mathematics

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Multi-Objective Green Closed-Loop Supply Chain Management with Bundling Strategy, Perishable Products, and Quality Deterioration

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Abstract: This study presents a four-objective mathematical model to improve closed-loop supply chain (CLSC) management. The aim of this research is to reduce the costs of the entire chain, risk, emission of pollutants, and time to deliver the product to the customer in uncertain demand condition. In this paper, the NSGAII algorithm is used to solve the model. In this algorithm, among the answers of each generation, a number of them are selected using the two-run tournament selection method. In the binary selection method, the answers are randomly selected from the population, and then a comparison is made between these two answers, and whichever is better is finally selected. The selection criteria in NSGA-II are, firstly, the rank, and secondly, the crowding distance related to the answer. Also, the performance of the NSGA-II algorithm on the same model and data has been compared with the MOPSO algorithm. In the proposed algorithm, if it encounters an impossible solution, it exits the local mode and solves the problem in global conditions. The results show that the proposed method strikes a better balance between discovery and efficiency criteria and avoids falling into local optima. Therefore, in addition to its effectiveness in discovering optimal answers, the genetic-based method has high speed and subsequently, high convergence and diversity rates compared to the particle swarm method. Also, compared to previous methods in the green closed-loop supply chain, the proposed method is better than the modified genetic algorithm, reducing the costs of the chain by about 2.38%.

Keywords: bundling strategy; closed-loop supply chain management; green supply chain management; perishable products; quality deterioration

MSC: 90B06

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Citation: Pakdel, G.H.; He, Y.; Pakdel, S.H. Multi-Objective Green Closed-Loop Supply Chain Management with Bundling Strategy, Perishable Products, and Quality Deterioration. *Mathematics* **2024**, *12*, 737. https://doi.org/10.3390/math12050737

Academic Editor: Ripon Kumar Chakrabortty

Received: 31 January 2024
Revised: 25 February 2024
Accepted: 28 February 2024
Published: 29 February 2024

1. Introduction

Supply Chain Management (SCM) represents the advancement of developing, implementing, and monitoring supply chain (SC) processes, professionally utilizing information and technology. SCM includes all operations that begin with the f raw material procurement, warehouses, work-in-process inventory, and finished goods, i.e., at consumption and origin points, and ensures organizational productivity while meeting customer demands and fulfilling and satisfying the customers (Alzoubi et al., 2022) [1]. However, in the past few decades, supply chains and their various stages have faced internal and external operational challenges, which may be in the environment, nature, or society. The increasing complexity and uncertainty of the environments in which supply chains operate double the significant role of adaptive planning and control, to guarantee delivery to end consumers with minimum delays and interruptions, avoiding unnecessary costs, and maintain business continuity. To implement compliance-based management principles, real-time coordination of production planning, inventory control, and delivery schedules will be essential, while system control parameters must be dynamically adjusted to minimize costs, maximize revenue, meet target service levels, or pursue any other measurable goals to account for dynamism, instability, and uncertainty (Rolf et al., 2022) [2]. Uncertainty of customer demand and unpredictable disturbances, such as short product life cycles and global sourcing, are challenges or problems that make supply chain management ineffective, unstable, vulnerable, and turbulent (Boskabadi et al., 2022; Chen et al., 2022; Roh et al., 2022) [3–5]. The application of supply chain design models has primarily failed to consider carbon emissions throughout cost minimization processes. However, many studies, including Zhu et al. (2015), Large et al. (2016), Abir et al. (2019), and Arani et al. (2020) [6–9], are among those recently taking into account eco-friendly production, hence considering carbon emissions and optimizing total costs.

The supply chain network has been known as a critically important aspect of supply chain management, affecting the chain's efficiency and effectiveness for many years. In a general classification, supply chain management is evaluated through two forward and reverse supply chain (FSC and RSC, respectively) approaches. The former includes a set of activities from the raw material to product conversion processes (Jabbarzadeh et al., 2018) [10], while the latter is defined as the returned products' collection and recovery within SCM. This FSC and RSC combination leads to CLSC formation (Devika et al., 2014) [11], which includes customers, collection centers, recycling, and destruction of used products. This chain focuses on collecting, inspecting, and sending the returned products from the customer to the relevant centers for recycling and destruction. Determining the location of the construction of recycling and destruction centers, along with operational variables such as the flow of returned materials, is one of the decision variables of these types of networks. The issue of integration in CLSC network design involves simultaneously determining the strategic and operational decisions of the two chain types (Farrokh et al., 2018) [12]. The reverse logistics order starts from the customer to first-class warehouses, then to second-class warehouses, and finally to the factory or other destinations. In this reverse logistics process, secondary warehouses play a role in recycling, classification, inspection, and transportation. First-class warehouses take responsibility for concentration, disposal, and transportation (Liu et al., 2018) [13]. The main goal in the CLSC network design problem is to maximize the profit of the entire supply chain by choosing the optimal number and location of facilities, their capacities, and the flow (direct and return) of products between facilities, while at the same time reducing environmental impact (through recycling or destruction of reciprocating products) and maximizing social benefits (Mohtashami et al., 2020) [14].

CLSC design comprises the location, number, and capacity determination of facilities and material flow through the network, all of which affect the flexibility, efficiency, and performance of the chains significantly (Rezae and Kheirkhah, 2017) [15]. Effectively designed CLSCs can help reduce adverse environmental effects caused by human intervention substantially (Garai et al., 2021) [16]. Through CLSC design, the chain of network processes helps reduce waste through reuse or recycling. In line with environmental priorities, economic savings also attract attention to the CLSC.

Considering the role of CLSC in improving the sustainable development process, this paper uses a supply chain model with four objective functions. Thus, the main contributions of the presented research paper include the following:

- Presenting a mathematical model of a CLSC encompassing the vectors of destruction and recycling of products under cost, time, pollutant, and risk reduction conditions.
- Considering the parts related to destruction and recycling under conditions of uncertainty, depending on the quality of the products, within a CLSC. Hence, the quality level of the returned products from the customer's side is evaluated, and based on the evaluation results, decisions are made regarding recycling or destruction.

This paper has been organized as follows: Section 2 discusses the literature review and research investigating CLSC management. Section 3 discusses the mathematical modeling and the developed method. In Section 4, we present the results obtained by implementing the presented method and compare the results with other methods. Ultimately, Section 5 provides the research conclusions.

2. Literature Review

To date, significant research has been allocated to the investigation of CLSC modeling and optimization. In this section, the most important articles from recent years are examined. Jerbiaa et al. (2018) investigated the CLSC network with multi-component recycling options, formulating deterministic problems with integer programming [17]. Their results showed that the solutions for stochastic problems are stable. Also, when using the stochastic model, the profit increased. Mohtashami et al. (2020) introduced a green CLSC design utilizing a queuing system to alleviate environmental impacts and energy consumption [14]. Their paper focused on designing a green supply chain under forward and reverse logistics and utilizing a queuing system to optimize transportation time and fleet network waiting, finally reducing environmental impacts. Santander et al. (2020) investigated a CLSC network for local and distributed plastic recycling for 3D printing [18]. Their research examined the economic and environmental dimensions of distributed plastic recycling from the perspective of logistics, validating their method. Goodarzian et al. (2020) introduced a novel mixed-integer multi-objective linear programming model in a drug supply chain network [19]. Their problem formulation of the Mixed Integer Linear Programming (MILP) model focused on minimizing economic costs and environmental impact while maximizing social outcomes. Zarbakhshnia et al. (2020) presented a multi-product, multi-stage, multi-period, and multi-objective MILP model for a forward and reverse logistics network problem [20]. Nasr et al. (2021) developed a multi-objective, multi-product, multi-period mathematical model within a sustainable CLSC, locating distribution, collection, recycling, and disposal centers while taking into account risk criteria [21]. The main objective of their study was to minimize total costs, along with reducing negative environmental outcomes and promoting social responsibility to provide more job opportunities. A fuzzy inference system was used to model and determine uncertainty in demand and parameters that are dependent on demand. Jian et al. (2021) introduced a green package SC comprising a manufacturer and a retailer and solved it using the Stackelberg game approach [22]. Their results showed that profit-sharing contracts improved the relationship between supply chain members, ensuring sustainable economic and environmental growth. Tavana et al. (2022) presented an inclusive framework for a sustainable CLSC network using the multi-objective MILP (MOMILP) model [23]. This study considered the design of stable CLSC networks with interconnection, location-inventory-routing, time window, supplier selection, order allocation, and transportation with simultaneous pickup and delivery in uncertain conditions. Cheng et al. (2022) examined optimal procedures regarding a CLSC network under economic constraints and greenhouse gas (GHG) emission control [24]. This paper investigated how related parameters, including carbon quotas, consumers' low carbon preferences, and recovery rates, affected the network status. Kouchaki Tajani et al. (2022) proposed a two-channel network of sustainable CLSC for rice, taking into account energy resources and consumption taxes [25]. Their paper sought to formulate an MILP model optimizing total costs, the number of pollutants, as well as job opportunities throughout the introduced SC network considering cost, supply, and demand uncertainties. Babaeinesami et al. (2022) developed a CLSC network considering the suppliers, assembly centers, retailers, customers, collection centers, refurbishing centers, disassembly centers, and disposal centers [26]. Their paper focused on designing a distribution network according to customer demands for simultaneous total cost and total CO_2 emission minimization. Alinezhad et al. (2022) presented a stable CLSC network under uncertainty according to fuzzy theory [27]. Their network was a multi-period multi-product problem formed utilizing a two-objective MILP model with fuzzy demand and return rates for SC profit and customer satisfaction maximization. Bathaee et al. (2023) developed an SLSC network, including used product collection as well as new product distribution [28]. The designed mathematical model included three objective functions: profit maximization, total risk minimization, and product scarcity. Wang et al. (2021) conducted a study on complex manufacturing planning (MP) tasks, aiming to optimize order fulfillment rates and minimize total costs [29]. To address the challenges of large-scale problems, they introduced a novel interactive multi-objective optimization-based MP system. This system utilizes a two-stage multi-objective optimization algorithm (TSMOA). Leung et al. (2020) addressed challenges faced by existing metaheuristic approaches like MOPSOs in solving problems with more than three objectives by introducing HGLSS, a Hybrid Global Leader Selection Strategy [30]. HGLSS incorporates two leader selection mechanisms for exploration and exploitation, enabling each particle to select its global best leader. Bahrampour et al. (2023) presented a novel nonlinear mathematical programming model using the mixed integer approach for sustainable CLSC design problem formulation [31]. Their article evaluated the CLSC model from three aspects of sustainability: social, environmental, as well as economic impacts. Wu et al. (2023) evaluated the choice of recycling channels in CLSCs, taking into account the retailer's competitive preferences [32]. The authors particularly considered the retailer's competitive preferences and made conclusions based on the three-channel structure of CLSC. They also examined the manufacturer's, the retailer's, and the third-party recycling channels (M, R, and T channels, respectively). Dey and Giri (2023) elaborated on a CLSC with two-channel waste recycling considering corporate social responsibility [33]. In their article, various game theory models were used to optimize design and reduce the economic costs of the model. In the following, the literature review summary is illustrated in Table 1.

Table 1. Literature review summary.

References	Objectives					Return System Type		Condition		Product Type	
	Cost	Time	Environment	Risk	Social	Recycling	Destruction	Certain	Uncertainty	Perishable	Imperishable
Jerbiaa et al. (2018) [17]	✓					✓		✓		✓	
Mohtashami et al. (2020) [14]		✓	✓			✓			✓		✓
Santander et al. (2020) [18]	✓		✓						✓		✓
Goodarzian et al. (2020) [19]	✓		✓		✓		✓	✓		✓	
Zarbakhshnia et al. (2020) [20]	✓	✓			✓	✓		✓			✓
Nasr et al. (2021) [21]	✓		✓		✓				✓		✓
Jian et al. (2021) [22]	✓		✓					✓		✓	
Tavana et al. (2022) [23]	✓	✓	✓						✓		✓
Cheng et al. (2022) [24]	✓		✓						✓		✓
Kouchaki Tajani et al. (2022) [25]	✓		✓		✓				✓	✓	
Babaeinesami et al. (2022) [26]	✓		✓			✓	✓		✓		✓
Alinezhad et al. (2022) [27]	✓				✓				✓	✓	
Bathaee et al. (2023) [28]	✓				✓			✓			✓
Bahrampour et al. (2023) [31]	✓		✓		✓				✓		✓
Wu et al. (2023) [32]	✓		✓			✓		✓			✓
Dey and Giri (2023) [33]	✓				✓	✓		✓			✓
Present Study	✓	✓	✓	✓		✓	✓		✓	✓	

3. Mathematical Modeling

Figure 1 highlights the schematic of the problem's mathematical model.

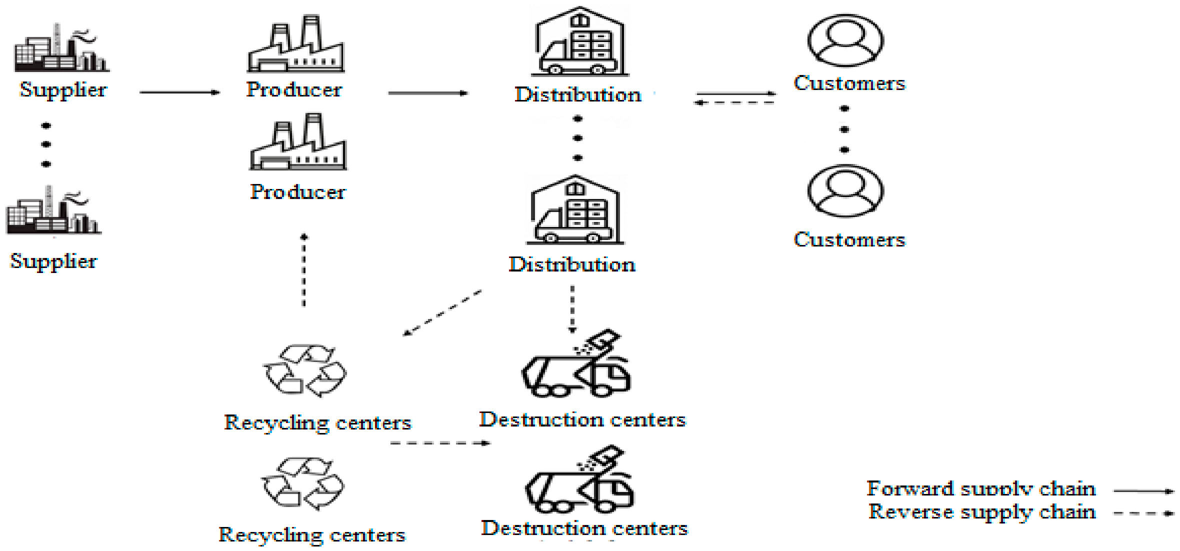

Figure 1. The schematic of the developed model.

3.1. Proposed Model Assumptions

The recent suppositions provided below formed the basis of the research model:

1. The problem represents a multi-objective, single-period, and multi-product model.
2. All customer demands must be met.
3. Material flow can only be established between two different levels of the network, and there is no material flow between facilities in one layer.
4. The capacity of the facility is limited.
5. The suppliers' location, production, distribution, collection, recycling, annihilation centers, and customers are known.
6. A part of returned products is recycled in the reverse supply chain and returned back into the chain, while part of it is excreted and removed from the network.
7. The packaging products' sales volume is usually greater than that of individual sold goods due to the lower price of packaging products than the total price of individual items combined.
8. The productive–technical risk considered in the proposed network model includes interruptions caused by equipment failure and a shortage of skilled labor.
9. Considering the uncertainties of demand in the real world, customer demand is uncertain in the model as well.
10. The amount of products returned from customers and the rates of recycling and destruction are considered uncertain. Disposal refers to the return of a product that enters the recycling stage, but destruction means returning the product to the destruction center. In fact, a product that cannot be recycled is transferred to the destruction center instead of the disposal center.

3.2. Notations and Formulations

The research model is introduced using the following related notations:

➢ **Sets:**

T	The entire sales period
s	Suppliers set $(s = 1, \ldots, N)$
i	Products set $(i = 1, \ldots, N)$
f	Production centers $(f = 1,\ 2)$
μ	Customers $(\mu = 1, \ldots, N)$
dc	Distribution-collection centers $(dc = 1, \ldots, N)$

di	Annihilation centers $(di = 1,\ 2)$
r	Recycling centers $(r = 1,\ 2)$
k	Staff $(k = 1, \ldots, N)$
l	Equipment set $(l = 1, \ldots, N)$
m	Vehicle types $(m = 1, \ldots, N)$
t	Decision cycle, pricing, and packaging phases $(t = 1, \ldots, N)$

➢ **Parameters:**

$n_{i,t}$	Number of type i products produced in period t
c_i	Inventory cost of type i product per decision period
$S_{i,t}$	Product i inventory in period t
q_i	Product i logistics cost
f_s	Purchasing costs for each raw material unit from supplier s
tr_{msf}	Raw material transportation costs from supplier s to production center f utilizing type m vehicle depending on distance
tr_{mfdc}	Product transportation costs from the production center f to the distribution-collection center dc by type m vehicle depending on distance
$tr_{mdc\mu}$	Product transportation costs from the distribution–collection center dc to customer μ by type m vehicle depending on distance
$tr_{m\mu dc}$	Transportation costs for the returned products from customer μ to the distribution–collection center dc by type m vehicle depending on distance
tr_{mdcr}	Transportation costs for the returned products from the distribution–collection center dc to the recycling center r by type m vehicle depending on distance
tr_{mdcdi}	Transportation costs for the returned products from the distribution–collection center dc to the annihilation center di by type m vehicle depending on distance
tr_{mrf}	Transportation costs for the recycled products from the recycling center r to the production center f by type m vehicle depending on distance
tr_{mrdi}	Transportation costs for the returned products from the recycling center r to the annihilation center di by type m vehicle depending on distance
C_h	Maintenance costs of type i products in the distribution–collection center dc
C_N	Equipment repair and maintenance costs
C_{tr}	Cost of staff training
C_{ri}	Recycling costs of type i products at the recycling center r
C_{di}	Costs of annihilating type i products in the annihilation center di
C_d	Delay costs per time
f_R	Inspection costs for each returned product unit in the distribution–collection center dc
f_H	Purchasing costs for each unit of type i product from customer μ
C_{rentm}	Renting costs for a car type m
C_{bm}	Purchasing costs for a car type m
T_{if_1d}	Person–hour needed to manufacture each type i product unit at the first production center
T_{if_2d}	Person–hour needed to manufacture each type i product unit at the second production center
T_{w_1}	Working hours during the order period at the first production center
T_{w_2}	Working hours during the order period at the second production center
k_{a_1}	Number of existing workers in the first production center
k_{a_2}	Number of existing workers in the second production center
k_{e_1}	Number of hired workers in the first production center
k_{e_2}	Number of hired workers in the second production center
e_{sf}	Transport-related CO_2 emission rates from supplier s to the production center of f per product unit
e_{fdc}	Transport-related CO_2 emission rates from the production center f to the distribution–collection center dc per product unit
$e_{dc\mu}$	Transport-related CO_2 emission rates from the distribution–collection center dc to customer μ per product unit
$e_{\mu dc}$	Transport-related CO_2 emission rates from customer μ to the distribution–collection center dc per product unit
e_{dcr}	Transport-related CO_2 emission rates from the distribution–collection center dc to the recycling center r per product unit

e_{rf}	Transport-related CO_2 emission rates from the recycling center r to the production center f per product unit
e_{rdi}	Transport-related CO_2 emission rates from the recycling center r to the annihilation center di per product unit
e_{dcdi}	Transport-related CO_2 emission rates from the distribution–collection center dc to the annihilation center di per product unit
e_i	CO_2 emission rates for producing each type i product unit
e_{ri}	CO_2 emission rates for the recycling process of each type i returned product unit
e_{dii}	CO_2 emission rates for the annihilation process of each type i returned product unit
e_{dc}	CO_2 emission rates for the returned product inspection process in the distribution–collection center dc
d_{sf}	Supplier s to the production center f distance
d_{fdc}	Production center f to the distribution–collection center dc distance
$d_{dc\mu}$	Distribution–collection center dc to client μ distance
$d_{\mu dc}$	Client μ to the distribution–collection center dc distance
d_{dcr}	Distribution–collection center dc to the recycling center r distance
d_{rf}	Recycling center r to the production center f distance
d_{rdi}	Recycling center r to the annihilation center di distance
d_{dcdi}	Distribution–collection center dc to the annihilation center di distance
Ca_s	Maximum capacity for supplier s
Ca_f	Maximum capacity for the production center f
Ca_{dc}	Maximum capacity for the distribution–collection center dc
Ca_r	Maximum capacity for the recycling center r
Ca_{di}	Maximum capacity for the annihilation center di
G	Maximum allowable CO_2 emissions from production
M_R	Maximum allowable production–technical risk
t_k	Maximum acceptable delivery time for customer μ
d_μ	Customer demand
d_f	Raw materials' demand of the production center f from supplier s
R_l	Device L failure risk
T_{ei}	CO_2 emission rate of total production at the production center
t_t	Total time from supplying raw materials from supplier s to sending final product to customer μ
t_{sf}	Length of time for supplying raw materials from supplier s to the production center f
t_{fdc}	Length of time for finished products to be sent from the production center f to the distribution–collection center dc
$t_{dc\mu}$	Length of time for sending the finished product from the distribution–collection center dc to customer μ
α	Product return rate
β	Product return rate from the distribution–collection center dc to the annihilation center di
γ	Product return rate from the distribution–collection center dc to the recycling center r
λ	Recycled product sending rate from the recycling center r to the production center f
τ	Recycled product sending rate from the recycling center r to the annihilation center di
$q_{s\mu}$	Customer μ expected quality
q_{sdcdi}	Quality level of the product that leads to transfer from the distribution–collection center dc to the annihilation center di
q_{sdcr}	Quality level of the product that leads to transfer from the distribution–collection center dc to the recycling center r
q_{srdi}	Quality level of the product level that leads to transfer from the recycling center r to the annihilation center di

Model's Decision Variables

The proposed mathematical model has two types of decision variables. The first category includes non-zero continuous decision variables to determine the material and product flow between different facilities and the number of employees in each production facility, while also determining the time period of product delivery between various facilities in the direct supply chain. The second category consists of zero and one variables, which are used to select facilities, automobiles, and equipment for production centers.

➢ **Continuous Decision Variables:**

$p_{i,t}$	Sale price of product i in cycle t
Y_{sf}	Raw material amounts sent from supplier s to the production center f
Y_{ifdc}	Type i product amounts sent from the production center f to the distribution–collection center dc
$Y_{idc\mu}$	Type i product amounts sent from the distribution–collection center dc to customer μ
$Y_{i\mu dc}$	Type i product amounts sent from customer μ to the distribution–collection center dc
Y_{idcr}	Type i product amounts delivered from the distribution–collection center dc to the recycling center r
Y_{irf}	Recycled product amounts delivered from the recycling center r to the production center f
Y_{irdi}	Product amounts delivered from the recycling center r to the annihilation center di
Y_{idcdi}	Returned product amounts delivered from the distribution–collection center dc to the annihilation center di
t_{sf}	Time to send raw materials from supplier s to the production center f
t_{fdc}	Time to send product from the production center f to the distribution–collection center dc
$t_{dc\mu}$	Time to send product from the distribution–collection center dc to customer μ
r_{μ}^{i}	Returned rate of product i with quality level qs from customer μ
$x_{\mu dc.q_s}$	Returned product amounts considering quality level q_s from customer μ to the distribution–collection center dc

➢ **Binary Variables:**

X_s	If supplier s is chosen, it is equal to 1; otherwise, it equals 0.
X_f	If the production center f is chosen, it is equal to 1; otherwise, it equals 0.
X_{dc}	If the distribution–collection center dc is chosen, it is equal to 1; otherwise, it equals 0.
X_{μ}	If customer μ is chosen, it is equal to 1; otherwise, it equals 0.
X_r	If the recycling center r is chosen, it is equal to 1; otherwise, it equals 0.
X_{di}	If the annihilation center di is chosen, it is equal to 1; otherwise, it equals 0.
X_v	If the vehicle type m is sent, it is equal to 1; otherwise, it equals 0.
X_{rm}	If the vehicle type m is rented, it is equal to 1; otherwise, it equals 0.
X_{im}	If the vehicle type m is purchased, it is equal to 1; otherwise, it equals 0.
X_l	If equipment l is used, it is equal to 1; otherwise, it equals 0.

3.3. Objective Functions

The study addresses a multi-objective, single-period, and multi-product model within a closed-loop supply chain network. The network design integrates environmental factors and imposes restrictions on material flow across different network levels. Facilities have limited capacities, and a dual-purpose location is implemented to minimize network costs for product distribution and collection. The locations of suppliers, production centers, distribution and collection centers, recycling centers, annihilation centers, and customers are known. The network consists of two production centers, two annihilation centers, two recycling centers, and various suppliers and distribution and collection centers. The reverse supply chain partially recycles returned products while removing the remaining ones from the network. Meeting specific inventory targets within a fixed sales period is crucial, particularly for perishable products. Packaging products have higher sales volumes due to their lower price compared to individual items. The total costs encompass several components, including sales, logistics, production, raw material procurement, transportation, delay, inventory, staff training, equipment maintenance, inspection, and recycling and annihilation costs. The model incorporates productive–technical risks associated with equipment failure and labor shortages. Uncertainty is considered in customer demand, product returns, recycling rates, and destruction. Greenhouse gas emissions are accounted for in production, transportation, and inspection processes throughout the supply chain network. The proposed model of the present study has four objective functions, all of which aim for minimization. Objective function (1) presented below, calculates and minimizes all network costs.

$$\begin{aligned} Min\ Z_1 = \ & \left(\sum_{t \in N} \sum_{i \in N} p_{i,t} n_{i,t} + \sum_{i \in N} S_{i,0} q_i + \sum_{t \in N} \sum_{i \in N} S_{i,t} - n_{i,t} c_i + \sum_{s \in S} \sum_{f \in F} f_s Y_{sf} X_s X_f \right) + \sum_{i \in N} \sum_{f \in F} c_i n_i X_f \\ & + \sum_{i \in N} \sum_{\mu \in N} \sum_{dc \in DC} f_H Y_{i\mu dc} X_{dc} + \sum_{i \in N} \sum_{\mu \in N} \sum_{dc \in DC} f_R Y_{i\mu dc} X_{dc} + \sum_{i \in N} \sum_{r \in R} \sum_{dc \in DC} C_{ri} Y_{idcr} X_r \\ & + \sum_{i \in N} \sum_{di \in i} C_{di} (Y_{idcdi} + Y_{irdi}) X_{di} + \sum_{l \in L} C_N X_l + \sum_{\mu \in N} \sum_{i \in N} \sum_{dc \in DC} C_d \max(0, t_t - t_k) Y_{idc\mu} \\ & + \sum_{m \in M} \sum_{s \in S} \sum_{f \in F} tr_{msf} d_{sf} Y_{sf} X_s X_f + \sum_{m \in M} \sum_{i \in N} \sum_{dc \in DC} \sum_{f \in F} tr_{mfdc} d_{fdc} Y_{ifdc} X_{dc} X_f \\ & + \sum_{m \in M} \sum_{i \in N} \sum_{\mu \in N} \sum_{dc \in DC} tr_{mdc\mu} d_{dc\mu} Y_{idc\mu} X_{dc} X_\mu + \sum_{m \in M} \sum_{i \in N} \sum_{\mu \in N} \sum_{dc \in DC} tr_{m\mu dc} d_{\mu dc} Y_{i\mu dc} X_{dc} X_\mu \\ & + \sum_{m \in M} \sum_{i \in N} \sum_{r \in R} \sum_{dc \in DC} tr_{mdcr} d_{dcr} Y_{idcr} X_{dc} X_r + \sum_{m \in M} \sum_{r \in R} \sum_{i \in N} \sum_{f \in F} tr_{mrf} d_{rf} Y_{irf} X_r X_f \\ & + \sum_{m \in M} \sum_{i \in N} \sum_{r \in R} \sum_{di \in DI} tr_{mrdi} d_{rdi} Y_{irdi} X_{di} X_r + \sum_{m \in M} \sum_{i \in N} \sum_{r \in R} \sum_{dc \in DC} tr_{mdcdi} d_{dcdi} Y_{idcdi} X_{di} X_{dc} \\ & + \sum_{i \in N} \sum_{dc \in DC} \sum_{f \in F} C_h Y_{idfc} X_{dc} + \sum_{m \in M} C_{rentm} X_{rm} + \sum_{m \in M} C_{bm} X_{im} + \sum_{k_{e_1} \in K} \sum_{k_{e_2} \in K} C_{tr} (k_{e_1} + k_{e_2}) \end{aligned} \quad (1)$$

The first statement represents the cost of sales and logistics of product i based on inventory levels, costs, and raw material purchasing costs from supplier s. The second statement represents the production costs of each product unit. The third and fourth statements represent the purchasing costs of each product unit returned from customers and the inspection costs of each returned product unit in the distribution–collection center, respectively. The fifth and sixth statements represent the recycling costs of each returned product unit and the annihilating costs of each returned and unrecyclable product unit, respectively. The seventh and eighth statements represent the cost of equipment repairs and maintenance, and the cost of delaying product delivery per unit of time, respectively. The ninth to sixteenth statements, respectively, represent the raw material transportation costs from suppliers to production centers, products transported from production to distribution–collection centers, products from distribution–collection centers to customers' locations, returned products transported from customers to distribution–collection centers, products from distribution–collection centers to recycling centers, products from recycling centers to production centers, products from recycling centers to annihilation centers, and products from distribution–collection centers to annihilation centers. The seventeenth statement represents maintenance costs in distribution–collection centers, and the eighteenth and nineteenth statements indicate the cost of renting and purchasing cars for transporting raw materials and products between facilities, respectively. Lastly, the twentieth statement is equivalent to the cost of training staff.

$$\begin{aligned} Min\ Z_2 = \ & \sum_{i \in N} n_i e_i + \sum_{i \in N} \sum_{r \in R} Y_{idcr} e_{ri} + \sum_{i \in N} \sum_{di \in DI} \sum_{r \in R} (Y_{idcdi} + Y_{irdi}) e_{dii} + \sum_{i \in N} \sum_{dc \in DC} Y_{i\mu dc} e_{dc} + \sum_{m \in M} \sum_{s \in S} \sum_{f \in F} Y_{sf} e_{sf} X_v \\ & + \sum_{m \in M} \sum_{i \in N} \sum_{dc \in DC} \sum_{f \in F} Y_{ifdc} e_{fdc} X_v + \sum_{m \in M} \sum_{i \in N} \sum_{dc \in DC} \sum_{c \in C} Y_{idc\mu} e_{dc\mu} X_v \\ & + \sum_{m \in M} \sum_{i \in N} \sum_{\mu \in N} \sum_{dc \in DC} Y_{i\mu dc} e_{\mu dc} X_v + \sum_{m \in M} \sum_{i \in N} \sum_{dc \in DC} \sum_{r \in R} Y_{idcr} e_{dcr} X_v + \sum_{m \in M} \sum_{i \in N} \sum_{r \in R} \sum_{f \in F} Y_{irf} e_{rf} X_v \\ & + \sum_{m \in M} \sum_{i \in N} \sum_{r \in R} \sum_{di \in DI} Y_{irdi} e_{rdi} X_v + \sum_{m \in M} \sum_{i \in N} \sum_{dc \in DC} \sum_{di \in DI} Y_{idcdi} e_{dcdi} X_v \end{aligned} \quad (2)$$

Objective function (2) aims to minimize greenhouse gas emissions from different supply chain network processes. The first and second statements indicate the amount of emissions caused by the production process of products in production centers and the amount of emissions caused by the process of recycling, respectively. The third and fourth statements indicate the amount of emissions caused by the annihilation process and the amount of emissions caused by the inspection process of returned products in distribution–collection centers, respectively. The fifth to twelfth terms also represent the amount of emissions from the transportation process: from suppliers to production centers, from production to distribution–collection centers, from distribution–collection centers to customers, from customers to distribution–collection centers for transporting returned products, from distribution–collection centers to recycling centers, from recycling centers to production centers, from recycling centers to annihilation centers, and from distribution–collection centers to annihilation centers.

$$Min\ Z_3 = \sum_{l \in L} R_l X_l \tag{3}$$

Objective function (3) aims to minimize the risk of device failure. This function is aimed at minimizing production–technical risk, which is the most critical risk in the green supply chain. As mentioned in the model assumptions, two factors of interruption, caused by equipment failure and a shortage of skilled labor, are considered as the main causes of production–technical risk. The repair and maintenance of network equipment seem necessary and inevitable to minimize the interruption caused by equipment failure. Therefore, the costs for repairing and maintaining equipment in the network to prevent equipment failure or reduce downtime are considered and modeled in objective function (1). Also, staff training is considered an effective solution to solve the problem of the shortage of skilled labor, so costs for training employees to compensate for this shortfall and increase the skills of employees are modeled in objective function (1):

$$Min\ Z_4 = \sum_{s \in S} \sum_{f \in F} t_{sf} X_f + \sum_{f \in F} \sum_{dc \in DC} t_{fdc} X_{dc} + \sum_{dc \in DC} \sum_{\mu \in N} t_{dc\mu} X_\mu \tag{4}$$

The fourth objective function aims to minimize product delivery time. The first to last statements indicate time taken for raw materials to be sent from the supplier to the production center, the time taken for products to be sent from production to distribution–collection centers, and the time taken for products to be sent from distribution–collection centers to customers, respectively.

3.4. Constraints

In the following, the constraints of the whole system is described in detail.

$$\sum_{s \in S} X_s Y_{sf} \leq Ca_s \tag{5}$$

The amount of raw materials sent from suppliers should be smaller than their capacity.

$$\sum_{f \in F} \sum_{i \in N} \sum_{dc \in DC} \sum_{\mu \in N} \left(Y_{ifdc} + Y_{i\mu dc} \right) X_{dc} \leq Ca_{dc} \tag{6}$$

The amount of products entering distribution–collection centers should be smaller than their capacity.

$$\sum_{\mu \in N} \sum_{i \in N} \sum_{dc \in DC} Y_{idc\mu} X_{dc} \geq \sum_{\mu \in N} d_\mu \tag{7}$$

All customer requests must be satisfied.

$$\sum_{i \in N} \sum_{r \in R} \sum_{dc \in DC} Y_{idcr} X_r \leq Ca_r \tag{8}$$

The total amount of goods sent from distribution–collection to recycling centers should be smaller than the capacity of recycling centers.

$$\sum_{i\in N}\sum_{r\in R}\sum_{f\in F}Y_{irf}X_r \le Ca_f \tag{9}$$

The total amount of products delivered from recycling centers to production centers must be smaller than the production center's capacity.

$$\sum_{i\in N}\sum_{dc\in DC}\sum_{r\in R}\sum_{di\in DI}Y_{idcdi}X_{dc}X_{di}+Y_{irdi}X_{di}X_r \le Ca_{di} \tag{10}$$

The total amount of goods sent to annihilation centers should be smaller than the capacity of annihilation centers.

$$\sum_{f\in F}\sum_{s\in S}X_sY_{sf} \ge d_f \tag{11}$$

The amount of raw materials sent from the suppliers to the production centers should be large enough to meet the demands of the production center.

$$\sum_{i\in N}\sum_{dc\in DC}\sum_{\mu\in N}Y_{i\mu dc}=\sum_{\mu\in N}\sum_{i\in N}\sum_{dc\in DC}\alpha Y_{idc\mu} \tag{12}$$

The total amount of returned products from customers to distribution–collection centers should be α% of the total products sent to customers.

$$\sum_{i\in N}\sum_{dc\in DC}\sum_{f\in F}Y_{ifdc}=\sum_{i\in N}N_i \tag{13}$$

The total number of type i products delivered from the production centers to distribution centers must equal the total production of type i products.

$$\sum_{i\in N}\sum_{dc\in DC}\sum_{di\in DI}Y_{idcdi}=\sum_{i\in N}\sum_{\mu\in N}\sum_{dc\in DC}\beta Y_{i\mu dc} \tag{14}$$

The total product delivered from the distribution–collection centers to annihilation centers can be represented as β% of the total returned products sent from customers to distribution–collection centers.

$$\sum_{i\in N}\sum_{dc\in DC}\sum_{r\in R}Y_{idcr}=\sum_{i\in N}\sum_{\mu\in N}\sum_{dc\in DC}\gamma Y_{i\mu dc} \tag{15}$$

The total number of products sent from distribution–collection centers to recycling centers can be indicated as γ% of the total returned products sent from customers to distribution–collection centers.

$$\sum_{di\in DI}\sum_{i\in N}\sum_{r\in R}Y_{irdi}=\sum_{i\in N}\sum_{dc\in DC}\sum_{r\in R}\tau Y_{idcr} \tag{16}$$

The total number of products sent from recycling centers to annihilation centers should be τ% of the total products sent from distribution–collection centers to recycling centers.

$$\sum_{i\in N}\sum_{dc\in DC}\sum_{\mu\in N}\sum_{f\in F}Y_{ifdc}+Y_{i\mu dc} \ge \sum_{i\in N}\sum_{dc\in DC}\sum_{\mu\in N}\sum_{r\in R}\sum_{di\in DI}Y_{idc\mu}+Y_{idcr}+Y_{idcdi} \tag{17}$$

The sum of products that enter distribution–collection centers must exceed the output sum from distribution–collection centers.

$$\sum_{i \in N} \sum_{r \in R} \sum_{f \in F} Y_{irf} = \sum_{i \in N} \sum_{dc \in DC} \sum_{r \in R} \lambda Y_{idcr} \tag{18}$$

The total product sent from recycling centers to production centers should be λ% of the total product amounts sent from distribution–collection centers to recycling centers.

$$\sum_{i \in N} \sum_{dc \in DC} \sum_{r \in R} Y_{idcr} = \sum_{f \in F} \sum_{i \in N} \sum_{r \in R} \sum_{di \in DI} Y_{irf} + Y_{irdi} \tag{19}$$

The total product amounts entering recycling centers must equal the total output of recycling centers.

$$\sum_{i \in N} \sum_{dc \in DC} \sum_{\mu \in N} Y_{idc\mu} = \sum_{i \in N} \sum_{dc \in DC} \sum_{f \in F} Y_{ifdc} \tag{20}$$

The sum of type i products delivered from distribution–collection centers to customers must equal the type i product total number sent from production centers to distribution–collection centers.

$$\sum_{m \in M} X_v \leq X_{rm} + X_{im} \tag{21}$$

The total number of vehicles on the journey must be less than or equal to the total purchased and rental vehicles in the organization.

$$\sum_{l \in L} R_l \leq M_R \tag{22}$$

Production–technical risk must be smaller than the maximum production–technical risk allowed.

$$\sum_{i \in N} T_{ei} \leq G \tag{23}$$

The total CO_2 emission rate of production in production facilities should be less than the maximum allowable rate of CO_2 emissions from production.

$$t_t = t_{sf} + t_{fdc} + t_{dc\mu} \tag{24}$$

The product delivery total time to the customer equals the total time for product transfer from the supplier to the production centers, the product transfer time from production centers to distribution–collection centers, and the product transfer time from distribution–collection centers to the customers.

$$\beta + \gamma + \lambda + \tau = 1 \tag{25}$$

The above constraint ensures that the value of 1 is obtained for the sum of the returned products' coefficients.

$$\sum_{dc \in DC} \sum_{\mu \in N} x_{\mu dc.q_s} = r^i_\mu \tag{26}$$

The above statement ensures the collection of all returned products from customer centers throughout the return process.

$$q_{sdcdi} + q_{sdcr} + q_{srdi} = q_{s\mu} \tag{27}$$

The above statement ensures that the total product quality in the whole chain (except the product transfer stage from recycling centers to manufacturing centers) equals the original product quality.

$$\sum_{l \in L}\sum_{i \in N} n_i X_l = \sum_{dc \in DC}\sum_{f \in F}\sum_{i \in N} Y_{ifdc} \tag{28}$$

The total production of type i equipment in each production center equals the number of products delivered from the desired production center to distribution–collection centers.

$$\sum_{f \in F}\sum_{i \in N} T_{if_1d} Y_{ifdc} \leq \sum_{k_{a_1} \in k}\sum_{k_{e_1} \in k} (k_{a_1} + k_{e_1}) T_{w_1} \tag{29}$$

Person–hours needed to manufacture each product type i unit in the first production center should be supplied by the existing labor force and by hiring new labor in case of shortages.

$$\sum_{f \in F}\sum_{i \in N} T_{if_2d} Y_{ifdc} \leq \sum_{k_{a_2} \in k}\sum_{k_{e_2} \in k} (k_{a_2} + k_{e_2}) T_{w_2} \tag{30}$$

Person–hours needed to manufacture each product type i unit in the second production center should be supplied by the existing labor force and by hiring new labor in case of shortages.

$$Y_{sf}, Y_{ifdc}, Y_{idc\mu}, Y_{i\mu dc}, Y_{idcr}, Y_{irf}, Y_{irdi}, Y_{idcdi}, t_{sf}, t_{fdc}, t_{dc\mu}, r^i_{\mu}, x_{\mu dc.q_s} > 0 \tag{31}$$

$$X_s, X_f, X_{dc}, X_{\mu}, X_r, X_{di}, X_v, X_{rm}, X_{im}, X_l \in \{0, 1\} \tag{32}$$

These two constraints ensure that the mentioned parameters and variables are positive and between zero and one, respectively.

$$t_{sf.min} \leq t_{sf} \leq t_{sf.max} \tag{33}$$

This constraint ensures that the time spent on raw material sending from supplier s to the production center f must be within the time frame set by the production center f.

$$t_{fdc.min} \leq t_{fdc} \leq t_{fdc.max} \tag{34}$$

This constraint ensures that the time it takes to send final products from the production center f to the distribution–collection center dc must be within the time frame set by the distribution–collection center dc.

$$t_{dc\mu.min} \leq t_{dc\mu} \leq t_{dc\mu.max} \tag{35}$$

This constraint ensures that the time it takes to send final products from the distribution–collection center dc to customer μ must be within the time frame set by customer μ.

$$\sum X_s, X_f, X_{dc}, X_r, X_{di}, X_v, X_{rm}, X_{im}, X_l \geq 1$$

$$\forall s \in S, \forall f \in F, \forall dc \in DC, \forall r \in R, \forall di \in DI, \forall m \in M, \forall l \in L \tag{36}$$

This constraint ensures that at least one facility is used during the product transfer to the customer.

$$q_i + c_i \leq p_{i,t} \leq p_i^{max} \tag{37}$$

This constraint ensures that pricing must be higher than the cost and below the maximum price reserved by consumers.

$$n_{i,t} \geq 0 \tag{38}$$

This constraint ensures that the volume of product sales in each decision cycle must be non-negative.

$$\sum n_{i,t} \leq S_i \tag{39}$$

This constraint is an indirect limiting condition to ensure that the sales volumes of the two types of products must be less than the total inventory.

$$max\{p_{1,t}, p_{2,t}\} < p_{3,t} < p_{1,t} + p_{2,t} \tag{40}$$

According to the bundling strategy, this constraint represents a package pricing that must be less than the sum of the separated pricing of two products and higher than the highest price of the two separate products sold. Otherwise, advertising through the bundling strategy is meaningless.

$$n_{3,t} < \min(S_{i,t}) \tag{41}$$

This constraint ensures that the sales volume of the bundling product must be less than the minimum inventory of two products.

$$\sum (n_{1,t} + n_{3,t}) \leq S_i, \sum (n_{2,t} + n_{3,t}) \leq S_i \tag{42}$$

This constraint is also a limited requirement to ensure that the sales volumes of two product types must be less than the total inventory.

4. Numerical Example and Results

4.1. Numerical Example

As a result of the NP-hard nature of the model and its computational complexity, it is not possible to solve it with exact methods. Hence, we will use a meta-heuristic algorithm to solve the model. Among multi-objective meta-heuristic algorithms, the NSGA-II algorithm has been selected in this research due to its significant advantages. The nature of this algorithm's random search in the problem space is considered a parallel search, because each of the random chromosomes generated by the algorithm is considered a new starting point for searching a part of the problem state space, and the search is conducted across all of them simultaneously. Also, due to the extensive dispersion of the points that are searched, it obtains favorable results for problems that have large search spaces. It is also considered a targeted random search and will reach different answers through different paths. In addition, it does not face any restrictions in the search and selection of random answers. Finally, due to competition among answers and selection of the best among the population, it will reach the global optimal point with a high probability. The proposed NSGA-II algorithm starts with a population initialization process that randomly generates populations with the values of each gene bounded by given values. Then, it uses a selection process to form a pool of parents to generate offspring using a crossover process. The genetic algorithm used in this research uses a simple crossover process that randomly selects two parents as parent1 and parent2 and then generates a random variable (r) from 0 to 1. The weight of this random variable is defined as R. We considered R as 0.8 and used $child = parent1 + r * R * (parent2 - parent1)$ to create each gene from a child. This is shown in Figure 2.

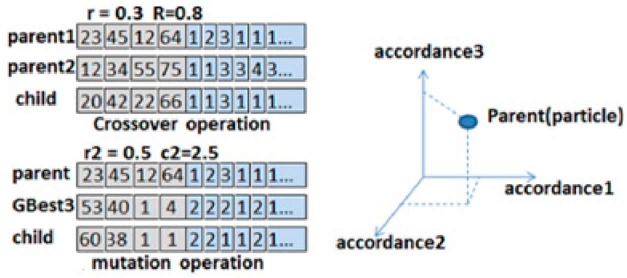

Figure 2. Crossover and mutation operators.

In the proposed NSGA-II algorithm, in order to improve population diversity and convergence speed, a combination of disorder mapping and conflict-based learning methods is used to generate the initial population. Also, an approach based on a penalty function is used for solutions that do not meet the time limit. This problem shows the differences between the proposed method and the classical NSGA-II and MOPSO methods.

The problem at hand is a multi-objective, single-period, multi-product green CLSC model. The settings for the NSGAII algorithm are presented in Table 2. It should be noted that the implementation of the proposed method was carried out using MATLAB version 2023 software, and the coding was performed on a system with a core i5 processor and 8 GB of RAM.

Table 2. Initial parameters of NSGA-II.

Parameter	Value
Population size	60
No. of generations	100
Selection method	Random
Non-dominant choice	Tournament DCD
Crossover method	Laplace
Probability of crossover	95%
Mutation method	Power
Probability of mutation	0.5%

Table 3 shows the initial values of some main parameters. These data were collected from a food packaging company in Tehran, Iran.

Table 3. Initial model parameters.

Parameter	Symbol	Value
Supplier	s	4
Production center	f	2
Distribution-collection center	Dc	5
Destruction center	Di	2
Recycling center	r	2
Customer	C	10
Staff	k	5
Set of products	p	3
Set of equipment	l	4
All vehicle types	m	3
Number of products produced	N_p	1000
Production costs per product unit	C_p	50,000
The costs of each raw material unit purchasing from the suppliers	f_s	10,000
The employee training costs	C_{tr}	1,200,000
Product recycling costs	C_{rp}	20,000
Product destruction costs	C_{di}	13,000
Inspection fee per returned product unit	F_{chp}	30,000

During the process of solving the model, some solutions were infeasible, which is due to the placement of the algorithm in local solutions. In order to overcome this issue, the proposed algorithm shifts from local mode and solves this problem under global conditions. The difference between feasible and infeasible solutions lies in establishing the necessary restrictions and conditions to solve the problem that is considered in the model.

Now, results related to all four objective functions have been obtained by setting the population number to 10, the operators' probability to 0.8, and the mutation operators' probability to 0.3. Nevertheless, as the developed model represents several different levels with 10 customers, five distributors, and two manufacturers (Table 3), the flow of products is determined considering the amount of customer demand. Hence, Table 4 illustrates the amount of demand for the 10 target customers separately.

Table 4. Customer demand values.

Customers	1	2	3	4	5	6	7	8	9	10
Demand	176	329	427	729	102	356	449	224	234	332

According to the above table, the first customer demands 176 pieces, the second demands 329 pieces, and so on until the end. It is necessary to note that the maximum time needed for product delivery to each customer without causing dissatisfaction is set at 120 h. Additionally, given the completely random determination of initial model values in problem-solving by the genetic algorithm (GA), unreasonable or infeasible solutions may arise, prompting the algorithm to promptly address the problem and find a practical answer. The above-mentioned process should be considered by the algorithm during 300 iterations. Table 5 presents the model implementation results with the genetic multi-objective algorithm for all four specific objectives.

Table 5. Problem-solving results with the genetic algorithm (NSGAII).

The Objective Function	**Cost Objective Function ($)**	**Pollutant Emission Objective Function (PPM)**	**Risk Objective Function (%)**	**Time Objective Function (h)**	**Execution Time (s)**
Value	10,981,185	11,744	0.27	117	14.5963

As shown in Table 5, the desired results are presented for the proposed model with a numerical example. The point that should be mentioned, regarding the presentation of results related to risk, is that in this research, supply chain risk assessment is related to two interruption factors: equipment failure and the lack of skilled labor, both considered the main factors contributing to production–technical risk. Any failure leads to an interruption in production of the product and increases the costs of the entire chain. Therefore, equipment maintenance costs and staff training costs are presented in the form of a cost model to compensate for this deficiency and increase the skills of employees. Therefore, by reducing risk, in addition to minimizing the delay in the production and shipping of the product, the costs of the entire chain are also reduced.

Tables 6 and 7 present the product transfer amounts from manufacturers to distributors and from distributors to customers to meet their expectations throughout the considered interval. The presented values highlight the desired figures to achieve the target functions' optimal amounts.

Based on Table 6, the first producer only transferred 1231 units of products to the fifth distributor, and the second producer only transferred 1853 units to the first distributor, 2 units to the third distributor, and 272 units to the fourth distributor. However, there have been no product deliveries to the second distributor. The issue that needs consideration is that the total customer demand, as indicated in Table 6, is 3358 units. As mentioned before, all demands should be answered. Therefore, the total amount of the provided products in Table 6 should equate to 3358 units as well. In addition, the maximum production capacities for the first and second producers were 1577 and 3071 units, adopting 1231 and 2127 units for each, respectively. In other words, the product amounts sent from manufacturers to distributors showed lower values than the manufacturers' maximum capacities. Table 7 presents the amounts of product transfers from each distributor to customers.

According to this table, the first customer takes all the demand of 176 units from the fourth distributor, and the ninth customer receives 9 and 225 product units from the first and second distributors, respectively, to satisfy its request of 234 units. As shown, each row's sum equals the total number of customer demands met.

Table 6. Transferring the products (units) from manufacturers to distributors.

	Distributors				
The first producer	0	0	0	0	1231
The second producer	1853	0	2	272	0

Table 7. Product transfer (units) from distributors to customers.

	Customers									
First Distributor	0	0	427	691	0	227	449	0	9	0
Second Distributor	0	0	0	0	0	0	0	0	0	0
Third Distributor	0	2	0	0	0	0	0	0	0	0
Fourth Distributor	176	0	0	0	96	0	0	0	0	0
Fifth Distributor	0	327	0	38	6	79	0	227	225	332

4.2. Different Sample Size Solution

Due to the complexity of the model and its limitations in the real world, this section aims to use different numerical multiples across different dimensions to make applications in the real world easier. So, in this section, we will examine the model's solution for various examples in small, medium, and large dimensions. Tables 8–10 highlight the findings for all four objective functions for all three problem dimensions.

Table 8. Objective function results for the problem in small dimensions.

Samples	1	2	3	4	5	6	7	8	9	10
Costumer No.	1	2	4	4	7	7	8	8	9	9
Distributer No.	2	2	2	3	3	4	4	4	5	5
Cost	103,813	104,190	104,938	109,889	110,440	120,444	133,912	145,530	145,838	147,781
Pollution (ppm)	350	384	399	450	459	632	885	935	1002	1027
Time (h)	7	8	10	13	19	25	39	44	68	75
Risk (%)	0.058	0.119	0.13	0.298	0.151	0.224	0.324	0.133	0.237	0.276

Table 9. Objective function results for the problem in medium dimensions.

Samples	1	2	3	4	5	6	7	8	9	10
Costumer No.	12	14	14	15	15	16	16	18	18	18
Distributer No.	6	6	7	7	8	8	9	12	13	14
Cost	1,086,833	1,180,532	1,209,745	1,222,165	1,232,836	1,295,891	1,302,785	1,339,529	1,344,999	1,377,401
Pollution (ppm)	1178	1208	1321	1342	1574	1622	1700	1765	1932	2120
Time (h)	50	51	52	62	64	69	73	77	80	84
Risk (%)	0.059	0.341	0.367	0.228	0.309	0.23	0.399	0.202	0.217	0.389

Table 10. Objective function results for the problem in large dimensions.

Samples	1	2	3	4	5	6	7	8	9	10
Costumer No.	30	45	50	50	60	65	65	70	70	70
Distributer No.	20	20	25	30	32	38	41	45	50	60
Cost	1,520,398	2,026,527	2,142,370	2,165,451	2,255,848	2,257,946	2,342,930	2,411,260	2,412,817	2,595,378
Pollution (ppm)	13,526	13,658	14,002	14,230	15,200	16,210	16,890	17,532	18,050	19,850
Time (h)	112	114	123	129	135	139	145	160	175	191
Risk (%)	0.177	0.346	0.443	0.303	0.391	0.408	0.479	0.587	0.599	0.631

Figures 3–6 are presented to compare the objective functions of cost, time, pollutant emission, and risk level, respectively, to better understand the results.

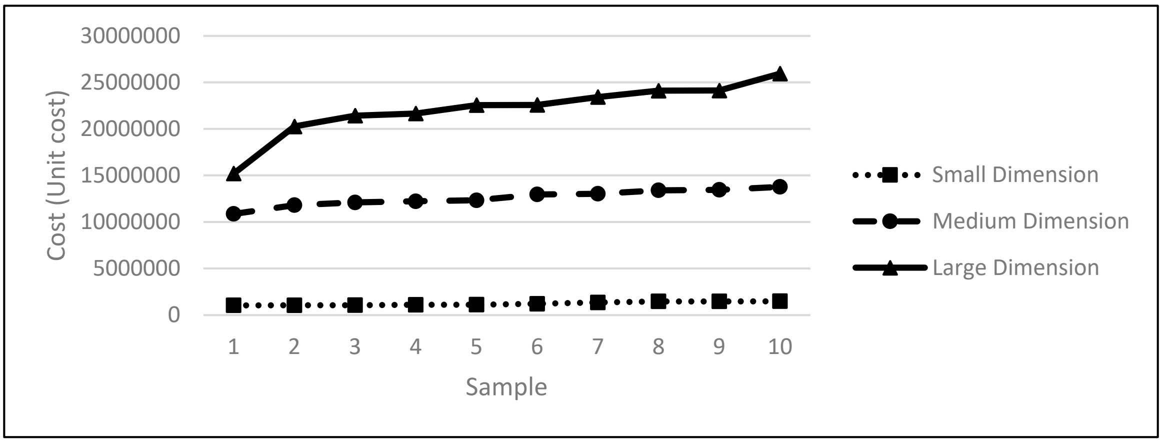

Figure 3. Comparison of costs in each dimension.

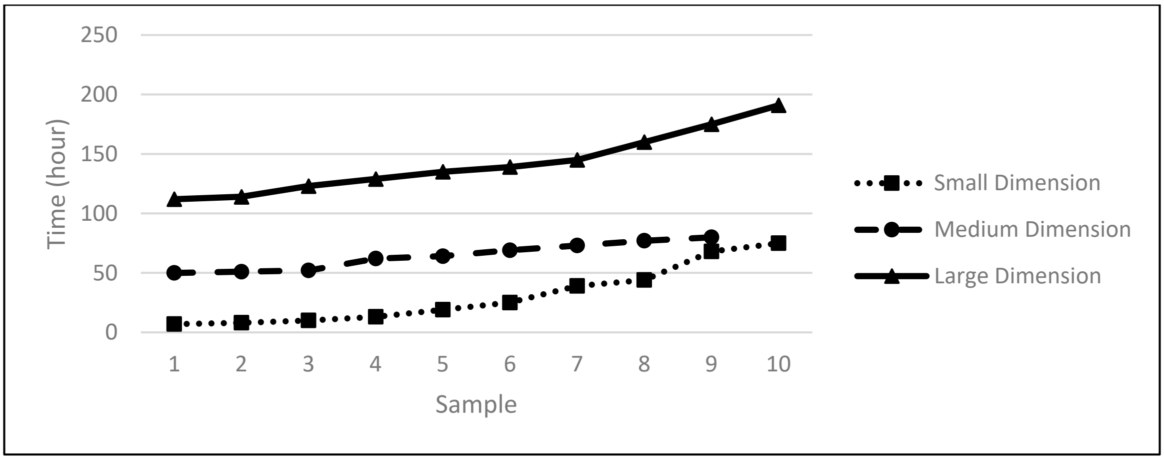

Figure 4. Comparison of times in each dimension.

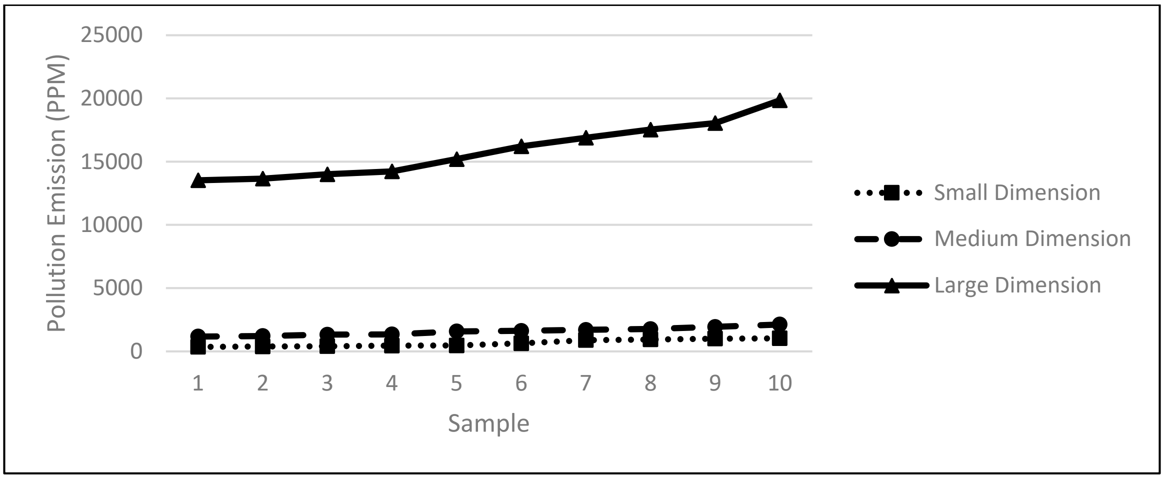

Figure 5. Comparison of pollution emissions in each dimension.

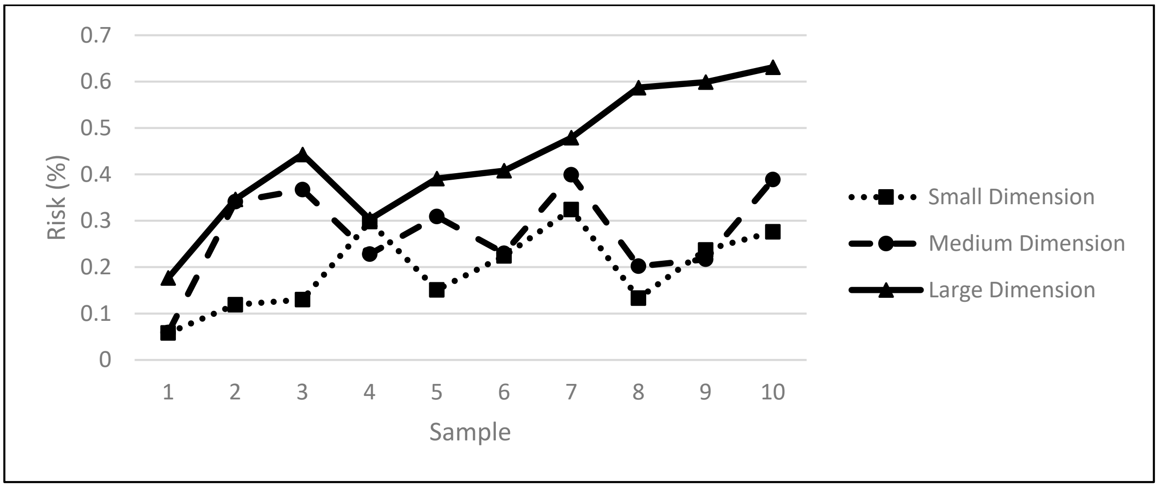

Figure 6. Comparison of risks in each dimension.

4.3. Sensitivity Analysis

Sensitivity analysis is a topic that can provide proper insight into solving problems. In other words, sensitivity analysis determines how much the dependent variable will change if the value of an independent variable changes in a specific and defined situation, assuming that other variables are constant. Here, the values presented in Table 3 are changed to find out how an increase or decrease in each parameter affects the final cost of the model. Based on sensitivity analyses performed on the main model parameters, the supplier, collection–distribution center, and producer numbers have the greatest impact on the target functions. It should be noted that the time required for product delivery to customers has an inverse relationship with the increase in these parameters. Hence, increased supplier, collection–distribution center, and producer numbers would lead to a decrease in the time required to transfer products to customers. Additionally, parameters related to destruction and recycling centers only have an effect on pollutant levels and chain costs, with no effects on objective functions related to time and risk. Thus, with an increase in destruction centers, the amount of pollutants increases more, while an increase in recycling centers results in a higher chain costs. The increased number of customers and produced products does not affect risk. Since the impact of other problem parameters, such as the costs of producing each product unit, purchasing raw materials, training, recycling, destruction, and inspection, as presented in Table 3, only affect chain costs and have no effects on other objective functions, they were not investigated in the sensitivity analysis section.

4.4. Comparison

We also use the MOPSO algorithm and compare its performance with the NSGA-II algorithm in solving large-scale problems to evaluate the developed methodology. Table 11 presents the comparison results.

Table 11. Comparing the performance of NSGA-II and MOPSO in model solving.

Distribution No.	Costumers No.	NSGA-II				MOPSO			
		Cost	Pollution (ppm)	Risk (%)	Time (h)	Cost	Pollution (ppm)	Risk (%)	Time (h)
20	30	15,203,980	13,526	0.177	112	15,878,009	15,321	0.201	122
20	45	20,265,270	13,658	0.346	114	16,508,714	16,807	0.359	126
25	50	21,423,701	14,002	0.443	123	21,046,485	17,243	0.481	131
30	50	21,654,514	14,230	0.303	129	21,245,259	17,296	0.329	135
32	60	22,558,487	15,200	0.391	135	22,857,772	17,633	0.405	141
38	65	22,579,460	16,210	0.408	139	23,429,838	18,828	0.415	154
41	65	23,429,301	16,890	0.479	145	23,968,083	19,309	0.502	161
45	70	24,112,607	17,532	0.587	160	24,099,886	19,655	0.592	167
50	70	24,128,172	18,050	0.599	175	25,479,452	19,738	0.621	181

As revealed by comparisons, the genetic optimization method (NSGA-II) has higher diversity in discovering solutions due to its ability to identify local and global optimal solutions and its continuity. Compared to MOPSO, a better balance is established between discovery and efficiency criteria to prevent the risk of falling into local optima. Therefore, in addition to its high power in discovering optimal answers, the genetics-based method shows higher speed and subsequently a higher convergence rate and diversity than MOPSO.

In the following analysis, we use the MGA, as employed by Gholizadeh and Fazlollahtabar (2020), to maximize the single objective model associated with the CLSC total costs [34]. The objective function presented here seeks to maximize the total profit of the closed-loop green SC. Gross profit equals the difference between income and expenses. Revenue sources are products sold to customers in both Tier 1 and Tier 2. The company's total costs also comprise operational and transportation costs. Thus, each period's operating costs within the future flow are equal to raw material purchasing costs, production of grade 1 products, assembly of grade 1 and 2 products, and the distribution centers' operating costs. A reverse supply chain also involves paying for the purchase of used products from customers, separation costs of returned products, quality checking of separated parts in the parts separation center, and waste disposal costs in the reverse flow. Hence, Table 12 presents the modeling results of the modified GA and the proposed model.

Table 12. Comparison of the developed algorithm (NSGA-II) and MGA, proposed by Gholizadeh and Fazlollahtabar (2020) [34].

Problem No.	1	2	3	4	5	6	7	8	9	10
Modified GA	11,005,413	10,363,216	15,344,758	20,483,956	16,050,510	28,996,989	20,668,679	22,790,123	23,998,908	14,999,575
Present Study	11,152,821	10,852,524	15,817,908	20,854,215	16,642,758	29,528,210	21,217,931	23,269,604	24,752,042	15,241,798
Diff. (%)	1.34	4.72	3.08	1.81	3.69	1.83	2.66	2.10	3.14	1.61

Based on Table 12, among the 10 examples of the solved problem, the algorithm introduced in this research has favorable performance in determining chain costs and enhacing profits, with the highest difference equal to 4.72% and the average difference equal to 2.38% compared to MGA.

The Non-dominated Sorting Genetic Algorithm II (NSGA-II) outperforms the modified genetic algorithm due to several key factors inherent in its design and operational mechanisms. NSGA-II's enhanced performance, which led to a 2.38% reduction in costs, can be attributed to its superior handling of multiple objectives, preservation of diversity among solutions, and efficient sorting and selection process.

5. Discussion and Conclusions

In this paper, the multi-objective genetic optimization method was used to find the optimal answer to the four-objective closed-loop supply chain nonlinear programming problem. The study involved comparing and analyzing the optimal values obtained from each method across different dimensions. The proposed algorithm was performed in several phases. In the first phase, the problem was modeled and initialized, encoding the supply chain network in question with a string of real numbers. Each solution (chromosome) in the genetic algorithm is equivalent to the components of suppliers, distribution centers, producers, repair centers, collection, renovation, destruction, and recycling, and the values of each sub-component of these parameters are randomly initialized within the intervals determined for each. Genetic algorithms usually use a higher quality population to speed up convergence. In the second phase, a criterion must be defined to evaluate the members of the population and enable the recognition of the better organisms in the population. This work, i.e., determining the suitability of an entity, is called the evaluation of that entity. The fitness function is equivalent to the planning problem discussed in Section 3, which deals with profit maximization and environmental impact minimization. The determined values for each of the components of suppliers, distribution centers, producers, and other investigated centers are placed in the objective function to calculate the objective functions and solve the problem according to the considered limitations. In the next step, Pareto solutions are extracted depending on the genetic algorithm model, representing the optimal values of regulatory parameters, including the number of disposals, renovation, repair, recycling, distributor, and supplier centers. The experimental results showed that the genetic algorithm had a favorable performance in finding solutions in all three dimensions, small, medium, and large, in finding the optimal solution, maximizing profit, and reducing the effects on the environment, risk and product transfer time. It was also determined by sensitivity analysis that the parameters related to the number of suppliers, collection–distribution centers, and manufacturers have the greatest impact on the performance of the proposed model's objectives. It was also found that the product delivery time to the customer will have the opposite effect with the increase in these parameters, and with the increase in the number of suppliers, collection–distribution centers, and manufacturers, the product transfer time to the customer will decrease. The results of the comparison of the proposed method with the MOPSO algorithm showed that the genetic optimization method has more diversity in discovering solutions due to finding local and global optimal solutions and its continuous nature, and a better balance is established between the discovery and efficiency criteria to avoid failing to local optima. It was also found that compared to the MOPSO method, it has a high speed and subsequently higher convergence and diversity in achieving optimal solutions. In other words, the advantage of the proposed method compared to other methods is in automatic subset creation and finding global optima and local optima to consciously maximize the profit from each stage of the supply chain. In addition, the proposed method has wider applicability, and we intend to focus on the design of supply chain systems with other objectives in the uncertain and ambiguous periods in the future. Also, in the future, the authors will attempt to perform a quantitative assessment of the environmental benefits resulting from pollutant reduction strategies, possibly including life cycle assessments (LCAs) and economic analyses of cost-saving measures, potentially incorporating a break-even analysis to assess financial feasibility.

Author Contributions: Conceptualization, G.H.P. and Y.H.; Methodology, G.H.P.; Software, G.H.P.; Validation, G.H.P.; Formal analysis, G.H.P.; Investigation, G.H.P.; Resources, G.H.P. and Y.H.; Data curation, G.H.P.; Writing—original draft, G.H.P.; Writing—review & editing, Y.H. and S.H.P.; Visualization, G.H.P.; Supervision, Y.H.; Project administration, Y.H.; Funding acquisition, Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: The current work received support from the National Natural Science Foundation of China (No. 72171047).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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