



Reducing Environmental Pollutions in Closed-loop Supply Chain Optimization through Fuzzy Complex Integer Programming

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ABSTRACT

The escalating volumes of greenhouse gases and pollutants, along with growing concerns about environmental issues, have compelled organizations and management academics to design networks that prioritize optimizing environmental factors and reducing pollutants within an economic framework. Supply chain management stands out as a critical business issue that impacts all organizational activities by enhancing production, improving quality, cutting costs, and delivering superior customer service. This study aims to enhance total profit within the supply chain while concurrently reducing environmental pollution. The research methodology employed here is descriptive-analytical. A dual-objective mathematical model is proposed for the design of a closed-loop supply chain. This model is built upon criteria such as product count, recycled product count, and item count. A solution approach is suggested using dual-objective fuzzy programming. Subsequently, the model is tested using available data through GAMS optimization software. The increase in the volume of the first objective function shows a linear relationship with the variation coefficient, whereas changes in demand exhibit a nonlinear relationship with the second objective function. Specifically, an increase in demand leads to a significant rise in environmental pollution. It is evident that fluctuations in demand can substantially impact the total costs of the supply chain. The application of this developed model can help mitigate the adverse effects on the environment while promoting a sustainable image of the supply chain through cost reduction and profit enhancement.

1. Introduction

The intense competition and rapid market changes, coupled with the swift technological advancements and the trend towards globalization, compel organizations to function as components of a supply chain rather than in isolation. It is widely acknowledged that organizations cannot thrive in isolation, and collaborative teamwork within a network is evidently more feasible. The underlying principle behind this assertion is to secure a competitive advantage in the market,

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ultimately aiming to increase market share. Consequently, the success of a business is contingent upon the collaborative efforts of the supply chain partners [1]. The supply chain comprises a network of suppliers, manufacturers, distributors, and customers involved in the receipt, transformation, production, and delivery of raw materials [2]. This network encompasses a cluster of relatively stable businesses engaged in a series of production and distribution activities essential for reaching the end-user [3]. Supply chain management aims to enhance supply chain activities and associated information flows through the cultivation of integrated relationships, particularly when striving to gain a competitive advantage. The essential components of supply chain management are outlined in Table 1.

Table 1. Key Elements of Supply Chain Management (Feyzabadi, 2003)

Elements	Common topics
Customers	Determining customer taste towards the product type
Prediction	Predicting the product volume and customer demand time
Design	Integrating customers, their requests and production capabilities time with the market
Computation	Quality control and planning work-time table
Inventory	Supplying the demand requirements and managing the inventory maintenance cost
Procurement	Evaluating the potential suppliers and support product operational needs and the used service
Suppliers	Supervising supplier quality, on-time delivery, flexibility and mutual relations with the supplier
Locating	Determining the deployment part of the facilities
Support/backup	Determining decisions on raw material haulage and purchase

The closed-loop supply chain comprises external suppliers, production and retrieval centers, combined distribution and collection centers, disposal centers, and customers [4]. The increasing recognition of closed-loop supply chain management is attributed to the surge in demand for sustainable, eco-friendly products. In response to escalating environmental concerns, manufacturers are actively seeking strategies to mitigate environmental risks and reduce pollutants to secure environmental permits/licenses, enhance their social standing, and boost customer satisfaction. The escalating environmental challenges, coupled with stringent state regulations and the imperative to conserve natural resources, underscore the importance of adopting eco-friendly practices to achieve sustainable development goals [2]. Among the environmental strategies employed are the calculation of environmental labels and the establishment of recycling centers within the supply chain. As environmental degradation worsens, the positive practice of collecting used materials for reuse and recycling has garnered significant attention from researchers [2]. Given the intensifying competitive landscape, effective supply chain management has emerged as a critical focal point for businesses, permeating all facets of organizational operations. The mounting volume of pollutants and the heightened emphasis on environmental concerns have compelled manufacturers to extend their supply chains to encompass closed-loop systems [5]. Rigorous and scientifically planned optimization through these innovative methods directly impacts productivity, quality, production costs, reliability, utilization, and profitability. To sustain growth and development and position Iranian industries in global markets, essential prerequisites

include enhanced quality, increased productivity, and reduced costs. Achieving these objectives necessitates a proactive response to the scientific methodologies outlined above.

In order for the supply chain to thrive in a dynamic and evolving market, having a tool that can effectively address environmental challenges is essential [6]. This tool is adaptable. The business environment is constantly changing, and change inherently brings risks. In their study, Hosseini et al. [7] assessed the effectiveness of supply chain management operations and found that procurement operations do not impact overall operations significantly. Demirel et al. [2] proposed a multi-period complex linear programming model for a closed-loop supply chain network, considering secondary market pricing and incentive policies. To solve the model at its actual scale, they modified the Genetic Algorithm (GA). In this model, demand is certain, and scarcity is not a concern. According to Demirel et al., the ability to adjust product chain design and planning capabilities is crucial for enhancing supply chain effectiveness. Strengthening this capability within the product chain would increase flexibility and drive improvement.

Hamidieh et al. [8] proposed a novel integration of sustainability and robust-feasibility planning for the design of a multi-product closed-loop supply chain under uncertain conditions. They emphasized that by managing the performance of the proposed models, effective control of the potential variability coefficient is crucial for optimizing the supply chain network. Pishvae et al. [9] introduced a multi-objective mixed-integer linear programming model aimed at maximizing network responsiveness and minimizing total costs in a closed-loop supply chain network that involves both direct and reverse flows. Fahimnia et al. presented a nonlinear mixed-integer programming model for green supply chain modeling, incorporating a trade-off between costs and environmental factors such as carbon emissions, energy consumption, and water usage. Their model included a multi-objective function designed to minimize costs, carbon emissions, energy consumption, and water usage, addressing the significance of green supply chains. The findings highlighted that certain manufacturing strategies, such as reducing delivery times and minimizing waste, contribute to the development of a green supply chain, while others, like using smaller vehicles and constructing additional warehouses, may increase environmental pollution. To solve the initial model using a heuristic algorithm, the nonlinear algorithm was converted into a linear algorithm through various iterations. Subsequently, the CPLEX method was employed in the algorithm iterations to solve the linear model.

Amin and Zhang [10] introduced a two-stage multi-objective model aimed at maximizing supplier profits and minimizing drawbacks. Initially, they developed a fuzzy method for evaluating suppliers based on qualitative criteria. Subsequently, they proposed a multi-objective linear mixed-integer scheduling model for supplier and site reconstruction, as well as optimizing the appropriate count of components and products in a closed-loop supply chain network. The model does not consider the dynamics and uncertainty associated with product returns. Additionally, all costs related to product procurement, collection, transportation, and inventory are disregarded, introducing a high level of uncertainty in network design.

Wang et al. [11], studied the dual-channel CLSC with product customization through direct retail channels. Three pricing models were presented to analyze the optimal decisions of supply chain members using game theory. Amra et al. [12] explored the concept of closed-loop supply chains (CLSCs) that consider the entire product lifecycle for sustainability. They discussed the

importance of viability in CLSCs, which must be profitable, sustainable, and socially responsible. Factors impacting viability was analyzed along with methods for improvement. A successful case study was presented, and future challenges for enhancing CLSC viability were deliberated. In his study, Karami [13] highlighted the importance of strategic partnerships in supply chains to achieve cost-effective and high-quality outcomes. The study introduces a single-objective model that optimizes supply chain configuration for cost reduction. The research emphasizes the necessity of mass customization in business models. The paper presents a method using particle swarm optimization to determine the optimal order quantity, minimizing facility location and shipment costs while meeting customer demands.

Govindan & Soleimani [14] proposed a multi-product closed-loop supply chain model with the objective of cost reduction. They identified a probable mixed-integer programming model by considering uncertain parameters such as demand, purchase price, and return rate. Safarinejadian et al. [15] introduced a multi-objective probabilistic model for designing an inverse/direct supply chain network under uncertainty. The performance of the chain is evaluated based on three indicators: profit, customer responsiveness, and supplier quality.

Amin-Tahmasbi et al. [5] evaluated the competitive advantage resulting from supply chain management and the environmental aspects of a closed-loop supply chain. They focused on optimizing departments, products, and the number of delivery trucks. Their conclusion highlighted that the model could mitigate negative environmental impacts, project a green image of the chain, reduce shipping costs, and increase company profits.

Borjian and Ali Nejad [16] assessed the configuration of a closed-loop supply chain with the goal of calculating environmental factors and evaluating the impact of policies on establishing recycling centers and investing in environmental issues. They applied a complex integer programming model to assess the environmental impact of products throughout supply chain activities using life cycle analysis. Their results indicated that the positive effects of policies, such as increasing recycling centers and environmental investments, justified the economic and environmental performance of the supply chain, even without considering their impact on pollutant emissions, by reducing raw material consumption.

Hassanpour et al. [17] utilized a two-level complex number planning model to reduce environmental pollution in both the public and private sectors when designing a closed-loop supply chain. They employed an innovative heuristic algorithm and conducted simulated numerical analyses on key parameters. Their conclusion emphasized the importance of implementing this two-level program, especially in cases where the state has more decision-making autonomy.

2. Materials and Methods

The method employed here is descriptive-analytical. The objective is to implement a closed-loop supply chain optimization model to reduce environmental pollution in industrial production units using fuzzy complex numbers. The options of concern are evaluated based on selection criteria. The data collection method introduced by Digalwar et al. [18] is utilized. The GAMS software is employed to evaluate qualitative issues.

The Mathematical Model Structure

A two-objective mathematical model is presented to design a closed-loop supply chain with the objectives of 1) increasing the total profit of the supply chain and 2) reducing environmental pollution.

This proposed solution method is based on fuzzy programming, where an ε -constraint method is applied. The advantage of the ε -constraint method is that it provides a range of solutions, including inefficient ones. These solutions assist the decision-maker in evaluating the entire set of solutions and selecting the best option. The chosen solution is not influenced by the ε -constraint method due to the scaling of the objective function. Efficient solutions can achieve a balance by facilitating a proper trade-off between environmental and economic objectives.

The design of a multi-product and multipurpose supply chain is illustrated in Figure 1, emphasizing the forward and reverse flows and their interactions in a simultaneous manner. This newly proposed framework aims to minimize environmental impacts, specifically carbon emissions resulting from transportation in the reverse supply chain, while maximizing the organization's profit. The network comprises a primary supply chain and five reverse supply chains, demonstrating a comprehensive approach to sustainable supply chain management.

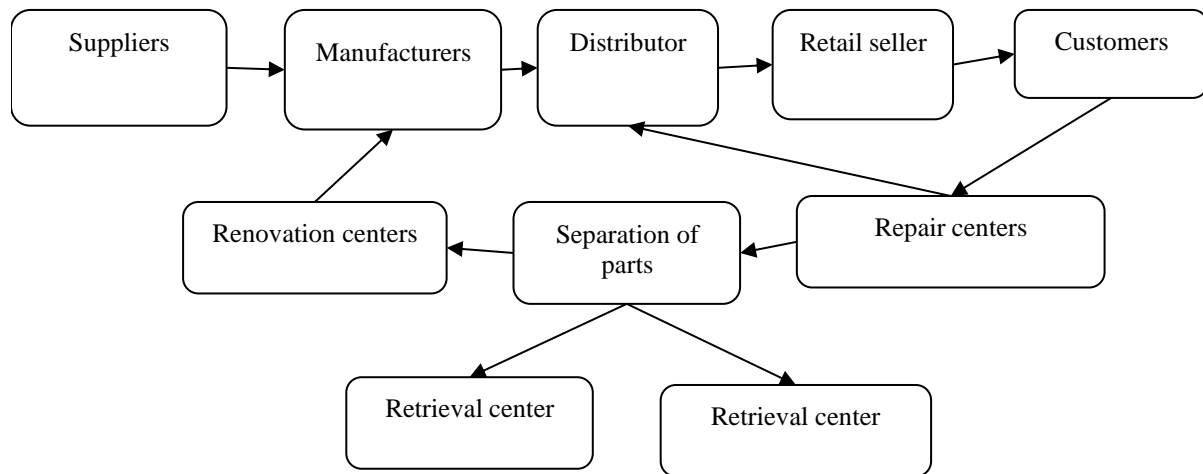


Fig. 1. Supply chain framework

2.2 The proposed multipurpose model

The indexes, parameters, and decision-maker variables applied in formulating this multi-objective model are expressed as follows:

2.2.1 Indexes

i is the set of parts, that is, $i = \{1, 2, \dots\}$,

j is the product set, that is, $j = \{1, 2, \dots\}$,

k is the supplier set, that is, $k = \{1, 2, \dots\}$,

l is the reconstruction center complex, that is, $l = \{1, 2, \dots\}$,

m is the collection/repair centers complex, that is, $m = \{1, 2, \dots\}$,

n is the set of separation centers, that is, $n = \{1, 2, \dots\}$,

c is the set of customer areas, that is, $c = \{1, 2, \dots\}$.

2.2.2 Decision variables

P_j is the count of products produced $j \in J$

C_{jcm} is the count of $j \in J$ products collected at the $m \in M$ collection center of the customer area $c \in C$

C_{jm} is the count of $j \in J$ products collected at the $m \in M$ collection center

A_{jm} is the count of $j \in J$ products reused at $m \in M$ collection center

R_{jmn} is the count of $j \in J$ products isolated at the $n \in N$ site at $m \in M$ collection center

S_{ik} is the count of parts $i \in I$ purchased from supplier $k \in K$

T_{in} is the count of parts by $i \in I$ deleting at site $n \in N$

F_{inl} is the count of $i \in I$ parts repaired at site $l \in L$ by disassembly at site $n \in N$

F_{il} is the count of parts $i \in I$ repaired in $l \in L$ repair center

2.2.3 Parameters

2.2.3.1 The objective functions

The following two conflicting objectives are assessed here:

Maximizing the overall benefit where the social factor is of concern as well

Minimizing environmental impacts

2.2.3.2 Maximize overall profit

Here, the objective function aims to maximize the economic and social factors contributing to the total profit of the organization, as shown in Equation (1). This function indicates that profits are generated from both the sales of manufactured products and recycled products.

$$\begin{aligned}
\text{Maximize } Z_1 = & \sum_j (P\tilde{F}_j) * (P_j + \sum_m A_{jm}) + \sum_n \sum_i (R\tilde{P})_i * Y_{in} - \sum_n \sum_i (P\tilde{C})_{ik} * S_{ik} \\
& - \sum_j \sum_c \sum_m (C\tilde{C})_{jcm} * C_{jcm} - \sum_m \sum_j (S\tilde{C})_{jm} * B_{jm} \\
& - \sum_m \sum_j (U\tilde{C})_{jm} * A_{jm} - \sum_n \sum_i (D\tilde{C})_{in} * T_{in} - \sum_n \sum_i (S\tilde{D})_{jn} * V_{jn} \\
& - \sum_l \sum_i (R\tilde{C})_{il} * F_{il} - \sum_l \sum_i (S\tilde{R})_{il} * U_{il} - \sum_n \sum_i (W\tilde{D}C)_i * W_{in} \\
& - \sum_j \sum_m \sum_c (R\tilde{F})_{jcm} * C_{jcm} - \sum_j \sum_c \sum_m (T\tilde{C}C)_{jcm} * C_{jcm} \\
& - \sum_j \sum_m \sum_n (T\tilde{C}D)_{jmn} * R_{jmn} - \sum_i \sum_n \sum_l (T\tilde{C}R)_{inl} * F_{inl} \\
& - \sum_i \sum_l (T\tilde{C}P)_{il} * F_{il} - \sum_j \sum_m (T\tilde{C}U)_{jm} * A_{jm}
\end{aligned} \tag{1}$$

2.3 Minimizing environmental impacts

The objective is to minimize the environmental impact of carbon emission due to transportation in the reverse supply chain in the environment, Eq. (2). The following objective function represents the carbon emission through customers when reaching the collection center next, the separation center, then, recycling center and finally the plant.

$$\begin{aligned}
\text{Minimum } Z_2 = & \sum_j \sum_c \sum_m (ETC)_{jcm} * C_{jcm} + \sum_j \sum_m \sum_n (ETD)_{jmn} * R_{jmn} \\
& + \sum_i \sum_n \sum_l (ETR)_{inl} * F_{inl} + \sum_i \sum_l (ETP)_{il} * F_{il}
\end{aligned} \tag{2}$$

2.4 The mathematical model constraints

$$\tilde{D}_j = P_j + \sum_m A_{jm} \quad \forall j \tag{3}$$

$$\begin{aligned}
C_{jm} &= A_{jm} + \sum R_{jmn} \quad \forall j.m \\
C_{jm} &= A_{jm} + \sum_n R_{jmn} \quad \forall j.m \tag{4}
\end{aligned}$$

$$T_{in} = Y_{in} + W_{in} + \sum_i F_{inl} \quad \forall i.n \tag{5}$$

$$\sum_j q_{ij} * P_j = \sum_l F_{il} + \sum_k S_{ik} \quad \forall i \tag{6}$$

$$T_{in} = \sum_m \sum_j q_{ij} R_{jmn} \quad \forall i.n \tag{7}$$

$$F_{il} = \sum_n F_{inl} \quad \forall i.l \tag{8}$$

$$R_{jn} = \sum R_{jmn} \quad \forall j.n \quad (9)$$

$$C_{jm} = \sum_c^m C_{jcm} \quad \forall j.m \quad (10)$$

$$\sum_m C_{jcm} \leq \tilde{\eta}_j * \tilde{D}_{jc} \quad \forall j.c \quad (11)$$

$$A_{jm} \leq \tilde{Y}_j * C_{jm} \quad \forall j.m \quad (12)$$

$$\sum_l F_{inl} \leq \tilde{\lambda}_i * T_{in} \quad \forall i.n \quad (13)$$

$$Y_{in} \leq \tilde{\beta}_i * T_{in} \quad \forall i.n \quad (14)$$

$$C_{jm} \leq (MC)_{jm} * B_{jm} \quad \forall j.m \quad (15)$$

$$\sum_m R_{jmn} \leq (MD)_{jn} * V_{jn} \quad \forall j.n \quad (16)$$

$$\sum_n F_{inl} \leq (MR)_{il} * U_{il} \quad \forall i.l \quad (17)$$

$$P_j \leq (MR)_j \quad \forall j \quad (18)$$

$$(MNS)_k \leq \sum_i S_{ik} \leq (MXS)_k \quad \forall k \quad (19)$$

$$B_{jm} \cdot V_{jn} \cdot U_{il} \in \{0,1\} \quad \forall i.j.m.n.l \quad (20)$$

$$P_j \cdot C_{jcm} \cdot A_{jm} \cdot R_{jmn} \cdot R_{jn} \cdot S_{ik} \cdot T_{in} \cdot F_{inl} \cdot F_{il} \cdot W_{in} \cdot Y_{in} \quad \forall i.j.m.n.l.k \quad (21)$$

Constraint 3 ensures that the demand for each product is met by the sum of new and reused products. Constraints 4, 5, and 6 indicate the flow constraints at the collection, separation, and reconstruction centers. Constraints 7, 8, and 9 calculate the count of components in the separation, remediation, and products in the isolation centers. Constraint 10 represents the count of products in each collection center from different customer areas. Constraints 11, 12, 13, and 14 define the maximum count of products collected, the turns of the reusable parts, the count of parts rebuilt, and the count of recyclable items. Constraints 15, 16, 17, and 18 ensure the capacity limits for collection centers, separation centers, repairs, and factories. Constraint 19 ensures the maximum and minimum capacity of the external suppliers. Constraints 20 and 21 are related to the binary integer values and the overall decision variables. All decision-making variables are positive.

3. The proposed solution method

This solution method consists of four steps:

Stage/step 1: determine the minimum degree of possibility of the decision vector (i.e. α) for deciding on the importance of each one of the goals.

Stage/step 2: determine α -optimal and α -nadir solutions for each objective function on the efficient set, to calculate α -optimal solutions.

$$(Z_1^{\alpha-optimal} \cdot X_1^{\alpha-optimal}) \text{ and } (Z_2^{\alpha-optimal} \cdot X_2^{\alpha-optimal}) \quad (22)$$

The equivalent transparent model is first, solved for each separate objective function and next, the α -nadir solution is calculated for each objective function as follows:

$$Z_2^{\alpha-nadir} = \min\{Z_2 \mid Z_1 \geq Z_1^{\alpha-optimal} \& x \in F(x)\} \quad (23)$$

$$Z_1^{\alpha-nadir} = \max\{Z_1 \mid Z_2 \leq Z_2^{\alpha-optimal} \& x \in F(x)\}$$

Where, $F(x)$ is the implementation region that contains the constraints of the equivalent model. Stage/step 3: the linear fuzzy membership function for each target function is determined as follows:

$$\mu_1(x) = \begin{cases} 1, & Z_1 > Z_1^{\alpha-optimal} \\ \frac{Z_1 - Z_1^{\alpha-nadir}}{Z_1^{\alpha-optimal} - Z_1^{\alpha-nadir}}, & Z_1^{\alpha-nadir} \leq Z_1 \leq Z_1^{\alpha-optimal} \\ 0, & Z_1 < Z_1^{\alpha-nadir} \end{cases}$$

$$\mu_2(x) = \begin{cases} 1, & Z_2 < Z_2^{\alpha-optimal} \\ \frac{Z_2^{\alpha-nadir} - Z_2}{Z_2^{\alpha-nadir} - Z_2^{\alpha-optimal}}, & Z_2^{\alpha-optimal} \leq Z_2 \leq Z_2^{\alpha-nadir} \\ 0, & Z_2 > Z_2^{\alpha-nadir} \end{cases} \quad (24)$$

Where, $\mu_1(x)$ and $\mu_2(x)$ are the degree of fuzzy membership for the first and second objectives. Stage/step 4: conversion of the multi-objective equivalent model into a single-objective model based on the ε -constraint Method:

$$\max\{\mu_1(x) \mid \mu_2(x) \geq \varepsilon, x \in F(x), 0 \leq \varepsilon \leq 1\}$$

In the above equation, any satisfaction rate can be considered either as a lateral constraint or an objective function. Here, the satisfaction due to the first objective is maintained in the objective function, and the satisfaction rate for the second objective is considered as a lateral constraint.

Stage/Step 5: The Epsilon value varies systematically between 0 and 1 to generate Pareto-optimal solutions across the efficient set.

Stage/Step 6: If the decision-maker is satisfied with one of the produced solutions, the process stops, and the accepted solution is chosen as the final decision. Otherwise, the decision-maker selects the more preferred line segment and proceeds to Step 5 to adjust ε in a new constraint and a new range, generating new Pareto optimal solutions. If the value of α changes, the algorithm must return to Step 1.

4. Results

4.1 Information about mathematical model parameters

The numerical results of a proposed multi-objective model for multiple, multilevel products subject to uncertain ambient environments are discussed. It is assumed that there are two types of products and three types of parts. The weights of products, components, and influencing factors are listed in Table 2. Additionally, it is assumed that there are three collection centers, two maintenance centers, two separation centers, two reconstruction centers, three external suppliers, one recycling center, and one disposal center. The transportation costs from customer areas to collection centers and from reconstruction centers to production centers are provided in Tables 3 and 4, respectively. The distances from the maintenance centers to the production centers are detailed in Table 6. The maximum capacities of the collection and separation centers are specified in Table 7, while the maximum capacities of the reconstruction centers are outlined in Table 8. Furthermore, the maximum purchase orders for suppliers 1, 2, and 3 are 4000, 5000, and 5000, respectively, and the minimum purchase order for each supplier is 100.

It is assumed:

$\tilde{\eta}_j$ is the (max. j product percentage) 0.7 and $\tilde{\gamma}_j$ is the (max. j product percentage) = 0.2 and $\tilde{\lambda}_i$ is the (max. i reconstruction section percentage) = 0.7 and $\tilde{\beta}_i$ is the (max. i recycling section percentage) 0.15.

Table 2. Product weight, piece, and productivity factor

Product weight	i=3	i=2	i=1	q_{ij}
72	2	3	2	$j=1$
82	2	3	3	$j=2$
	8	12	10	Weight of each piece

Table 3. Cost of transportation (p/km) from the customer area (c) to the collection center (m) for each product (j)

	$T\tilde{C}C_{jcm} (j = 1)$			$T\tilde{C}C_{jcm} (j = 2)$		
	$m = 2$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
C=1	0.4	0.6	0.8	0.5	0.6	0.8
C=2	0.5	0.5	0.7	0.5	0.5	0.7
C=3	0.4	0.6	0.8	0.3	0.6	0.8

Table 4. Cost of transportation (p/km) from the reconstruction center to the production center (l) for each item (i)

$(T\tilde{C}P)_{il}$	i=1	i=2	i=3
$l=1$	0.3	0.5	0.6
$l=2$	0.4	0.4	0.5

Table 5. Distance of transportation (km) of customer area (c), disassembly center (n) and distribution center of collection (m)

Space	C=1	C=2	C=3	n=1	n=2	Distributor
m = 1	3	4	5	20	20	3
m = 2	4	2	4	18	22	2
m = 3	6	5	3	25	15	5

Table 6. Transportation distance (km) of separation center (n) and production center from the reconstruction center (l)

Factory	n=2	n=1	Space
6	12	10	l = 1
8	8	10	l = 2

Table 7. Maximum Capacity in Collector Centers (m) and Separation Centers (n) for each product (j)

Capacity	$(MC)_{jm}$			$(MD)_{jn}$	
	m=1	m=2	m=3	n=1	n=2
j=1	600	800	600	1000	1000
j=2	700	600	600	1000	800

Table 8. Maximum capacity at the reconstruction center (l) for each piece (i)

Capacity	$(MD)_{il}$	
	l = 1	l = 2
i=1	1500	1800
i=2	2000	1800
i=3	1500	1000

To analyze the performance of the proposed model, the model is coded and optimized using GAMS software. In the model, the satisfaction rate of economic objectives is stored in the objective function, while the same environmental objectives are treated as lateral constraints. The Pareto optimal solutions are obtained by employing the modified ε -constraint method with a possibility level of 0.5 (i.e., α -level = 0.5).

4.2 Numerical results

The relevant results are obtained after solving the two-objective mathematical model in the GAMS software environment. As shown in Table 9, the two objectives (i.e., maximizing total profits and minimizing environmental impacts) are in conflict with each other. Reducing environmental impacts leads to an increase in total costs, resulting in a reduction in profit. The details of the price paid for environmental protection, specifically the loss of the organization's economic benefit for the sake of environmental protection, are presented in Table 9.

Table 9. A briefing of the results for the first repetition at $\alpha = 0.5$ and $\varepsilon = [0.1]$

$Z_1(\text{Eco.})$	$Z_2(\text{Env.})$	$\mu(Z_1)$	$\mu(Z_2)$
518,126	252026,8	0.9999	0
475,629	251937,5	0.9929	.2
433,272	251371,7	0.9480	.4
390,845	250477,8	0.8771	.6
348,418	249168,9	0.7733	.8
305,991	238417,0	0.3300	.9999

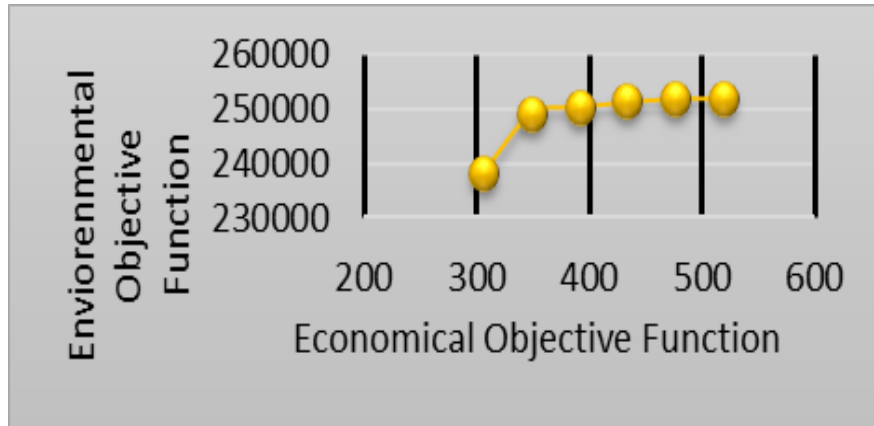


Fig. 2. The values of environmental and economic objectives in the first iteration

The same applies to the second iteration, where the Epsilon parameter varies between 0.6 and 0.8, and the values of both the objective functions and their membership rates are specified. The results of this section are presented in Table 10 and Figure 3.

Table 10. Summarizes the results of the second repetition for $\varepsilon = [0.6, 0.8]$

$Z_2(\text{Env.})$	$Z_1(\text{Eco.})$	$\mu(Z_1)$	$\mu(Z_2)$
390,845	250477,8	.877141	.6
386,6023	250477,8	.896307	.62
382,3596	250279,3	.861406	.64
378,1169	250186,9	.854078	.66
373,8322	250078,7	.845493	.68
369,6315	250014	.840362	.70
365,3888	249900	.831346	.72
361,1416	249678,9	.820931	.74
356,9034	249674,3	.813429	.76
352,6607	249460,3	.796454	.78
348,418	249168,9	.773646	.80

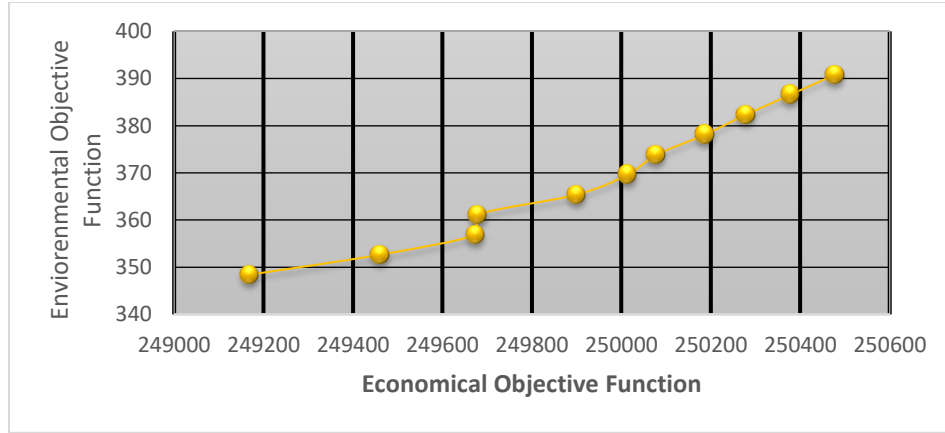


Fig. 3. The values of environmental and economic objectives in the second iteration

As evident from the two-stage outputs, the Epsilon constraint method can offer a comprehensive range of diverse solutions. As depicted in these figures, the decision-maker can trade off between the values of the economic and environmental objective functions across various scenarios to gain a deeper insight into the output within different efficient boundary responses. The values of the decision variables in three distinct effective boundary responses are specified and presented in Tables 11, 12, and 13.

Table 11. The count of items purchased from the external supplier S_{ik} , the count of the separated item T_{in} , the count of reconstructed items F_{il} , the count of recycled item Y_{in} , and the count of waste W_{in} at $\mu(Z_2 = 0.66)$

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	k=1	k=2	k=3	n=1	n=2	l=1	l=2	n=1	n=2	n=1	n=2
i=1	4000	293	0	1680	1380	1500	642	252	207	252	207
i=2	0	793	5000	1680	1380	342	1800	252	207	252	207
i=3	0	3862	0	1120	920	428	1000	168	138	168	138

Table 12. The count of items purchased from the external supplier S_{ik} , the count of the separated item T_{in} , the count of reconstructed items F_{il} , count of cycled item Y_{in} , and the count of waste W_{in} at $\mu(Z_2 = 0)$

	k=1	k=2	k=3	n=1	n=2	l=1	l=2	n=1	n=2	n=1	n=2
i=1	3590	0	0	1680	2120	1500	1160	252	318	252	318
i=2	0	0	4767	1680	2460	1098	1800	252	369	252	369
i=3	0	3178	0	112	1640	932	1000	168	246	168	246

Table 13. The count of items purchased from the external supplier S_{ik} , the count of separated items T_{in} , the count of reconstructed items F_{il} , the count of cycled items Y_{in} , and the count of waste W_{in} at $\mu(Z_2 = 0.9999)$

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	k=1	k=2	k=3	n=1	n=2	l=1	l=1	n=1	n=2	n=1	n=2
i=1	0	324	0	1680	1348	1176	943	252	03	252	202
i=2	0	806	5000	1680	1368	1175	957	253	06	252	205

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	k=1	k=2	k=3	n=1	n=2	l=1	l=1	n=1	n=2	n=1	n=2
i=3	0	3870	0	1120	912	777	645	168	38	168	136

At this stage, the quantities of items to be purchased, parts required for maintenance, disposable items, and recyclable items are tabulated in Tables 11 to 13. In these tables, all decision-making variables and the level of satisfaction with the environmental objective function range between 0 and 1. When the weight of the environmental objective function is set to zero, the results in Table 12 deviate from the optimal solution obtained by considering all criteria. Similarly, if the weight of the economic objective function is zero, the results differ. These findings aid management in making decisions regarding optimal location allocation, recycling center placement, selection of items purchased from external suppliers, and responsiveness to customer demand within the closed-loop supply chain.

4.3 Sensitivity analysis

One of the advantages of mathematical models is their capability to evaluate changes and fluctuations in each addressed parameter and observe their impact on the final output of the model. After conducting the assessment, it became apparent that demand, being highly dependent on production conditions and constraints, may exhibit varying fluctuations. In such scenarios, this behavior of demand can significantly influence the entire supply chain. Therefore, conducting a sensitivity analysis of this parameter is essential. In this analysis, the demand for each product is incrementally increased, and its impact on various targets is evaluated. To perform this analysis, a variation coefficient ranging from 0.9 to 1.5 is considered, leading to minor fluctuations relative to the initial demanded quantity [5]. Subsequently, in each scenario, the base demand volume of each product is multiplied by the resulting coefficient, and the model is executed to assess its effect on the total function value, as presented in Table 14.

Table 14. Results of sensitivity analysis of demand

Change coefficient	0.9	1	1.1	1.2	1.3	1.4	1.5
Demand	4.5	5	5.5	6	6.5	7	7.5
Economic target value	16260	16400	16540	16820	16820	169960	17100
Environmental target value	395	482	598	776	1358	2772	3951

As evident from this table, a direct relationship is observed between the demand volume and the economic and environmental objective functions, as illustrated in Figures 4 and 5.

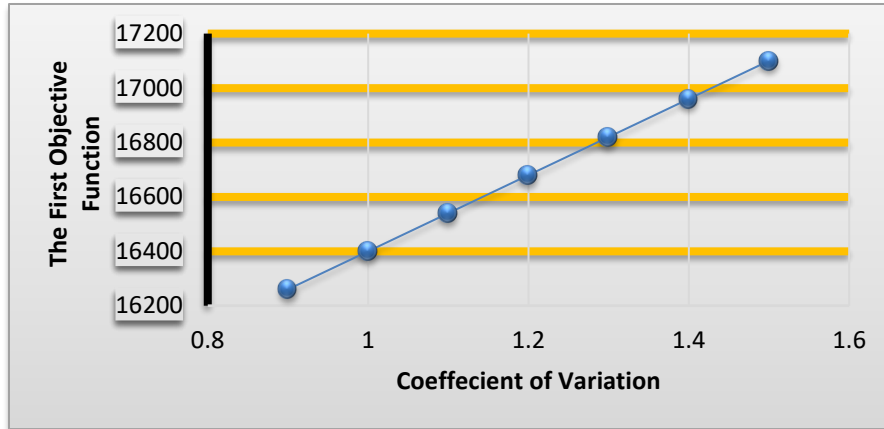


Fig. 4. Sensitivity analysis of demand for the first objective function

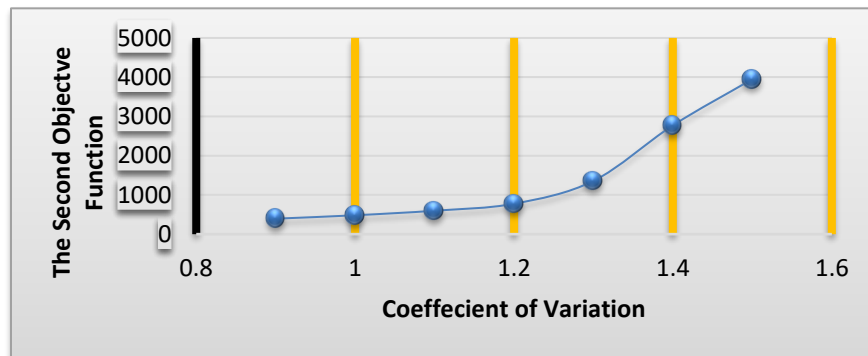


Fig. 5. Sensitivity analysis of demand for the second objective function

As depicted in these figures, there is a linear relationship between the increase in the volume of the first objective function and the increase in the variation coefficient. However, the change in demand exhibits a nonlinear pattern in the second objective function, specifically resulting in a significant rise in environmental pollution. It can be inferred at this juncture that any increase or decrease in demand directly impacts the total costs of the chain with a high level of linearity. Detecting the volume of environmental pollution due to its nonlinear relationship is not feasible, eliminating the necessity to re-optimize the relevant mathematical model.

5. Conclusions

The focus here is on the closed-loop green supply chain problem, emphasizing an economic perspective on environmental issues. An attempt is made to propose a new two-objective mathematical model along with a corresponding solution method to optimize the closed-loop supply chain. The primary objective is to increase the total profit of the supply chain, followed by reducing environmental pollution. Additionally, a solution based on a fuzzy programming model is introduced to achieve a balanced solution that appropriately trades off between environmental and economic objectives.

In the economic context, organizations must aim to maximize total profits while meeting the demands of the manufacturing sector concurrently. To evaluate the performance of this proposed model, it is solved using the GAMS optimization software. In this approach, the satisfaction from economic objectives is maintained within the objective function, and the satisfaction from environmental objectives is incorporated as a side constraint.

The numerical results reveal a conflict between these objectives, as a reduction in environmental impact leads to an increase in total costs, subsequently reducing organizational profits. Increasing the volume of the first objective function shows a linear relationship by enhancing the variation coefficient, whereas the change in demand exhibits a nonlinear pattern with the second objective function, resulting in a sharp increase in environmental pollution.

It can be inferred that any increase or decrease in demand directly affects the total chain costs. Detecting the volumes of environmental pollution due to their nonlinear relationship is not feasible, eliminating the need to re-optimize the mathematical model.

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