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# SUSTAINABLE CLOSED-LOOP SUPPLY CHAIN MODELING WITH NEUTROSOPHIC PARAMETERS FOR THE HOME APPLIANCES INDUSTRY (REFRIGERATORS AND FREEZERS)

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**Abstract**

With growing concerns over environmental and social issues, the concept of sustainability has become a key pillar in the design and management of supply chains. In this context, closed-loop supply chains, aimed at reducing waste, recycling resources, and creating added value through circular processes, have gained special importance. This study aims to develop a mathematical model for designing a sustainable closed-loop supply chain in the home appliances industry (refrigerators and freezers). The proposed model considers three dimensions of sustainability, including cost, environmental impacts, and social indicators, and employs neutrosophic theory and trapezoidal neutrosophic fuzzy sets to manage uncertainties and ambiguities in the data. To solve the model, a genetic algorithm in the MATLAB environment is utilized. The results indicate that integrating the neutrosophic approach with closed-loop modeling can lead to more effective and sustainable decision-making in the supply chain of the home appliances industry. This model can serve as a practical tool for managers and decision-makers in achieving sustainable development goals and enhancing resource efficiency.

**Keywords:** Closed-loop supply chain, Mathematical modeling, Neutrosophic theory, Home appliances industry, Genetic algorithm, Sustainable development

## Introduction

In today's world, rapid economic changes and increasing market competition compel companies to focus on and adopt integrated supply chain and logistics strategies. A supply chain network with a suitable structure provides a competitive advantage for companies and helps them manage the growing environmental uncertainties. Essentially, the supply chain is the backbone of the economy and society and interacts extensively with nature. These interactions are highly complex and arise from reciprocal relationships and feedback loops between the supply chain, nature, and the economy. Environmental supply chain management in a highly competitive context requires companies to be innovative in their production systems.

Today, ensuring sustainable development in any country depends on the preservation and optimal use of limited and irreplaceable resources, and various actions have been undertaken by governments to address this issue. Closed-loop supply chains involve return and value-creating processes aimed at reducing resource waste and improving efficiency. Consequently, they play an important role in lowering costs and enhancing the sustainability of supply chains. The transition of supply chains from linear models to closed-loop supply chains represents a significant step toward a circular economy.

One of the most challenging aspects in designing supply chain networks is uncertainty. Under uncertain conditions, proper and reliable planning is required. Appropriate supply chain network design provides the basis for an optimal structure that enables demand fulfillment at minimal cost and with minimal waste efficiently and effectively. In this context, it can be concluded that the growing adoption of neutrosophic logic in decision-making, including multi-criteria decision-making techniques, demonstrates its effectiveness in managing uncertainty.

**Theoretical Background**

Today, supply chain management is considered one of the foundational pillars for implementing e-business worldwide. In the current global competition, diverse products must be made available to customers according to their requests. In the existing competitive market, economic and production enterprises, in addition to managing internal organization and resources, need to oversee and control external resources and related components. The supply chain can be divided into four types: green, sustainable, closed-loop, and circular, which were fully defined and examined in previous sections. One ambiguous aspect regarding these four types of supply chain sustainability is the lack of conceptual distinction, particularly concerning restorative or regenerative outcomes.

Table 1. The Four Concepts of Supply Chain

| Types of Supply Chains | Features | Expected Results |
|---|---|---|
| Green | Integrate forward and reverse supply chains | Environmental Focus |
| Sustainable | Customer and stakeholder engagement | Holistic Triple Topics |
| Closed-loop | Maximize value creation throughout the product life cycle and reduce waste | Environmental and Economic Focus |
| Circular | Creating value through the business ecosystem | Holistic Triple Topics |

**Circular Supply Chain**

The circular supply chain is a model for managing the processes of sourcing, production, and recycling of products, designed to conserve natural resources and reduce environmental pollution. In this model, products are recycled in a circular manner after use and re-enter the production process. This approach emphasizes creativity in product design, optimal resource utilization, increased recycling, and reduction of energy and material consumption.

In recent years, corporate, social, and environmental responsibility has become part of the objectives of manufacturing and service organizations and has positively turned into a standard for organizational activities. Additionally, several factors drive organizations to adopt sustainable supply chain management, especially in the upstream sections of the supply chain. These factors can be external or internal. External factors include legal regulations, the nature of business activities, competitors, and shareholder actions. Internal factors include senior management perspectives, sustainable supplier incentives, and customer requirements.

Some of the most important barriers in the supply chain include financial costs, return on investment rates, product pricing, senior management commitment, organizational culture of supplier companies, production capacity, human resources, supply chain structure, geographical location, and the size of supplier companies, among others.

The adoption of sustainable supply chain management is crucial for organizational competitiveness in terms of price, quality, reliability, flexibility, and accountability. The benefits of sustainable supply chain management include customer satisfaction, quality, innovation, trust, supply speed, optimized inventory, flexibility, lead time, and cost control. When using sustainable supply chain management incentives, the above factors should be considered. Examples include ISO 14001 standards, green transportation, green manufacturing, recycling, remanufacturing, green product and process design, carbon footprint reduction, and product life cycle assessment.

Today, incorporating sustainability in supply chain network design has become a significant issue for organizations, governments, and the public, particularly environmental advocates, due to the impacts of global population growth on the environment and, consequently, the increase in human activities.

In the home appliances industry, the circular supply chain is recognized as an important approach to improve product sustainability and reduce negative environmental impacts. In this model, products are returned to the supply chain for recycling after reaching the end of their useful life. For example, old parts or components from end-of-life vehicles can be collected and sent to recyclers or recycling plants to extract useful materials. These materials can then be reused as raw materials for producing new parts or appliances.

Circular supply chain modeling is an analytical method that helps improve the supply chain and move it toward sustainability and efficiency. In this study, to implement a circular supply chain, the model is designed across three levels: supplier, manufacturer, and distributor, ensuring sustainability. Variables such as costs, $CO_2$ emissions, capacities, produced and returned products, and employment opportunities are considered across the entire flow, and the model is designed using neutrosophic parameters.

As shown in Figure 1, in the forward flow, components required for products are first sent from suppliers to manufacturers, then finished products are sent to distribution centers, and from there delivered to customers. In the reverse flow, returned products from customers are collected through collection centers, inspected and tested, and sent to recycling centers. If the products are recyclable, they are processed and sent back to suppliers, manufacturers, and distributors according to recycling conditions. Products that cannot be recycled are categorized as waste. In other words, repairable products are sent to manufacturing centers to be converted into resalable goods, recyclable products are sent to recycling centers and then to suppliers as raw materials, and non-recyclable returned products are sent to waste disposal sites.

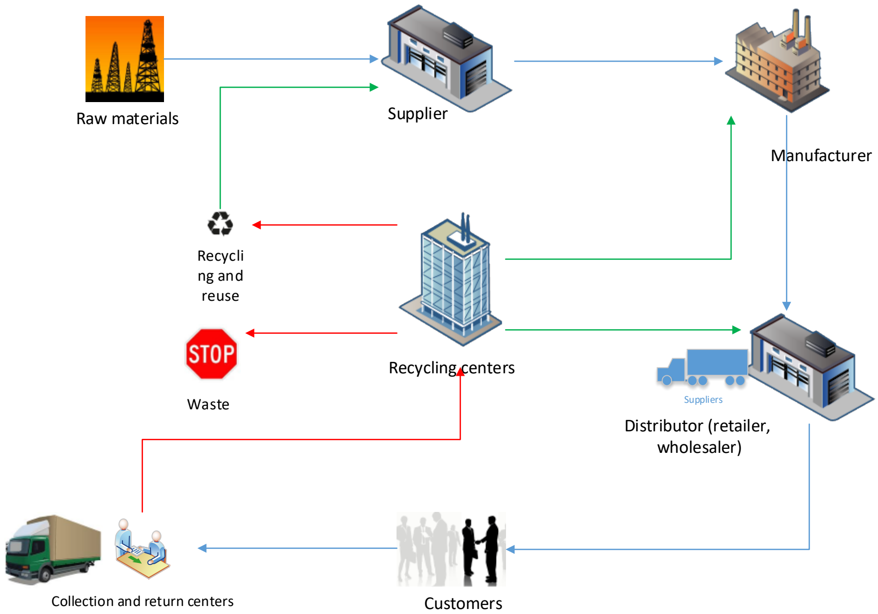


Figure 1. Conceptual model of a circular supply chain network

**Literature Review**

Research on circular supply chains and their modeling using neutrosophic approaches is particularly important given various global challenges and advancements in modern technologies. The circular supply chain, as a complex and dynamic network of organizations, processes, and resources, is continuously exposed to various risks that can disrupt operations, increase costs, and reduce organizational efficiency and effectiveness. In this context, the use of mathematical models and modern methods to improve the management of circular supply chains, especially during crises and fluctuations, has attracted the attention of researchers. This literature review summarizes key studies in this field.

Farokhzad et al. (2019) proposed a new multi-product, multi-period, multi-echelon nonlinear integer programming model for a green closed-loop supply chain under uncertainty. They solved small-scale problems using GAMS software and applied the NSGA-II algorithm for large-scale problems due to the NP-hard nature of the problem.

One notable study by Sajadian et al. (2023), titled "Circular Supply Chain: Network Structure Analysis and Scientometric Review in Scopus," presented a bibliometric analysis of scientific outputs on the topic using open-source software such as Bibliometrix and VOSviewer. They clustered collaboration and co-occurrence networks to create a comprehensive framework for systematically analyzing research on circular supply chain management. The study analyzed co-occurring keywords, author, country, and institution collaborations, as well as co-citation patterns from Scopus data. They concluded that existing studies are limited to developed and developing economies such as the UK, Italy, China, and Iran. The study aimed to draw researchers' attention to using the concept of circular supply chain management in the context of a circular economy and supply chain sustainability through bibliometric mapping and social network analysis.

Karbasi et al. (2022) presented a technology roadmap model for Industry 4.0 in the power equipment and energy supply sector. Through literature review, interviews, and structural equation modeling, they identified four indices across 40 components in four dimensions: drivers, market, product, technology, R&D, resources, and infrastructure. Structural equation results demonstrated strong model fit and significant impacts of these components on Industry 4.0 technology roadmap development.

Abdelbaset et al. (2020) evaluated uncertainty in project time and cost exchanges using a neutrosophic approach, designing a framework to address scheduling problems with neutrosophic activity durations. They considered critical time and cost aspects under uncertain project conditions, aiming to minimize project costs using trapezoidal neutrosophic numbers for activity durations.

Apchi et al. (2022) examined the principles and factors affecting visibility in sustainable supply chains. Visibility represents the extent to which stakeholders have access to or share key operational information and is considered critical for achieving sustainability objectives. High visibility helps minimize risks associated with waste and environmental footprint while improving social, ethical, and operational performance. The study highlighted that visibility depends heavily on information quality, automation, green absorptive capacity, and information sharing among supply chain stakeholders.

Fernam et al. (2021) introduced a shortest-path optimization problem in networks using neutrosophic data. Trapezoidal neutrosophic numbers, as a generalization of fuzzy theory with truth, falsity, and indeterminacy membership functions, effectively handle uncertainties in assigning numerical values to network arcs. They proposed a Dijkstra-based approach for finding the shortest path in a neutrosophic network and demonstrated its performance with a numerical example.

Vafadar Nikjoo (2023) developed a robust optimization model to address supply chain risks and mitigation strategies, incorporating circular activities within a sustainable supply chain framework. A multi-objective mathematical model was formulated to maximize social and environmental scores of suppliers and minimize delivery delays alongside economic objectives. The Epsilon-constraint method and LP-metric were used for objective balancing, and numerical examples with sensitivity analysis validated model performance.

Zanat Mohammad et al. (2023) applied a neutrosophic multi-criteria decision-making method for sustainable supplier selection. Key sustainability performance criteria—including environmental performance, social responsibility, and economic capability—were incorporated. The TOPSIS method with single-valued neutrosophic sets was used to handle uncertain information, and a case study of a food company demonstrated supplier ranking.

Recently, the use of modern technologies, especially AI and machine learning, has increased in supply chain risk management. Zhao et al. (2023) studied the impact of supply chain digitalization on flexibility and performance, presenting a multi-agent model. The COVID-19 pandemic accelerated the need for resilient supply chains, and digitalization has emerged as a powerful tool for this purpose. The study highlighted the roles of three types of supply chain flexibility—absorptive (pre-disruption), responsive (during disruption), and recovery (post-disruption)—in affecting supply chain performance.

Finally, the recoverable value of products has made circular supply chain design increasingly important. Circular supply chains aim to retain products, components, and materials at their highest environmental and technical utility throughout their lifecycle. Achieving zero waste and addressing carbon emission concerns become more critical under raw material shortages and demand uncertainty, which are key supply chain challenges. Hence, this study is novel and innovative, contributing to the literature and addressing gaps in sustainable circular supply chain research.

**Research Methodology**

Although the implementation of circular supply chains has recently gained significant importance, questions remain regarding the methods used to examine implementation, key considerations, and how circular economy strategies are applied in supply chains within companies. Choosing essential criteria for managing sustainable circular supply chains is crucial. Therefore, a comprehensive approach based on neutrosophic decision-making logic is proposed. Since neutrosophic logic can address incompleteness, ambiguity, and uncertainty, this study models the supply chain using neutrosophic parameters.

Based on the conceptual model of a circular supply chain, a mathematical model is formulated. The model considers three levels: suppliers, manufacturers, and distributors (including wholesalers and retailers), and the relationships between these levels are defined. The model ensures sustainability by optimizing economic, environmental, and social aspects across all levels.

**Problem Modeling**

The problem assumptions are first stated, followed by the formulation of the model. The current model is a mixed-integer mathematical programming model, considering three levels—suppliers, manufacturers, and distributors (wholesalers and retailers) and optimizing economic, social, and environmental objectives.

**Assumptions of the Model**

- The model is multi-level, including suppliers, manufacturers, wholesalers, retailers, collection centers, recycling centers, and customers.
- The locations of all facilities, except for collection and recycling centers, are fixed and predetermined. Due to the uncertainty regarding the establishment of collection and recycling centers, a maximum of 10 centers is considered.
- Collection costs are considered for collection centers, while processing costs are assigned to manufacturing and recycling centers.
- Capacities of the facilities are fixed, and associated costs are considered constant. For manufacturing, collection, and recycling centers, holding and inventory costs are included.
- Inventories of wholesalers and retailers are maintained in the factory warehouse.
- Wholesalers receive products in bulk and fully packaged; thus, product defects can only be detected after opening by the retailer or final customer. Only the retailer and end customer can observe product quality and defects.
- No flows exist between facilities within the same level.
- Shortages are not allowed, and no discount policies are applied in the design.
- In each period, returned products are defined as a specific percentage of the previous period's production.
- $CO_2$ emissions are considered throughout the supply chain, including the operation of collection and recycling centers, as well as production, transportation, and recycling processes.

Table 2. Definitions of the indices of the proposed model

| Definition | Andis |
|---|---|
| Supplier Collection i={1,2,3,…,I} | i |
| Production Center Complex j={1,2,3,…,I} | j |
| Wholesale centers collection k={1,2,3,…,K} | k |
| Shopping mall complex m={1,2,3,…,M} | m |
| Set of potential collection centers q={1,2,3,…,Q} | q |
| Collection of potential recycling centers s={1,2,3,…,S} | s |
| Collection of time periods t={1,2,3,…,T} | t |
| c={1,2,3,…,C} Customer Collectio | c |

Table 3. Definition of the parameters of the proposed model

| parameter | Definition |
|---|---|
| $\widetilde{Cf_q}$ | Uncertain cost of building collection centers at potential location q |
| $\widetilde{Cf_s}$ | Uncertain cost of building collection centers at potential location s |
| $\widetilde{CPB}$ | Uncertain cost of selling recyclable raw material |
| $\widetilde{E_q}$ | Uncertain amount of CO2 emissions from opening collection center q |
| $\widetilde{E_s}$ | Uncertain amount of CO2 emissions from opening recycling center s |
| $\widetilde{EP_J}$ | Uncertain amount of CO2 emissions from producing each unit of product at manufacturing center j |
| $\widetilde{EB_s}$ | Uncertain amount of CO2 emissions from recycling each unit of raw material at recycling center s |
| $\widetilde{ER_{\iota J}}$ | Uncertain amount of CO2 emissions from transporting each unit of raw material from supplier i to manufacturing center j |
| $\widetilde{EP_{Jk}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from manufacturing center j to wholesale center k |
| $\widetilde{EP_{Jm}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from manufacturing center j to retail center m |
| $\widetilde{EP_{kc}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from wholesale center k to customer c |
| $\widetilde{EP_{mc}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from retail center m to customer c |
| $\widetilde{EP_{Jq}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from production center j to collection center q |

| | |
|---|---|
| $\widetilde{EP_{cJ}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from customer to production centers j |
| $\widetilde{EP_{mJ}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from retailer center m to production centers j |
| $\widetilde{EP_{cq}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from customer c to collection center q |
| $\widetilde{EP_{mq}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from retailer center m to collection center q |
| $\widetilde{EP_{qs}}$ | Uncertain amount of CO2 emissions from transporting each unit of product from collection center q to recycling center s |
| $\widetilde{EB_S}$ | Uncertain amount of CO2 emissions from transporting each unit of recycled material from recycling center s to the secondary market |
| $\widetilde{Job_q}$ | Uncertain number of job opportunities resulting from the construction of collection centers q |
| $\widetilde{Job_s}$ | Uncertain number of job opportunities resulting from the construction of recycling centers s |
| $FL_q$ | Lost days due to damage during the construction of collection centers q |
| $FL_s$ | Lost days due to damage during the construction of centers Recycling s |
| $W_c$ | Weighting factor of job opportunities created |
| $W_w$ | Weighting factor of lost worker opportunities |
| $CAPB_i$ | Supplier i capacity for raw material |
| $CAPP_j$ | Production center j capacity for product production |
| $CAPP_q$ | Collection center q capacity for returned product |
| $CAPP_s$ | Recycling center s capacity for returned product |
| $\widetilde{\alpha_{ct}}$ | Uncertain customer c demand for product in period t |
| $I\widetilde{N}V_J$ | Production center j storage capacity for raw material |
| $I\widetilde{\acute{N}}V_J$ | Production center j storage capacity for product |
| $\widetilde{I\acute{N}V_q}$ | Collection center q storage capacity for returned product |
| $\widetilde{I\acute{N}V_s}$ | Recycling center s storage capacity for recycled material |
| $I\widetilde{NVB}_s$ | Amount of raw material used in product production |
| $\lambda$ | Uncertain product return rate from customer c |
| $\widetilde{REP_c}$ | Uncertain product return rate from retailer m |
| $\widetilde{REP_m}$ | Conversion rate of returned product to saleable material at recycling centers |
| $\delta$ | Maximum number of collection centers q allowed to be built |
| $MAX^q$ | Maximum number of recycling centers s allowed to be built |

| | |
|---|---|
| $MAX^s$ | Uncertain cost of transporting each unit of raw material r from supplier i to manufacturer j in period t |
| $\widetilde{CTR}_{ijt}$ | The uncertain cost of transporting each unit of product from manufacturer j to wholesaler k in period t |
| $\widetilde{CTP}_{jkt}$ | The uncertain cost of transporting each unit of product from manufacturer j to retailer m in period t |
| $\widetilde{CTP}_{jmt}$ | The uncertain cost of transporting each unit of returned product from retailer m to manufacturing facility j in period t |
| $\widetilde{CTP}_{mjt}$ | The uncertain cost of transporting each unit of returned product from end customer c to manufacturing facility j in period t |
| $\widetilde{CTP}_{cjt}$ | The uncertain cost of transporting each unit of returned product from manufacturing facility j to potential collection facility q in period t |
| $\widetilde{CTP}_{jqt}$ | The uncertain cost of transporting each unit of returned product from retailer m to potential collection facility in period t |
| $\widetilde{CTP}_{mqt}$ | The uncertain cost of transporting each unit of returned product from end customer c to potential collection facility q in period t |
| $\widetilde{CTP}_{cqt}$ | The uncertain cost of transporting each unit of returned product from potential collection facility q to potential recycling facility s in period t |
| $\widetilde{CTP}_{qst}$ | The uncertain cost of transporting each unit of returned product from recycled material b to recycling facility s to secondary market s in period t |
| $\widetilde{CTPB}_{st}$ | Uncertain cost of purchasing a unit of raw material r from supplier i in period t |
| $\widetilde{CVR}_{it}$ | Uncertain cost of purchasing a unit of raw material r from manufacturer j in period t |
| $\widetilde{CVR}_{jt}$ | Uncertain cost of collecting the returned product at collection center q in period t |
| $\widetilde{CVP}_{qt}$ | Uncertain cost of processing the returned product at recycling center s in period t |
| $\widetilde{VCP}_{st}$ | Uncertain cost of holding each unit of raw material at manufacturing center j in period t |
| $\widetilde{CHR}_{jt}$ | Uncertain cost of holding each unit of product inventory at manufacturing center j in period t |
| $\widetilde{CHP}_{jt}$ | Uncertain cost of holding each unit of returned product inventory at collection center q in period t |
| $\widetilde{CHP}_{qt}$ | Uncertain cost of holding each unit of returned product inventory at recycling center s in period t |
| $\widetilde{CHP}_{st}$ | Uncertain cost of selling the recycled raw material |
| $\widetilde{CHB}_{st}$ | Uncertain cost of building collection centers at potential location q |
| $\widetilde{CPB}$ | Uncertain cost of building collection centers at potential location s |

Table 4. Definitions of variables of the proposed model

| Variable | Definition |
| --- | --- |
| $Y^s$ | Variable zero and one if recycling center s is built at potential location 1 otherwise zero |
| $Y^q$ | Variable zero and one if collection center q is built at potential location 1 otherwise zero |
| $\widetilde{XR_{ijt}}$ | Uncertain amount of raw material shipped from supplier i to production center j in period t |
| $\widetilde{XP_{jkt}}$ | Uncertain amount of product shipped from production center j to wholesale center k in period t |
| $\widetilde{XP_{jmt}}$ | Uncertain amount of product shipped from production center j to retailer center m in period t |
| $\widetilde{XP_{kct}}$ | Uncertain amount of product shipped from wholesale center k to customer c in period t |
| $\widetilde{XP_{mct}}$ | Uncertain amount of product shipped from retailer center m to customer c in period t |
| $\widetilde{XR_{mjt}}$ | Uncertain amount of returned product shipped from retailer m to production centers j in period t |
| $\widetilde{XP_{cjt}}$ | Uncertain amount of returned product shipped from customer c to production centers j in period t |
| $\widetilde{XP_{jqt}}$ | Uncertain amount of returned product shipped from production centers j to collection center q in period t |
| $\widetilde{XP_{mqt}}$ | Uncertain amount of returned product shipped from retailer m to collection center q in period t |
| $\widetilde{XP_{cqt}}$ | Uncertain amount of Definite amount of returned product shipped from customer c to collection center q in period t |
| $\widetilde{XP_{qst}}$ | Uncertain amount of returned product shipped from collection center q to recycling center s in period t |
| $\widetilde{XP_{jt}}$ | Uncertain amount of product produced at manufacturing center j in period t |
| $\widetilde{XP_{st}}$ | Uncertain amount of product processed at recycling center s in period t |
| $\widetilde{XB_{st}}$ | Uncertain amount of recycled material available for sale at recycling center s in period t |
| $\widetilde{X\acute{B}_{st}}$ | Uncertain amount of recycled material sent to the secondary market from recycling center s in period t |
| $\widetilde{IP_{jt}}$ | Uncertain amount of manufactured product inventory at manufacturer j at the end of period t |
| $\widetilde{IP_{qt}}$ | Uncertain amount of returned product inventory at collection center q at the end of period t |
| $\widetilde{IP_{st}}$ | Uncertain amount of returned product inventory at recycling center s at the end of period t |
| $\widetilde{IB_{st}}$ | Uncertain amount of recycled material inventory at recycling center s at the end of period t |

| | |
|---|---|
| $\widetilde{IR_{jt}}$ | Uncertain amount of returned product inventory at manufacturer j at the end of period t |

**Mathematical model**

$$FC=\sum_{q\in Q}\widetilde{Cf_q Y^q}+\sum_{q\in Q}\widetilde{Cf_s Y^s} \quad (1)$$

$$CV=\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}CV\widetilde{R_{it}X}R_{ijt}+\sum_{j\in J}\sum_{t\in T}CV\widetilde{R_{jt}X}P_{jt}+\sum_{q\in Q}\sum_{t\in T}\widetilde{CVP_{qt}}(\sum_{j\in J}\widetilde{XP_{jqt}}+\sum_{m\in M}\widetilde{XP_{mqt}}+\sum_{c\in C}\widetilde{XP_{cqt}})+\sum_{s\in S}\sum_{t\in T}V\widetilde{CP_{st}X}P_{st}+\sum_{s\in S}\sum_{t\in T}CPB\widetilde{X\acute{B}_{st}} \quad (2)$$

$$CT=\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}CT\widetilde{R_{ijt}X}R_{ijt}+\sum_{j\in J}\sum_{k\in K}\sum_{t\in T}CT\widetilde{P_{jkt}X}P_{jkt}+\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}CT\widetilde{P_{jmt}X}P_{jmt}+\sum_{k\in K}\sum_{c\in C}\sum_{t\in T}CT\widetilde{P_{kct}X}P_{kct}+\sum_{m\in M}\sum_{c\in C}\sum_{t\in T}CT\widetilde{P_{mst}X}P_{mct}+\sum_{m\in M}\sum_{j\in J}\sum_{t\in T}CT\widetilde{P_{mjt}X}P_{mjt}+\sum_{c\in C}\sum_{j\in J}\sum_{t\in T}CT\widetilde{P_{cjt}X}P_{cjt}+\sum_{j\in J}\sum_{q\in Q}\sum_{t\in T}CT\widetilde{P_{jqt}X}P_{jqt}+\sum_{m\in M}\sum_{q\in Q}\sum_{t\in T}CT\widetilde{P_{mqt}X}P_{mqt}+\sum_{c\in C}\sum_{q\in Q}\sum_{t\in T}CT\widetilde{P_{cqt}X}P_{cqt}+\sum_{q\in Q}\sum_{s\in S}\sum_{t\in T}CT\widetilde{P_{qst}X}P_{qst}+\sum_{s\in S}\sum_{t\in T}CT\widetilde{P\acute{B}_{st}}XB_{st} \quad (3)$$

$$CH=\sum_{j\in J}\sum_{t\in T}CH\widetilde{R_{jt}I}P_{st}+\sum_{j\in J}\sum_{t\in T}C\widetilde{HP_{jt}I}P_{jt}+\sum_{q\in Q}\sum_{t\in T}C\widetilde{HP_{qt}I^P_{qt}}+\sum_{s\in S}\sum_{t\in T}C\widetilde{HP_{St}I}P_{St}+\sum_{s\in S}\sum_{t\in T}C\widetilde{HB_{st}}IB_{st} \quad (4)$$

Objective functions • •

$$Minz1=CF+CV+CT+CH \quad (5)$$

$$Minz2=\sum_{q\in Q}\widetilde{E_q}\,Y^q+\sum_{s\in S}\widetilde{E_s}\,Y^s+\sum_{j\in J}\sum_{t\in T}E\widetilde{P_J X}P_{jt}+\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\widetilde{ER_{ij}}\widetilde{XR_{ijt}}+\sum_{j\in J}\sum_{k\in K}\sum_{t\in T}\widetilde{EP_{Jk}}\widetilde{XP_{jkt}}+\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\widetilde{EP_{Jm}}\,\widetilde{XP_{jmt}}+\sum_{k\in K}\sum_{c\in C}\sum_{t\in T}EP_{kc}\widetilde{XP}_{kct}+\sum_{m\in M}\sum_{c\in C}\sum_{t\in T}EP_{mc}\widetilde{XP_{mct}}+\sum_{j\in J}\sum_{q\in Q}\sum_{t\in T}\widetilde{EP_{Jq}}\,\widetilde{XP_{jqt}}+\sum_{c\in C}\sum_{j\in J}\sum_{t\in T}EP_{cJ}\widetilde{XP_{cjt}}+\sum_{m\in M}\sum_{j\in J}\sum_{t\in T}EP_{mJ}\widetilde{XP_{mjt}}+\sum_{p\in P}\sum_{c\in C}\sum_{q\in Q}\sum_{t\in T}\widetilde{EP_{qJ}}\widetilde{XP_{cqt}}+\sum_{q\in Q}\sum_{s\in S}\sum_{t\in T}\widetilde{EP_{qs}}\widetilde{XP_{qst}}+\sum_{s\in S}\sum_{t\in T}\widetilde{EB_S}\widetilde{X\acute{B}_{st}} \quad (6)$$

$$Maxz3=W_c\left(\sum_{q\in Q}\widetilde{Job_q}\,Y^q+\sum_{s\in S}\widetilde{Job_s}\,Y^s\right)-W_w\left(\sum_{q\in Q}FL_q\,Y^q+\sum_{s\in S}FL_s\,Y^s\right) \quad (7)$$

• Limitations:

St:

$$\lambda\widetilde{XP_{jt}}\le\sum_{i\in I}\widetilde{XR_{ijt}} \qquad \forall\, j\in J,(t>1)\in T \quad (8)$$

$$\sum_{k\in K}\widetilde{XP_{kct}}+\sum_{m\in M}\widetilde{XP_{kmt}}\ge\widetilde{\alpha_{ct}} \qquad \forall\, j\in J,t\in T \quad (9)$$

$$\sum_{k\in K}\widetilde{XP_{jkt}}+\sum_{m\in M}\widetilde{XP_{jmt}}\le\widetilde{XP_{jt}} \qquad \forall\, t\in T \qquad (10)$$

$$\sum_{k\in K}\widetilde{XP_{jkt}}+\sum_{m\in M}\widetilde{XP_{jmt}}\le\widetilde{IP_{j(t-1)}} \qquad \forall\, j\in J\,,(t>1)\in T \qquad (11)$$

$$\sum_{c\in C}\widetilde{XP_{kct}}\le\sum_{j\in J}\widetilde{XP_{jkt}} \qquad \forall k\in K\,,\ t\in T \qquad (12)$$

$$\sum_{c\in C}\widetilde{XP_{mct}}\le\sum_{j\in J}\widetilde{XP_{jmt}}-\sum_{q\in Q}\widetilde{XP_{mqt}}-\sum_{j\in J}\widetilde{XP_{mjt}} \qquad \forall m\in M\ ,t\in T \qquad (13)$$

$$\sum_{j\in J}\widetilde{XP_{cjt}}+\widetilde{XP_{cqt}}=\widetilde{REP_{c}}\left(\sum_{k\in K}\widetilde{XP_{kct}}+\sum_{m\in M}\widetilde{XP_{mct}}\right) \qquad \forall c\in C\,,\ t\in T \qquad (14)$$

$$\sum_{j\in J}\widetilde{XP_{mjt}}+\sum_{q\in Q}\widetilde{XP_{mqt}}=\widetilde{REP_{m}}\sum_{m\in M}\widetilde{XP_{jmt}} \qquad \forall m\in M\,,t\in T \qquad (15)$$

$$\sum_{q\in Q}\sum_{t\in T}\widetilde{XP_{jqt}}=\sum_{t\in T}(\sum_{c\in C}\widetilde{XP_{cjt}}+\sum_{m\in M}\widetilde{XP_{mjt}}) \qquad \forall\ j\in J \qquad (16)$$

$$\sum_{s\in S}\sum_{t\in T}\widetilde{XP_{qst}}=\sum_{t\in T}(\sum_{c\in C}\widetilde{XP_{cqt}}+\sum_{j\in J}\widetilde{XP_{jqt}}+\sum_{m\in M}\widetilde{XP_{mqt}}) \qquad \forall\, q\in Q \qquad (17)$$

$$\sum_{t\in T}\widetilde{XP_{jt}}=\sum_{k\in K}\sum_{t\in T}\widetilde{XP_{jkt}}+\sum_{m\in M}\sum_{t\in T}\widetilde{XP_{jmt}} \qquad \forall\, j\in J \qquad (18)$$

$$\sum_{j\in J}\widetilde{XR_{ijt}}\le CAPB_{i} \qquad \forall\, i\in I,t\in T \qquad (19)$$

$$\widetilde{XR_{ijt}}\le CAPP_{j} \qquad \forall\, j\in J,t\in T \qquad (20)$$

$$\widetilde{IR_{jt}}=\sum_{i\in I}\widetilde{XR_{ijt}}-\widetilde{XP_{jt}} \qquad \forall\, j\in J,t\in T \qquad (21)$$

$$\widetilde{IR_{jt}}=\widetilde{IR_{jt-1}}+\sum_{i\in I}\widetilde{XR_{ijt}}-\widetilde{XP_{jt}}\,\lambda \qquad \forall\, j\in J,t>1\in T \qquad (22)$$

$$\widetilde{IR_{jt}}=\widetilde{IR_{jt-1}}+\widetilde{XP_{jt}}+\sum_{m\in M}\widetilde{XR_{mjt}}-\sum_{c\in C}\widetilde{XP_{cjt}}-\sum_{k\in K}\widetilde{XP_{jkt}}-\sum_{m\in M}\widetilde{XP_{jmt}} \qquad \forall\, j\in J,t>\in T \qquad (23)$$

$$\widetilde{IR_{Jt}} \leq \widetilde{INV_J} \quad \forall\, j \in J, t \in T \quad (24)$$

$$\widetilde{IP_{Jt}} \leq \widetilde{I\acute{N}V_J} \quad \forall\, j \in J, t \in T \quad (25)$$

$$\sum_{q\in Q} \widetilde{XP_{Jqt}} + \sum_{m\in M} \widetilde{XP_{mqt}} + \sum_{c\in C} \widetilde{XP_{cqt}} \leq CAPP_q Y^q \quad \forall\, q \in Q, t \in T \quad (26)$$

$$\sum_{q\in Q} \widetilde{XP_{qst}} \leq CAPP_s Y^s \quad \forall s \in S, t \in T \quad (27)$$

$$\widetilde{XB_{st}} = \widetilde{XP_{st}}\delta \quad \forall s \in S, t \in T \quad (28)$$

$$\sum_{q\in Q} Y^q \leq MAX^q \quad (29)$$

$$\sum_{s\in S} Y^s \leq MAX^s \quad (30)$$

$$\widetilde{XP_{st}} = \sum_{q\in Q} \widetilde{XP_{qst}} \quad \forall\, s \in S, t \in T \quad (31)$$

$$\widetilde{IP_{qt}} = \sum_{c\in C} \widetilde{XP_{cqt}} + \sum_{j\in J} \widetilde{XP_{Jqt}} + \sum_{m\in M} \widetilde{XP_{mqt}} - \sum_{s\in S} \widetilde{XP_{qst}} \quad \forall\, q \in Q, t \in T \quad (32)$$

$$\widetilde{IP_{qt}} = \widetilde{IP_{qt-1}} + \sum_{c\in C} \widetilde{XP_{cqt}} + \sum_{j\in J} \widetilde{XP_{Jqt}} + \sum_{m\in M} \widetilde{XP_{mqt}} \; \sum_{s\in S} \widetilde{XP_{qst}} \quad \forall q \in Q, t > 1 \in T \quad (33)$$

$$\widetilde{IP_{st}} = \widetilde{IP_{st-1}} + \sum_{s\in S} \widetilde{XP_{qst}} + \sum_{b\in B} \widetilde{X_{st}^{b}}\, \delta_b^p \quad \forall\, s \in S, t > 1 \in T \quad (34)$$

$$\widetilde{IP_{st}} = \sum_{q\in Q} \widetilde{XP_{qst}} + \widetilde{XB_{st}}\delta \quad \forall\, s \in S, t > 1 \in T \quad (35)$$

$$\widetilde{IB_{st}} = \widetilde{IB_{st-1}} + \widetilde{XB_{st}} - \widetilde{X\acute{B}_{st}} \quad \forall\, s \in S, t > 1 \in T \quad (36)$$

$$\widetilde{IB_{st}} = \widetilde{XB_{st}} - \widetilde{X\acute{B}_{st}} \quad \forall\, s \in S, t = 1 \in T \quad (37)$$

$$\widetilde{XB_{st}} \le \widetilde{X\acute{B}_{st}} \qquad \forall\, s \in S, t \in T \tag{38}$$

$$\widetilde{IP_{st}} \le INV_p^q \qquad \forall\, q \in Q, t \in T \tag{39}$$

$$\widetilde{IP_{st}} \le \widetilde{I\acute{N}V_s} \qquad \forall s \in S, t \in T \tag{40}$$

$$\widetilde{IB_{st}} \le \widetilde{INVB_s} \qquad \forall\, s \in S, t \in T \tag{41}$$

$$\widetilde{XR_{ijt}}, \widetilde{XP_{jkt}}, \widetilde{XP_{jmt}}, \widetilde{XP_{kct}}, \widetilde{XP_{mct}}, \widetilde{XR_{mjt}}, \widetilde{XP_{mct}}, \widetilde{XR_{mjt}}, \widetilde{XP_{cjt}}, \widetilde{XP_{jqt}}, \widetilde{XP_{mqt}}, \widetilde{XP_{cqt}}, \widetilde{XP_{qst}}, \widetilde{XP_{jt}}, \widetilde{XP_{st}}, \widetilde{XB_{st}}, \widetilde{X\acute{B}_{st}} \tag{42}$$

$$\widetilde{IR_{jt}}, \widetilde{IP_{jt}}, \widetilde{IP_{qt}}, \widetilde{IP_{st}}, \widetilde{IB_{st}} \ge 0$$

$$Y^q, Y^s \in \{0,1\} \tag{43}$$

Constraint (8) indicates that the raw materials used in the product produced in each period at the production center are less than or equal to the total raw materials available at the production center. Constraint (9) indicates that the output flow of the product quantity sent from the retail and wholesale centers to the customer is at least equal to the customer demand. Constraint (10) indicates that the quantity of product sent from the production center to the wholesaler and retailer in the first period is less than or equal to the quantity of product produced at the production center. Constraint (11) indicates that the quantity of product sent from the production centers to the wholesaler and retailer in subsequent periods is less than or equal to the inventory of the production center at the beginning of the current period. Constraint (12) indicates that the quantity of product sent from the wholesaler to the customer is less than or equal to the quantity of product sent to the wholesaler. Constraint (13) indicates that the quantity of product sent from the retailer to the customer of the collection center and manufacturer is less than or equal to the quantity sent to the retailer. Constraint (14) indicates that the product returned from the customer to the production centers and the collection center is equal to a certain percentage of the amount of goods shipped to the customer. Constraint (15) indicates that the flow of product returned from the retailer to the production centers and the collection center is equal to a certain percentage of the amount of goods shipped to the retailer. Constraint (16) indicates the flow of product returned from the production centers to the collection center, which is equal to the total product returned to the factory. Constraint (17) indicates that the total amount of input to the collection center is equal to its output. Constraint

(18) indicates that the total amount of production in each factory is sent to the retail and wholesale centers. Constraint (19) indicates the capacity of the supplier. Constraint (20) indicates the capacity of each production center. Constraints (21) and (22) indicate the inventory of raw materials in the production centers. Constraint (23) indicates the inventory of the product in the production center. Constraints (24) and (25) indicate the storage capacity for raw materials and products at the production center. Constraints (26) and (27) indicate the storage capacity for collection and recycling centers. Constraint (28) indicates the amount of recyclable materials that can be sold. Constraints (29) and (30) indicate the maximum number of collection and recycling centers that can be built. Constraint (31) indicates the amount of goods processed at the recycling center. Constraints (32) and (33) indicate the product inventory at the collection centers. Constraints (34) and (35) indicate the product inventory at the recycling centers. Constraints (36) and (37) indicate the inventory of recyclable materials that can be sold at the recycling centers. Constraint (38) indicates the maximum amount of sales of recyclable materials that can be sold. Constraints (39), (40), and (41) indicate the capacity of the product in the collection and recycling centers and the recyclable material that can be sold in the recycling centers. Constraints (42), and (43) indicate the type of variables.

**Model Solution**

• Solving the Multi-Objective Model Using Neutrosophics

Multi-objective decision models are the most common mathematical models that can include several conflicting objectives. The Neutrosophic programming method includes 3 membership sets: truth (degree of belonging), indeterminacy (partial degree of belonging), and falsehood (non-belonging), so each objective function has 3 membership functions. A multi-objective model is considered in which D represents the fuzzy decision set, G represents the fuzzy function set, and C represents the fuzzy constraints. The fuzzy neutrosophic decision set represents the fuzzy function set, and the fuzzy neutrosophic constraints, which are expressed as follows:

$$D_n = (\prod_{o=1}^{o} G_n)(\prod_{n=1}^{n} L_n) = (P_d(w), Q_d(w), R_d(w) \tag{44}$$

$$P_d(w) = \begin{cases} min\ PG_d(w)\ , \forall o \in O \\ st \\ VL_d(w)\ , \forall n \in N \end{cases} \tag{45}$$

$$Q_d(w) = \begin{cases} max\ QG_d(w)\ , \forall o \in O \\ st \\ QL_d(w)\ , \forall n \in N \end{cases}$$

$$R_d(w) = \begin{cases} max\ RG_d(w)\ , \forall o \in O \\ st \\ RL_d(w)\ , \forall n \in N \end{cases}$$

P_d (w) is the truth membership function, Q_d (w) is the indeterminacy membership function, and R_d (w) is the lie membership function. For simplicity, a neutrosophic number is represented as a trapezoid with parameters a≤b≤c≤d, e≤f≤g≤h, l≤m≤n≤p in the set of real numbers R as n={(a,b,c,d),(e,f,g,h),(l,m,n,p)}. Each of the above functions is as follows:

$$D_n = (\prod_{o=1}^{o} G_n)(\prod_{n=1}^{n} L_n) = (P_d(w), Q_d(w), R_d(w)) \tag{46}$$

St:

$$P_d(z_{n=1,2,3}(X)) = \begin{cases} \frac{x-a}{b-a} & if\ a \le x \le b; \\ 1 & if\ \ b \le x \le c; \\ \frac{d-x}{d-c} & if\ \ c \le x \le d; \\ 0 & otherwise\ , \end{cases} \tag{47}$$

$$Q_d(z_{n=1,2,3}(X)) = \begin{cases} \frac{f-a}{f-e} & if\ e \le x \le f; \\ 0 & if\ \ f \le x \le g; \\ \frac{x-g}{h-g} & if\ \ g \le x \le h; \\ 1 & otherwise\ , \end{cases}$$

$$R_d(z_{n=1,2,3}(X)) = \begin{cases} \frac{m-x}{m-l} & if\ m \le x \le l; \\ . & if\ \ l \le x \le n; \\ \frac{x-n}{p-n} & if\ \ n \le x \le p; \\ 1 & otherwise\ , \end{cases}$$

The final model of solving the model using the neutrosophic method, taking into account all the relationships stated above, is as follows:

$$Max \sum_{o=1}(\mu_o + \vartheta_o - \delta_o) \tag{48}$$

S.t.

$P_o(Z_o(x)) \ge \mu_o\ ,\ \ \forall o$

$Q_o(Z_o(x)) \ge \vartheta_o\ ,\ \ \forall o$

$R_o(Z_o(x)) \ge \delta_o\ ,\ \ \forall o$

$\mu_o \ge \vartheta_o\ ,\ \ \forall o$

$\mu_o \ge \delta_o\ ,\ \ \forall o$

$0 \le \delta_o + \mu_o + \vartheta_o\ \ ,\ \forall o$

$\delta_o, \mu_o, \vartheta_o \in (0,1)$

**Solution Using Genetic Algorithm**

In this study, after formulating the mathematical model, the problem is solved using a genetic algorithm (GA). Since the proposed mathematical model is a mixed-integer linear programming model and, moreover, is NP-hard, the genetic algorithm is considered one of the most suitable and effective solution methods for this type of problem.

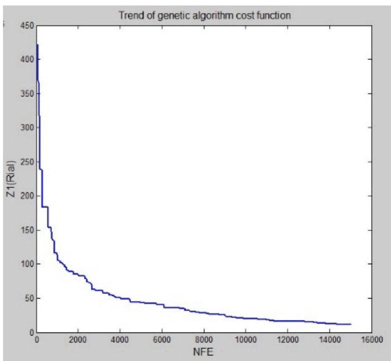
**Findings and Results**

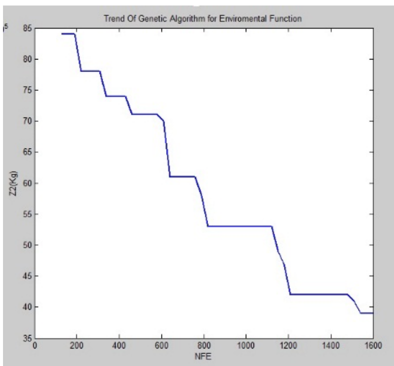
Table 5 presents the values and interval ranges of the deterministic and uncertain parameters of the proposed model. To solve the model, an uncertainty level of ( \alpha = 0.7 ) is assumed. It should be noted that throughout all stages of the model, the collection and recycling centers were considered based on available data from the electrical appliances (refrigerators and freezers) manufacturing industry in Iran.

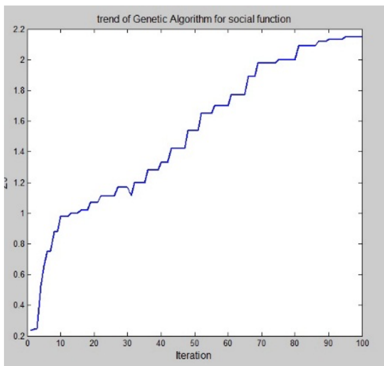
For further analysis of the objective functions under uncertain conditions and sensitivity analysis, the objective function rates are examined across the entire defined range. The proposed model is solved using the Genetic Algorithm in MATLAB, with the following settings: 200 generations (iterations), an initial population of 100, a crossover rate of 0.2, and a mutation rate of 0.1.

Table 5. Software output from solving the model

| | Generation repetition | Population size | Intersection value | Amount of mutation | $Z_1$ (Rial) | $Z_2$ (Kg) | $Z_3$ |
|---|---|---|---|---|---|---|---|
| 1 | 200 | 100 | 0.2 | 0.1 | 426.9782E+05 | 84.96E+05 | 0.2356 |
| 2 | 200 | 100 | 0.2 | 0.1 | 360.9438E+05 | 78.49E+05 | 0.66 |
| 3 | 200 | 100 | 0.2 | 0.1 | 167.1523E+05 | 69.72E+05 | 0.984 |
| 4 | 200 | 100 | 0.2 | 0.1 | 167.1523E+05 | 65.40E+05 | 1 |
| 5 | 200 | 100 | 0.2 | 0.1 | 103.0084E+05 | 61.19E+05 | 1.28 |
| 6 | 200 | 100 | 0.2 | 0.1 | 74.1809E+05 | 57.81E+05 | 1.98 |
| 7 | 200 | 100 | 0.2 | 0.1 | 31.8931E+05 | 53.31E+05 | 2.09 |
| 8 | 200 | 100 | 0.2 | 0.1 | 16.0963E+05 | 46.68E+05 | 2.121 |
| 9 | 200 | 100 | 0.2 | 0.1 | 11.9036E+05 | 42.50E+05 | 2.133 |
| 10 | 200 | 100 | 0.2 | 0.1 | 11.8056E+05 | 38.52E+05 | 2.148 |



($z_1$) First objective function Second objective function ($z_2$) ($z_3$) Third objective function

Figure 1. Software output diagrams of objective functions

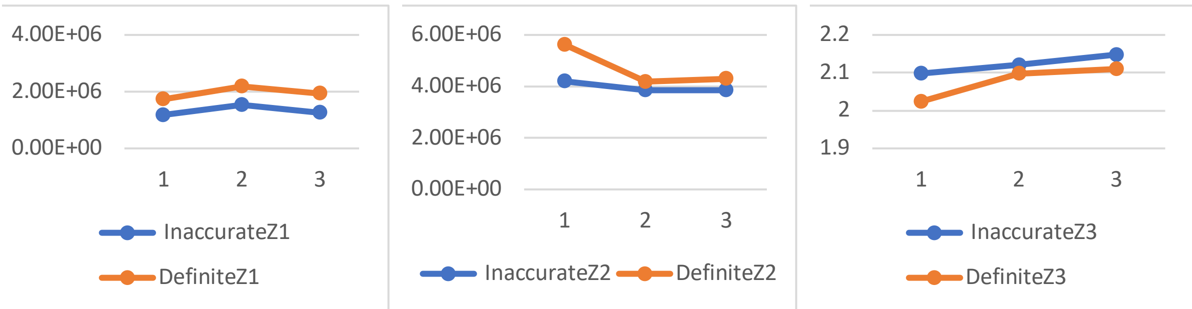
The results indicate that the first objective function reached its optimal solution after 1,500 iterations over 100 generations. The second objective function (Z2) achieved its optimal solution after 1,600 iterations over 100 generations. The third objective function (Z3) reached its optimal and maximum value after 100 iterations.

**Model Evaluation**

To verify the validity of the model, it was solved under deterministic conditions, and the optimal solutions of the objective functions were obtained, which are presented in Table 6 for comparison under deterministic and uncertain conditions. The first objective function corresponds to minimizing the total cost of the closed-loop supply chain, the second objective function corresponds to minimizing CO2 emissions, and the third objective function corresponds to maximizing social responsibility.

Table 6. Objective function values of the proposed model in imprecise and definite conditions

| | | $Z_1$ (Rial) | $Z_2$ (Kg) | $Z_3$ |
|---|---|---|---|---|
| Inaccurate | $Z_1$ (Rial) | 11.8056E+05 | 41.98E+05 | 2.98 |
| | $Z_2$ (Kg) | 15.3451E+05 | 38.52E+05 | 2.121 |
| | $Z_3$ | 12.6357E+05 | 38.52E+05 | 2.148 |
| Definite | $Z_1$ (Rial) | 17.3250E+05 | 56.23E+05 | 2.024 |
| | $Z_2$ (Kg) | 21.8451E+05 | 41.87E+05 | 2.098 |
| | $Z_3$ | 19.4101E+05 | 42.98E+05 | 2.11 |




(a) (b) (c)

Figure 8. Comparison graphs of functions in two imprecise and definite cases: (a) Graph of the first objective function (z1), (b) Graph of the second objective function (z2), and (c) Graph of the third objective function (z3).

**Pareto Analysis of the Model**

Pareto analysis is an important technique in optimization and decision-making that examines the trade-offs between different objectives in a model. This analysis is typically applied in multi-objective optimization problems, especially when there are conflicts or the need to balance among various objectives.

A Pareto-efficient solution refers to a solution that is not worse than any other solution in any of the objective functions and performs better in at least one objective function compared to other solutions. The collection of all such Pareto-efficient solutions constitutes the Pareto front of the problem.

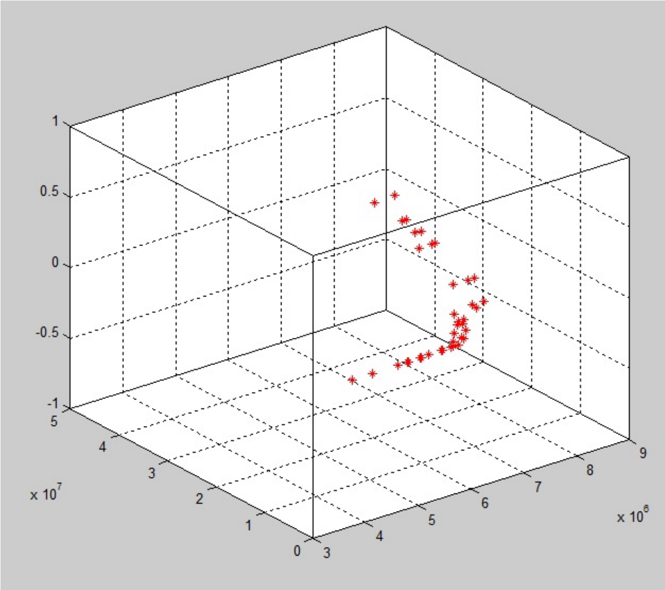



Figure 9. Pareto Evaluation of the Objective Functions of the Proposed Model (Uncertain Conditions)

The points shown in Figure 9 each represent a solution, with the corresponding objective function values indicated at each point. A solution is considered acceptable if it minimizes the cost function while ensuring that the other objectives maintain their conditions. Similarly, the environmental impact function should be kept at a minimum, while the social objective function reaches its maximum value, provided that the other two functions are minimized and optimized. Each marked point in the figure represents an optimal solution that satisfies the model's conditions.

**Conclusion**

The results indicate that the proposed model provides feasible solutions under uncertain conditions, maintaining the sustainability of the closed-loop supply chain. The model is also valid under deterministic conditions, confirming its reliability. Subsequently, the Pareto analysis of the model was conducted and illustrated in the figure. An acceptable point is one that minimizes the cost function while preserving the conditions of the other objectives, keeps the environmental impact function at a minimum, and maximizes the social objective function, ensuring that the other two functions remain minimized and optimized.

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