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Multi-objective Green Supply Chain Network Design Considering Carbon Emissions and Electricity Consumption

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This study aims to design a green closed-loop supply chain network (GCLSCN) for battery products, targeting a balance among economic efficiency, environmental responsibility, and timely customer delivery. The main objectives include minimizing total cost, energy consumption, and carbon emissions. A multi-objective mathematical model is developed for the GCLSCN, incorporating multiple echelons suppliers, production plants, distribution centers, customers, collection centers, recycling units, and disposal facilities under different capacity levels and production technologies. To address the problem, two multi-objective metaheuristic algorithms, NSGA-II and NRGA, are implemented. Their performance is compared using indicators such as solution diversity, proximity to the ideal solution, the number of Pareto-optimal points, and computation time. The model also considers demand uncertainty to better reflect real-world conditions. The results show that NSGA-II produces a broader and more diverse set of solutions, offering decision-makers greater flexibility. In contrast, NRGA demonstrates superior computational efficiency. The inclusion of variable capacities and uncertain demand further enhances the model's practical applicability and robustness. This research contributes a comprehensive and flexible framework for designing sustainable, closed-loop supply chains in the battery industry. It integrates environmental factors like carbon emissions and electricity consumption into supply chain optimization. The study offers valuable insights for industry practitioners seeking to implement green strategies and serves as a basis for future research, including dynamic modeling, a consideration of socio-cultural elements, and advanced uncertainty techniques.

Keywords:
green closed-loop supply chain, network design, metaheuristic algorithm, multi-objective optimization, supply chain management.

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1) Introduction

Nowadays, industrial companies face increasing pressures and challenges to improve their environmental interactions. They attempt to mitigate these pressures and create competitive advantages by implementing various guidelines and practices. This has led to a growing interest among industrial firms in adopting Green Supply Chain Management (GSCM) practices to enhance both economic and environmental performance. GSCM is an approach used to minimize or eliminate the negative environmental impacts of operations within companies. Green practices have emerged as a strong approach for reducing the adverse effects of industrial activities on the environment (Zhu & Sarkis, 2006). Environmental harm can occur throughout the product life cycle, from the extraction of raw materials to the final product stages, including manufacturing, usage, reuse, remanufacturing, and disposal (Zhu et al., 2007). However, there are numerous concerns and obstacles that companies encounter when implementing green supply chain management. Major internal barriers include organizational values, structural factors, and human resources, while prominent external barriers involve suppliers and customers (De Sousa Jabbour & De Souza, 2015). The GSCM refers to the integration and application of environmental considerations throughout the entire supply chain in order to improve environmental performance (Faris & Maan, 2020). Green practices may encompass various aspects such as green design, green procurement, green manufacturing, green packaging, green logistics, reverse logistics, and more (Tseng & Chiu, 2012). Some studies have shown that poor environmental performance in companies is primarily driven by economic performance and reverse logistics. Specifically, economic performance leads to reduced investments in green practices, while reverse logistics increases waste management costs (Faris & Maan, 2020). Economic and environmental objective functions often conflict with one another, meaning that improvements in one may result in deteriorations in the other. Additionally, the percentage of expired product disposal increases when the values of the second objective function worsen, indicating that higher levels of product disposal lead to more adverse environmental impacts (Ghalandari et al., 2023).

The Green Bullwhip Effect is a phenomenon that occurs when environmental pressures are transmitted from one level of the supply chain to another. This can lead to the adoption of GSCM practices across all tiers of the supply chain. It has been warned that companies failing to anticipate and invest in the development of environmental management practices are likely to suffer adverse consequences (Seles et al., 2016). There is a positive relationship between the maturity level of an organization’s environmental management and the number of GSCM practices it adopts (Ferreira et al., 2017). Moreover, process innovation can significantly enhance recycling performance and increase the recycling rate among supply chain members. While competitive mechanisms are generally beneficial for suppliers, the supply chain as a whole, and the environment, they may not always be advantageous for manufacturers. Governments and companies should seize this opportunity to reduce the environmental impact of green products and work toward building more sustainable supply chains (Chai et al., 2021). The production of electric vehicle (EV) batteries poses a significant environmental challenge due to high carbon emissions. Green collaboration with suppliers of raw materials and equipment can help reduce these emissions. Among various factors, the ability to meet buyer requirements is considered the most critical criterion for collaboration in improving the green supply chain (He & Chen, 2022). Lithium-ion batteries (LIBs) can contribute to reducing carbon emissions by powering electric vehicles and supporting energy storage for renewable-based power grids. A vast number of these batteries are currently used in EVs, and this trend is expected to grow exponentially in the coming years (Yang et al., 2022). However, improper recycling and reuse of batteries, battery disposal, and inadequate charging infrastructure are identified as three major challenges in the EV battery supply chain in India (Kumar et al., 2021). Lithium-ion batteries play a vital role in energy storage systems and electric mobility. Nonetheless, their production and use can result in significant environmental impacts (Ren et al., 2023). Achieving sustainable development goals through LIBs requires meticulous supply chain management and strict adherence to sustainability standards (da Silva Lima et al., 2023). In fact, electric vehicles cannot achieve true sustainability unless three key conditions are met: the use of renewable resources, local industrial development, and effective battery recycling (D’Adamo et al., 2023).

The main objective of this study is to design a GCLSCN for battery products. The proposed mathematical model incorporates three objective functions. The first objective aims to minimize the total cost, including production costs, transportation costs, facility establishment fixed costs, and shortage costs. The second objective seeks to minimize electricity consumption and water wastage, while the third objective focuses on minimizing product delivery time or, equivalently, maximizing the level of customer service. The key innovation of this research compared to previous studies lies in the inclusion of shortage costs in the economic objective function. Shortages occur due to insufficient supply to meet customer demand, and the associated cost is modeled as a penalty added to the total cost. Furthermore, unlike most prior research that concentrated on minimizing carbon emissions as the main environmental concern, this study emphasizes the minimization of electricity usage and water loss as core environmental criteria. Additionally, the model parameters are initially considered as fuzzy variables, and the Jiménez algorithm is used for their defuzzification. Finally, metaheuristic algorithms are employed to solve the multi-objective mathematical model, and the results are analyzed accordingly.

2) Theoretical Foundations

In today’s competitive market, organizations must fully satisfy customer needs to survive. Customer satisfaction depends on all components of the supply chain. The supply chain encompasses various segments, including suppliers, manufacturers, customers, distributors, transportation providers, and retailers that directly or indirectly fulfill the customer's demand for a product (Chopra et al., 2007). Therefore, one of the primary objectives of a supply chain is to meet customer needs and create value. Some definitions of supply chain emphasize the central role of material flow. A supply chain is defined as a set of activities related to the movement and transformation of goods from the extraction of raw materials to the final delivery to the consumer. This flow not only includes physical materials but also the associated information, financial, and credit flows (Laudon & Laudon, 2004). Moreover, the process of planning, implementing, and controlling the efficient and effective flow of goods, services, and information from the point of origin (supplier) to the point of consumption (customer) to meet customer requirements is referred to as logistics (Hugos, 2018). In fact, logistics can be considered a part of the broader supply chain. While supply chain management focuses on the entire product life cycle, logistics places greater emphasis on transportation and warehousing of goods. Supply chain management is essentially about creating coordination among production, location, inventory, and transportation decisions to achieve the optimal balance between responsiveness and efficiency, with the ultimate goal of market success among the participants in a supply chain (Burgess et al., 2006). When a supply chain evolves from a simple, linear structure into a complex system with multiple interconnections, it becomes a supply chain network. In fact, supply chain networks are designed to optimize inventory costs, transportation expenses, risks, working capital, and other targeted business variables across three levels: strategic, tactical, and operational. The design of a supply chain network encompasses all internal and external components of Supply Chain Management (SCM) (Tiwari et al., 2016). Therefore, it can be concluded that most supply chains are, in practice, structured as networks. Today, in addition to traditional objectives, such as reducing transportation and inventory costs, environmental and social considerations have become key goals in the design of supply chain networks. Beyond satisfying customer needs, domestic and international regulations and requirements have driven industries and, consequently, research in this field toward the adoption of green supply chains. A green supply chain is one in which environmental design principles are given special attention throughout the supply chain processes (Soleimani et al., 2017). In recent years, the term "green" has been added to the traditional concept of supply chains, forming the new notion of the Green Supply Chain, which reflects the implementation of environmentally friendly policies across the entire chain. This concept not only introduces an environmental perspective to supply chain management but also aims to reduce pollution, environmental problems, and ecological challenges from the individual level to the organizational level within the supply chain (Zhu et al., 2010). Previous studies have extensively applied multi-objective mathematical programming to green and sustainable supply chain network design problems. In this stream, environmentally oriented closed-loop and green supply chain networks have been modeled by explicitly incorporating environmental objectives alongside economic criteria. For instance, multi-objective formulations have been developed to address environmental factors in closed-loop supply chain network design under uncertainty, demonstrating the effectiveness of mathematical optimization frameworks in capturing sustainability trade-offs (Fathi et al., 2019; Fathi & Jandaghi, 2022). More recent studies further confirm that multi-objective network design provides a robust foundation for analyzing sustainable supply chain configurations in real-world industrial contexts (Fathi et al., 2024).

3) Literature Review

Over the past years, numerous studies have been conducted in the field of green supply chain management. Seles et al. (2016) examined how different institutional pressures from stakeholders can reinforce the green ripple effect. They found that the green ripple effect is stronger in mature institutional environments, where normative pressures are more influential than coercive pressures. On the other hand, Ferreira et al. (2017) investigated the relationship between the maturity level of environmental management and the adoption of green supply chain management practices. Using an integrated framework and evidence from multiple case studies, they proposed an innovative model for assessing green supply chain maturity levels. The framework was then applied to five companies operating in supply chains with high environmental impact in Brazil. Some studies in the field of green supply chain management have specifically focused on the battery supply chain. De Sousa Jabbour and De Souza (2015) investigated how leading companies in the automotive battery industry in Brazil addressed the barriers to adopting green supply chain management. They also identified the opportunities and challenges related to implementing green supply chain practices in this sector. Maurício and De Sousa Jabbour (2017) identified and analyzed the Critical Success Factors (CSFs) influencing the adoption of green supply chain management practices among top automotive battery manufacturers in Brazil. Similarly, Chiapetta Jabbour et al. (2017) employed the Resource-Based View (RBV) theory to examine the relationship between CSFs and the development of green supply chain management. Furthermore, Chai et al. (2021) studied the impact of process innovation on recycling and remanufacturing of green products within closed-loop supply chains. Some other studies in this field have focused on the batteries of electric vehicles. Kumar et al. (2021) examined the challenges facing the sustainable supply chain of electric vehicle batteries using a hybrid Delphi and Best-Worst Method approach. After conducting a comprehensive literature review and consulting with experts, they identified 17 key challenges for sustainability in the electric vehicle battery supply chain in India. He and Chen (2022) developed a green supplier evaluation system for the Chinese electric vehicle battery manufacturing industry. They employed case studies to design the analytic process and utilized decision laboratory experiments, Analytic Hierarchy Process (AHP), and Best-Worst Method (BWM) to develop the methodology. Rajaeifar et al. (2022) investigated the challenges and recent advancements in the supply and value chains of electric vehicle batteries from a sustainability perspective. Yang et al. (2022) reviewed life cycle assessment studies to evaluate the environmental impacts of lithium-ion batteries and compared electric vehicles with internal combustion engine vehicles in terms of environmental sustainability.

Moreover, Mokhlesabadi et al. (2021) conducted a comprehensive review of evaluation methods in the lithium-ion battery industry, taking into account its multifaceted impacts. They proposed a comprehensive multi-attribute assessment method (4A), which includes environmental impact assessment, resource significance evaluation, economic analysis, and material flow analysis. Ren et al. (2023) reviewed 30 existing studies on the comprehensive evaluation of lithium-ion batteries. Based on their findings, they proposed a comprehensive multi-attribute assessment system (4A), which includes environmental impact assessment, resource significance evaluation, economic analysis, and material flow analysis. da Silva Lima et al. (2023) examined the role of raw materials in achieving the Sustainable Development Goals (SDGs). They assessed the impacts of cobalt production and use within the lithium-ion battery supply chain in the European Union and worldwide.

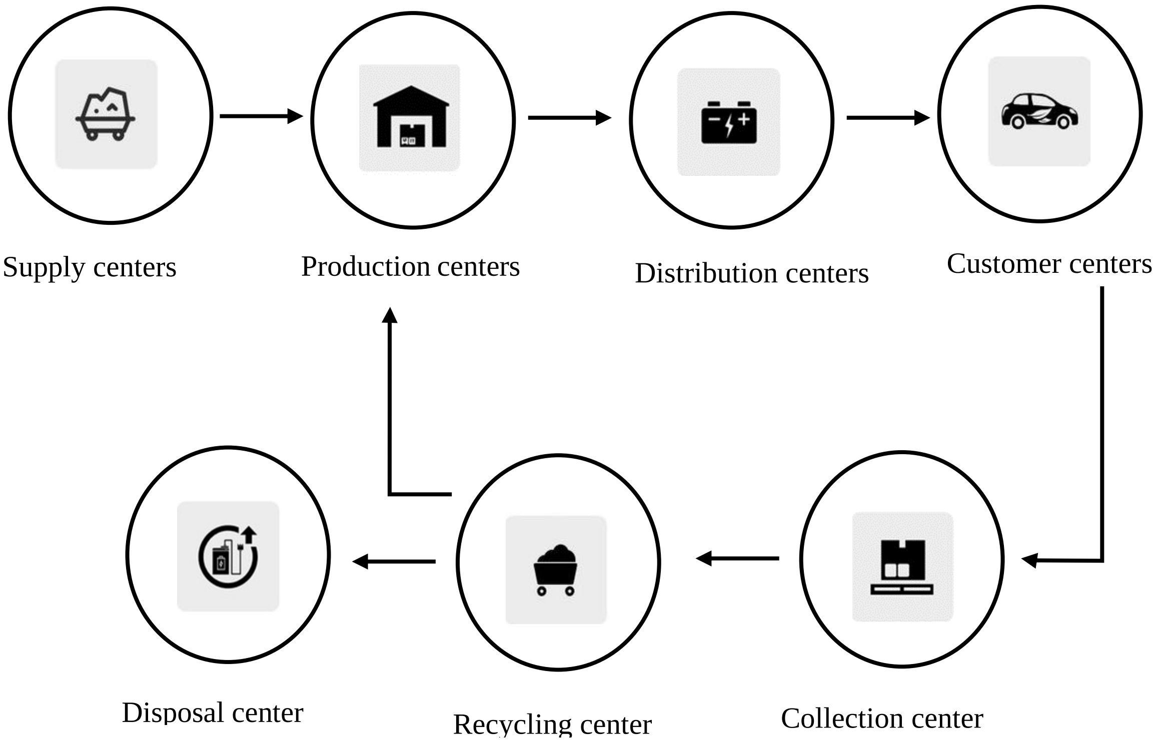
Significant studies in this field have focused on the design of green supply chain networks and the use of mathematical modeling and quantitative methods. Fazli-Khalaf et al. (2017) proposed a novel model for designing a reliable GCLSCN for lead-acid battery supply. This model aimed to minimize total costs and harmful gas emissions while considering parameter uncertainty and the decision output's risk aversion level. The model was based on a robust hybrid fuzzy stochastic linear programming approach that allowed controlling uncertainty and risk aversion in the decision-making process. Using reliable and unreliable facilities as strategic options, the model could effectively mitigate the adverse impacts of disruptions. Faris and Maan (2020) evaluated green supply chain management practices under uncertainty. They developed a hybrid model combining fuzzy set theory and the DEMATEL method to assess green practices that could influence the implementation of green supply chains in the battery industry. Etemad et al. (2021) proposed a mixed-integer linear programming model for designing a closed-loop supply chain network for Saba Battery Company, aiming to minimize costs and environmental impacts. The main objective of their study was to present a fuzzy mathematical programming model for a green closed-loop supply chain network considering customer relationship management (CRM). The CRM concept was incorporated as the third objective function by maximizing the amount of collected obsolete products. They used a multi-objective genetic algorithm to solve the model and ultimately obtained Pareto-optimal solutions, which indicated a conflict between the economic and environmental objectives. Sherif et al. (2021) investigated a two-echelon supply chain network in the battery industry and proposed an integrated optimization method to solve the green transportation and inventory problem at the first echelon, and the heterogeneous multi-depot vehicle routing problem with simultaneous pickup and delivery at the second echelon. The objective was to minimize a green objective function including transportation costs, inventory holding costs, and carbon emission costs. The problem was formulated as a Mixed-Integer Nonlinear Programming (MINLP) model and solved using the Simulated Annealing Algorithm (SAA). Niranjan et al. (2022) investigated a multi-channel closed-loop green supply chain (MCLSC) for a battery manufacturer in southern India. The main objective of their study was to develop a mathematical model considering both economic and environmental goals. To solve the model, they developed a Particle Swarm Optimization (PSO) algorithm and used a Modified Particle Swarm Optimization (MPSO) algorithm. The problem was formulated as a Mixed-Integer Nonlinear Programming (MINLP) model. The objective function included economic costs such as production, transportation, distribution, and waste collection, as well as environmental costs including carbon emissions and waste management expenses. Ghalandari et al. (2023) proposed a hybrid model for the sustainable design of a closed-loop supply chain network for lead-acid batteries in the automotive industry. This two-stage model employs Data Envelopment Analysis (DEA) and Robust Possibilistic Programming (RPP). In the first stage, candidate locations for recycling centers are identified using DEA based on their efficiency scores. Unlike previous studies, not only economic but also technical and geographical criteria were used for selecting these locations. In the second stage, a bi-objective programming model was developed to simultaneously determine tactical and strategic decisions in the supply chain. Due to the presence of uncertainty in some data, a robust probabilistic approach was also proposed. Beyond network configuration, sustainability research has emphasized the identification, structuring, and prioritization of sustainability indicators to support decision-making in supply chains. Prior research has shown that environmental sustainability drivers and performance indicators are highly interdependent and require structured analytical approaches for proper representation (Nasrollahi et al., 2020). In this regard, fuzzy cognitive mapping and DEMATEL-based methods have been employed to structure sustainable supply chain performance indicators and to clarify causal relationships among environmental and operational criteria (Fathi et al., 2024). These findings highlight the importance of explicitly modeling sustainability dimensions rather than treating them as aggregated or implicit measures.

4) Research Methodology

This study is classified as developmental research in terms of research orientation, as it aims to expand and develop existing models for designing green supply chain networks. Therefore, the researcher's work is more advanced and in-depth compared to previous studies. Additionally, in terms of nature and approach, it is exploratory research. The problem under investigation in this study is the design of a green closed-loop supply chain network for Sepahan Battery Company. This network is a multi-level, multi-product network where products are initially manufactured at production centers and then sent to customer centers through distribution centers. End-of-life products, which customers no longer wish to use, are collected and sorted at collection centers. Subsequently, the products are sent from collection centers to recycling centers. After recycling, a portion of the products is transferred back to production centers, and another portion is sent to disposal centers.

Energy-related considerations represent a critical yet often underexplored dimension of sustainability modeling in supply chain networks. While carbon emissions are frequently adopted as the primary environmental indicator, energy and electricity consumption capture operational efficiency and technology-related decisions more directly. Previous research has demonstrated that energy carrier consumption can be explicitly optimized within industrial and operational systems, providing actionable insights for decision-makers (Fathi et al., 2022). Moreover, recent energy-focused studies emphasize the strategic importance of modeling energy consumption separately from emission-based indicators, especially in systems where electricity use and carbon intensity do not move proportionally (Fathi et al., 2025). These insights motivate the explicit inclusion of electricity consumption as a distinct objective in green supply chain network design. The supply chain network under study is illustrated in Figure 1.

Figure 1) The Studied Supply Chain Network



The problem assumptions are presented as follows:

- The model is multi-level and multi-product.
- Product flow occurs only between consecutive different facilities; product flow between similar facilities is not allowed.
- The locations and number of customers and suppliers are fixed and known.
- Demand is a variable subject to uncertainty.
- Potential locations for production, distribution, collection, recycling, and disposal centers are identified.
- For each facility that can be established, three capacity levels are considered.

The studied supply chain network consists of four levels (supplier, production, distribution, and customers) in the forward network and three levels (collection centers, recycling centers, and disposal centers) in the reverse network. The proposed mathematical model includes three objective functions: (1) minimizing total costs, (2) minimizing electricity consumption and water waste, and (3) minimizing product delivery time. In this section, the proposed mathematical programming model and the notations used in the design of the supply chain network are specified.

Indices

$l = 1.2..3. \dots$	Fixed supplier locations set
$o = 1.2..3. \dots$	Potential production center locations set (for establishment)
$t = 1.2..3. \dots$	Potential distribution center locations set (for establishment)
$w = 1.2..3. \dots$	Fixed customer locations set
$z = 1.2..3. \dots$	Potential collection center locations set (for establishment)
$y = 1.2..3. \dots$	Potential recycling center locations set (for establishment)
$c = 1.2..3. \dots$	Potential disposal center locations set (for establishment)
$k = 1.2..3. \dots$	Product set
$a = 1.2..3. \dots$	Raw materials set
$e = 1.2..3. \dots$	Capacity levels set for potential locations
$b = 1.2..3. \dots$	Production technologies set in production centers

Parameters

$\widetilde{BT}_{kob}$	Production cost per unit of product k at production center o using production technology b
$\widetilde{BC}_{kc}$	Disposal cost per unit of product k at disposal center c
$\widetilde{BG}_{kz}$	Collection and inspection cost per unit of product k at collection center z
$\widetilde{BA}_{ky}$	Recycling cost per unit of product k at recycling center y
$\widetilde{AH}_{ko}$	Inventory holding cost of product k at production centers o
$\widetilde{MH}_{kt}$	Inventory holding cost of product k at distribution centers t
JAR_k	Penalty cost for unmet demand of product k
JBR_k	Penalty cost for uncollected returned product k
$\widetilde{KH}_{al}$	Purchase cost per unit of raw material aa from supplier l
$\widetilde{BKH}_{kw}$	Purchase cost per unit of returned product k from customer w
OC	Maximum number of production centers to be established
OD	Maximum number of distribution centers to be established
OF	Maximum number of collection centers to be established
OE	Maximum number of recycling centers to be established
OG	Maximum number of disposal centers to be established
$\widetilde{TA}_{kw}$	Demand quantity of product k at customer center w
$\widetilde{BAR}_{kw}$	Quantity of returns of product k from customer w
$\widetilde{ZAR}_{obe}$	Production capacity of production center o using technology bb at capacity level e
$\widetilde{ZBR}_{te}$	Distribution capacity of distribution center t at capacity level e
$\widetilde{ZCR}_{l}$	Capacity of supplier l
$\widetilde{ZPR}_{ze}$	Collection capacity of collection center z at capacity level e
$\widetilde{ZDR}_{ye}$	Recycling capacity of recycling center y at capacity level e
$\widetilde{ZER}_{ce}$	Disposal capacity of disposal center cc at capacity level e
$\widetilde{HAZ}_{alo}$	Transportation cost per unit of raw material aa from supplier l to production center o

$\widetilde{HBZ}_{kot}$	Transportation cost per unit of product k from production center o to distribution center t
$\widetilde{HCZ}_{ktw}$	Transportation cost per unit of product k from distribution center t to customer region w
$\widetilde{HDZ}_{kwz}$	Transportation cost per unit of product k from customer region w to collection center z
$\widetilde{HFZ}_{kzy}$	Transportation cost per unit of product k from collection center z to recycling center y
$\widetilde{HEZ}_{kyo}$	Transportation cost per unit of product k from recycling center y to production center o
$\widetilde{HHZ}_{kyc}$	Transportation cost per unit of product k from recycling center y to disposal center c
NR_{ak}	Usage rate of raw material a in the production of product k
$\widetilde{NRB}_{kwz}$	Return rate of used product k from customer region w to collection center z
$\widetilde{NRC}_{k}$	Recycling rate of used product k
$\widetilde{HCC}_{k}$	Disposal rate of used product k
$\widetilde{FE}_{obe}$	Fixed establishment cost of production center o using technology b at capacity level e
$\widetilde{EF}_{te}$	Fixed establishment cost of distribution center t at capacity level e
$\widetilde{CFF}_{ye}$	Fixed establishment cost of recycling center y at capacity level e
$\widetilde{DFE}_{ze}$	Fixed establishment cost of collection center z at capacity level e
DXE_{ce}	Fixed establishment cost of disposal center cc at capacity level e
$\widetilde{CO}_{kob}$	Carbon emissions per unit of product k produced at production center o using production technology bb
$\widetilde{COD}_{ky}$	Carbon emissions per unit of product k recycled at recycling center y
$\widetilde{COB}_{kc}$	Carbon emissions per unit of product k disposed of at disposal center c
$\widetilde{COA}_{kob}$	Electricity consumption per unit of product k produced at production center o using production technology b
$\widetilde{COC}_{ky}$	Electricity consumption per unit of product k recycled at recycling center y
$\widetilde{HHZ}_{kyc}$	Electricity consumption per unit of product k disposed of at disposal center c
$\widetilde{ZM}_{alo}$	Transportation time of raw material aa from supplier l to production center o
$\widetilde{ZMA}_{kot}$	Transportation time of product k from production center o to distribution center t
$\widetilde{ZMB}_{ktw}$	Transportation time of product k from distribution center t to customer w
$\widetilde{ZCB}_{kab}$	Production time of product k at production center o using production technology b

Decision Variables

MIZ_{alo}	Amount of raw material a shipped from supplier l to production center o
MIA_{kot}	Quantity of product k shipped from production center o to distribution center t
MIB_{ktw}	Quantity of product k shipped from distribution center t to customer zone w
MIC_{kzy}	Quantity of product k shipped from collection center z to recycling center y
MID_{kwz}	Quantity of product k shipped from customer zone w to collection center z
MIE_{kyo}	Quantity of product k shipped from recycling center y to production center o
MIF_{kyc}	Quantity of product k shipped from recycling center y to disposal center c
MOJ_{ko}	Inventory level of product k at production center o
MAJ_{kt}	Inventory level of product k at distribution center t
MAC_{kob}	Quantity of product k produced at production center o using technology b
TAZ_{wk}	Number of unmet demands for product k by customer w
TAB_{kw}	Number of uncollected returned products k from customer w

CC_{obe}	Equals 1 if a production center o with technology b and capacity level e is established; otherwise, 0
CDO_{te}	Equals 1 if a distribution center t with capacity level e is established; otherwise, 0
BDO_{ze}	Equals 1 if a collection center z with capacity level e is established; otherwise, 0
DDO_{ye}	Equals 1 if a recycling center y with capacity level e is established; otherwise, 0
ODO_{ce}	Equals 1 if a disposal center c with capacity level e is established; otherwise, 0
QDO_{ao}	Equals 1 if raw material a is supplied by supplier l; otherwise, 0

Objective Functions

$$\begin{aligned}
\min z_1 = {} & \sum_{o}\sum_{b}\sum_{e}(\widetilde{FE}_{obe} * CC_{obe}) + \sum_{t}\sum_{e}(\widetilde{EF}_{te} * CDO_{te}) \\
& + \sum_{z}\sum_{e}(\widetilde{DFE}_{ze} * BOO_{ze}) \\
& + \sum_{y}\sum_{e}(\widetilde{CFF}_{ye} * DDO_{ye}) \\
& + \sum_{c}\sum_{e}(\widetilde{DXE}_{ce} * ODO_{ce}) \\
& + \sum_{a}\sum_{l}\sum_{o}(\widetilde{HAZ}_{alo} * MIZ_{alo}) \\
& + \sum_{k}\sum_{o}\sum_{t}(\widetilde{HBZ}_{kot} * MIA_{kot}) \\
& + \sum_{k}\sum_{t}\sum_{w}(\widetilde{HCZ}_{ktw} * MIB_{ktw}) \\
& + \sum_{k}\sum_{w}\sum_{z}(\widetilde{HDZ}_{kwz} * MID_{kwz}) \\
& + \sum_{k}\sum_{z}\sum_{y}(\widetilde{HFZ}_{kzy} * MIC_{kzy}) \\
& + \sum_{k}\sum_{y}\sum_{o}(\widetilde{HEZ}_{kyo} * MIE_{kyo}) \\
& + \sum_{k}\sum_{y}\sum_{c}(\widetilde{HHZ}_{kyc} * MIF_{kyc}) \\
& + \sum_{k}\sum_{o}\sum_{b}(\widetilde{BT}_{kob} * MAC_{kob}) \\
& + \sum_{y}\sum_{k}\sum_{c}(\widetilde{BC}_{kc} * MIF_{ykc}) \\
& + \sum_{k}\sum_{z}\sum_{y}(\widetilde{BG}_{kz} * MIC_{kzy}) \\
& + \sum_{k}\sum_{y}\sum_{o}(\widetilde{BA}_{ky} * MIE_{kyo}) \\
& + \sum_{k}\sum_{o}(MOJ_{ko} * \widetilde{AH}_{ko}) \\
& + \sum_{k}\sum_{t}(MAJ_{kt} * \widetilde{MH}_{kt}) \\
& + \sum_{a}\sum_{l}\sum_{o}(\widetilde{KH}_{kl} * MIZ_{alo}) \\
& + \sum_{k}\sum_{w}\sum_{z}(\widetilde{Bkh}_{kw} * MID_{kwz})
\end{aligned} \tag{1}$$

$$\begin{aligned}
\min z_2 = & \left[\sum_k \sum_o \sum_b \sum_e CO_{kob} * CC_{obe} \right. \\
& + \sum_k \sum_y \sum_e COD_{ky} * DDO_{yc} \\
& \left. + \sum_k \sum_c \sum_e COB_{kc} * ODO_{ce} \right] \\
& + \left[\sum_k \sum_o \sum_b \sum_t COA_{kob} * MIA_{kot} \right. \\
& + \sum_k \sum_y \sum_c COF_{kc} * MIF_{kyc} \\
& \left. + \sum_k \sum_y \sum_o COC_{ky} * MIE_{kyo} \right]
\end{aligned} \tag{2}$$

$$\begin{aligned}
\min z_3 = & \sum_a \sum_l \sum_o (\widetilde{ZM}_{alo} * MIZ_{alo}) \\
& + \sum_o \sum_b \sum_e \sum_k (\widetilde{ZCB}_{kob} * CC_{obe}) \\
& + \sum_e \sum_k \sum_o \sum_t \sum_b (\widetilde{ZMA}_{kot} * CC_{obe}) \\
& + \sum_e \sum_k \sum_t \sum_w (\widetilde{ZMB}_{ktw} * CDO_{te})
\end{aligned} \tag{3}$$

Model Constraints

This section presents and examines the constraints of the proposed mathematical model.

$$\sum_e CDO_{te} \leq 1 \qquad \forall\, t \tag{4}$$

$$\sum_e BDO_{ze} \leq 1 \qquad \forall\, z \tag{5}$$

$$\sum_e DDO_{yc} \leq 1 \qquad \forall\, y \tag{6}$$

$$\sum_e ODO_{ce} \leq 1 \qquad \forall\, c \tag{7}$$

$$\sum_b \sum_e CC_{obe} \leq 1 \qquad \forall\, o \tag{8}$$

$$\sum_o \sum_b \sum_e CC_{obe} \leq OC \tag{9}$$

$$\sum_t \sum_e CDO_{te} \leq OD \tag{10}$$

$$\sum_z \sum_e BDO_{ze} \leq OF \tag{11}$$

$$\sum_{y}\sum_{e} DDO_{ye} \le OE \tag{12}$$

$$\sum_{c}\sum_{e} ODO_{ce} \le OG \tag{13}$$

$$\sum_{z} MIC_{kzy} \ge \sum_{o} MIE_{kyo} + \sum_{c} MIF_{kyc} \qquad \forall\, k.y \tag{14}$$

$$\sum_{y} MIC_{kzy} \ge \sum_{o} \widetilde{NRC}_{k} * \sum_{w} MID_{kwz} \qquad \forall\, k.z \tag{15}$$

$$\sum_{l}\sum_{o} NR_{ak} *\ MIZ_{alo} \ge \sum_{o}\sum_{b} MAC_{kob} \qquad \forall\, a.k \tag{16}$$

$$\sum_{a}\sum_{o} MIZ_{alo} \le \widetilde{ZCR}_{l} \qquad \forall\, l \tag{17}$$

$$\sum_{k}\sum_{b} MAC_{kob} \le \sum_{b}\sum_{e} CC_{obe} * \widetilde{ZAR}_{obe} \qquad \forall\, o \tag{18}$$

$$\sum_{k}\sum_{w} MIB_{ktw} \le \sum_{e} CDO_{te} * \widetilde{ZBR}_{te} \qquad \forall\, t \tag{19}$$

$$\sum_{k}\sum_{w} MID_{kwz} \le \sum_{e} BDO_{ze} * \widetilde{ZPR}_{ze} \qquad \forall\, z \tag{20}$$

$$\sum_{k}\sum_{z} MIC_{kzy} \le \sum_{e} DDO_{ye} * \widetilde{ZDR}_{ye} \qquad \forall\, y \tag{21}$$

$$\sum_{k}\sum_{y} MIF_{kyc} \le \sum_{e} ODO_{ce} * \widetilde{ZER}_{ce} \qquad \forall\, c \tag{22}$$

$$\sum_{t} MIB_{ktw} \le\ \widetilde{TA}_{kw} \qquad \forall\, k.w \tag{23}$$

$$\sum_{z} MID_{kwz} \le\ \widetilde{TA}_{kw} *\ \widetilde{BAR}_{wk} \qquad \forall\, k.w \tag{24}$$

$$\widetilde{TA}_{kw} - \sum_{t} MIB_{ktw} =\ TAZ_{wk} \qquad \forall\, k.w \tag{25}$$

$$\widetilde{BAR}_{wk} - \sum_{z} MID_{kwz} =\ TAB_{kw} \qquad \forall\, k.w \tag{26}$$

$$CC_{obe}\,.CDO_{te}\,.\,.BDO_{ze}\,.\,.DDO_{ye}\,.\,.ODO_{ce}\,.\,.QDO_{ao} \in \{0.1\} \qquad \forall\, o.b.e.t..\,.a \tag{27}$$

$$\begin{gathered} MIZ_{alo}\,.MIA_{kot}\,.MIB_{ktw}\,.MIC_{kzy}.MID_{kwz}.MIE_{kyo}\,.MIF_{kyc}\,.MOJ_{ko}\,.MAJ_{k} \\ .MAC_{kob}\,.\ TAZ_{wk}\,.TAB_{kw}\ \ge 0 \end{gathered} \qquad \forall\, a.l.o.k.\,.w.y.z.b \tag{28}$$

The first objective function is an economic objective aiming to minimize the total costs associated with supply, production, distribution, collection, recycling, and disposal. The second objective function minimizes energy consumption and the generation of pollutants, including carbon emissions. The third objective function seeks to minimize the total time taken for the product to reach the customer. This function considers the time required for the transportation of raw materials from suppliers to manufacturers, the transportation of products from manufacturers to distribution centers, from distribution centers to customers, and the production time at manufacturing facilities. Constraints (4) to (7) ensure that each distribution center, collection center, recycling center, and disposal center is established, at most, at one capacity level. Constraint (8) guarantees that only one capacity level and one production technology are assigned to each production facility. Constraints (9) to (13) define the maximum number of productions, distribution, collection, recycling, and disposal centers that may be established based on potential locations. Constraint (14) ensures that the inflow to recycling centers is greater than or equal to the outflow from these centers. Constraint (15) ensures that the amount transferred from collection centers to recycling centers is at least a fixed proportion of the total inflow to the collection centers. Constraint (16) indicates that production centers require a proportion of raw materials supplied by suppliers in order to manufacture products. Constraint (17) ensures that for each raw material, the total outbound flow from each supplier to all production centers does not exceed the supplier's capacity. Constraints (18) through (22) determine the maximum allowable capacity for production, distribution, collection, recycling, and disposal centers. Constraint (23) states that the product flow reaching customers through distribution centers shall not exceed the customer demand. Constraint (24) establishes the relationship between customer demand and the flow of returned products from customers to collection centers. Constraint (25) defines the amount of unmet demand. Constraint (26) limits the number of uncollected returns. Finally, constraints (27) and (28) represent logical constraints on the decision variables, where constraint (27) applies to binary (discrete) variables and constraint (28) applies to continuous variables.

In this study, due to the presence of fuzzy parameters in the model, the defuzzification process was carried out using the Jiménez approach (Jiménez et al., 2007). This method transforms fuzzy numbers into their corresponding crisp values based on the concept of mean comparison, enabling the model to be solved using conventional mathematical programming techniques.

$$
\begin{aligned}
\min z_1 = {} & \sum_{o}\sum_{b}\sum_{e}\left(\frac{FE^{a}_{obe} + 2FE^{b}_{obe} + FE^{e}_{obe}}{4}\right) * CC_{obe} \\
& + \sum_{t}\sum_{e}\left(\frac{EF^{a}_{te} + 2EF^{b}_{te} + EF^{e}_{te}}{4}\right) * CDO_{te} \\
& + \sum_{z}\sum_{e}\left(\frac{DFE^{a}_{ze} + 2DFE^{b}_{ze} + DFE^{e}_{ze}}{4}\right) * BDO_{ze} \\
& + \sum_{y}\sum_{e}\left(\frac{CFF^{a}_{ye} + 2FF^{b}_{ye} + CFF^{e}_{ye}}{4}\right) * DDO_{ye} \\
& + \sum_{c}\sum_{e}\left(\frac{DXE^{a}_{ce} + 2DXE^{b}_{ce} + DXE^{e}_{ce}}{4}\right) * ODO_{ce} \\
& + \sum_{a}\sum_{l}\sum_{o}\left(\frac{HAZ^{a}_{alo} + 2HAZ^{b}_{alo} + HAZ^{e}_{alo}}{4}\right) * MIZ_{alo} \\
& + \sum_{k}\sum_{o}\sum_{t}\left(\frac{HBZ^{a}_{kot} + 2HBZ^{b}_{kot} + HBZ^{e}_{kot}}{4}\right) * MIA_{kot} \\
& + \sum_{k}\sum_{t}\sum_{w}\left(\frac{HCZ^{a}_{ktw} + 2HCZ^{b}_{ktw} + HCZ^{e}_{ktw}}{4}\right) * MIB_{ktw} \\
& + \sum_{k}\sum_{w}\sum_{z}\left(\frac{HDZ^{a}_{kwz} + 2HDZ^{b}_{kwz} + HDZ^{e}_{kwz}}{4}\right) * MID_{kwz} \\
& + \sum_{k}\sum_{z}\sum_{y}\left(\frac{HFZ^{a}_{kzy} + 2HFZ^{b}_{kzy} + HFZ^{e}_{kzy}}{4}\right) * MIC_{kzy} \\
& + \sum_{k}\sum_{y}\sum_{o}\left(\frac{HEZ^{a}_{kyo} + 2HEZ^{b}_{kyo} + HEZ^{e}_{kyo}}{4}\right) * MIE_{kyo} \\
& + \sum_{k}\sum_{y}\sum_{c}\left(\frac{HHZ^{a}_{kyc} + 2HHZ^{b}_{kyc} + HHZ^{e}_{kyc}}{4}\right) * MIF_{kyc} \\
& + \sum_{k}\sum_{o}\sum_{b}\left(\frac{BT^{a}_{kob} + 2BT^{b}_{kob} + BT^{e}_{kob}}{4}\right) * MAC_{kob} \\
& + \sum_{y}\sum_{k}\sum_{c}\left(\frac{BC^{a}_{kc} + 2BC^{b}_{kc} + BC^{e}_{kc}}{4}\right) * MIF_{ykc} \\
& + \sum_{k}\sum_{z}\sum_{y}\left(\frac{BG^{a}_{kz} + 2BG^{b}_{kz} + BG^{e}_{kz}}{4}\right) * MIC_{kzy} \\
& + \sum_{k}\sum_{y}\sum_{o}\left(\frac{BA^{a}_{ky} + 2BA^{b}_{ky} + BA^{e}_{ky}}{4}\right) * MIE_{kyo} \\
& + \sum_{k}\sum_{o}\left(\frac{AH^{a}_{ko} + 2AH^{b}_{ko} + AH^{e}_{ko}}{4}\right) * MOJ_{ko} \\
& + \sum_{k}\sum_{t}\left(\frac{MH^{a}_{kt} + 2MH^{b}_{kt} + MH^{e}_{kt}}{4}\right) * MAJ_{kt} \\
& + \sum_{a}\sum_{l}\sum_{o}\left(\frac{KH^{a}_{al} + 2KH^{b}_{al} + KH^{e}_{al}}{4}\right) * MIZ_{alo} \\
& + \sum_{k}\sum_{w}\sum_{z}\left(\frac{BKH^{a}_{kw} + 2BKH^{b}_{kw} + BKH^{e}_{kw}}{4}\right) * MID_{kwz}
\end{aligned}
\tag{29}
$$

$$\begin{aligned}\min z_2 = \Bigg[&\sum_{k}\sum_{o}\sum_{b}\sum_{e} CO_{kob} * CC_{obe} \\ &+ \sum_{k}\sum_{y}\sum_{e} COD_{ky} * DDO_{yc} + \sum_{k}\sum_{c}\sum_{e} COB_{kc} \\ &* ODO_{ce}\Bigg] \\ &+ \Bigg[\sum_{k}\sum_{o}\sum_{b}\sum_{t} COA_{kob} * MIA_{kot} \\ &+ \sum_{k}\sum_{y}\sum_{c} COF_{kc} * MIF_{kyc} + \sum_{k}\sum_{y}\sum_{o} COC_{ky} \\ &* MIE_{kyo}\Bigg]\end{aligned} \tag{30}$$

$$\begin{aligned}\min z_3 = &\sum_{a}\sum_{l}\sum_{o}\left(\frac{ZM^{a}_{alo} + 2ZM^{b}_{alo} + ZM^{e}_{alo}}{4}\right) * MIZ_{alo} \\ &+ \sum_{o}\sum_{b}\sum_{e}\sum_{k}\left(\frac{ZCB^{a}_{kob} + 2ZCB^{b}_{kob} + ZCB^{e}_{kob}}{4}\right) * CC_{obe} \\ &+ \sum_{e}\sum_{k}\sum_{o}\sum_{t}\sum_{b}\left(\frac{ZMA^{a}_{kot} + 2ZMA^{b}_{kot} + ZMA^{e}_{kot}}{4}\right) \\ &* CC_{obe} \\ &+ \sum_{e}\sum_{k}\sum_{t}\sum_{w}\left(\frac{ZMB^{a}_{ktw} + 2ZMB^{b}_{ktw} + ZMB^{e}_{ktw}}{4}\right) \\ &* CDO_{te}\end{aligned} \tag{31}$$

$$\sum_{e} CDO_{te} \le 1 \qquad \forall\, t \tag{32}$$

$$\sum_{e} BDO_{ze} \le 1 \qquad \forall\, z \tag{33}$$

$$\sum_{e} DDO_{yc} \le 1 \qquad \forall\, y \tag{34}$$

$$\sum_{e} ODO_{ce} \le 1 \qquad \forall\, c \tag{35}$$

$$\sum_{b}\sum_{e} CC_{obe} \le 1 \qquad \forall\, o \tag{36}$$

$$\sum_{o}\sum_{b}\sum_{e} CC_{obe} \le OC \tag{37}$$

$$\sum_{t}\sum_{e} CDO_{te} \le OD \tag{38}$$

$$\sum_{z}\sum_{e} BDO_{ze} \le OF \tag{39}$$

$$\sum_{y}\sum_{e} DDO_{ye} \leq OE \tag{40}$$

$$\sum_{c}\sum_{e} ODO_{ce} \leq OG \tag{41}$$

$$\sum_{z} MIC_{kzy} \geq \sum_{o} MIE_{kyo} + \sum_{c} MIF_{kyc} \qquad \forall\, k.y \tag{42}$$

$$\sum_{y} MIC_{kzy} \geq \left[\alpha * \left(\frac{NRC_{k}^{b} + NRC_{k}^{e}}{2}\right) + (1-\alpha) * \left(\frac{NRC_{k}^{a} + NRC_{k}^{b}}{2}\right)\right] * \sum_{w} MID_{kwz} \qquad \forall\, k.z \tag{43}$$

$$\sum_{l}\sum_{o} NR_{ak} * \; MIZ_{alo} \geq \sum_{o}\sum_{b} MAC_{kob} \qquad \forall\, a.k \tag{44}$$

$$\sum_{a}\sum_{o} MIZ_{alo} \leq \alpha * \left(\frac{ZCR_{l}^{a} + ZCR_{l}^{b}}{2}\right) + (1-\alpha) * \left(\frac{ZCR_{l}^{b} + ZCR_{l}^{e}}{2}\right) \qquad \forall\, l \tag{45}$$

$$\sum_{k}\sum_{b} MAC_{kob} \leq \sum_{b}\sum_{e} CC_{obe} * \left[\alpha * \left(\frac{ZAR_{obe}^{a} + ZAR_{obe}^{b}}{2}\right) + (1-\alpha) * \left(\frac{ZAR_{obe}^{b} + ZAR_{obe}^{e}}{2}\right)\right] \qquad \forall\, o \tag{46}$$

$$\sum_{k}\sum_{w} MIB_{ktw} \leq \sum_{e} CDO_{te} * \left[\alpha * \left(\frac{ZBR_{te}^{a} + ZBR_{te}^{b}}{2}\right) + (1-\alpha) * \left(\frac{ZBR_{te}^{b} + ZBR_{te}^{e}}{2}\right)\right] \qquad \forall\, t \tag{47}$$

$$\sum_{k}\sum_{w} MID_{kwz} \leq \sum_{e} BDO_{ze} * \left[\alpha * \left(\frac{ZPR_{ze}^{a} + ZPR_{ze}^{b}}{2}\right) + (1-\alpha) * \left(\frac{ZPR_{ze}^{b} + ZPR_{ze}^{e}}{2}\right)\right] \qquad \forall\, z \tag{48}$$

$$\sum_{k}\sum_{z} MIC_{kzy} \leq \sum_{e} DDO_{ye} * \left[\alpha * \left(\frac{ZDR_{ye}^{a} + ZDR_{ye}^{b}}{2}\right) + (1-\alpha) * \left(\frac{ZDR_{ye}^{b} + ZDR_{ye}^{e}}{2}\right)\right] \qquad \forall\, y \tag{49}$$

$$\sum_{k}\sum_{y} MIF_{kyc} \leq \sum_{e} ODO_{ce} * \left[\alpha * \left(\frac{ZER_{ce}^{a} + ZER_{ce}^{b}}{2}\right) + (1-\alpha) * \left(\frac{ZER_{ce}^{b} + ZER_{ce}^{e}}{2}\right)\right] \qquad \forall\, c \tag{50}$$

$$\sum_{t} MIB_{ktw} \leq \left[\alpha * \left(\frac{TA_{kw}^{a} + TA_{kw}^{b}}{2}\right) + (1-\alpha) * \left(\frac{TA_{kw}^{b} + TA_{kw}^{e}}{2}\right)\right] \qquad \forall\, k.w \tag{51}$$

$$\sum_{z} MID_{kwz} \le \left[\alpha * \left(\frac{TA^{a}_{kw} + TA^{b}_{kw}}{2}\right) + (1-\alpha) * \left(\frac{TA^{b}_{kw} + TA^{e}_{kw}}{2}\right)\right] * \left[\alpha * \left(\frac{BAR^{a}_{wk} + BAR^{b}_{wk}}{2}\right) + (1-\alpha) * \left(\frac{BAR^{b}_{wk} + BAR^{e}_{wk}}{2}\right)\right] \qquad \forall\, k.w \qquad (52)$$

$$\left[\frac{\alpha}{2} * \left(\frac{TA^{b}_{kw} + TA^{e}_{kw}}{2}\right) + \left(1-\frac{\alpha}{2}\right) * \left(\frac{TA^{a}_{kw} + TA^{b}_{kw}}{2}\right)\right] - \sum_{t} MIB_{ktw} \le TAZ_{wk} \qquad \forall\, k.w \qquad (53)$$

$$\left[\left(1-\frac{\alpha}{2}\right) * \left(\frac{TA^{b}_{kw} + TA^{e}_{kw}}{2}\right) + \frac{\alpha}{2} * \left(\frac{TA^{a}_{kw} + TA^{b}_{kw}}{2}\right)\right] - \sum_{t} MIB_{ktw} \ge TAZ_{kw} \qquad \forall\, k.w \qquad (54)$$

$$\left[\frac{\alpha}{2} * \left(\frac{BAR^{b}_{wk} + BAR^{e}_{wk}}{2}\right) + \left(1-\frac{\alpha}{2}\right) * \left(\frac{BAR^{a}_{wk} + BAR^{b}_{wk}}{2}\right)\right] - \sum_{z} MID_{ktw} \le TAB_{wk} \qquad \forall\, k.w \qquad (55)$$

$$\left[\left(1-\frac{\alpha}{2}\right) * \left(\frac{BAR^{b}_{wk} + BAR^{e}_{wk}}{2}\right) + \frac{\alpha}{2} * \left(\frac{BAR^{a}_{wk} + BAR^{b}_{wk}}{2}\right)\right] - \sum_{z} MID_{kwz} \ge TAB_{wk} \qquad \forall\, k.w \qquad (56)$$

$$CC_{obe}\,.CDO_{te}\,.\,.BDO_{ze}\,.\,.DDO_{ye}\,.\,.ODO_{ce}\,.\,.QDO_{ao} \in \{0.1\} \qquad \forall\, o.b.e.t..\,z.y.a \qquad (57)$$

$$MIZ_{alo}\,.MIA_{kot}\,.MIB_{ktw}\,.MIC_{kzy}.MID_{kwz}.MIE_{kyo}\,.MIF_{kyc}\,.\,MOJ_{ko}\,.MAJ_{kt}\,.MAC_{kob}\,.\,TAZ_{wk}\,.TAB_{kw} \ge 0 \qquad \forall\, a.l.o.k.\,.w.y.z.b \qquad (58)$$

5. Results

Based on the analyses conducted in this study, the proposed model involves the design of GCLSCN for battery products. The network considers five types of battery products, four supplier centers, six production facilities, five distribution centers, eight customer zones, four collection centers, three recycling facilities, and two disposal centers. To evaluate the model's performance under a multi-objective framework, a goal-prioritization approach was adopted, focusing on minimizing total economic cost, minimizing energy and water consumption, and minimizing product delivery time to customers. Using this prioritization strategy, the Pareto-optimal solutions were generated for 10 different weight scenarios, with up to 100 non-dominated solutions in the solution space, as shown in Table 1.

Table 1) Pareto Frontier Outputs Based on Objective Function Prioritization

Objective Priority	**Objective 1 Value (Cost)**	**Objective 2 Value (Energy & Water Consumption)**	**Objective 3 Value (Delivery Time)**	**Best Objective Value**
Priority on Objective 1	18,785,698	1,196	15.2	18,785,698
Priority on Objective 2	19,741,855	988	16.7	988

Priority on Objective 3	20,113,246	1,221	12.4	12.4

Real-world problems often involve complexities such as nonlinearity and non-convexity, which reduce the efficiency of classical methods. Therefore, metaheuristic algorithms are frequently employed to address such challenges. Although these algorithms lack a strong mathematical foundation, they perform well in delivering satisfactory approximate solutions within reasonable time frames. Among the metaheuristics commonly applied to multi-objective problems are the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) and the Non-Dominated Ranked Genetic Algorithm (NRGA). Given that the objective functions in this research exhibit Pareto characteristics and conflicting directions, multi-objective metaheuristic algorithms were utilized to determine the optimal weighting of objectives. NSGA-II is recognized as one of the most fundamental and widely used metaheuristic algorithms for solving multi-objective problems. Its main steps include initializing the population, evaluating fitness, sorting the population based on dominance criteria, calculating crowding distance, selection, crossover and mutation operations, merging the initial and offspring populations, and finally replacing the population. The specific parameter values used in the algorithms are presented in Table 2, where the mutation or crossover rate indicates the percentage of the initial population selected for these operations.

Table 2) Algorithm Parameters

Values	**Parameters**
Number of iterations (generations)	130
Initial population size	100
Crossover probability (rate)	0.9
Mutation probability (rate)	0.1

In this study, to evaluate the proposed model, the results of the NSGA-II algorithm are compared with those of the NRGA algorithm. For this purpose, several performance metrics have been defined, including the distance from the ideal solution or mean distance from the origin (MID), the diversity of solutions, the number of Pareto solutions (NPS), and computer processing time (TIME). Based on these standard criteria and the Pareto points obtained from solving the model with both NRGA and NSGA-II algorithms, the solution results are presented in Table 3.

Table 3) Comparison of NSGA-II and NRGA Algorithms Based on Performance Metrics

Problem No.	**NSGA-II**				**NRGA**			
	NPS	MID	Diversity	TIME	NPS	MID	Diversity	TIME
1	44	51234	311245	12.1	50	543212	324678	6.9
2	51	376543	312876	9.8	60	221345	655123	7.5
3	70	398765	667891	10.4	59	532876	112345	13.2
4	78	245678	510987	17.6	73	312456	530123	20.4
5	41	167890	270987	22.1	60	545678	310987	23.7
6	59	498765	785432	25.3	78	421345	660234	27.8
7	33	378901	750123	32.9	62	299876	700123	35.6
8	39	655321	4423450	47.2	72	745123	640987	50.1
9	66	266789	6400123	73.4	85	634567	6432109	79.9
10	63	434321	7901234	26.7	68	465432	4212345	28.3
Total	544	3474207	22334348	277.5	667	4721910	14579054	293.4

In this study, the performance of two multi-objective metaheuristic algorithms NSGA-II and NRGA was compared using four standard evaluation metrics: The Number of Pareto Solutions (NPS), Mean Ideal Distance (MID), Diversity, and Execution Time (TIME). Regarding NPS, the NRGA algorithm outperformed NSGA-II by generating 667 Pareto-optimal solutions compared to 544, indicating a stronger capability in producing non-dominated solutions.

However, for the MID metric, where lower values represent closer proximity to the ideal solution, NSGA-II performed better than NRGA, demonstrating its effectiveness in finding more optimal solutions. With respect to Diversity, which reflects the spread and coverage of the solution space across the Pareto front, NSGA-II significantly outperformed NRGA, showing its strength in maintaining solution diversity.

Although the difference in execution time between the two algorithms was not drastic, NSGA-II showed slightly better computational efficiency with a lower total run time. Overall, despite NRGA's advantage in the number of Pareto solutions, NSGA-II demonstrated superior performance across key quality metrics, particularly in MID and Diversity, and maintained acceptable computational efficiency. These findings suggest that NSGA-II is a more suitable and reliable approach for solving complex multi-objective problems, such as the GCLSCN design model addressed in this study. Furthermore, Figures (2) to (5) illustrate the comparison between the algorithms based on the four aforementioned criteria.

Figure 2) Comparison of NRGA and NSGA-II Algorithms Based on the NPS Metric

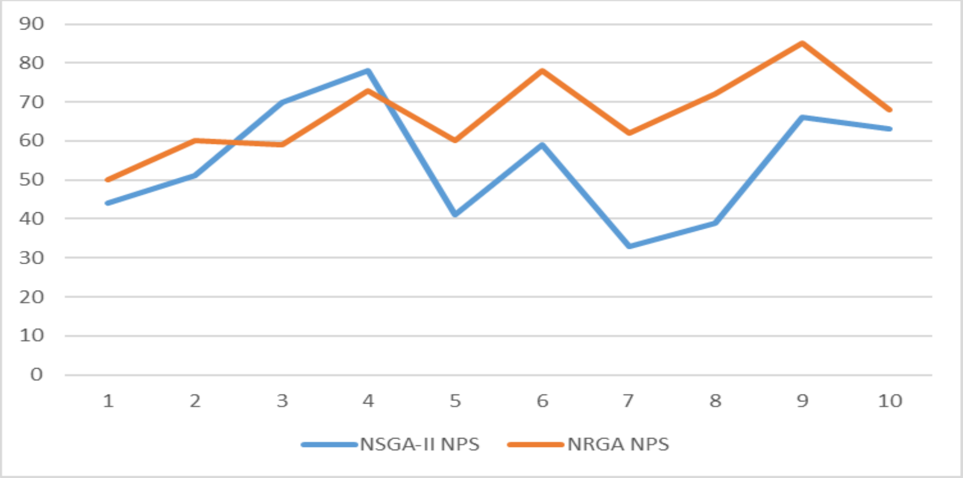


Figure 3) Comparison of NRGA and NSGA-II Algorithms Based on the MID Metric

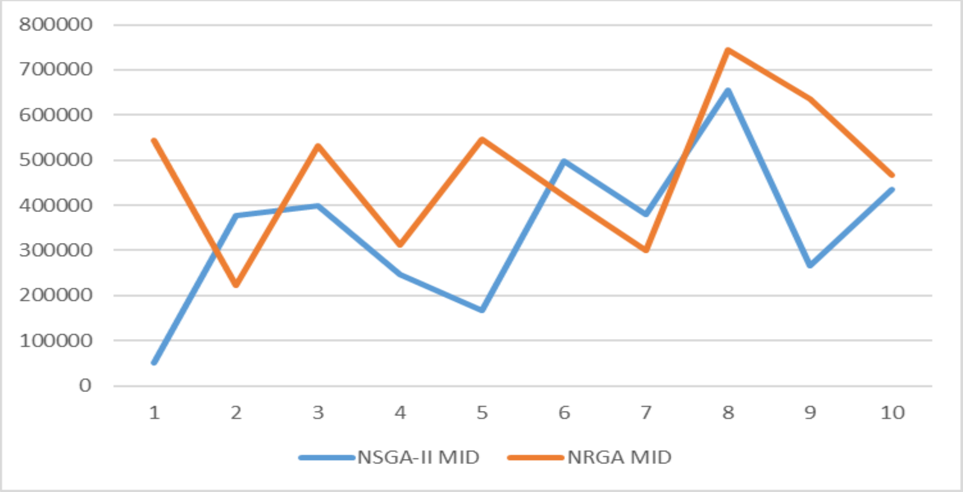


Figure 4) Comparison of NRGA and NSGA-II Algorithms Based on the TIME Metric

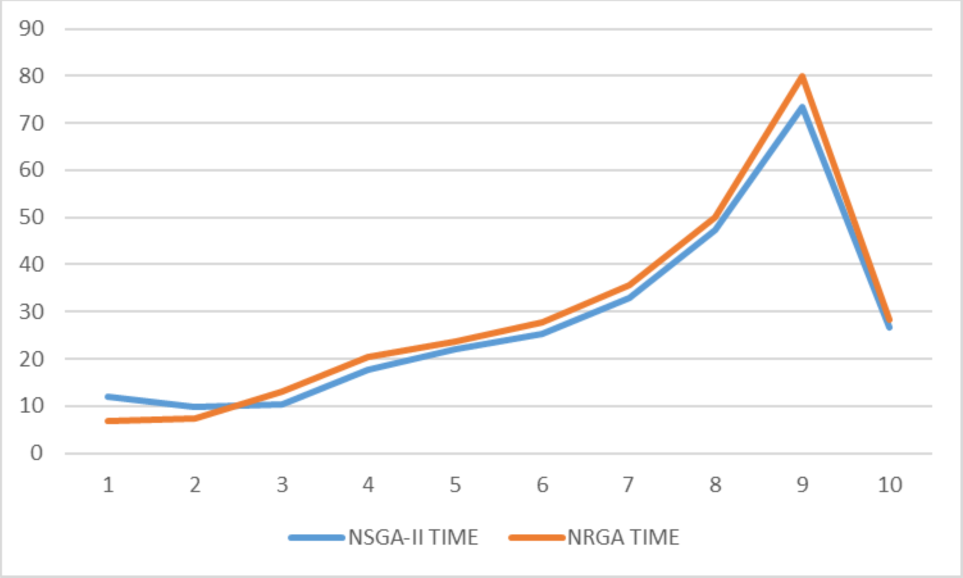
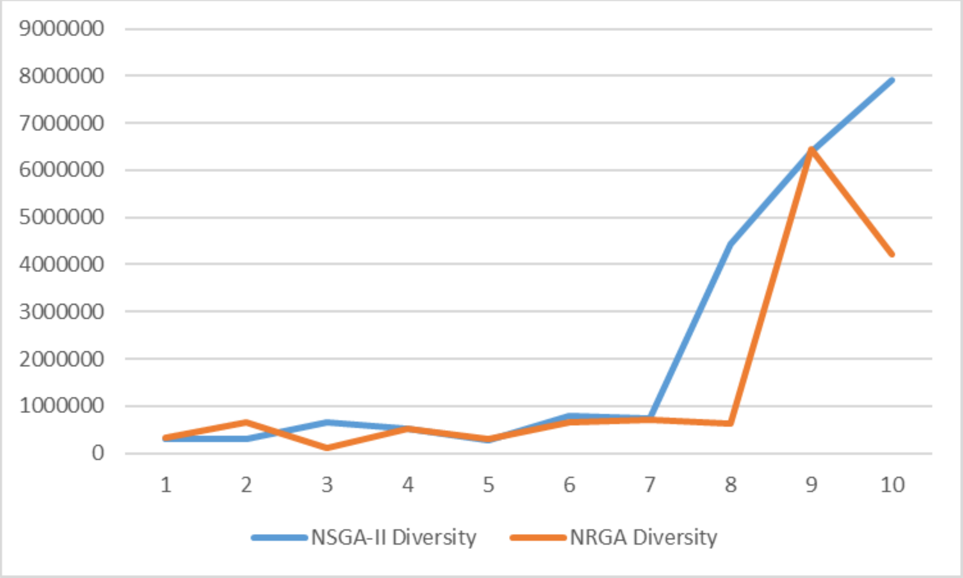


Figure 5) Comparison of NRGA and NSGA-II Algorithms Based on the Diversity Metric



6) Discussion and Conclusion

This study focused on the design of a green closed-loop supply chain network for battery products using a multi-objective approach. The proposed model, by considering economic, environmental, and temporal dimensions simultaneously, provided a comprehensive perspective on the challenges and opportunities in sustainable management of this supply chain. By aiming to minimize total costs, reduce energy consumption and pollutants, and accelerate product delivery time, the model was able to achieve a suitable balance among these conflicting objectives. The optimized decisions at the network level brought significant benefits to the organization. The findings revealed a trade-off between economic and environmental objectives; reducing total costs might lead to increased energy consumption or longer delivery times, and vice versa. This highlights the necessity of multi-objective approaches and intelligent optimization algorithms to identify Pareto-optimal solutions that balance these variables effectively. Results obtained from the NSGA-II and NRGA algorithms demonstrated that both are capable of efficiently solving multi-objective supply chain problems. However, NSGA-II provided more diverse and widespread solutions based on the diversity metric, which is critically important in multi-objective optimization. On the other hand, NRGA exhibited better computational time performance, an advantage that can be crucial for practical applications with time constraints. Incorporating different capacity levels in supply chain facilities and considering various production technologies enhanced the model's flexibility and enabled more precise strategic decision-making. Furthermore, by addressing demand uncertainty, the model exhibited higher realism and applicability in practical scenarios. Beyond theoretical contributions, this research offers substantial practical implications. Battery manufacturing companies and related supply chain stakeholders can utilize this model to reduce operational costs, improve environmental performance, and optimize product delivery times. Moreover, the proposed framework can serve as a foundation for future studies in sustainable and closed-loop supply chains across other industries. Although some parameters in this study were modeled with inherent uncertainty using fuzzy sets and then defuzzified through the Jiménez method, several limitations remain that warrant future investigation. Firstly, certain cultural and social factors affecting supply chain performance were not comprehensively integrated. Developing models that simultaneously and accurately capture these multidimensional aspects under uncertainty could enhance result precision. Secondly, the current model is static with parameters assumed over fixed time intervals, while real markets and demand conditions are dynamic and variable. Future research should explore dynamic modeling approaches using real-time data to improve model responsiveness and alignment with real-world conditions. Moreover, while risk and uncertainty analyses were partially addressed via fuzzy-to-crisp conversion, employing more advanced uncertainty analysis techniques, such as fuzzy probabilities or scenario analysis, could deepen the insights. Finally, expanding the model to incorporate emerging technologies, such as artificial intelligence and the Internet of Things, within green supply chain management presents a promising direction for forthcoming research. It is also recommended that future studies consider diverse industrial sectors and products with varying characteristics to develop tailored models and solutions, thereby enhancing the generalizability of findings.

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