from the first market c to the collection center k to scenario s

$QRV^s_{r,q,p}$: The number of products transported p that is sent from the collection center recycle center r to second market q in scenario s

$X_{\breve{m},h}$: Binary variable and equal to 1 if the production center $\breve{m}$ is established with capacity level h

$Y_{j,h}$: Binary variable and equal to 1 if the distribution center j is established with a capacity level of h

$T_{k,h}$: Binary variable and equal to 1 if the collection center k is established with a capacity level of h

$W_{l,h}$: Binary variable and equal to 1 if the repair center l is established with a capacity level of h

$O_{\overline{d},h}$: Binary variable and equal to 1 if redistribution center $\overline{d}$ with capacity level h is established

$\gamma_{r,h}$: Binary variable and equal to 1 if the recycling center r is established with capacity level h 1, otherwise zero

$L_i^{\overline{w}t^s}$: The number of dismissed employees related to the $\overline{w} \in w$ part, belonging to $i \in \breve{m} \cup \tilde{m}$ in the period t under scenario s

$\text{ŋ}_i^{\overline{w}t^s}$: The number of employees hired for the $\overline{w} \in w$ part, belonging to $i \in \breve{m} \cup \tilde{m}$ in the period t under scenario s

$T\text{ŋ}_i^{\overline{w}t^s}$: The number of employees working in the $\overline{w} \in w$ part, belonging to $i \in \breve{m} \cup \tilde{m}$ in the time period t under scenario s

$\overline{\text{ŋ}}_i^{t^s}$: The number of employees of the distribution center owned by $i \in \overline{d} \cup \tilde{d}$ in the period t under scenario s

$T\overline{\text{ŋ}}_i^{t^s}$: The number of employees of the distribution center owned by $i \in \overline{d} \cup \tilde{d}$ in the period t under scenario s

$\overline{L}_i^{t^s}$: The number of employees fired from the distribution center owned by $i \in \overline{d} \cup \tilde{d}$ during the period t under scenario s

$\overline{W}^{et^s}_{i,j,r}$: The number of families of raw materials e that is sent by transport r through the transfer arc $(i,\overline{j},\overline{r})$ in period t under scenario s

$\delta_i^{\overline{w}_{t^s}}$: Expansion of production capacity in each time period of the $\overline{w} \in \mathrm{w}$ section, owned by $i \in \check{m} \cup \widetilde{m}$ in the time period t under scenario s

$\overline{\delta}_i^{t^s}$: Expansion of storage capacity in the time period related to the distribution center owned by $i \in \overline{d} \cup \widetilde{d}$ with the time start of period t under scenario s

$\zeta_i^{\mathrm{p}t^s}$: The number of products that each $i \in m$ plant produces in the period t under scenario s

$\pi_i^{\mathrm{p}t^s}$: The inventory of product p that the $i \in m$ distribution center maintains over the period t under scenario s.

Data Availability

The data are available upon the request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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