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A Multi-Objective Optimization Model for a Green Supply Chain with Greenhouse Gas Impacts

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Abstract

In the previous literature, scholars have focused on designing closed-loop and green supply chain (SC) networks with government regulations, environmental risks, and resource constraints. Nowadays, focusing on reverse logistics, and integrating the reverse flow with a forward flow for supply chains (SCs) is of great importance to reduce SC costs. Hence, this study proposes a bi-objective mathematical model, which simultaneously minimizes the costs of a supply chain network and the amount of released carbon. Also, a multi-goal programming method is used to solve the developed model. Moreover, 10 test problems are provided to analyze the performance of the proposed model using Lingo software. In addition, sensitivity analyses are carried out.

Keywords: Closed-loop supply chain, Green supply chain, Greenhouse gas, Multi-choice goal programming with a utility function, Multi-objective optimization.

1 | Introduction

Nowadays, dealing with the problem of SC networks is of great importance. The SC network problem includes facilities for converting raw materials to final products, distributing centers for distributing final products, and after-sales service providers to meet customer satisfaction. This problem determines location, capacity, technology, and the number of required equipment. Also, it identifies transportation flows and the amount of purchase, consumption, production, distribution, and transportation. As per the theoretical review, the field of SC network design is divided into forward and reverse logistics. The forward flow deals with the forward network. However, the reverse flow deals with the return network, which is known as a recycling network. When the reverse network is integrated with a forward network, a closed-loop network is created. Generally, in the forward flow, firstly, raw materials are supplied from suppliers. Then, these are converted to final products in factories. Afterward, the final products are distributed to customers through distribution centers. This study contributes to the literature by analyzing the simultaneous impacts of remanufacturing and carbon emissions on the performance of a closed-loop supply chain (CLSC) with competitive collection channels. As noted by Shekarian et al. (2021), pricing decisions and profits of SC managers are more affected by customer willingness to purchase remanufactured products than by their

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sensitivity to carbon footprints. Through efficient recovery systems, manufacturers must form closed-loop SCs to reduce the environmental impacts of their activities. Garg et al. (2015) proposed an interactive multi-objective programming algorithm to address environmental concerns in a CLSC network. As noted by Chaharmahali et al. (2022), an increasing trend of transportation and developing SCs lead to increased carbon emissions. One of the most effective strategies to reduce CLSC costs is to reduce carbon dioxide emissions. Yang et al. (2021) used game-theoretic models to investigate the impacts of compliance and non-compliance in a CLSC.

According to the previous studies, this study minimizes total SC costs and released carbon dioxide by proposing a bi-objective optimization model. In addition, multi-choice goal programming with a utility function is used to find optimal solutions.

The rest of this paper is organized as follows. The literature review is provided in the next section. In Section 3, the problem under investigation is described, assumptions are discussed, and notations are presented. In Section 4, a bi-objective model is explained, and a multi-choice goal programming method with a utility function is proposed to solve the model. In Section 5, the proposed solution method is validated using test problems. Finally, the conclusions of the paper and future research paths are explained in Section 6.

2. literature review

Nowadays, designing a stable SC network is a challenging issue due to the continually changing business environment and also competition in the market. Due to the environmental concerns, researchers have mainly considered developing reverse, closed-loop, and green SCs, reusing defective goods, preventing further loss of resources, reducing environmental pollution, making profits, and bringing social benefits.

2.1. Green supply chain

Green supply chain management (SCM) was introduced by the Industrial Research Association of the University of Michigan in 1996, which is a new management model for environmental protection. From the product lifecycle perspective, green SCM includes all stages, such as raw materials, product design and manufacturing, product sales and transportation, product use, and product recycling. Due to the growing awareness about global warming and climate change, green SCM has become an increasingly important part of the industrial implementation, and carbon management is among the key branches (Jin, 2021). In sustainable supply chain management (SSCM), in addition to the economic aspect, social and environmental aspects are taken into account. An extended energy analysis, one of the most powerful thermodynamic tools, can be used to assess the sustainability of an industrial system. The energy consumed by sustainable SCs is estimated using an energetic analysis. In this study, financial, social, and environmental objectives are considered to select the most sustainable SC which produces and distributes products. In addition, simulated annealing and genetic algorithms are used to create a hybrid metaheuristic algorithm based on global and local searches (GLGASA). As noted by Naderi et al. (2021), one unit of additional cost can approximately reduce environmental destruction by minimizing energy costs. Considering the green concern in SCs is the process of taking the environmental measures or concerns throughout SCs into account. To evaluate the environmental impacts of SC operations, a product lifecycle analysis is used.

2.2. Closed-loop supply chain

Sets In managing closed-loop supply chains, several issues, such as remanufacturing process innovation, pricing decisions, and cost-sharing mechanisms, are important. Chen et al. (2021) maximized the economic performance of power structures by dividing retail costs. Luo et al. (2022) developed four game-theoretic models to examine the effects of a carbon tax policy on manufacturing and

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remanufacturing decisions for a closed-loop supply chain (CLSC). They investigated two scenarios: no investment in carbon-reduction technology and investment in the centralized and decentralized CLSC. Golpîra and Javanmardan (2022) used some carbon emission schemes, such as carbon tax, cap-and-trade, and carbon cap, to develop a sustainable CLSC with demand uncertainty. They applied a scenario-based conditional value-at-risk (CVaR) method to formulate robust mixed integer linear programming (MILP).

A lot of businesses struggle with reducing supply chain costs while also improving sustainability and customer service. One solution to this issue is creating a sustainable closed-loop supply chain (CLSC) network, which hasn't been studied in depth until now. This study introduces a new integrated approach that utilizes mixed-integer linear programming (MOMILP) and fuzzy goal programming to design sustainable CLSC networks that account for various factors such as cross-docking, location-inventory-routing, and transportation modes. An intelligent simulation algorithm is employed to generate feasible solutions in uncertain situations. The proposed model is tested with eight different problems and proved to be effective in terms of performance and sensitivity analysis (Tavana et al., 2022). Mohtashami et al. (2020) investigated a green SC with forward and reverse logistics with queuing systems for optimizing the transportation network and the waiting time of transportation fleets. Jauhari et al. (2021) developed a two-echelon inventory model for a stochastic CLSC system. They used a hybrid system of production and remanufacturing processes. Liu et al. (2022) proposed three decentralized models based on fuzzy demand and different quality levels for a CLSC of second-hand products.

A cost-sharing mechanism is one of the common contracts among players in green SCs. Song et al. (2022) explored a game-theoretical model for a green manufacturer-retailer SC considering two products with different environmental properties. Nayeri et al. (2020) considered a mathematical model to optimize a sustainable CLSC network with financial, environmental, and social considerations. They used a fuzzy robust optimization approach to deal with uncertainty.

Researchers have primarily focused on designing closed-loop green SCs due to environmental risks, limited resources, and government regulations. Gholizadeh and Fazlollahtabar (2020) investigated a closed-loop green SC in the melting industry to optimize profits and environmental hazards. They used a robust optimization technique to deal with demand uncertainty. Moreover, they applied an improved version of a genetic algorithm to solve the investigated problem.

As noted by Gholizadeh et al. (2020), focusing on the transportation sector in SCs is of great significance, as it has a high carbon footprint. Therefore, organizations should attempt to maximize the performance of their transportation sectors (by reducing their environmental footprint) and minimize total costs in SCs. Gholizadeh et al. (2021) used robust optimization and heuristics approaches for a sustainable CLSC in the dairy industry to maximize total profits and minimize environmental impacts. Panda et al. (2017) examined how pricing decisions influence product quality levels and recycling for a two-echelon CLSC with quality-price-sensitive demand. Safaei et al. (2017) proposed a mixed integer linear programming model for optimizing a cardboard recycling network. They utilized a robust optimization approach to deal with demand uncertainty .

Moshtagh and Taleizadeh (2017) assumed that demand for manufactured items is not equal to remanufactured ones. They considered lost sales through shortage periods of both manufactured and remanufactured products.

To sum up, this study minimizes total costs and released carbon for a supply chain. This study proposes a multi-goal model with a utility function to find an optimal and accurate solution.

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3. Problem description

In the problem under investigation, at first, raw materials are supplied from suppliers, and then they are received by manufacturing sectors. Afterward, final products are distributed to distribution centers, and finally, products are sent to customers from warehouses. In this study, four kinds of goods are considered, which are explained as follows:

1. The products with a desirable quality level are entered into distribution centers as second-hand products.
2. The products which need to be reproduced are sent to manufacturing sectors for reproducing.
3. The products which need to be recovered are entered into recycling centers. The recycling centers provide raw materials for production centers.
4. The other products are entered into disposal centers.

Because products are re-entered to reverse and forward flows, the SC network is closed-loop. The flow of products in the forward flow is dependent on customers' demand. The reverse flow is dependent on the number of returned products from customers. In the reverse flow, customers, who purchase goods, decide to return or not to return used products. The proposed model is bi-objective, multi-period, and multi-product. The first objective function relates to SC cost, and the second one is about the amount of released carbon in the SC network. The integrated SC network includes forward and reverse flows. Figure 1 shows the considered SC network.

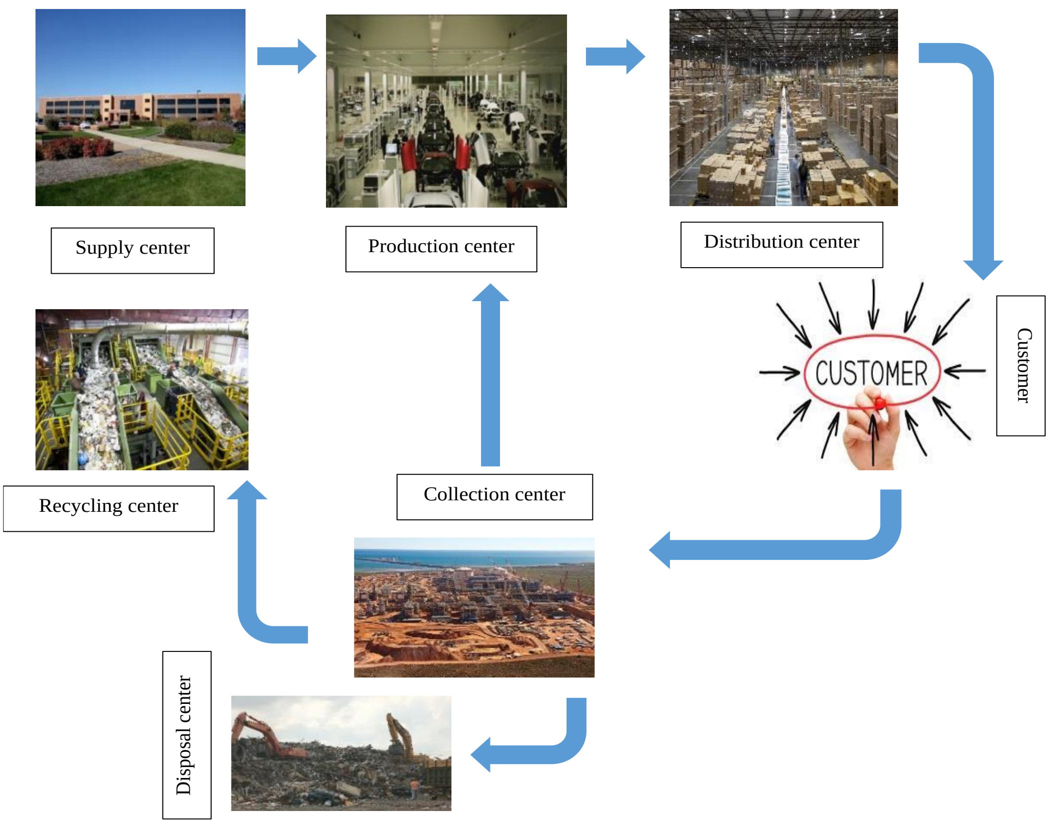

Figure 1. The proposed SC network.

3.1. Assumptions

- The capacity of facilities is limited.
- Demand and the quantities of returned products are considered to be deterministic.
- The solving space of the problem is discrete.

- It is assumed that the demand for new and second-hand products is equal.
- The location of suppliers, producers, and customers is fixed. However, the location of distribution, collection, recycling, and disposal centers is not fixed.
- The quality of second-hand products is lower than that of new goods.
- It is considered that all demand is met, and all returned goods are collected and transferred to collection centers.
- Products are imported into collection, recycling, and destruction centers during each period, and they have left these centers during the same period. These products are not entered the next period.

3.2. The mathematical model

Indices

$i \in I$	Stationary points for supplier centers
$j \in J$	Stationary points for manufacturing centers
$q \in Q$	Potential points for distribution centers
$l \in L$	Stationary points for customer centers
$n \in N$	Potential points for collecting centers
$p \in P$	Potential points for recycling centers
$m \in M$	Potential points for disposal centers
$c \in C$	Products
$t \in T$	Periods

Parameters

K_{clt}	Demand for product *c* from customer *l* in period *t*
M_{clt}	The return amount of product *c* from customer *l* during period *t*
Rj_{cnj}	The return rate of product *c* from collection center *n* to manufacturing center *j*
Tp_{cnp}	The return rate of product *c* from collection center *n* to recycling center *p*
An_{cnm}	The return rate of product *c* from collection center *n* to disposal center *m*
Zk_{cnq}	The return rate of product *c* from collection center *n* to distribution center *q*
S_{cijt}	The unit moving cost of product *c* from supply center *i* to production center *j* during period *t*
S_{cjqt}	The unit moving cost of product *c* from production center *j* to distribution center *q* during period *t*
S_{cqlt}	The unit moving cost of product *c* from distribution center *q* to customer center *l* during period *t*
S_{clnt}	The unit moving cost of product *c* from customer center *l* to collection center *n* during period *t*
S_{cnpt}	The unit moving cost of product *c* from collection center *n* to recycling center *p* during period *t*
S_{cnmt}	The unit moving cost of product *c* from collection center *n* to disposal center *p* during period *t*
S_{cnjt}	The unit moving cost of product *c* from collection center *n* to production center *j* during period *t*
S_{cnqt}	The unit moving cost of product *c* from collection center *n* to distribution center *q* during period *t*
S_{cpjt}	The unit moving cost of product *c* from recycling center *p* to production center *j* during period *t*
B_m	The fixed cost of building disposal center *m*
B_q	The fixed cost of building distribution center *q*
B_n	The fixed cost of building collection center *n*
B_p	The fixed cost of building recycling center *p*
W_{cijt}	The amount of carbon dioxide released by transferring each product unit *c* from supplier center *i* to manufacturing center *j* during period *t*
W_{cjqt}	The amount of carbon dioxide released by transferring each product unit *c* from manufacturing center *j* to distribution center *q* during period *t*

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W_{cqlt}	The amount of carbon dioxide released by transferring each product unit c from the distribution center q to customer l during period t
W_{clnt}	The amount of carbon dioxide released by transferring each product unit c from customer l to collection center n during period t
W_{cnpt}	The amount of carbon dioxide released by transferring each product unit c from collection center n to recycling center p during period t
W_{cnmt}	The amount of carbon dioxide released by transferring each product unit c from collection center n to disposal center m during period t
W_{cnjt}	The amount of carbon dioxide released by transferring each product unit c from collection center n to manufacturing center j during period t
W_{cnqt}	The amount of carbon dioxide released by transferring each product unit c from collection center n to distribution center q during period t
W_{cpjt}	The amount of carbon dioxide released by transferring each product unit c from recycling center p to manufacturing center j during period t
Z_{cit}	The amount of carbon dioxide released by manufacturing each product in manufacturing center j during period t
Z_{cpt}	The amount of carbon dioxide released by recycling each product in recycling center p during period t
Z_{cmt}	The amount of carbon dioxide released by disposing of each product in disposal center m during period t
Z_{1cjt}	The amount of carbon dioxide released by reproducing in manufacturing center j during period t
Z_{2cjt}	The amount of carbon dioxide released by reproducing in manufacturing center j during period t
Ca_i	The capacity of supplier center i
Ca_j	The capacity of production center j
Cap_{1j}	The reproducing capacity of products collected by collection center m at manufacturing center j
Cap_{2j}	The reproducing capacity of products collected by recycling center p at manufacturing center j
Ca_q	The capacity of distribution center q
Cap_q	The capacity of returned products at distribution center q
Ca_n	The capacity of collection center n
Ca_p	The capacity of recycling center p
Ca_m	The capacity of disposal center m
P_j	All production costs of each product in manufacturing center j during each period
P_q	All processing costs of each product in distribution center q during each period
P_n	All processing costs of each product in collection center n during each period
P_p	All recycling costs of each recyclable product at recycling center p during each period
P_m	All disposal costs of each unrecyclable product in disposal center m during each period
A	The capacity of carbon released by transportation from supply center i to production center j
B	The capacity of carbon released by transportation from production center j to distribution center q
C	The capacity of carbon released by transportation from distribution center q to customer l
D	The capacity of carbon released by transportation from customer l to collecting center n
E	The capacity of carbon released by transportation from collecting center n to recycling center p
F	The capacity of carbon released by transportation from collecting center n to disposal center m
G	The capacity of carbon released by transportation from collecting center n to production center j
H	The capacity of carbon released by transportation from collecting center n to distribution center q
I	The capacity of carbon released by transportation from recycling center p to production center j
BB	The capacity of carbon released in production center j
EE	The capacity of carbon emitted in recycling center p

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FF	The capacity of carbon emitted in disposal center *m*
GG	The capacity of carbon emitted in reverse type 1 to production center
II	The capacity of carbon emitted in reverse type 2 to production center

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Decision variables

$Y_n = 1$	1 if Collection center *n* built; 0 otherwise
$Y_q = 1$	1 If Distribution center *q* built; 0 otherwise
$Y_p = 1$	1 If Recycling center *p* built; 0 otherwise
$Y_m = 1$	1 If Disposal center *m* built; 0 otherwise
X_{cijt}	The amount of product *c* flow from Supplier center *i* to Production center *j* during each period
X_{cjqt}	The amount of product *c* flow from Production center *j* to Distribution center *q* during each period
X_{cqlt}	The amount of product *c* flow from Distribution center *q* to Customer *l* during each period
X_{clnt}	The amount of product *c* flow from Customer *l* to Collection center *n* during each period
X_{cnjt}	The amount of product *c* flow from Collection center *n* to Production center *j* during each period
X_{cpjt}	The amount of product *c* flow from Recycling center *p* to Production center *j* during each period
X_{cnmt}	The amount of product *c* flow from Collection center *n* to Disposal center *m* during each period
X_{cnqt}	The amount of product *c* flow from Collection center *n* to Distribution center *q* during each period
X_{cnpt}	The amount of product *c* flow from Collection center *n* to Recycling center *p* during each period
X_{jqt}	The number of products transferred from Production center *j* to Distribution center *q* during period *t*
X_{qt}	The number of products transferred from Distribution center *q* during period *t*
X_{nt}	The total quantity of reverse products in Collecting center *n*, which transferred to the separation center during period *t*

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$$
\begin{aligned}
\min f_1 = {} & \sum_q B_q Y_q + \sum_n B_n Y_n + \sum_p B_p Y_p + \sum_m B_m Y_m \\
& + \sum_c \sum_i \sum_j \sum_t \left(S_{cijt} X_{cijt}\right) + \sum_c \sum_i \sum_q \sum_t \left(P_j + S_{cjqt} X_{cjqt}\right) \\
& + \sum_c \sum_q \sum_l \sum_t \left(P_q + S_{cqlt} X_{cqlt}\right) + \sum_c \sum_l \sum_n \sum_t \left(P_n + S_{clnt} X_{clnt}\right) \\
& + \sum_c \sum_n \sum_p \sum_t \left(P_p + S_{cnpt} X_{cnpt}\right) \\
& + \sum_c \sum_n \sum_m \sum_t \left(P_m + S_{cnmt} X_{cnmt}\right) + \sum_c \sum_n \sum_j \sum_t \left(S_{cnjt} X_{cnjt}\right) \\
& + \sum_c \sum_n \sum_q \sum_t \left(S_{cnqt} X_{cnqt}\right) + \sum_c \sum_p \sum_j \sum_t \left(S_{cpjt} X_{cpjt}\right)
\end{aligned}
\tag{1}
$$

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$$\min f_2 = \sum_c\sum_i\sum_j\sum_t (W_{cijt}X_{cijt}) + \sum_c\sum_j\sum_q\sum_t (B_{cjt} + W_{cjqt}X_{cjqt}) + \sum_c\sum_q\sum_l\sum_t (W_{cqlt}X_{cqlt}) + \sum_c\sum_l\sum_n\sum_t (W_{clnt}X_{clnt}) + \sum_c\sum_n\sum_p\sum_t (B_{cpt} + W_{cnpt}X_{cnpt}) + \sum_c\sum_n\sum_m\sum_t (B_{cnt} + W_{cnmt}X_{cnmt}) + \sum_c\sum_n\sum_j\sum_t (B_{1cjt} + W_{cnjt}X_{cnjt}) + \sum_c\sum_n\sum_q\sum_t (W_{cnqt}X_{cnqt}) + \sum_c\sum_p\sum_j\sum_t (B_{2cjt} + W_{cpjt}X_{cpjt}) \quad (2)$$

s.t.

$$\sum_q X_{cqlt} = K_{clt} \qquad \forall c \in C, \forall l \in L, \forall t \in T \quad (3)$$

$$\sum_n X_{clnt} = M_{clt} \qquad \forall c \in C, \forall l \in L, \forall t \in T \quad (4)$$

$$\sum_q X_{cnqt} = ZK_{cnq}\sum_l X_{clnt} \qquad \forall c \in C, \forall n \in N, \forall t \in T \quad (5)$$

$$\sum_j X_{cnjt} = Rj_c\sum_l X_{clnt} \qquad \forall c \in C, \forall n \in N, \forall t \in T \quad (6)$$

$$\sum_p X_{cnpt} = Tp_c\sum_l X_{clnt} \qquad \forall c \in C, \forall n \in N, \forall t \in T \quad (7)$$

$$\sum_n X_{cnmt} = An_c\sum_l X_{clnt} \qquad \forall c \in C, \forall n \in N, \forall t \in T \quad (8)$$

$$\sum_j X_{cjqt} = \sum_l X_{cqlt} - \sum_n X_{cnqt} \qquad \forall c \in C, \forall q \in Q, \forall t \in T \quad (9)$$

$$\sum_i X_{cijt} + \sum_n X_{cnjt} + \sum_p X_{cpjt} = \sum_p X_{cpjt} \qquad \forall c \in C, \forall q \in Q, \forall t \in T \quad (10)$$

$$\sum_n X_{cnpt} = \sum_j X_{cpjt} \qquad \forall c \in C, \forall p \in P, \forall t \in T \quad (11)$$

$$\sum_c\sum_j X_{cijt} \le Ca_i \qquad \forall i \in I, \forall t \in T \quad (12)$$

$$\sum_c\sum_q X_{cjqt} \le Ca_j \qquad \forall j \in J, \forall t \in T \quad (13)$$

$$\sum_c\sum_l X_{cqlt} \le Ca_q Y_q \qquad \forall i \in I, \forall t \in T \quad (14)$$

$$\sum_c\sum_q Zk_c X_{cnqt} + \sum_c\sum_j Rj_c X_{cnjt} + \sum_c\sum_m An_c X_{cnmt} + \sum_c\sum_p Tp_c X_{cnpt} \le Ca_n Y_n \qquad \forall n \in N, \forall t \in T \quad (15)$$

$$\sum_c\sum_n X_{cnjt} \le Cap_{1j} \qquad \forall j \in J, \forall t \in T \quad (16)$$

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$$\sum_c \sum_n X_{cnqt} \leq Cap_q Y_q \qquad \forall q \in Q, \forall t \in T \qquad (17)$$

$$\sum_c \sum_n X_{cnmt} \leq Ca_m Y_m \qquad \forall m \in M, \forall t \in T \qquad (18)$$

$$\sum_c \sum_n X_{cnpt} \leq Ca_p Y_p \qquad \forall p \in P, \forall t \in T \qquad (19)$$

$$\sum_c \sum_p X_{cpjt} \leq Cap_{2j} \qquad \forall p \in P, \forall t \in T \qquad (20)$$

$$Rj_c + Zk_c + Tp_c + An_c = 1 \qquad \forall c \in C \qquad (21)$$

$$(W_{cijt} X_{cijt}) \leq A \qquad \forall c \in C, \forall i \in I, \forall j \in J, \forall t \in T \qquad (22)$$

$$(W_{cjqt} X_{cjqt}) \leq B \qquad \forall c \in C, \forall q \in Q, \forall j \in J, \forall t \in T \qquad (23)$$

$$(W_{cqlt} X_{cqlt}) \leq CY_q \qquad \forall c \in C, \forall q \in Q, \forall l \in L, \forall t \in T \qquad (24)$$

$$(W_{clnt} X_{clnt}) \leq DY_n \qquad \forall c \in C, \forall n \in N, \forall l \in L, \forall t \in T \qquad (25)$$

$$(W_{cnpt} X_{cnpt}) \leq EY_p \qquad \forall c \in C, \forall n \in N, \forall p \in P, \forall t \in T \qquad (26)$$

$$(W_{cnmt} X_{cnmt}) \leq FY_n \qquad \forall c \in C, \forall n \in N, \forall m \in M, \forall t \in T \qquad (27)$$

$$(W_{cnjt} X_{cnjt}) \leq G \qquad \forall c \in C, \forall n \in N, \forall j \in J, \forall t \in T \qquad (28)$$

$$(W_{cnqt} X_{cnqt}) \leq HY_q \qquad \forall c \in C, \forall n \in N, \forall q \in Q, \forall t \in T \qquad (29)$$

$$(W_{cpjt} X_{cpjt}) \leq I \qquad \forall c \in C, \forall p \in P, \forall j \in J, \forall t \in T \qquad (30)$$

$$\left(\sum_q B_{cjt} X_{cjqt}\right) \leq BB \qquad \forall c \in C, \forall j \in J, \forall t \in T \qquad (31)$$

$$\left(\sum_n B_{cpt} X_{cnpt}\right) \leq EE(Y_p) \qquad \forall c \in C, \forall p \in P, \forall t \in T \qquad (32)$$

$$\left(\sum_n B_{cmt} X_{cnmt}\right) \leq FF(Y_m) \qquad \forall c \in C, \forall m \in M, \forall t \in T \qquad (33)$$

$$\left(\sum_n B_{1cjt} X_{cnjt}\right) \leq GG \qquad \forall c \in C, \forall m \in M, \forall t \in T \qquad (34)$$

$$\left(\sum_p B_{2cjt} X_{cpjt}\right) \leq II \qquad \forall c \in C, \forall j \in J, \forall t \in T \qquad (35)$$

$$\sum_j X_{jqt} = X_{qt} \qquad \forall q, t \qquad (36)$$

$$X_{ct} = \sum_l X_{lct} \qquad \forall c, t \qquad (37)$$

$$Y_k, Y_m, Y_p, Y_n \in (0,1) \qquad (38)$$

$$X_{cijt}, X_{cjqt}, X_{cqlt}, X_{clnt}, X_{cnjt}, X_{cnqt}, X_{cnpt}, X_{cnmt}, X_{cpjt} \geq 0 \qquad (39)$$

The first objective function minimizes costs of (i) movement and transferring products in forward and reverse flows and (ii) internal operation centers and facility construction. The second objective function minimizes the carbon dioxide released by centers and vehicles' movements across centers. Constraint 3 ensures that demand is met in forward flow. This constraint ensures that all returned goods are collected and transferred to the collection centers during the return process. Constraints 5 to 8 guarantee that the number of products entering the collection centers equals those departing them. Constraint 9 ensures that the number of goods entering the distribution center is identical to those leaving it. Constraint 10 ensures that the number of goods entering the production center equals those leaving it. Also, Constraint 11 guarantees that the number of products entering the recycling center equals those leaving it. Constraints 12 to 20 are related to the capacity of supply, production, distribution, and collection centers. Moreover, these constraints indicate the number of returned products transferring from collection centers to production centers, the number of returned products at distribution, disposal, and recovery centers, and

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the number of products transferring from recycling centers to production centers. Constraint 21 shows that the sum of coefficients relating to returning products should equal 1. Constraints 22-30 indicate the amount of carbon dioxide released by transporting across centers for each product type. Constraints 31-35 indicate the amount of emitted carbon dioxide in production, recycling, disposal centers, and it shows return 1 in production centers and return 2 in production centers. Constraint 36 shows that the quantities of produced goods in Production center *j*, which are transported to Distribution center *q* during period t are equal to the quantities of manufactured products shipping from Distribution center *q* in Period t. Constraint 37 shows the total amount of returned products to each collection center during each period. Constraints 38 and 39 indicate the type of decision variables.

4. Solution procedure

In this section, firstly, a numerical example is provided to illustrate the performance of the proposed model, then result analysis is discussed, and finally, sensitivity analyses are conducted.

4.1. The multi-choice goal programming with a utility function

Various methods have been used by scholars to solve the multi-objective problem. In this paper, we use a method proposed by Chang (2011), which is a multi-choice goal programming with utilities (MCGP-U). Applying this method, decision makers (DM) can formulate multi-objective models according to their priorities. In his paper, the expected utility should be maximized. In the problem under investigation, linear objective functions (i.e., $u_k(y_k)$) are as follows:

$$u_k(y_k)=\begin{cases}1 & \text{if } y_k \le g_{k,\min,} \\ \dfrac{g_{k,\max}-y_k}{g_{k,\max}-g_{k,\min}} & \text{if } g_{k,\min} \le y_k \le g_{k,\max,} \\ 0 & \text{if } y_k \ge g_{k,\max,}\end{cases} \qquad \text{case I}$$

$$u_k(y_k)=\begin{cases}1 & \text{if } y_k \ge g_{k,\max,} \\ \dfrac{y_k-g_{k,\min}}{g_{k,\max}-g_{k,\min}} & \text{if } g_{k,\min} \le y_k \le g_{k,\max,} \\ 0 & \text{if } y_k \le g_{k,\min,}\end{cases} \qquad \text{case II}$$

where$g_{k,max}$and $g_{k,min}$ are lower and upper bounds for the *k*th goal. Cases I and II are defined to maximize and minimize objective functions, respectively. In real situations, decision-makers aim to increase the utility value λ_k. To improve the utility of MCGP, a left linear utility function (LLUF) and a proper linear utility function (RLUF) should be defined. When the objective function is minimized, the value of it is better to be as close as possible to RLUF and LLUF values. The utility value $u_k(y_k)$ should be increased as much as possible in the case of LLUF when the objective function is maximized. To achieve this goal, the value of $y_k$should be as close as possible to the target value $g_{k,min}$.

$$Min \quad \sum_{k=1}^{K}[w_k(d_k^+ + d_k^-) + \beta_k f_k^-]$$

$$s.t.$$

$$\lambda_k \le \frac{gk_{k,max}}{gk, min_{k,max}} \qquad k = 1,2,\dots,K \qquad (24)$$

$$f_k(x) - d_k^+ + d_k^- = y_k \qquad k = 1,2,\dots,K \qquad (25)$$

$$\lambda_k + f_k^- = 1 \qquad k = 1,2,\dots,K \qquad (26)$$

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$g k_{k,max\,k,min}$ $\quad k = 1,2,\dots,K$ (27)

$d_k^+, d_k^-, f_k^-, \lambda_k \geq 0 \quad k = 1,2,\dots,K$

$x \in X$

in which w_k and β_k are weights relating to deviations d_k^+, d_k^- and f_k^-. The role of weight β_k is an excellent part of the utility value $u_k(y_k)$. λ_k is the utility value of the linear utility function.

To minimize the objective function in the case of RLUF, the value of y_k should be close to the target value $g_{k,max}$. Therefore, this case should be formulated as follows:

$$Min \quad \sum_{k=1}^{K}[w_k(d_k^+ + d_k^-) + \beta_k f_k^-]$$

$s.t.$

$$\lambda_k \leq \frac{y_k - g_{k,min}}{gk,min_{k,max}} \qquad k = 1,2,\dots,K \qquad (28)$$

$$f_k(x) - d_k^+ + d_k^- = y_k \qquad k = 1,2,\dots,K \qquad (29)$$

$$\lambda_k + f_k^- = 1 \qquad k = 1,2,\dots,K \qquad (30)$$

$$g k_{k,max\,k,min} \qquad k = 1,2,\dots,K \qquad (31)$$

$$d_k^+, d_k^-, f_k^-, \lambda_k \geq 0 \qquad k = 1,2,\dots,K$$

$$x \in X$$

4.2. The numerical example

In the provided numerical example, the values of parameters are considered based on the previous studies. The considered problem includes five suppliers, four manufacturers, five distributors, eight customers, five potential collection centers, three potential recycling centers, four potential disposal centers, eight products, and two periods, which are summarized in the following table:

Table 1. The number of sets in the considered numerical example.

Sets	**Suppliers**	**Manufacturer**	**Distributor**	**Customer**	**Collection**	**Recycling**	**Disposal**	**Product**	**Period**
Value	5	4	5	8	5	3	4	8	2

To validate the proposed model, the numerical example is solved using multi-choice goal programming with a utility function (MCGP-U) and Lingo 16.0 software package. The values of parameters are used as input data. The first step is to run only the first objective function (OB1) of the model. Considering OB1 contains the cost of the SC network, the following results are achieved:

In this step, the cost of the proposed SC network is 1760953 dollars, and the value of the second objective function is 4380.

In the next step, only the second objective function (OB2) is run, and the following results are obtained:

In this step, the value of OB2 is 4150, and the value of the first objective function is 1916534 dollars.

Thus, the values of $g_{1,min}$ and $g_{2,min}$ are 1760953 and 4150, respectively. Also, according to the experts' opinion, the values of $g_{1,max}$ and $g_{2,max}$ are 2,000,000 and 5135, respectively.

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Table 2. The values of upper and lower bounds for each objective function.

Objective function	f_{min}	f_{max}
Z_1	1760953	2000000
Z_2	4150	5135

In Table 2, f_{max} is the upper bound for each objective. As a remark, considering the upper bound for OB1 and OB2 functions is unreasonable, as they are minimization functions. Also, f_{min} is the lower bound for each objective. Considering the lower bound for minimization functions (i.e., OB1 and OB2) is reasonable. In Table 3, the values of W_1, W_2, β_1, and β_2 are shown.

Table 3. The weights of deviation (*d* and *f*) for each objective function.

	Objective function	
	OB1	OB2
W	0.45	0.35
β	0.5	0.3

The results of running the proposed model using the MCGP-U method are provided in Table 4.

Table 4. Result of MCGP-U.

Objective function	*d*	*Value**	*GAP%*
Z_1	135416	1896369	7.8
Z_2	217	4367	5.2

In Table 4, d is the deviation between the value of each objective function and the ideal one. The last column in Table 4 shows the gap between the ideal value and the value of each objective, which is obtained by solving the MCGP-U problem. For example, the gap between the first objective function and the ideal value is calculated in the following.

$$Gap\% = \frac{value^* - f_{1.min}}{f_{1.min} \times 100}$$

Based on the results presented in Table 4, all values of objectives 1 and 2 are within the permitted range (i.e., between the upper and lower bounds, which are specified in Table 2).

4.3. Result analysis

Considering the values of parameters in Section 4.2, the investigated problem is solved under different dimensions and examples as test problems to evaluate the efficiency of the proposed model. The dimensions of the problem are increased in each sample. The results are shown in Table 5.

Table 5. Result of running the proposed model under different test problems.

Problem	Supplier	Production	Distribution	Period	Collecting	Recycling	Disposal	Customer	Product	Solving tome (Min)	Solving situation	MCGP-U
1	2	2	2	1	2	1	2	4	4	18	Global optimum	0.095
2	3	2	2	2	3	2	3	5	5	23	Global optimum	0.105
3	4	2	3	2	3	2	3	6	6	29	Global optimum	0.19
The rest of the table 5												
4	6	3	4	2	4	2	4	7	11	47	Global optimum	0.35
5	5	3	5	3	5	3	5	9	9	68	Global optimum	0.31
6	5	4	5	2	5	3	4	8	8	102	Global optimum	0.412
7	6	5	6	3	6	4	5	13	10	117	Global optimum	0.524
8	7	4	7	4	6	4	6	11	13	150	Feasible, interrupt	0.647
9	8	5	7	4	7	5	7	14	14	-	-	-
10	9	6	8	5	7	7	8	12	15	-	-	-

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As presented in Table 5, there are three situations for solving the linear problem in Lingo.

1) In examples 1 to 7, the optimal value is obtained in less than 2.5 hours.

2) In Example 8, the problem is feasible, and we interrupt the problem after 2.5 hours.

3)In examples 9 and 10, Lingo does not find a feasible solution in 2.5 hours due to the dimensions of the example and the value of parameters.

According to the obtained results, it can be derived that as the dimension of the problem increases, the result of the proposed MCGP-U method becomes worse .

The results of running test problems are shown in Figure 2 .

Figure 3 shows the timeline for solving the problem. According to Figure 3, as the dimensions of the problem increase, the time of solving the problem nonlinearly increases.

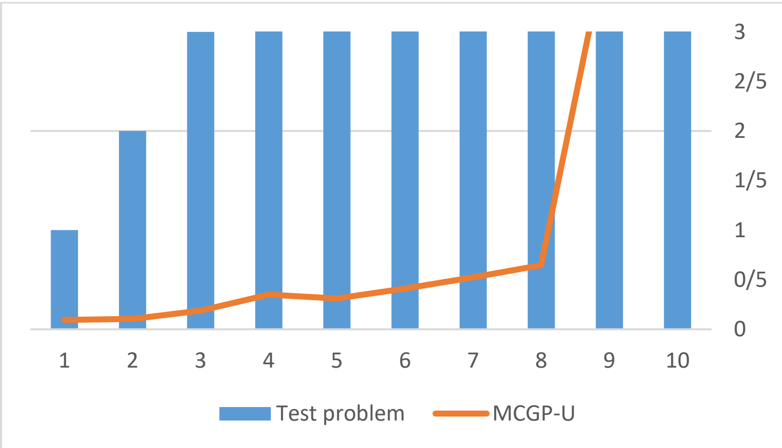

Figure2. Results of test problems using MCGP-U.

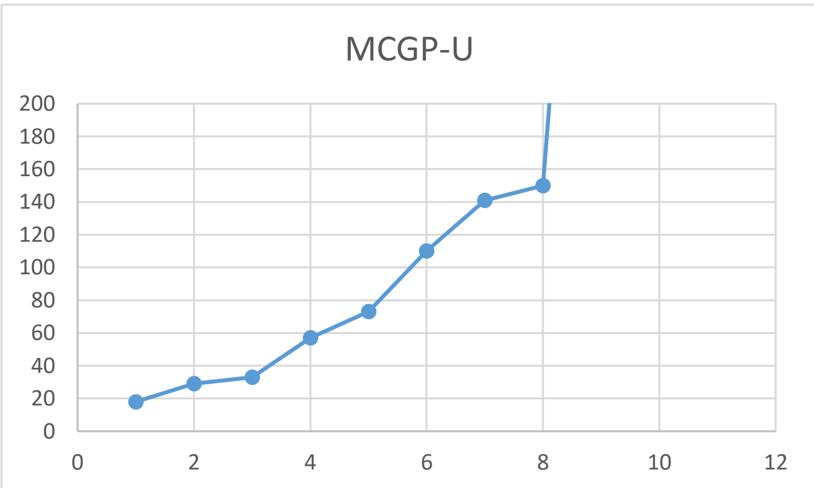

Figure 3. The timeline for the test problem.

4.4. Sensitivity analysis

• Demand for product *c* from customer *l*: K_{clt}

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This section investigates how changes in product demand influence the cost of the SC network and the amount of released carbon. Hence, firstly, a sample problem is considered in which only the value of K_{clt} changes, then the problem is solved under different demand quantities to determine their impacts on OB1 and OB2, which are shown in figures 4 and 5, respectively.

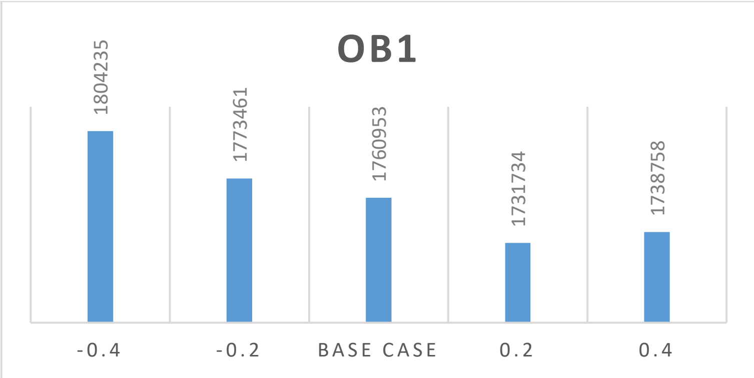

Figure 4. The impact of K_{clt} on OB1.

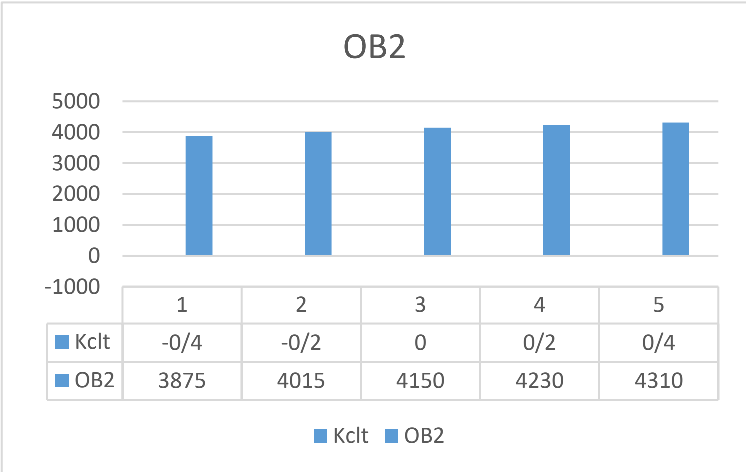

Figure 5. The impact of K_{clt} on OB2.

In Figure 4, at first, as demand increases, the cost of the SC decreases. However, when demand is higher than a specific value, SC cost increases. This is because shipping, recycling, and destruction costs increase.

According to Figure 5, as demand grows, the amount of released carbon increases. Since carbon emissions increase due to vehicle transportation across disposal centers.

- The return rate of product *c* from Collection center *n* to Production center *j*: Rj_{cnj}

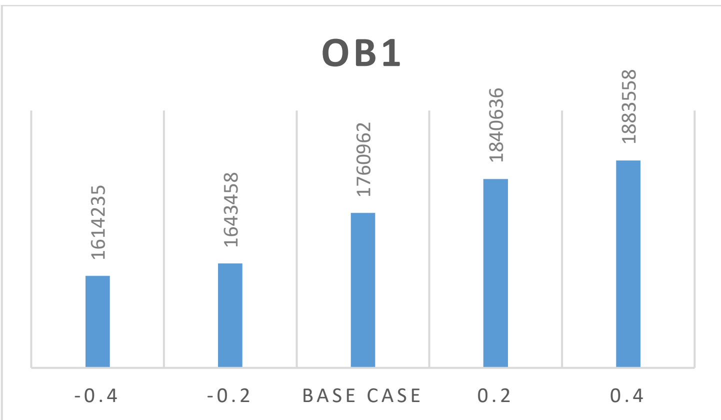

Figure 6. The impact of Rj_{cnj} on OB1.

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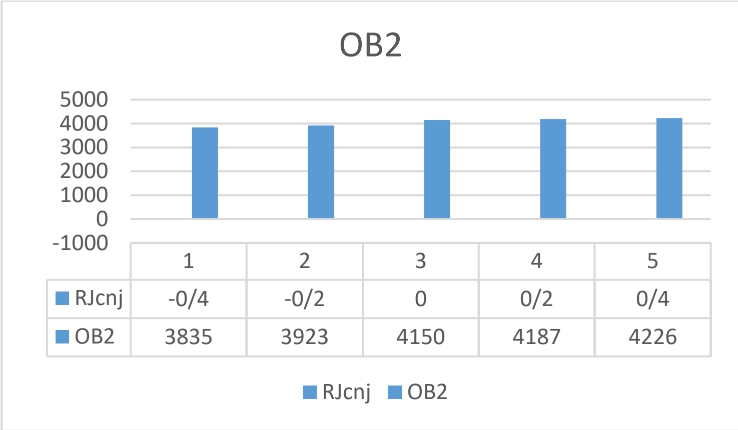

Figure 7. The impact of Rj_{cnj} on OB2.

As shown in Figure 6, by increasing the returns rate of Product *c* from Collection center *n* to Production center *j*, the SC cost rises because improving the flow of the product may lead to improve transportation, recycling, and destruction costs.

In Figure 7, as the return rate of the product increases, the amount of released carbon rises. Because carbon emissions increase due to vehicle transportation across dumping centers, as a remark, other parameters relating to the return rate, such as Tp_{cnp}, An_{cnm}, and Zk_{cnq}, have the same behavior. The OB2 increases by growing the return rate.

- The capacity of Production center *j*: Ca_j

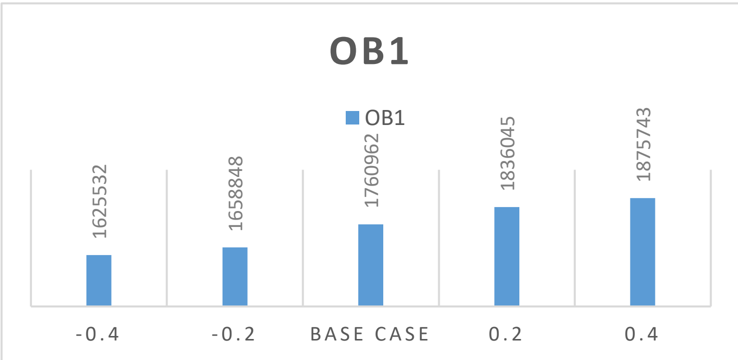

Figure 8. The impact of Ca_j on OB1.

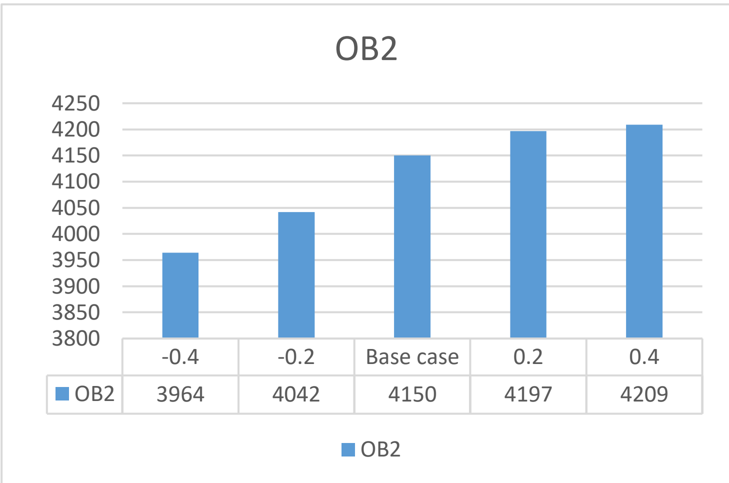

Figure 9. The impact of Ca_j on OB2.

By increasing the production capacity, the values of objective functions growingly and nonlinearly increase. Specifically, as the capacity of production increases, the flow of the product increases, which leads to increased transportation, production, and recycling costs. Therefore, the amount of released carbon and SC cost rise. As a remark, other parameters relating to the capacity, including recycling, distribution, and disposal capacity, have similar behavior toward the production capacity.

5. Conclusion

In today's business environment, supply chain management and environmental consideration are two challenging issues. Hence, in this research, to integrate programming (forward and reverse flows) in a closed-loop supply chain, a mixed integer linear programming model was developed with deterministic and multi-objective purposes. Specifically, the first objective minimizes costs relating to transportation across centers, building potential centers, and internal processing centers. The second objective minimizes the total amount of carbon emissions released by transporting across centers. In this model, the multi-choice goal programming with a utility function was used to solve the multi objective mathematical model. Moreover, a numerical example was carried out using the Lingo software to validate the proposed model. For future studies, the following paths are suggested. First, this study considers that demand and the return rate are deterministic. Considering demand uncertainty and uncertain return rates under a fuzzy method is valuable for the future. Second, this study can be extended by considering the multi-objective SC network design problem using a robust optimization method. Third, investigating pricing as a decision variable is worthwhile.

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