Multi-Objective Sustainable Closed-Loop Supply Chain Network Design Considering Multiple Products with Different Quality Levels

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Abstract: International laws and increasing consumer awareness have led to drastic changes in traditional supply chain network designs. Moreover, because of environmental and social requirements, traditional supply chain networks have changed to sustainable supply chain networks. On the other hand, reverse logistics can be effective in terms of environmental and economic aspects, so the design of the supply chain network as a closed loop is necessary. In addition, customers have a demand for different products with different quality levels. Considering different types of customers with a variety of consumption trends can be a challenging issue, and is addressed in this study. The main contributions of this research are considering different quality levels for products as well as different tendencies of customers towards environmental issues. In this study, a sustainable closed-loop supply chain model is designed that seeks to balance economic, environmental, and social responsibilities. In this paper, costs and customer demands for different types of products at different quality levels are considered under uncertain conditions using a robust possibilistic programming method. The proposed multi-objective model is solved using the Augmented Epsilon Constraint (AEC) method that provides an efficient set of solutions for all decision-making levels. The results show that the robust possibilistic programming method is more effective in dealing with uncertainties than the possibilistic programming method.

Keywords: reverse logistics; supply chain network design; robust possibilistic programming; uncertainty; customer consumption trend; Augmented Epsilon Constraint (AEC)

1. Introduction

Forward supply chain management is defined as the management of product flow from suppliers to manufacturers, distributors, retailers, and ultimately end customers [1–3]. The forward supply chain does not deal with recycling products; however, recycling products have attracted the attention of researchers and scholars in recent years, which has led to the emerging reverse supply chain networks. The growth of technologies for recycling products and global environmental concerns have resulted in paying more attention to recyclable items and returning them to the production cycle [4]. As a result, closed-loop supply chains have attracted the attention of researchers and scholars in recent years. If forward supply chain networks are combined with reverse supply chain...
networks, a closed-loop supply chain network (CLSC) is created, which is a more complex network than traditional (forward) logistics [5]. The forward and reverse supply chains are interdependent at some levels and affect each other’s performance, which has led researchers to design a supply chain network that simultaneously considers both forward and reverse routes. Both developing and developed countries have taken closed-loop supply chain networks into account [6]. Companies face challenges in reducing their supply chain costs while increasing sustainability and customer service levels [7]. It is essential for organizations to take competitive advantages by focusing on reducing costs or increasing profits [8]. Many supply chain companies face challenges in minimizing network costs when increasing the level of sustainability and customer service [9]. Reusing defective products can reduce the use of raw materials, energy, etc., and can play an important role in the profitability of manufacturing industries by reducing costs [10]. The value of these products collected by reverse logistics can be over hundreds of millions of dollars for a logistics company [11]. Organizations try to balance the reduction of costs and detrimental environmental impacts to improve sustainable competitiveness [12]. The traditional supply chain operations have been changed due to the worldwide global warming issue. The industry sector accounted for about 54% of the total energy consumption and 21% of carbon emissions [13].

Environmental concerns have led to "green" practices throughout the product life cycle. Designing products and processes and forward and reverse distribution networks based on green principles are very important decision-making issues related to sustainability [14]. In 2009, it was argued that sustainable development is not limited to economic benefits but also includes social development [15]. Sustainable supply chain management is defined in terms of information and flow management and supply chain coordination, taking into account the sustainability aspects. Sustainable supply chains enable companies to respond to growing customer needs in the most appropriate manner. In the past, less attention has been paid to social responsibility, however, all aspects of sustainability should be considered in supply chain network design [15].

In addition, it is necessary to consider the uncertainty of the parameters in the closed-loop supply chain network [12,16,17]. Not paying attention to uncertainty in supply chain network design can cause a huge loss in the manufacturing industry. It is clear that considering uncertainty is very effective in how decisions are made at the strategic, tactical, and operational levels [6]. In general, uncertainty can be considered in both environmental and systemic categories [18].

The whole supply chain is a kind of pull system created by consumer demand, whose success is achieved by meeting consumer expectations [19]. For optimal utilization of natural resources, consumer behavior is one of the vital factors that must be considered by decision makers of supply chain entities. In other words, a product must be introduced to the market with a variety of quality levels corresponding with customer demand. Consumer purchase attitudes toward products of different quality levels are important to the management of entire supply chain networks [20]. Considering customer demand for products at different quality levels allows managers within the manufacturing industry to gain significant insight into the supply chain [21]. There are some studies to understand consumer behavior towards products with diverse quality levels. These studies show that the impact of environmental issues on consumer purchase attitudes in the U.S. is not significant [20]. The results of a study in Turkey showed that 13% of the statistical population often use high quality and environmentally friendly products and more than half of consumers use the same product with lower quality due to the high product cost [19]. In other words, the attitude of consumers towards the consumption of environmentally friendly products has not kept pace with the concerns towards environmental issues. As a result, if all three sustainability aspects are considered in a supply chain network, but the variety of customer demand for products is not considered, that supply chain will not be efficient.
Due to the fact that customers have different purchase attitudes, customers are generally divided into two categories: green customers (consume products in compliance with environmental standards) and non-green customers (consume products with lower cost, such as recycled products with a lower quality level).

The main purpose of this study is to provide a mathematical programming model for the design of a sustainable closed-loop supply chain network, taking into account the uncertainty of the parameters and different customer demands for a variety of products with several quality levels. On the other hand, due to the useless of traditional supply chain networks that consider only economic goals, in this study, environmental and social responsibility goals are considered in addition to economic goals, and the trade-off between these goals and objectives is addressed.

In general, the aim of this research can be described as follows:

- Designing a robust multi-objective mathematical programming model for a sustainable closed-loop supply chain that can integrate the design of forward and reverse networks (horizontal integration) and optimize strategic and tactical decisions simultaneously (vertical integration). It should be mentioned that the strategic decisions are mainly related to the structure of the supply chain in the upcoming years; how the supply chain is configured, how resources are allocated, and what processes take place at each level of the supply chain. Strategic decisions in this study are to determine the location of facilities such as factories, distribution centers, and collection centers (long-term decisions). The tactical decisions deal with satisfying demands, binding contracts, inventory management and control policies, and so on. In the planning phase, organizations need to consider demand uncertainty within the planning time horizon. Therefore, in this research, it is determined how many products should be sent to each warehouse and which warehouses should satisfy the demand of which market segment under uncertainty conditions.
- Considering several products with various quality levels (green/non-green) for different types of customers with different consumption trends.
- Taking the uncertainty of supply chain parameters such as cost and demand into account. Nowadays, costs are swiftly increasing, leading to changes in customer demands. This fact must be considered in decision-making so that more reliable and accurate decisions can be made.

2. Literature Review

Supply chain networks are recognized as one of the major economic activities of any country (regardless of whether it is developed or developing). The significance of these networks lies in the production and timely delivery of various products (services) such as medicine, fuel, food, etc., which has indeed brought an incentive for researchers and experts in different industries to perform analysis studies on them [22]. The growing importance of environmental goals and constraints in today’s world has led decision-makers to pay attention to this issue and has convinced them to consider environmental factors in the decision-making process at forward and reverse supply chain levels [14]. Environmental and business factors seem to enhance the interest in investing in reverse supply chains [23]. Many companies have focused on reconstruction and recovery activities in recent decades and achieved remarkable successes in this area [24]. However, the consensus on focusing on the sustainability of supply chain networks has come true in recent years [25]. Different goals concerning economic, environmental, and social dimensions are usually considered in a sustainable supply chain. A lot of researchers have addressed this issue in recent years.

According to the literature in the field of sustainable supply chain management, all studies have considered economic problems and issues as either minimizing costs or maximizing profits. However, the attitude seems different when it comes to environmental issues. The Life Cycle Assessment (LCA) is known as the best method to evaluate environmental issues [26]. Govindan et al. have studied the design of a sustainable reverse logistic network by regarding economic, environmental, and social aspects in their research [27].
In their article, the LCA thinking and the eco-indicator 99 methods have been used to model environmental problems. However, this process appears highly difficult and time-consuming due to the complexity, lack of data, and the need for environmental experts; however, it has been widely used in developed countries [28–30]. Researchers have introduced some strategies to assess environmental problems in the form of four general criteria: greenhouse gases, recycling, waste generation, and energy use. In addition, social responsibility includes the five main groups of working conditions, commitment to society, customers-related issues, human rights (child and forced labor, freedom of assemblies, discrimination) and business practices (fight against corruption, fair trade, promotion of corporate social responsibility in the sphere of influence) [29]. Moradi Nasab and Amin-Naseri presented a mathematical programming model for the oil supply chain [31]. This model is multi-period, multi-level, and considers different transportation methods. The goal of the mathematical model has been designed to maximize profits [31]. In the model presented by Dando and Mendez [32], planning for direct and reverse logistics networks has been provided in a multi-stage supply chain. A distribution and regeneration problem are presented in the mentioned model, regarding green logistic considerations [32]. Versei and Polyakovskiy designed a sustainable supply chain network for the Australian beverage industry. They considered environmental issues as calculating greenhouse gas emissions and regarded two groups of social responsibility, namely working conditions and community development, to evaluate the social dimension [33]. Yu and Solvang [34] studied the inverse logistic network, considering the flexible capacities. The aspect of social responsibility has been neglected in this study [34]. Soleimani et al. focused on the problem of designing a closed-loop supply chain network. This chain was modeled by taking into account environmental factors, increasing the profit of the whole chain, and enhancing the response to customer needs [35]. Roni et al. proposed a multi-objective, hub-and-spoke model for designing and managing a sustainable environmental fuel supply chain by considering the emission of pollutants and social issues to create jobs [36]. Mousavi and Bozorgi provided a multi-objective model, which reduces the cost of material shipping and maximizes the purchase likelihood in all customers’ areas. Their other goal was to minimize CO\textsubscript{2} emissions from the transportation sector by establishing hubs on the paths of suppliers and customers [37]. Uncertainty has affected the purchase, processing, markets, and other levels of the closed-loop supply chain and significantly enhanced the complexity of rebuilding and reduced the efficiency of the process. Uncertainty has also hindered the sustainable development of industries [38]. Supply chain planning at the strategic level as well as the dynamic nature of industries generally lead to environmental and systemic uncertainties; thus, strategic planning appears to be a difficult task and can be associated with a high rate of potential error [6]. Uncertainty in manufacturing systems in the real world is categorized into two classes: environmental and systemic uncertainties. Environmental uncertainty includes uncertainty in the amounts of demand and supply, originating from the behavior of consumers and suppliers. Systemic uncertainty also addresses issues such as uncertainty in manufacturing products, distribution, collection, and recycling. For example, uncertainties found in the capacity of facilities, production costs, and inventory control fall into this category. Vahdani et al. provided a multi-layered, multi-period model to seamlessly model the forward and reverse supply chain under uncertainty. The uncertainty in the parameters is considered to be fuzzy in this model [39]. Sahebjamnia et al. proposed a model to evaluate the design of a sustainable supply chain network under uncertainty conditions. In their research, a multi-objective model is provided designed to optimize the costs, environmental effects, and social impacts, which has been solved using metaheuristic algorithms [4]. Zhen et al. provided a two-objective model for planning a sustainable forward and reverse supply chain network under uncertainty conditions aimed at minimizing the costs and greenhouse gas emissions. They used a scenario-based method in the study to deal with uncertainty [12]. Dehghan et al. considered uncertainty conditions as a combination of possibility, probability, and stability [40]. A multi-period, multi-product model has been developed in this research. The uncertainty in the parameters has been
examined in two scenario-based and fuzzy types. A case study has also been provided in this study for testing the model [40]. Fathollahi-Fard et al. suggested an integrated Water Supply and Wastewater Collection System (WSWCS) under stochastic uncertainty [41]. Khorshidvand et al. proposed a new hybrid method where SCC decisions and CLSCND goals are involved simultaneously. This decision-making approach is first implemented on price, greenness, and advertising and is then focused on maximizing profits and minimizing CO₂ emissions under demand uncertainty conditions [42]. Tehrani and Gupta proposed a sustainable closed-loop supply chain network for the tire industry under environmental uncertainty conditions by considering several recovery options, including energy, recycling, and recovery. The study was set to design and develop a multi-objective, multi-product, multi-layered, and multi-capacity supply chain network under fuzzy random programming uncertainty [16]. Sazvar et al. presented a scenario-based multi-objective mixed integer linear programming model to design a sustainable CLPSC, which evaluates the reverse flow of expired drugs as three classes (should be discarded, can be reproduced, and can be recycled) [43]. Gholizadeh et al. presented an environmentally friendly multi-objective model for a supply chain. The objectives of this study were to minimize costs, maximize vehicle productivity, and minimize information fraud in the process of sharing information in supply chain elements [44]. A summary of the related studies is presented in Table 1.

### Table 1. A brief of relevant studies.

| Research          | Network Structure | Sustainability Aspects | Multi-Product | Types of Customers | Solution Methods          |
|-------------------|-------------------|------------------------|---------------|--------------------|---------------------------|
|                   | Forward | Reverse | Closed-Loop | Economic | Environmental | Social | Main | Variety of Quality | Recycled |                        |
| [22]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | Heuristic/LR            |
| [24]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | CPLEX                   |
| [25]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | HCC&CF                  |
| [27]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | MOPSO/EC                |
| [28]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | Lexicograph             |
| [30]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | AEC                      |
| [31]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | Heuristic               |
| [41]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | Hybrid method            |
| [42]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | LR                       |
| [43]              | *       | *       | *           | *        | *                | *      | *    | *                    | *        | Heuristic               |
| Our research      | *       | *       | *           | *        | *                | *      | *    | *                    | *        | Lexicograph/AEC         |

### 3. Problem Statement and the Mathematical Programming Model

This study aims to propose a multi-objective mathematical programming model for the sustainable closed-loop supply chain network considering the reduction of costs and environmental impacts as well as the increase of social benefits under uncertainty conditions. The Total Cost (TC) criterion is used to calculate all financial costs in the supply chain design for the cost issue, while the Total Emission (TE) of pollution is considered as a measure of environmental performance. Moreover, the number of jobs created is taken into account for social issues due to the locating of facilities. Therefore, these three criteria are considered a multi-objective mathematical programming model. The model allows the organization to design the best supply chain network through identifying facilities (factories, warehouses, disassembly centers (DC)) required by the network and the unit flow of products between different parts and choosing the most appropriate transportation mode for the shipment of the product unit along the supply chain. The best scenario for
When a product has reached the end of its life cycle, it is either sent to disposal centers or duly disposed of. There are three types of products (a new product, a product that is supposed to be discarded, and a product that should be disassembled) that flow through the closed-loop network in the proposed mathematical model. The “End of Life (EOL)” is a term used for products that are either to be disposed of or to be disassembled. It is assumed that products have all the specifications of an “End of Life (EOL)” product just like electronic products. The “End of Life (EOL)” is a term used for products offered to customers, indicating that the product is at the end of its useful life (from the seller’s perspective), and a would seller stop its marketing or selling and deliver it. When a product has reached the end of its life cycle, it is either sent to disposal centers or dismantled and enters the cycle. In the research problem, there are several transportation options (road, rail, etc.) by considering communications. Since certain amounts of product units are distributed through these communication channels and different behaviors are implemented for product units in each entity, the product form is not always identical. There are three types of products (a new product, a product that is supposed to be discarded, and a product that should be disassembled) that flow through the closed-loop network in the proposed mathematical model.

The details of the product movement based on the product form are as follows:

- New goods, whether brand new or remanufactured, are transported to the forward path of the network (factory to warehouse and warehouse to customer) to meet the customer’s demand.
- The products to be disposed of are collected from the customers and sent to the DCs for the disassembly process. In the disassembly centers, if the product is reconstructed, then it will enter the production cycle, and if it is non-recyclable, it is sent to disposal centers.
- The disassembled product is delivered from the DCs to the factory for the reproduction process.

The proposed model is non-deterministic and multi-objective, in which the uncertain parameters such as costs and customers’ demands are considered as trapezoidal fuzzy numbers. In addition, a robust possibilistic programming method is used to deal with uncertainty. The proposed mathematical model of the sustainable closed-loop supply chain problem has five entities: factories, warehouses, customers, disassembly centers (DC), and disposal centers (Figure 1).

**Figure 1.** A schematic view of a closed-loop supply chain network.

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- The disassembled product is delivered from the DCs to the factory for the reproduction process.
Factories have two production processes. One is the assembly of products sent from DCs and another is the supply of raw materials from suppliers and manufacturing of new products.

The assumptions of the mathematical model are as follows:

- The demands of all customers are defined as fuzzy numbers.
- All products that are produced in a factory and stored in the warehouse are always free of defects.
- All customer demands are supplied by factories or through warehouses.
- All disposed of products that are entered into DCs will be recovered with a specified probability of $\theta$ and disposed of with a probability of $1-\theta$.
- The fixed and variable costs of constructing supply chain institutions are pre-determined and fuzzy in nature.
- The model is examined in the multi-product mode with green and non-green quality levels.
- The customers are divided into two categories of green customers and non-green customers according to their attitude towards product consumption (green/non-green) and their demands for green and non-green products are analyzed under uncertainty conditions (green products are products made of environmentally friendly material).
- Products can be produced in both green and non-green modes according to the customers’ demands.

The model consists of two parts. In the first part, the objective functions are specified, followed by stating the constraints in the second part. The proposed mathematical model includes three objective functions as follows: minimizing the total cost (TC), minimizing CO$_2$ emissions along the supply chain, and maximizing economic benefits (Social Indicator (SI)). The proposed mathematical model is presented as follows:

**Sets**

| Symbol | Description |
|--------|-------------|
| $P$    | Products index |
| $Q$    | Products quality level index (green/non-green) |
| $F$    | Potential factories index |
| $W$    | Potential warehouses index |
| $C$    | Customers’ index |
| $I$    | Index of potential DCs |
| $N$    | Potential centers index |
| $TF$   | Transportation options for factories |
| $TW$   | Transportation options for warehouses |
| $TK$   | Transportation options for customers |
| $TN$   | Transportation options for disposal centers |

**Parameters**

| Symbol | Description |
|--------|-------------|
| $\tilde{d}_{pc}$ | The demand for product $p$ with quality level $q$ for customer $c$ |
| $\tilde{c}_{tf}$ | The transfer cost per unit from factory $f$ to warehouse $w$ with transportation mode $tf$ |
| $\tilde{h}_{tw}$ | The transfer cost per unit from warehouse $w$ with transportation mode $tw$ to customer $c$ |
| $\tilde{r}_{tk}$ | The transfer cost per unit from customer $c$ with transportation mode $tk$ to collection/disassembly site $i$ |
| $\tilde{d}_{if}$ | The transfer cost per unit from disassembly center $i$ with transportation mode $ti$ to the factory site $f$ |
| $\tilde{h}_{tn}$ | The transfer cost per unit from disassembly center $i$ with transportation mode $tn$ to landfill $n$ |
| $\tilde{r}_{fw}$ | The transportation rate from factory $f$ to warehouse $w$ with transportation mode $tf$ |
τ
\[ \text{tw} \]
\[ \text{wc} \]
The transportation rate from warehouse w with transportation mode \( \text{tw} \) to customer c

\[ \tau_{\text{tk}}^{\text{ci}} \]
The transportation rate from disassembly center i with transportation mode \( \text{tk} \) to collection/disassembly site f

\[ \tau_{\text{ti}}^{\text{fn}} \]
The transportation rate from disassembly center i with transportation mode \( \text{ti} \) to landfill n

\[ \tilde{v}_{\text{pq}}^{\text{f}} \]
The variable cost per producing a unit of product p with quality level q in factory f

\[ \tilde{v}_{\text{bw}} \]
The variable cost per maintaining a unit of product in the warehouse w

\[ \tilde{v}_{\text{ca}} \]
The variable cost per collecting a unit of product from customer c for the recovery operation

\[ \tilde{v}_{\text{dd}}^{\text{pq}} \]
The variable cost per disassembling a unit of product p with quality level q at the DC site i

\[ \tilde{v}_{\text{er}}^{\text{pq}} \]
The variable cost per reproduction of a unit of product p with quality level q assembled at factory f

\[ h_{\text{al}}^{\text{pq}} \]
The maximum production capacity of product p with quality level q in factory f

\[ h_{\text{rl}}^{\text{pq}} \]
The minimum percentage of product p with quality level q that is collected for recycling from the customer.

\[ \theta \]
A percentage of products that are shipped intactly from the ith DC to the factory.

\[ ma_{/w} \]
The distance from factory f to warehouse w

\[ mb_{/w} \]
The distance from warehouse w to customer c

\[ mc_{/c} \]
The distance from customer c to collection/DC site i

\[ md_{/f} \]
The distance of DC i from factory site f

\[ mn_{/n} \]
The transportation rate from DC i to landfill n

Environmental Parameters

\[ ea_{\text{pq}}^{\text{f}} \]
The CO\(_2\) emission rate per manufacturing of a unit product p with quality level q in factory f

\[ ea_{\text{pq}}^{\text{f}} \]
The CO\(_2\) emission rate per production of a unit product p with quality level q in factory f

\[ eb_{\text{pq}}^{\text{w}} \]
The CO\(_2\) emission rate per processing of a unit product p with quality level q in warehouse w

\[ ed_{\text{pq}}^{\text{i}} \]
The emission rate of CO\(_2\) per recovery of a unit product p with quality level q in DC i

\[ er_{\text{pq}}^{\text{f}} \]
The CO\(_2\) emission rate per reproduction of a unit product p with quality level q in factory f

\[ et\alpha_{tf} \]
The emission rate of CO\(_2\) with transportation mode tf to transfer a unit product p from factory to warehouse in unit of length

\[ et\beta_{tw} \]
The CO\(_2\) emission rate corresponding with transportation mode tw to transfer a unit product p from the warehouse to the customer in unit of length

\[ et\kappa_{tk} \]
The emission rate of CO\(_2\) with transportation mode tk to collect a unit product from customer to DC in unit of length

\[ etd_{ti}^{\text{fn}} \]
The CO\(_2\) emission rate corresponding with transportation mode ti to collect a unit product from DC to factory in unit of length

\[ f_{\text{a}} \]
The fixed cost of constructing factory f

\[ f_{\text{b}}^{\text{w}} \]
The fixed cost of constructing the warehouse w

\[ f_{\text{d}}^{\text{i}} \]
The fixed cost of constructing DC site i

\[ h_{\text{b}} \]
The maximum processing capacity in the warehouse

\[ h_{\text{d}} \]
The maximum capacity for recovery operation in DC i

\[ \hat{h}_{\text{n}} \]
The maximum capacity to dispose of products in n

Decision variables

\[ xa_{f} \]
is equal to one if factory f is open and otherwise equal to zero

\[ xb_{w} \]
is equal to one if warehouse w is open, otherwise equal to zero

\[ xd_{i} \]
is equal to one if DC i is open, otherwise equal to zero
Continuous variables (the amount of product transferred by modes of transportation)

| Matrix            | Description                                                                 |
|-------------------|-----------------------------------------------------------------------------|
| $Y_{df,tf}$       | The number of $p$-type products with quality level $q$ that are transferred from factory $f$ to warehouse $w$ with transportation option $tf$ |
| $Y_{dw,tf}$       | The number of $p$-type products with quality level $q$ that are transferred from the warehouse $w$ and the customer $c$ with transportation option $tw$ |
| $Y_{c,f,tk}$      | The number of $p$-type products with quality level $q$ that are sent from customer $c$ to the DC site $i$ with transportation option $tk$ for recycling |
| $Y_{w,n,tn}$      | The number of products $p$ with quality level $q$ that are passed transferred from the DC $i$ to the disposal site $n$ with transportation option $tn$ for disposal |
| $X_{pf,ti}$       | The amount of product that is sent from DC $i$ to factory $f$ with transportation option $ti$ |
| $X_{pf}$          | The amount of product $p$ with the new quality level $q$ that should be produced in factory $f$ |

Objective Functions

**Economic Objective Function**

The total cost includes total fixed costs (TFC), total variable costs (TVC), and total transportation costs (TTC). Transportation services were assumed to be provided by an external logistics provider with a pre-defined unit transportation cost for each mode. Thus, according to the definitions of research parameters and variables, the following formulas are given for the total cost objective function:

\[
\text{Min } Z_1 = TC = TFC + TVC + TTC
\]

\[
\text{TFC} = \sum f faw \times Xa_f + \sum wfbw \times Xbw + \sum dfi \times Xdi
\]

\[
\text{TVC} = \sum q \sum p \sum Y_{pf} \sum w \sum tf \sum Y_{df,tf}
\]

\[
+ \sum w \sum Y_{bw} \times \sum \sum \sum \sum \sum Y_{w,tw} \times \sum \sum \sum \sum \sum Y_{c,tk}
\]

\[
\text{TTC} = \sum f \sum w \sum tf \sum p \sum q \sum tf \sum \sum \sum \sum \sum Y_{df,tf}
\]

\[
+ \sum f \sum c \sum tw \sum p \sum q \sum tw \times \sum Y_{w,tf} \times \sum \sum \sum \sum \sum Y_{c,tk}
\]

**Environmental Objective Function**

The objective function of TE, i.e., the CO$_2$ total emission was obtained by summing the phrases of the CO$_2$ total emission due to production (EP), the CO$_2$ total emission due to storage in the warehouse (EH), the CO$_2$ total emission due to product disassembly (ED), the CO$_2$ total emission due to product reproduction (ER), and the CO$_2$ total emission due to transfer (ET). A transportation rate described in the previous sections was used to calculate the emission in each transportation model.

\[
\text{Min } Z_2 = TE = EP + EH + ED + ER + ET
\]

\[
\text{EP} = \sum q \sum p \sum ea_{pqf} \times \sum w \sum Tf \sum Y_{df,tf}
\]
### Social Responsibility Objective Function

Two employment-related indicators of decent work and labor practices were used in this research to evaluate social impacts based on the Global Reporting Initiative (GRI). In fact, economic incentives need to be considered for projects that contribute to creating jobs and regional development. Moreover, the employment-related criteria have to be regarded when deciding on the location of a factory. Hence, an indicator that is known as the Social Benefit Indicator (SB) and related to job creation in less developed areas, was used in this research. This index can be calculated using the following formula:

$$\text{Max } Z_3 = SB = SBP + SBH + SBD$$

In the above formula, employment has been assessed in three areas of employment in factories (SBP), employment in warehouses (SBH), and employment in disassembly centers (SBDs).

- **SBP**
  $$SBP = \sum_f W_f \times X_{af}$$

- **SBH**
  $$SBH = \sum_w W_w \times X_{bw}$$

- **SBD**
  $$SBD = \sum_i W_i \times X_{di}$$

Where $W_{f,wo,j}$ in the above formulas is the number of jobs that are created for the construction of a factory, warehouse, or disassembly center.

The constraints:

The total number of products that are shipped from the factory to each warehouse via transportation options should be lower than or equal to the maximum capacity of the examined factory:

$$\sum_w \sum_{tf} \sum_p \sum_q Y_{af,tf}^{pq} \leq \sum_q \sum_p h_{af}^{pq} \times X_{af} \quad \forall f$$

The total number of products that are delivered to the warehouse from any factory with any shipping option should be lower than or equal to the maximum warehouse capacity:

$$\sum_f \sum_{tf} \sum_p \sum_q Y_{fw,tf}^{pq} \leq h_{bw}^{pq} \times X_{bw} \quad \forall w$$
The total number of products that are transferred from the warehouse to each customer with each shipping option should be lower than or equal to the total number of products that are delivered from each factory to the relevant warehouse with any shipping option:

$$\sum_c \sum_{tw} \sum_p \sum_q Y_{tw,cw}^{pq} \leq \sum_f \sum_{t_f} \sum_p \sum_q Y_{t_fw,fw}^{pq} \quad \forall w$$  \hspace{1cm} (17)

The total number of products distributed from each warehouse to a specific customer with any shipping option should be greater than or equal to the relevant customer demand:

$$\sum_w \sum_{tw} Y_{tw,cw}^{pq} \geq d_{tw}^{pq} \quad \forall c, p, q$$  \hspace{1cm} (18)

The total number of products sent for recycling from a customer to a DC with any shipping option should be lower than or equal to the relevant customer demand:

$$\sum_i \sum_{tk} Y_{tk,ci}^{pq} \leq d_{tk}^{pq} \quad \forall c, p, q$$  \hspace{1cm} (19)

The total number of products collected in a DC through customers with any means of transportation for disassembly should be lower than or equal to the maximum capacity of the relevant DC:

$$\sum_p \sum_q \sum_c \sum_{tk} Y_{tk,ci}^{pq} \leq hd_{tk} \times X_{ti} \quad \forall i$$  \hspace{1cm} (20)

The total number of products sent by a customer for disassembly to any DC by any means of transportation should be greater than or equal to the minimum return percentage of the total demand of the relevant customer:

$$\sum_i \sum_{tk} Y_{tk,ci}^{pq} \geq qd \times d_{tk}^{pq} \quad \forall c, p, q$$  \hspace{1cm} (21)

The number of products that are sent from a factory to any warehouse by any means of transportation should be equal to the factory production amount plus the amount of products that enter the relevant factory from any DC with any transportation means:

$$\sum_i \sum_{ti} \sum_p \sum_q Y_{ti,fi}^{pq} + \sum_p \sum_q X_{ti}^{pq} = \sum_w \sum_{t_f} \sum_p \sum_q Y_{t_f,wi,tw}^{pq} \quad \forall f$$  \hspace{1cm} (22)

The products that are delivered to the DC are recycled at the $\theta$ rate and sent to the manufacturing plants and transferred to the disposal centers at the $1-\theta$ rate.

$$\theta \times \sum_p \sum_q \sum_c \sum_{tk} Y_{tk,ci}^{pq} = \sum_f \sum_{ti} \sum_p \sum_q Y_{ti,fi}^{pq} \quad \forall i$$  \hspace{1cm} (23)

$$1 - \theta \times \sum_p \sum_q \sum_c \sum_{tk} Y_{tk,ci}^{pq} = \sum_n \sum_{tn} \sum_p \sum_q Y_{tn,fin}^{pq} \quad \forall i$$  \hspace{1cm} (24)

The total number of products entering the nth disposal center from each DC should be lower than or equal to the capacity of the relevant disposal center:

$$\sum_i \sum_{tn} \sum_p \sum_q Y_{tn,fin}^{pq} \leq hn_n \quad \forall n$$  \hspace{1cm} (25)

The total number of dismantled products shipped from each DC to a factory with any transportation mode for reproduction must be less than or equal to the maximum reproduction capacity of the factory:

$$\sum_i \sum_{ti} \sum_p \sum_q Y_{ti,fi}^{pq} \leq \sum_p \sum_q hr_f^{pq} \times X_{tf} \quad \forall f$$  \hspace{1cm} (26)
The next constraints are related to the limits of the problem decision variables:

\[ Y_{di,f_{ij}}, Y_{ni,f_{ij}}, Y_{ci,k}, Y_{fi,w}, Y_{bi,w} \geq 0 \]

\[ X_{af}, X_{di}, X_{bi} \in \{0 \text{ or } 1\} \]  

(27)

3.1. Robust Possibilistic Programming Model

Sustainability is considered the most basic concept among supply chain managers to develop a sustainable system based on economic, environmental, and social criteria to improve the overall performance of organizations [45]. Each operation in supply chain management (SCM) requires decision-making [46]. When the evaluation process is performed by human judgment, uncertainty of information is inevitable. Fuzzy set theory is one of the most efficient tools for dealing with uncertainty [47]. Due to the existing uncertainty and the lack of sufficient information regarding the parameters of the proposed model in the previous section, it seems a highly difficult and, in some cases, impossible task to determine the exact value of the parameters. The model provided in the previous section is a multi-objective linear programming model for a sustainable location-routing problem in which the parameters related to costs and capacity are uncertain and expressed using fuzzy numbers. According to the literature review of the problem at hand, fuzzy mathematical programming is divided into two categories: possibilistic and flexible programming. Thus, a robust possibilistic programming model is presented to address the uncertainty of the problem. Possibilistic programming is used to deal with uncertainties in the coefficients of the objective functions and constraints of the problem aimed at considering the data based on previous observations and the decision-maker’s opinion in the modeling. However, flexible programming is utilized to make decisions in flexible conditions to achieve goals or meet constraints. Therefore, the robust possibilistic programming method based on the chance constraint introduced by Pishvaei et al. [6] is used in this study.

A solution to the optimization problem is a robust solution if it has feasibility robustness and optimality robustness. Feasibility robustness suggests that the solution should uphold its uncertainty for all (the vast majority) of possible states of the parameters. Optimality robustness also implies that the value of the objective function per the robust solution should have the minimum deviation from its optimal value for almost all of the non-deterministic parameters.

3.2. The Proposed Robust Model for the Sustainable Closed-Loop Supply Chain Problem

We should first explain the necessity measure to be used in this research for defuzzifying fuzzy numbers.

If the non-deterministic parameters of the model are considered as chance constraint-based and fuzzy trapezoidal numbers of \( \omega = (\omega_1, \omega_2, \omega_3, \omega_4) \), the equivalent crisp value of this fuzzy number can be calculated using the following formula [48]:

\[ E(\omega) = \frac{\omega_1 + \omega_2 + \omega_3 + \omega_4}{4} \]  

(28)

The Nec symbol denotes the necessity measure in chance-constrained programming. The constraint necessity \( \hat{\omega} \leq r \) is defined as follows:

\[ \text{Nec}(\hat{\omega} \leq r) = \begin{cases} 
1 & \omega_4 \leq r \\
\frac{r - \omega_3}{\omega_4 - \omega_3} & \omega_3 \leq r \leq \omega_4 \\
0 & \omega_3 \geq r 
\end{cases} \]  

(29)

According to the above formula, if \( \alpha \geq 0.5 \):

\[ \text{Nec}(\hat{\omega} \leq r) \geq \alpha \leftrightarrow r \geq (1 - \alpha) \times \omega_3 + \alpha \times \omega_4 \]  

(30)
Equation (30) can be used directly to convert fuzzy constraints to their equivalent crisp values.

It was assumed in this study that transportation costs, fixed costs, and variable costs are fuzzy in nature and are displayed as trapezoidal fuzzy numbers as follows (Table 2):

| Fuzzy parameters | Equivalent crisp values |
|-------------------|-------------------------|
| \( f_{a11} \) | \( f_{a11}^{11} \), \( f_{a21}^{11} \), \( f_{a31}^{11} \), \( f_{a41}^{11} \) |
| \( f_{b1w} \) | \( f_{b1w} \), \( f_{b2w} \), \( f_{b3w} \), \( f_{b4w} \) |
| \( f_{d1d} \) | \( f_{d1d} \), \( f_{d2d} \), \( f_{d3d} \), \( f_{d4d} \) |
| \( d_{pc}^{1q} \) | \( d_{pc}^{1q} \), \( d_{pc}^{2q} \), \( d_{pc}^{3q} \), \( d_{pc}^{4q} \) |
| \( \bar{v}_{pq}^{1pq} \) | \( \bar{v}_{pq}^{1pq} \), \( \bar{v}_{pq}^{2pq} \), \( \bar{v}_{pq}^{3pq} \), \( \bar{v}_{pq}^{4pq} \) |
| \( \bar{v}_{pc}^{pq} \) | \( \bar{v}_{pc}^{pq} \), \( \bar{v}_{pc}^{2pq} \), \( \bar{v}_{pc}^{3pq} \), \( \bar{v}_{pc}^{4pq} \) |
| \( \bar{v}_{f}^{pq} \) | \( \bar{v}_{f}^{pq} \), \( \bar{v}_{f}^{2pq} \), \( \bar{v}_{f}^{3pq} \), \( \bar{v}_{f}^{4pq} \) |

According to Equations (29) and (30), the non-deterministic mathematical model, which was explained in the previous section for the sustainable closed-loop green supply chain problem, can be converted to the deterministic model as follows:

\[
\min Z_1 = E(TC) = \sum_{f} E[f_{a1f}] \times X_{a1f} + \sum_{w} E[f_{b1w}] \times X_{b1w} \\
+ \sum_{i} E[f_{d1i}] \times X_{d1i} \bigg[ \sum_{q} \sum_{p} \sum_{f} E[V_{a}^{pq}] \times \sum_{w} Y_{a}^{pq}_{i,f,w} \bigg] \\
+ \sum_{w} E[V_{b1w}] \times \sum_{p} \sum_{q} \sum_{c} Y_{b}^{pq}_{w,c} + \sum_{c} \sum_{w} E[V_{c}] \\
\times \sum_{p} \sum_{q} \sum_{i} Y_{c}^{pq}_{i,c} + \sum_{i} \sum_{q} \sum_{f} E[V_{f}^{pq}] \times \sum_{n} Y_{d}^{pq}_{i,i,n} \\
+ \sum_{q} \sum_{p} \sum_{f} E[V_{f}^{pq}] \times \sum_{i} \sum_{n} Y_{d}^{pq}_{i,i,n} \\
+ \sum_{f} \sum_{w} \sum_{i} \sum_{p} E[t_{a_{11}}^{pq}] \times Y_{a}^{pq}_{f,w,i,f} \\
+ \sum_{c} \sum_{w} \sum_{i} \sum_{p} E[t_{a_{11}}^{pq}] \times Y_{b}^{pq}_{w,c,i} \\
+ \sum_{i} \sum_{q} \sum_{p} E[t_{c}^{pq}] \times Y_{c}^{pq}_{i,c} \\
+ \sum_{i} \sum_{q} \sum_{p} E[t_{c}^{pq}] \times Y_{d}^{pq}_{i,i} \\
+ \sum_{n} \sum_{i} \sum_{p} \sum_{q} E[t_{c}^{pq}] \times Y_{c}^{pq}_{i,c} \\
\text{EQ5 and EQ11 – EQ15} - 18
\]

\[
\text{Nec} \left\{ \sum_{w \in W} \sum_{i \in T_W} Y_{b}^{pq}_{w,c,i} \geq d_{c}^{pq} \right\} \geq \alpha \quad \forall c \in C, q \in Q, f \in F
\] (32)

\[
\text{Nec} \left\{ \sum_{i \in I} \sum_{t \in T} Y_{c}^{pq}_{i,c,t} \leq d_{c}^{pq} \right\} \geq \beta \quad \forall c \in C, p \in P, q \in Q
\] (34)

\[
\text{EQ20}
\]
Since only the first objective function and some constraints have fuzzy numbers in the proposed primary model, therefore, only the parts that are changed are shown. The robust model can be expressed by considering the feasibility robustness and optimality robustness as follows:

\[
\min \ E(\text{TC}) + \gamma (\text{TC}_{\text{max}} - \text{TC}_{\text{min}}) + \delta_1 \left(d_{pq}^{op} - (1 - \alpha)d_{pq}^{op} - \alpha d_{pq}^{op}\right)
\]

\[
+ \delta_2 (\beta d_{pq}^{op} + (1 - \beta)d_{pq}^{op} - d_{pq}^{op}) + \delta_3 \left(d_{pq}^{op} - (1 - \lambda)d_{pq}^{op} - \lambda d_{pq}^{op}\right)
\]

\[\text{EQ5 and EQ11 - EQ15 - 18}\]

\[
\sum_{i \in W} \sum_{t \in TW} Y_{\text{tw},p}^{pq} \geq (1 - \alpha)d_{pq}^{op} + \alpha d_{pq}^{op} \quad \forall c \in C, p \in P, q \in Q
\]

\[\text{EQ5 and EQ11 - EQ15 - 18}\]

\[
\sum_{i \in I} \sum_{t \in TK} Y_{\text{cttw},i}^{pq} \leq \beta d_{pq}^{op} + (1 - \beta)d_{pq}^{op} \quad \forall c \in C, p \in P, q \in Q
\]

\[\text{EQ20}\]

\[
\sum_{i \in I} \sum_{t \in TK} Y_{\text{cttw},i}^{pq} \geq qd. \left((1 - \lambda)d_{pq}^{op} + \lambda d_{pq}^{op}\right) \quad \forall c \in C, p \in P, q \in Q
\]

\[\text{EQ22 - 27}\]

The decision maker should determine the minimum confidence level of the fuzzy constraints (\(\alpha, \beta \) and \(\lambda\)) in the proposed model; thus, similar to the sensitivity analysis method, the decision maker needs to change the values of the parameters. The number of tests required to determine the right values of confidence levels will increase significantly with the enhanced number of fuzzy constraints. Moreover, the model is not sensitive to the deviation of the value of the objective function from its optimal value, which may impose a high risk on the decision-maker in real problems. Therefore, applying a robust possibilistic approach will be highly effective in minimizing the existing risk [12].

The first phrase \(E(\text{TC})\) in the objective function indicates the expected value of the first objective function, while the second phrase, i.e., \(\gamma (\text{TC}_{\text{max}} - \text{TC}_{\text{min}})\), denotes the difference between the two boundary values of \(\text{TC}_{\text{max}}\) and \(\text{TC}_{\text{min}}\). The \(\text{TC}_{\text{max}}\) value is obtained by substituting the upper limit values of the parameters in the TC objective function and the \(\text{TC}_{\text{min}}\) value is also obtained by substituting the lower limit values of the parameters. The \(\gamma\) reflects the degree of importance of this phrase in comparison with other phrases of the objective function. Therefore, the presence of the second phrase minimizes the maximum positive and negative deviation from the expected optimal value of TC. Moreover, this phrase controls the optimality robustness of the solution vector. The next phrases determine the confidence level of each of the fuzzy constraints, in which, \(\delta_1\) is the possible deviation penalty of constraint \(i\) that contains the non-deterministic parameter. \(\delta_1 \left(d_{pq}^{op} - (1 - \alpha)d_{pq}^{op} - \alpha d_{pq}^{op}\right)\) and \(\delta_3 \left(d_{pq}^{op} - (1 - \lambda)d_{pq}^{op} - \lambda d_{pq}^{op}\right)\) determine the difference between the worst parameter value under uncertainty and the value used in the fuzzy constraint.

In addition, \(\delta_2 (\beta d_{pq}^{op} + (1 - \beta)d_{pq}^{op} - d_{pq}^{op})\) determines the difference between the value used in the chance-based constraint and the best value of the non-deterministic parameter. Besides, these phrases (expressions) control the feasibility robustness.

3.3. Solving the Proposed Three-Objective Model with the AEC Approach

Different answers are achieved in the EC method by changing the values of \(e_i\) that are either efficient or weak efficient. An efficient solution can always be obtained by partially
modifying/completing the classical Epsilon constraint model. This method is known as the AEC method [49]. The proper range of epsilons (\(e_i\)) can be first obtained using the Lex method to better implement the AEC method [50]. In the AEC method, the appropriate range of \(e_i\) changes need to be first determined to subsequently obtain the Pareto Front for different values of \(e_i\). The two major steps in the AEC method are as follows:

3.3.1. Determining the Range of Epsilons’ Values

In order to find the appropriate interval for \(e_i\) corresponding with \(i\)th objective function \((i = 2, \ldots, n)\), first, the following optimization problems are solved for each of the objective functions \((j = 1,2, \ldots, n)\):

\[
\text{PayOff}_{jj} = \min f_j(x) \\
x \in X
\]

(43)

in which, \(x^{j^{*}}\) denotes the optimal value for the decision variable and \(\text{PayOff}_{jj} = f_j(x^{j^{*}})\) denotes the optimal value for the \(j\)th objective function. Now the optimal value of the \(i\)th objective function is obtained as follows, while each time one of the objective functions \((j = 1,2, \ldots, n; j \neq i)\) is in its optimal value:

\[
\text{PayOff}_{ij} = \min f_i(x) \\
f_j(x) = \text{PayOff}_{jj} \\
x \in X \\
j \neq i
\]

(44)

in which, \(x^{i^{*}}\) denotes the optimal value for the decision variable and \(\text{PayOff}_{jj} = f_i(x^{i^{*}})\) denotes the optimal value for the \(i\)th objective function. As a result, the following Payoff matrix is formed using Lex method:

\[
\text{PayOff} = [\text{payOff}_{ij}]
\]

(45)

After determining the Payoff matrix, we have the following definitions for the \(i\)th \((i = 1, \ldots, n)\) objective function:

\[
\min(f_i) = \min_j \{\text{payOff}_{ij}\} = \text{payOff}_{ii} \\
\max(f_i) = \max_j \{\text{payOff}_{ij}\}.
\]

(46)

\[
R(f_i) = \max(f_i) - \min(f_i)
\]

By the above definitions, the appropriate interval \(e_i \in [\min(f_i), \max(f_i)]\) is determined for \(e_i\). The value of \(R(f_i)\) is also used to normalize the objective functions of the AEC method.

3.3.2. The AEC Model

The following programming model is developed to solve a multi-objective decision-making (MODM) problem using the AEC method:

\[
\begin{cases}
\min f_1(x) - \sum_{i=2}^{n} \phi_i s_i \\
f_i(x) + s_i = e_i \quad i = 2, 3, \ldots, n \\
x \in X \\
s_i \geq 0
\end{cases}
\]

(47)

where, \(s_i\) denotes the non-negative slack variables and \(\phi_i\) is a parameter for normalizing the value of the first objective function relative to the \(i\)th objective function \((\phi_i = \frac{R(f_i)}{R(f_j)})\).

According to the proposed AEC method, first the \(e_i\) values: \(e_i \in [\min(f_i), \max(f_i)]\) are determined for binding the values of the objective functions, then, the above single-
objective model is solved to find an efficient Pareto solution. It should be noted that another efficient Pareto solution is obtained by changing the value of $\epsilon_i$ within its interval.

4. Numerical Example

A numerical example is provided, which encompasses three potential producers, two potential warehouses, and three potential distribution centers. Moreover, two types of products with two different quality levels are considered for eight types of customers in this example. In addition, transportation options are taken into account for the facilities of the factory 2, warehouse 4, customer 3, distribution center 4, and the disposal center 2.

The deterministic model was implemented and validated. The model was solved by the AEC method and its Pareto diagram was illustrated as shown in Figure 2. The products flow was presented schematically in Figure 2 for the points $F_1 = 95780.08$, $F_2 = 19725.25$, and $F_3 = 23$.

![Figure 2. The obtained Pareto frontier for the deterministic model.](image)

Analyzing the outputs of the General Algebraic Modeling System (GAMS) software in one of the mentioned Pareto points revealed that the manufacturing Factory 2 out of the three potential factories and the Warehouse 2 are active, while all three collection centers are active. The quantity of 4677 products sent by the transportation mode $TF = 2$ has been transferred to Warehouse 2 (Figure 3). The process of sending products to customers is given in Table 3.

![Figure 3. The schematic view of the closed-loop supply chain.](image)

Table 3 shows the volume of products returned by customers to the collection center.
Table 3. The shipment methods of products from the warehouse to the customer.

| Customer | Product | Quality Level | TW = 1 | TW = 2 | Quality Level | TW = 1 | TW = 2 |
|----------|---------|---------------|--------|--------|---------------|--------|--------|
| 1        | 117     | 185           |
| 2        | 129     | 122           |
| 3        | 106     | 150           |
| 4        | P = 1   | 200           | 176    |
| 5        | 116     | 125           |
| 6        | 136     | 135           |
| 7        | 159     | 183           |
| 8        | 178     | 130           |
| 1        | Q = 1   | 155           | 130    |
| 2        | 135     | 186           |
| 3        | 200     | 158           |
| 4        | P = 2   | 113           | 164    |
| 5        | 167     | 143           |
| 6        | 113     | 115           |
| 7        | 123     | 167           |
| 8        | 111     | 150           |

Table 3 shows the volume of products returned by customers to the collection center. Of this returned product volume, 611,924 products are sent to the disposal center and 170,316 products are brought back to the production cycle. It should be noted that if we intend to provide the production plan for the next period under the same conditions and the customer demand of 4677 units considering the reverse loop, the production plan for purchasing raw materials no longer needs to be the same as before, and the planning should be made to produce 4506 units.

4.1. Solving the Problem under Uncertainty Conditions

The values of objective functions obtained by using the AEC method are shown in Table 4, followed by the Pareto front diagram (Figure 4), and a comparison between objective functions. Firstly, the model was solved by focusing on the economic objective function to achieve the best value for this goal, while the other objective functions would not be definitely optimal under such conditions, and thereby, values other than optimal values would be obtained for the other objective functions (environmental and social responsibility). Then, the environmental objective function was taken into account to obtain its optimal value. Finally, the same procedure was implemented for the third (social responsibility) objective function to find the best value for the third goal. As a result, nine values were achieved so that the epsilon limits would be available for each objective function. After determining the epsilons, the multi-objective model was run, and its outputs were obtained as the following in Table 4.

Table 4. Total outputs of the AEC method.

| Optimal | Obj1   | Obj2   | Obj3   | Epsilon2 | Epsilon3 |
|---------|--------|--------|--------|----------|----------|
| 1       | 110310.1| 34298.26| 17     | 34298.26 | 13.508   |
| 2       | 109848.8| 38474.18| 17     | 38865.33 | 16.731   |
| 3       | 111084.8| 27381.6 | 17     | 27381.6  | 11.229   |
| 4       | 110140.2| 38131.43| 18     | 38131.43 | 17.838   |
| 5       | 198484.2| 21043.82| 18     | 21043.82 | 17.7     |
| 6       | 110581.8| 34023.52| 18     | 34023.52 | 17.994   |
| 7       | 110771  | 30186.08| 17     | 30186.08 | 10.546   |
| 8       | 132514.5| 22876.38| 18     | 22876.38 | 16.438   |
| 9       | 110465.1| 34909.98| 18     | 34909.98 | 17.854   |
| 10      | 110393.2| 35457.03| 18     | 35457.03 | 17.743   |
| 11      | 151137.2| 21206.96| 16     | 21206.96 | 12.044   |
| 12      | 111650.8| 26409.57| 18     | 26409.57 | 17.808   |
Figure 4. The Pareto frontier obtained using the AEC method.

Figure 4 depicts the Pareto front obtained using the AEC method considering the economic, environmental, and social responsibility objective functions.

It is assumed to have a bi-objective model aimed at displaying the relationships between the environmental and economic goals as well as economic and social responsibility objective functions. Subsequently, the bi-objective model was implemented and the relationships between the objective functions were displayed in Figures 5 and 6.

Figure 5. The relationship between the first and second objective functions.

Figure 6. The relationship between the first and third objective functions.
Table 5 presents the outputs of solving the model using the AEC method, taking into account the first and second (economic and environmental) objective functions.

Table 5. The outputs of the bi-objective model considering the first and second objective functions.

| Optimal | Obj1   | Obj2   | Epsilon2 |
|---------|--------|--------|----------|
| 1       | 257609.1 | 20858.02 | 20858.02 |
| 2       | 126651  | 23489.32 | 23489.32 |
| 3       | 111254.8 | 26120.62 | 26120.62 |
| 4       | 110846.1 | 28751.91 | 28751.91 |
| 5       | 110681  | 30897.68 | 31383.21 |
| 6       | 110316.6 | 34014.51 | 34014.51 |
| 7       | 109922.1 | 36645.81 | 36645.81 |
| 8       | 109808.3 | 38474.18 | 39277.11 |

As seen in Figure 5, the organization must bear higher costs to comply with the environmental obligations since costs increase when the pollution emissions decrease.

Table 6 presents the outputs of solving the model using the AEC method, taking into account the first and third (economic and social responsibility) objective functions.

Table 6. The outputs of the bi-objective model considering the first and third objective functions.

| Optimal | Obj1   | Obj3   | Epsilon3 |
|---------|--------|--------|----------|
| 1       | 109956.5 | 18     | 18       |
| 2       | 109956.5 | 18     | 17.556   |
| 4       | 109686.7 | 17     | 16.667   |
| 5       | 109666.3 | 16     | 15.778   |
| 6       | 109662.1 | 15     | 14.889   |
| 7       | 109647.7 | 14     | 14       |

As seen in Figure 6, increasing the value of the third (social responsibility) objective function leads to increasing the value of the first (economic) objective function. Thus, if decision-makers focus on the social aspect of sustainability, higher costs will be incurred on the organization.

4.2. Analyzing the Results and Solving the Model Considering the Different Sizes of the Problem

There are three major problems with the possibilistic programming model: The first problem is that many tests need to be conducted to find the right level of confidence given the high number of constraints that are associated with uncertainty, which is time-consuming. The second problem is that there is no guarantee that the chosen confidence level would be the best. Eventually, the third problem is the deviations in the constraints that include uncertainty. As a result, this factor may make the constraints infeasible, which is a significant problem and has not been considered in this method. Hence, a robust possibilistic programming model is also proposed to resolve these problems.

A numerical example is considered to implement both robust possibilistic programming and possibilistic programming models, which encompasses three potential producers, two potential warehouses, and three potential distribution centers. Since this model is multi-product, two products with two quality levels are considered for eight types of customers in this example. In addition, 2, 4, 3, 4, and 2 transportation modes were considered for the facilities of the factory, warehouse, customer, distribution center, and disposal center, respectively.

There exist many deterministic and non-deterministic parameters in the mathematical model of this research. It should be noted that the trapezoidal fuzzy numbers are given for the uncertain demand parameter shown in Figure 7.
The parameter C3 is considered equal to the nominal value according to the above figure. The lower limit, i.e., C1 is considered 40% lower than the nominal value, C2 is 20% less than the nominal value, and finally, C4 is considered 40% higher than the nominal value. The demand parameter is described as follows:

\[
D_3(C, p, q) = \text{Uniformint}(100, 200)
\]

\[
D_1(C, p, q) = \text{Round}(D_3(C, p, q) - 0.4 \times D_3(C, p, q))
\]

\[
D_2(C, p, q) = \text{Round}(D_3(C, p, q) - 0.2 \times D_3(C, p, q))
\]

\[
D_4(C, p, q) = \text{Round}(D_3(C, p, q) + 0.4 \times D_3(C, p, q))
\]

The same procedure applies to other non-deterministic parameters.

In this section, both robust possibilistic programming and possibilistic programming models are implemented for validation. The possibilistic programming model is optimized by considering the confidence levels of 0.7, 0.8, and 0.9, and the corresponding values are shown in Figure 8. The outputs are also presented in Table 7.

![Figure 7. Trapezoidal fuzzy numbers.](image)

![Figure 8. Impact of different degrees of feasibility on costs.](image)

**Table 7.** Comparing the results of the robust possibilistic programming and possibilistic programming models.

| \(\alpha, \beta, \lambda\) | \(\text{Possibilistic Programming}\) | \(\text{Robust Possibilistic Programming}\) |
|--------------------------|---------------------------------|-------------------------------------------|
| \(\text{Obj1}\)         | \(\text{Obj2}\)                 | \(\text{Obj3}\)                           | \(\text{Obj1}\) | \(\text{Obj2}\) | \(\text{Obj3}\) |
| 1                       | 0.7                             | 112492.98                                 | 36736.85       | 17             | 149040.568       | 44036.731       | 17             |
| 2                       | 0.8                             | 115988.58                                 | 42318.86       | 17             |                                                                 |               |                |

According to Figure 5, which shows the values of \(\alpha, \beta, \lambda\) as 0.7, 0.8, and 0.9, respectively, for the economic objective function, the results reveal that increasing the minimum degree of feasibility has led to an increase in costs due to increasing demand.

The objective function value of the possibilistic programming model at a confidence level of 0.9 is less than the objective function value with a penalty amount of 0.5. That
is, the objective function value of the possibilistic programming model at the highest level of confidence is lower than the objective function value of the robust possibilistic programming model with the lowest penalty level (Figure 9).

Figure 9. Comparison of the robust possibilistic programming and possibilistic programming at a confidence level of 0.9.

4.3. Analyzing the Results and Solving the Model Considering Various Problems with Different Sizes

The GAMS optimization software and CPLEX Solver were used on a Core i5 laptop with 4G RAM to solve the proposed model in numerous sample problems with different sizes, as shown in Table 8.

Table 8. Problem design for closed-loop supply chain network in different sizes.

| Sample Problem | F | W | C | I | N | TF | TW | TK | TI | TN | P | Q |
|----------------|---|---|---|---|---|----|----|----|----|----|---|---|
| 1              | 3 | 2 | 8 | 3 | 3 | 2  | 4  | 3  | 4  | 2  | 2 | 2 |
| 2              | 3 | 5 | 12| 3 | 3 | 2  | 4  | 3  | 4  | 2  | 2 | 2 |
| 3              | 3 | 5 | 14| 3 | 3 | 2  | 4  | 3  | 4  | 2  | 2 | 2 |
| 4              | 3 | 9 | 16| 4 | 4 | 2  | 4  | 3  | 4  | 2  | 2 | 2 |
| 5              | 4 | 9 | 18| 4 | 4 | 2  | 4  | 3  | 4  | 2  | 2 | 2 |
| 6              | 4 | 9 | 20| 4 | 4 | 3  | 5  | 4  | 5  | 3  | 3 | 3 |
| 7              | 5 | 11| 22| 5 | 5 | 3  | 5  | 4  | 5  | 3  | 4 | 4 |
| 8              | 5 | 11| 24| 5 | 5 | 3  | 5  | 4  | 5  | 3  | 4 | 4 |
| 9              | 5 | 11| 26| 5 | 5 | 4  | 6  | 5  | 5  | 3  | 3 | 4 |
| 10             | 5 | 13| 28| 6 | 6 | 4  | 6  | 5  | 5  | 3  | 3 | 4 |
| 11             | 6 | 13| 30| 6 | 6 | 4  | 6  | 5  | 5  | 4  | 5 | 5 |
| 12             | 6 | 13| 32| 6 | 6 | 4  | 6  | 5  | 5  | 6  | 4 | 5 |
| 13             | 6 | 15| 34| 7 | 7 | 4  | 7  | 6  | 6  | 4  | 6 | 6 |
| 14             | 8 | 15| 36| 7 | 7 | 5  | 7  | 6  | 6  | 4  | 6 | 6 |
| 15             | 8 | 15| 38| 7 | 7 | 5  | 7  | 6  | 6  | 4  | 6 | 6 |
The possibilistic programming model at a confidence level of 0.9 and the robust possibilistic programming model were implemented for all problems using the GAMS software and the values of economic, environmental, and social responsibility objective functions as well as the solution times are provided in Table 9.

| Table 9. Comparison of the results of the robust possibilistic programming and possibilistic programming models. |
|--------------------------------------------------|
| Possibilistic Programming | Robust Possibilistic Programming |
| Obj1 | Obj2 | Obj3 | Solution Time | Obj1 | Obj2 | Obj3 | Solution Time |
|---|---|---|---|---|---|---|---|
| 1 | 112493 | 36736.85 | 17 | 32.2 | 149040.6 | 44036.73 | 17 | 31.8 |
| 2 | 187169 | 29267.91 | 29 | 35.1 | 226106 | 31864.99 | 29 | 33.2 |
| 3 | 226508.6 | 51318.52 | 30 | 34.6 | 280990.5 | 56885.9 | 30 | 34 |
| 4 | 221298.8 | 37652.39 | 35 | 43.95 | 275637.5 | 42646.97 | 35 | 38.5 |
| 5 | 495118.2 | 79996.83 | 44 | 52.3 | 614204.3 | 88622.48 | 41 | 58.3 |
| 6 | 371434.2 | 105694.7 | 44 | 58.9 | 459974.3 | 116882 | 44 | 82.4 |
| 7 | 645098.4 | 119017.6 | 45 | 86.7 | 802963.3 | 134888 | 44 | 85.3 |
| 8 | 623957.8 | 116261.9 | 57 | 82.8 | 776619 | 131765.5 | 57 | 15.6 |
| 9 | 598870.6 | 125125.3 | 56 | 10.2 | 744473.2 | 144066.5 | 55 | 15.65 |
| 10 | 819076.4 | 228144.6 | 61 | 14.28 | 1017886 | 246844 | 61 | 17.32 |
| 11 | 895641.9 | 295736.8 | 83 | 14.78 | 1113248 | 330478.7 | 83 | 18.2 |
| 12 | 1031021 | 406372.7 | 57 | 15.6 | 1282136 | 438746.5 | 57 | 18.8 |
| 13 | 1202309 | 379571.3 | 83 | 27 | 1494380 | 444382.5 | 82 | 31 |
| 14 | 1226793 | 346850.2 | 75 | 28.7 | 1524536 | 385002.7 | 75 | 34.6 |
| 15 | 1265524 | 438293.4 | 73 | 35.2 | 1572802 | 496758.6 | 73 | 46.7 |

After solving various problems by the AEC method, the environmental and social responsibility objective functions were limited to an epsilon that was previously described. Table 9 presents the results. Figure 10 shows a comparison of the economic objective functions of the robust possibilistic programming and possibilistic programming models. It can be said that the value of the economic objective function of the possibilistic programming model at the confidence level of 0.9 is lower than the value of the economic objective function value of the robust possibilistic programming model with a penalty amount of 0.5 for all problems. That is, the objective function value of the possibilistic programming model at the highest confidence level is lower than the objective function value of the robust possibilistic programming model with the lowest penalty level.

![Figure 10. Values of the economic objective functions of the robust possibilistic programming and possibilistic programming models.](image)

According to Figure 11, which shows a comparison of the environmental objective functions between the robust possibilistic programming and possibilistic programming models, the value of the possibilistic programming model at the confidence level of 0.9 is...
lower than the value of the robust possibilistic programming model with a penalty amount of 0.5 for all problems. That is, the objective function value of the possibilistic programming model at the highest confidence level is lower than the objective function value of the robust possibilistic programming model with the lowest penalty level. This chart varies among risk-averse and risk-taking managers. Risk-taking managers are mostly willing to follow the possibilistic programming, while risk-averse managers are more willing to follow the robust possibilistic programming since it has a higher safety margin, and the decisions will probably be more accurate.

![Figure 11](image1.png)

**Figure 11.** Values of the environmental objective functions of the robust possibilistic programming and possibilistic programming models.

Figure 12 shows the solution time of the two methods used in this study: increasing the problem size leads to increasing the solution time. Moreover, the solution time of the robust possibilistic programming method is more than the other method.

![Figure 12](image2.png)

**Figure 12.** Solution time of the robust possibilistic programming and possibilistic programming methods.

5. Discussion

Analyzing the changes in consumption attitudes of the customers.

Since it was assumed that there are two groups of green and non-green customers, the analysis is performed in this section on the consumption attitudes under six scenarios, each of which was solved using the AEC method. Each scenario has 20% increase in demand for green products and 20% increase in demand for non-green products. The results are presented in Table 10 and in Figures 13 and 14.
Table 10. Comparing the results of changing the consumption attitudes of green and non-green customers.

| Scenario | Obj1   | Obj2   | Obj3   | Epsilon2 | Obj1   | Obj2   | Obj3   | Epsilon2 |
|----------|--------|--------|--------|----------|--------|--------|--------|----------|
| 0        | 95502.610 | 18508.589 | 17     | 18508.589 | 17     | 95502.610 | 18508.589 | 17     |
| 0/2      | 104548.366 | 20015.360 | 17     | 20015.360 | 18     | 105380.050 | 20116.889 | 17     |
| 0/3      | 109068.938 | 20903.887 | 17     | 20903.887 | 17     | 110324.145 | 21042.220 | 17     |
| 0/4      | 113590.680 | 21565.449 | 17     | 21776.655 | 18     | 115270.113 | 21801.261 | 17     |
| 0/5      | 118091.996 | 22440.993 | 17     | 22664.224 | 17     | 120206.676 | 22727.276 | 17     |
| 0/6      | 122613.476 | 22735.056 | 17     | 22135.056 | 18     | 125164.781 | 22800.815 | 17     |
| 0/7      | 127115.501 | 22970.552 | 17     | 22970.552 | 17     | 130409.262 | 23284.226 | 17     |

Figure 13. The effect of changing consumer attitudes on the economic objective function.

Figure 14. The effect of changing consumer attitudes on the environmental objective function.

According to the tables and charts, increasing demand in the green sector leads to more pressure on the supply chain. Customer categorization is useful since it provides managers with excellent insight into supply chain management. If the demand of each segment of customers increases (or decreases), the managers can better cooperate with the suppliers of that segment to meet the demands.

The results of the numerical example showed that among the production plants and potential distribution centers, factory 2 and distribution center 2 are more cost-effective to set up.

Considering the demand of 4677 for two green and non-green types of products, the same amount of product was transferred from the facility 2 with the transportation modes shown in the Figure. In addition, 170 products were recycled and saved from disposal.
Managerial Discussions and Practical Implications

Nowadays, organizations pay more attention to their customers in order to survive in this competitive global market. In addition, the push supply chain network is no longer applicable, and pull supply chain networks are designed in compliance with the variety of products and customers so that customers can purchase products at various quality levels. In fact, the customers’ purchasing power is different, leading to them buying different green or non-green products. If the supply chain network does not cover both green and non-green products, it will definitely lose a significant number of customers, which means a great reduction in profits. This study can guide managers to coordinate with the suppliers if demand for any type of product increases or decreases.

6. Conclusions

In this research, a robust multi-objective mathematical model was presented for a sustainable closed-loop supply chain network. In addition, a flexible supply chain network was considered which could meet different types of customers’ demands with varied quality levels (green and non-green). Given the fact that supply chain networks should be a pull system, this issue can be very useful for supply chain entities as these two groups of consumers with different perspectives cannot be ignored.

The proposed multi-objective mathematical programming model facilitates strategic decisions on the location of facilities such as factories, warehouses, and collection centers. In addition, the proposed model determines which type of vehicle should be used to ship the products from the manufacturers to the warehouses and from the warehouses to the customers. In this study, the Augmented Epsilon Constraint (AEC) method that was used resulted in an efficient Pareto Frontier. The findings show that compliance with environmental and social responsibility incurs higher costs on organizations. Moreover, environmentally friendly (green) products are more recyclable. The Pareto Frontier obtained by the AEC method helps decision-makers to choose the most ideal Pareto solution regarding the organization’s financial capabilities.

Due to the fact that cost and demand were considered as uncertain parameters in this study, the robust possibilistic programming method is more effective than the possibilistic programming method, which means that the robust possibilistic programming method is a very useful decision-making tool for risk averse managers.

Since the products are shipped directly, it is recommended for further research to incorporate vehicle routing models for the transportation of products. In this paper, the proposed model was implemented in small- and medium-sized problems. It is also suggested to implement this model in large-scale problems and solve them using other exact or metaheuristic methods such as Bender’s decomposition or the NSGA-II algorithm. Moreover, it can be assumed to have defective products. Furthermore, other robust methods may be exploited and compared with the robust possibilistic programming method.

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