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Amir M. Fathollahi-Fard

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ORIGINAL STUDY

An Integrated Decision-Making Framework for a Closed-Loop Supply Chain Network Redesign Problem

Amir M. Fathollahi-Fard [a,b]

[a] Département d'Analytique, Opérations et Technologies de l'Information, Université du Québec à Montréal, B.P. 8888, Succ. Centre-ville, Montréal, QC H3C 3P8, Canada
[b] New Era and Development in Civil Engineering Research Group, Scientific Research Center, Al-Ayen University, Nasiriyah, Thi-Qar 64001, Iraq

ABSTRACT

The rapid growth in demand and environmental concerns in industries like glass manufacturing necessitate the redesign of closed-loop supply chain (CLSC) networks to address both operational inefficiencies and sustainability challenges. Unlike conventional supply chain design, redesigning CLSC networks involves strategic decisions such as opening new facilities, closing existing ones, and managing the cost trade-offs associated with these transitions. Motivated by these challenges, this paper proposes an integrated decision-making framework to tackle the closed-loop supply chain network redesign (CLSCNR) problem. The proposed framework is formulated as a mixed-integer programming (MIP) model, specifically tailored for the glass industry. The forward supply chain includes suppliers, manufacturers, distributors, and customers, while the reverse supply chain comprises collection centers that allocate returned and waste products to recycling, remanufacturing, or disposal centers. This redesign approach addresses critical challenges in facility location, capacity planning, and customer assignment to better align supply chain operations with increasing demand and sustainability goals. Extensive numerical analyses were conducted using 16 test instances, revealing significant improvements through network redesign. For example, the number of open centers decreased by 1 in several instances (such as T5 and T9), while in other instances, up to 3 centers were closed (e.g., T13). The difference in the number of open centers before and after the redesign highlights the ability of the proposed framework to streamline network operations while maintaining service levels. The computational time ranged from 27.48 seconds for smaller instances to 62.26 seconds for larger ones, demonstrating the model's efficiency and scalability. The findings demonstrate the proposed MIP's ability to optimize network configurations, enhancing operational efficiency and demand satisfaction. These insights provide a practical decision-support tool for supply chain designers, enabling companies in high-demand industries to achieve adaptive and sustainable CLSC networks.

Keywords: Closed-loop supply chain network redesign, Demand satisfaction, Glass industry, Mixed-integer program, Optimization

1. Introduction

The rising global emphasis on sustainability and the circular economy has underscored the importance of efficient closed-loop supply chain (CLSC) networks [1]. CLSC systems play a vital role in minimizing waste, reducing environmental impacts, and optimizing resource utilization by integrating forward and reverse logistics processes [2, 3]. Industries such as the glass sector, which face rapid growth in demand and increasing regulatory pressures, are particularly in need of efficient supply chain solutions to enhance operational efficiency and sustainability [4]. However, existing CLSC networks often struggle to satisfy

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E-mail address: fathollahifard.amirmohammad@courrier.uqam.ca (A. M. Fathollahi-Fard).

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escalating customer demands while addressing environmental concerns, necessitating a strategic redesign of these CLSC systems. Based on this motivation, this paper explores the closed-loop supply chain network redesign (CLSCNR) problem which can enable businesses to achieve significant cost savings, improve service levels, and align their operations with sustainability goals.

Despite its potential, the CLSCNR process involves complex challenges. Unlike traditional supply chain design, redesigning a CLSC requires making interdependent decisions about opening new facilities, closing or upgrading existing ones, and adapting capacity configurations, while balancing fixed and variable costs. Additionally, the glass industry's unique characteristics, such as handling fragile products, recycling constraints, and remanufacturing complexities, add layers of intricacy to the redesign process. Addressing these challenges demands an integrated decision-making framework capable of simultaneously optimizing forward and reverse supply chain operations through the novel CLSCNR problem.

To this end, this study proposes a novel CLSCNR framework formulated as a mixed-integer programming (MIP) model tailored for the glass industry. The framework integrates key decision variables related to facility location, allocation, and customer assignment across the forward and reverse supply chain. Specifically, the forward supply chain encompasses suppliers, manufacturers, distributors, and customers, while the reverse supply chain includes collection centers, recycling facilities, remanufacturing units, and disposal centers.

In conclusion, the primary contributions of this research are threefold:

- To develop a comprehensive decision-making model that addresses the CLSC network redesign in the glass industry.
- To evaluate the impact of critical factors such as redesign costs, on network performance.
- To provide actionable insights and a decision-support tool for supply chain managers to optimize CLSC configurations, ensuring adaptability and sustainability in high-demand industries.

This paper's contributions lie in its ability to bridge the gap between theory and practice by providing an efficient methodology to solve CLSCNR problems. Extensive sensitivity analyses validate the proposed framework's effectiveness, demonstrating its practical applicability for addressing real-world supply chain challenges. By advancing the field of supply chain management, this research provides a foundation for future studies aimed at enhancing the adaptability and efficiency of CLSC systems in various industries.

The structure of this paper is organized as follows: Section 2 defines the problem setting, explaining the scope and framework of the CLSCNR process. Section 3 reviews prior research on CLSC networks, highlighting key studies and identifying unresolved challenges that this work aims to address. Section 4 develops the CLSCNR problem using MIP model, incorporating factors tailored to the glass industry's unique requirements. Section 5 analyzes the model's performance, presenting results along with analyses to evaluate its effectiveness and practical relevance. Lastly, Section 6 concludes by summarizing the key outcomes, offering practical recommendations, addressing study limitations, and suggesting avenues for future exploration.

2. Problem settings

This section introduces the problem setting for redesigning a CLSC network in the glass industry. The structure and components of the problem under study are detailed as follows: Section 2.1 describes the physical layout of the conceptual CLSC network, illustrating the integration of forward and reverse flows. Section 2.2 focuses on the role and characteristics of suppliers, highlighting their contributions to the forward supply chain. Section 2.3 examines manufacturers, emphasizing their operational requirements and specific features within the glass industry. Section 2.4 discusses the role of distributors, detailing their responsibilities in delivering glass products to various markets and their critical position in the supply chain. Section 2.5 provides an overview of customer demands, explaining how these are quantified and addressed within the network.

In the reverse flow, Section 2.6 highlights the role of collectors, focusing on the collection and management of returned glass products and waste. Section 2.7 explores the role of recyclers, underlining their importance in processing waste and returned products to promote sustainability. Section 2.8 discusses remanufacturers and their role in restoring returned products for reuse in distributing centers. Finally, Section 2.9 examines the role of disposal centers in managing non-recyclable and non-usable wastes within the CLSC network.

2.1. Physical network

Fig. 1 provides a comprehensive illustration of the physical network structure for both forward and reverse flows in the proposed CLSC network. This

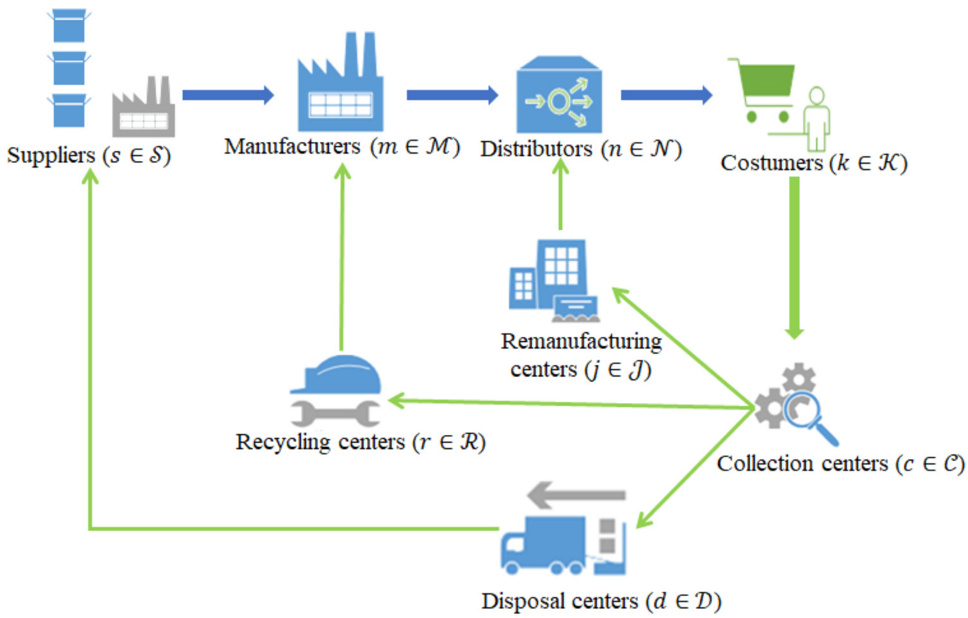

Fig. 1. CLSC network for the glass industry [5].

network integrates the forward and reverse supply chains to ensure efficient material flow, sustainability, and demand satisfaction.

In the forward supply chain, the process begins with suppliers, $s \in \mathcal{S}$, who supply the raw materials necessary for glass production. These raw materials are delivered to manufacturers, $m \in \mathcal{M}$, who transform them into finished glass products. Once production is complete, the finished goods are transported to distributors, $d \in \mathcal{D}$, who serve as intermediaries by channeling these products to customers, $k \in \mathcal{K}$, based on their demand. This linear flow of materials, from suppliers through manufacturers and distributors to customers, represents the forward flow of the CLSC network.

The reverse supply chain begins at the customer level, where collectors, $c \in \mathcal{C}$, take on the crucial task of retrieving returned glass products and waste. These collectors are responsible for sorting and categorizing the returned materials into three distinct streams: recyclable materials, remanufacturable items, and non-reusable waste. The highest-quality returned products are prioritized for remanufacturing, where they are reprocessed to meet production standards. Materials that do not qualify for remanufacturing but remain suitable for reuse are directed to recycling centers. Lastly, the lowest-quality materials, deemed non-reusable, are sent to disposal centers for safe and environmentally compliant handling.

The highest-quality waste products are directed to remanufacturing centers, $j \in \mathcal{I}$, where they are reprocessed and converted into components or products that are subsequently returned to manufacturers for reintegration into the production cycle. This process not only extends product life cycles but also significantly minimizes waste generation.

For waste items that are unsuitable for direct remanufacturing but still retain potential for reuse, the recyclable materials are sent to recyclers, $r \in \mathcal{R}$. Here, the recyclers process these materials, transforming them into reusable inputs for the forward supply chain, particularly for manufacturing centers. This recycling loop enhances resource efficiency by reducing dependence on virgin materials and supports the sustainable operation of the production process.

The lowest-quality waste materials, which cannot be recycled or remanufactured, are directed to disposal centers, $d \in \mathcal{D}$. These centers manage the final treatment of waste, ensuring environmentally responsible disposal methods. Additionally, byproducts or materials generated from the disposal process may occasionally be redirected to suppliers as raw material inputs, thereby closing the loop in this supply chain.

This study aims to redesign the CLSC for the glass industry, focusing on both strategic and tactical planning levels to enhance its efficiency and responsiveness. The core objective is to identify optimal facility locations and effectively allocate these facilities across different supply chain tiers, ensuring all customer demands are fully satisfied.

Strategic planning encompasses high-level decisions, such as the establishment of new facilities and the closure of underperforming or redundant ones.

These decisions are crucial for adapting the network to evolving market demands and sustainability goals. Tactical planning, on the other hand, involves the allocation of material and product flows between facilities across various supply chain levels, optimizing the network's internal operations while maintaining alignment with strategic objectives.

It is important to note that this study does not delve into the operational planning aspects of the CLSC network, such as vehicle routing, pickup, and delivery scheduling, or detailed fleet management. While these operational considerations are vital for the day-to-day functionality of the supply chain, they fall outside the scope of this research, which is concentrated on higher-level planning decisions to support long-term network efficiency and adaptability.

2.2. Suppliers

Suppliers play a critical role in the CLSCNR problem for the glass industry by providing the raw materials needed by manufacturers to produce glass products. In this context, suppliers are treated as independent entities that are not owned or directly managed by the network, meaning their location decisions are not part of the network redesign problem. However, the geographical locations of suppliers have a significant impact on transportation costs and the overall efficiency of the CLSCNR problem, making them an important factor in the network redesign process.

Let $\vartheta^{\mathcal{S}}_{sm}$ represent the distance between supplier $s \in \mathcal{S}$ and manufacturer $m \in \mathcal{M}$, and $tc^{\mathcal{S}}_{sm}$ denote the unit transportation cost for transferring each unit of material. The total transportation cost from suppliers to manufacturers is determined by these parameters as well as the quantity of materials being transported. Furthermore, the cost of raw materials is given by $pc^{\mathcal{S}}_{s}$ per unit, reflecting the price manufacturers must pay to procure the materials.

Another important consideration is the capacity limitations of suppliers, denoted as $u^{\mathcal{S}}_{s}$, which specify the maximum quantity of materials that each supplier can provide. These capacity constraints are crucial for ensuring the efficient functioning of the CLSCNR problem. Proper planning and allocation of material flows are necessary to prevent overloading suppliers beyond their capacity, thereby maintaining a balance between supply and demand within the network.

2.3. Manufacturers

Manufacturers are a critical component of the CLSCNR problem in the glass industry, as they ensure that customer demands for glass products are met. In the context of the network redesign, manufacturers are categorized into two groups: existing facilities, denoted as $m \in \mathcal{M}^{\mathcal{L}}$, and potential facilities, denoted as $m \in \mathcal{M}^{\mathcal{NL}}$, which have yet to be established but can be added to the network to extend its capacity. The overall set of manufacturers is represented by $\mathcal{M} = \{\mathcal{M}^{\mathcal{L}} \cup \mathcal{M}^{\mathcal{NL}}\}$, encompassing both currently operational and prospective facilities.

Strategic decisions in the redesign process must consider the fixed costs associated with facility location planning. For an existing manufacturer $m \in \mathcal{M}^{\mathcal{L}}$, the cost of closing the facility is denoted by $f^{\mathcal{ML}}_{m}$, while for a potential manufacturer $m \in \mathcal{M}^{\mathcal{NL}}$, the cost of opening the facility is represented by $f^{\mathcal{MNL}}_{m}$. Notably, opening new facilities typically incurs higher costs than closing existing ones. These fixed costs play a crucial role in evaluating the feasibility and efficiency of the network redesign.

From a tactical planning perspective, each manufacturer has limited production capacity, denoted as $u^{\mathcal{M}}_{m}$ for $m \in \mathcal{M}$, which restricts the maximum volume of glass products they can produce. The production process also incurs a variable manufacturing cost per unit, represented as $vc^{\mathcal{M}}_{m}$, which significantly influences the overall operational costs of the network.

Transportation between manufacturers and distributors is another important consideration in the CLSCNR problem. Let $\vartheta^{\mathcal{M}}_{mn}$ represent the distance between a manufacturer $m \in \mathcal{M}$ and a distributor $n \in \mathcal{N}$, and $tc^{\mathcal{M}}_{mn}$ denote the unit transportation cost per glass product. The total transportation cost from manufacturers to distributors is influenced by these parameters, as well as the quantity of glass products being transported, which must be factored into the overall cost structure of the CLSC network.

2.4. Distributors

Distributors play an integral role in the CLSCNR problem for the glass industry, serving as essential intermediaries that facilitate the flow of glass products from manufacturers to end customers. In this study, distributors are categorized into two groups: existing distributors, denoted as $\mathcal{N}^{\mathcal{L}}$, and potential distributors, represented as $\mathcal{N}^{\mathcal{NL}}$, which are candidates for future inclusion in the network. The total set of distributors is represented by $\mathcal{N} = \{\mathcal{N}^{\mathcal{L}} \cup \mathcal{N}^{\mathcal{NL}}\}$, highlighting the need to balance the optimization of current infrastructure with the strategic expansion of the network to enhance its capacity and performance.

From a strategic planning perspective, decisions regarding the location and number of distribution facilities are critical. For existing distributors $n \in \mathcal{N}^{\mathcal{L}}$, there are fixed costs associated with closing the distribution centers, denoted as $f^{\mathcal{NL}}_{n}$. Conversely, establishing new distribution centers where $n \in \mathcal{N}^{\mathcal{NL}}$

incurs a fixed cost, represented by $f_n^{\mathcal{NL}}$. Notably, the cost of opening new distribution centers is generally higher than the cost of closing existing ones. These fixed costs must be carefully evaluated in the context of network efficiency and the objective of minimizing overall costs while ensuring the timely delivery of products to meet customer demand.

Tactical planning focuses on operational aspects of distributor activities. Each distributor $n \in \mathcal{N}$ faces a unit distribution cost, denoted as $vc_n^{\mathcal{N}}$, which represents the expense of handling and delivering one unit of glass products. In addition to cost considerations, distributors also operate within capacity constraints, denoted as $u_n^{\mathcal{N}}$, which limit the volume of glass products they can distribute. Transportation costs are another significant factor, influenced by the distance $\vartheta_{nk}^{\mathcal{N}}$ between each distributor $n \in \mathcal{N}$ and the customers $k \in \mathcal{K}$, as well as the unit transportation cost per glass product, $tc_{nk}^{\mathcal{N}}$. The combined effect of these parameters determines the total cost of transporting glass products from distributors to customers, which is a crucial element in the optimization of the CLSC network. In conclusion, distributors are a pivotal component of the CLSCNR problem, serving as the critical link between manufacturers and customers.

2.5. Customers

Each customer, denoted by $k \in \mathcal{K}$, represents a demand source within the CLSC network. These demands are quantified by a specified volume of glass products, q_k, which are characterized by standardized packing, loading, transportation, and warehousing requirements. The uniformity of these characteristics facilitates the joint loading of goods, allowing for efficient and divisible allocation of demand across multiple distributors within the network. This flexibility ensures that the CLSC network can meet customer demands while simultaneously optimizing transportation and inventory management costs.

In addition to fulfilling customer demand, markets also contribute to the reverse flow within the CLSC network. Specifically, markets are responsible for collecting waste and returned glass products from customers and ensuring their timely transfer to designated collectors. It is estimated that a percentage, α_k, of the total demand volume can be recovered as waste or returned glass products. This fraction reflects the recyclable or reusable portion of the glass, which plays a crucial role in promoting sustainability within the network.

The transfer of collected waste from customers to collection centers introduces additional logistical costs. These costs are influenced by the distance, $\vartheta_{kc}^{\mathcal{K}}$, between a customer $k \in \mathcal{K}$ and a collection center $c \in \mathcal{C}$, as well as the unit transportation cost per waste or returned glass product, $tc_{kc}^{\mathcal{K}}$. The combination of these parameters dictates the overall cost of reverse logistics operations within the CLSC network. Effectively managing these reverse logistics costs, while ensuring the efficient and reliable collection of waste, is critical for achieving the sustainability goals of the CLSCNR problem. The success of this reverse flow process directly impacts the network's environmental footprint and contributes to the overall efficiency of the glass industry's CLSC.

2.6. Collection centers

The collection centers, $c \in \mathcal{C}$, are integral to the CLSCNR for the glass industry, serving as key facilities for gathering, sorting, and processing waste and returned glass products from customers. These centers are divided into two categories: existing centers, $\mathcal{C}^{\mathcal{L}}$, which are currently operational within the network, and potential centers, $\mathcal{C}^{\mathcal{NL}}$, which may be established to increase network capacity and resilience. Together, they form the complete set of collection centers, $\mathcal{C} = \{\mathcal{C}^{\mathcal{L}} \cup \mathcal{C}^{\mathcal{NL}}\}$.

Strategic decisions for collection centers involve fixed costs associated with their operation. Closing an existing center, $c \in \mathcal{C}^{\mathcal{L}}$, incurs a fixed cost, $f_c^{\mathcal{CL}}$, while opening a potential center, $c \in \mathcal{C}^{\mathcal{NL}}$, requires a higher fixed cost, $f_c^{\mathcal{CNL}}$, than the closing this facility if existed. Balancing these costs is crucial to maintaining a cost-effective network while ensuring sufficient capacity to manage the flow of returned glass products and waste effectively. These decisions significantly impact the network's ability to handle reverse logistics efficiently.

At the tactical level, collection centers face operational costs and capacity constraints. Each center incurs a unit collection cost, $vc_c^{\mathcal{C}}$, representing the expense of processing and classifying each unit of waste and returned glass products. Capacity limitations, $u_c^{\mathcal{C}}$, restrict the maximum volume of materials that each center can handle. Collection centers allocate the processed materials to recycling centers, remanufacturing centers, and disposal facilities. The allocation follows predefined capacity proportions:

- A maximum proportion, β_c, of the materials can be sent to recycling centers.
- A maximum proportion, γ_c, is designated for remanufacturing centers.
- The remaining proportion $(1 - \beta_c - \gamma_c)$ represents non-recyclable and non-remanufacturable waste, which must be sent to disposal centers.

Transportation costs significantly influence the efficiency of reverse logistics operations for collection centers. These costs vary depending on the destination facility:

- **Recycling centers:** Transportation costs depend on the distance, $\vartheta_{cr}^{\mathcal{CR}}$, between a collection center, $c \in \mathcal{C}$, and a recycler, $r \in \mathcal{R}$, and the unit transportation cost $tc_{cr}^{\mathcal{CR}}$ per waste and returned glass product.
- **Remanufacturing centers:** Transportation costs depend on the distance $\vartheta_{cj}^{\mathcal{CJ}}$ between a collection center $c \in \mathcal{C}$, and a remanufacturing center, $j \in \mathcal{J}$, and the unit transportation cost, $tc_{cj}^{\mathcal{CJ}}$.
- **Disposal centers:** Transportation costs depend on the distance, $\vartheta_{cd}^{\mathcal{CD}}$, between a collection center, $c \in \mathcal{C}$, and a disposal center, $d \in \mathcal{D}$, and the unit transportation cost $tc_{cd}^{\mathcal{CD}}$.

2.7. Recycling centers

Recyclers are a cornerstone of the reverse supply chain in the glass industry, playing a vital role in converting waste materials into recycled inputs for manufacturing. In the context of the CLSCNR problem, recyclers are divided into two categories: existing recycling centers $\mathcal{R}^{\mathcal{L}}$, which are currently operational, and potential centers, $\mathcal{R}^{\mathcal{NL}}$, identified as candidate sites for future development. Together, these groups form the comprehensive set of recyclers, $\mathcal{R} = \{\mathcal{R}^{\mathcal{L}} \cup \mathcal{R}^{\mathcal{NL}}\}$.

Strategic decisions regarding recyclers revolve around fixed costs. Closing an operational recycling center, $r \in \mathcal{R}^{\mathcal{L}}$, incurs a closure cost, $f_r^{\mathcal{RL}}$, whereas opening a new center, $r \in \mathcal{R}^{\mathcal{NL}}$, requires a higher fixed cost, $f_r^{\mathcal{RNL}}$, than closing this center if it exists. These costs directly affect the network's structure and its capacity to handle reverse logistics effectively.

On the tactical level, recyclers are responsible for processing waste products into recycled materials that are sold to manufacturers for remanufacturing. Each recycler, $r \in \mathcal{R}$, incurs a unit recycling cost, $vc_r^{\mathcal{R}}$, for processing materials, while their operations are limited by capacity constraints, $u_r^{\mathcal{R}}$, which define the maximum volume of waste they can handle.

Recycling centers add value by generating revenue through the sale of recycled materials. Each unit sold to manufacturers, $m \in \mathcal{M}$, earns the recycler a unit revenue, $pc_{rm}^{\mathcal{R}}$, creating an economic incentive to maximize efficiency and throughput. These revenues offset operational costs and enhance the financial viability of the recycling process.

Transportation is a critical factor influencing the overall operational costs for recyclers. Recycled products must be transported from recycling centers to manufacturers. The total transportation cost depends on the distance, $\vartheta_{rm}^{\mathcal{R}}$, between a recycler, $r \in \mathcal{R}$, and a manufacturer, $m \in \mathcal{M}$, as well as the unit transportation cost per recycled product, $tc_{rm}^{\mathcal{R}}$. These parameters collectively determine the feasibility and profitability of the recycling-remanufacturing loop.

By balancing strategic and tactical planning, recyclers can effectively support the reverse supply chain, ensuring sustainability while maintaining economic efficiency within the CLSCNR framework.

2.8. Remanufacturing centers

Remanufacturing centers play a crucial role in the CLSCNR problem by processing high-quality waste products from collection centers and converting them into remanufactured products, which are then distributed to customers through distribution centers. In this context, remanufacturing centers are classified into two categories: existing centers, $\mathcal{J}^{\mathcal{L}}$, which are currently operational, and potential centers, $\mathcal{J}^{\mathcal{NL}}$, which are identified for future development. Collectively, these form the complete set of remanufacturing centers, $\mathcal{J} = \{\mathcal{J}^{\mathcal{L}} \cup \mathcal{J}^{\mathcal{NL}}\}$.

Strategic decisions concerning remanufacturing centers involve fixed costs. Closing an existing remanufacturing center, $j \in \mathcal{J}^{\mathcal{L}}$, incurs a closure cost, $f_j^{\mathcal{JL}}$, while opening a new center, $j \in \mathcal{J}^{\mathcal{NL}}$, requires a higher fixed cost, $f_j^{\mathcal{JNL}}$ than closing this facility if it exists. These costs significantly impact the network's structure, influencing decisions on whether to consolidate or expand the remanufacturing centers to effectively support reverse logistics operations.

On the tactical level, remanufacturing centers, $j \in \mathcal{J}$, process waste products into remanufactured goods for distribution. Each center incurs a unit remanufacturing cost, $vc_j^{\mathcal{J}}$, for processing these materials and is subject to capacity constraints, $u_j^{\mathcal{J}}$, which define the maximum volume of waste products they can handle. Efficient utilization of this capacity is critical to maintaining the flow of materials in the network.

Remanufacturing centers generate added value by producing remanufactured goods that are sold to distribution centers, $n \in \mathcal{N}$. Each unit of remanufactured product sold generates revenue $pc_{jn}^{\mathcal{J}}$, which offsets operational costs and contributes to the financial sustainability of the remanufacturing process.

Transportation costs play a pivotal role in the overall operational expenses for remanufacturing centers. Remanufactured products must be transported to distribution centers, with the total transportation cost influenced by the distance, $\vartheta_{jn}^{\mathcal{J}}$, between a remanufacturing center, $j \in \mathcal{J}$, and a distribution center, $n \in \mathcal{N}$, as well as the unit transportation cost per remanufactured product $tc^{\mathcal{J}}_{jn}$. These parameters collectively determine the economic viability of the remanufacturing-distribution loop and affect the efficiency of the supply chain. By optimizing strategic and tactical decisions, remanufacturing centers contribute to a sustainable and cost-effective CLSCNR, ensuring the successful reintegration of waste products into the supply chain.

2.9. Disposal centers

Low-quality waste products, unsuitable for remanufacturing or recycling, are sent to disposal centers for final treatment. These centers ensure environmentally responsible waste management and, in some cases, generate byproducts or materials that can be redirected to suppliers as raw material inputs, thereby contributing to a CLSC. Disposal centers in the CLSCNR framework are divided into two categories: existing centers, $\mathcal{D}^{\mathcal{L}}$, which are operational, and potential centers, $\mathcal{D}^{\mathcal{NL}}$, earmarked for future development. Together, these comprise the complete set of disposal centers, $\mathcal{D} = \{\mathcal{D}^{\mathcal{L}} \cup \mathcal{D}^{\mathcal{NL}}\}$.

Strategic decisions regarding disposal centers revolve around fixed costs. Closing an operational center, $d \in \mathcal{D}^{\mathcal{L}}$, incurs a closure cost, $f^{\mathcal{DL}}_{d}$, while establishing a new center, $d \in \mathcal{D}^{\mathcal{NL}}$, requires a higher fixed cost, $f^{\mathcal{DNL}}_{d}$, than closing this facility if it exists. These costs shape the structure of the network and influence decisions on expanding or consolidating disposal capacities to meet the demands of reverse logistics effectively.

At the tactical level, disposal centers, $d \in \mathcal{D}$, process waste products into forms suitable for disposal or conversion into raw materials for suppliers. Each center incurs a unit disposal cost $vc^{\mathcal{D}}_{d}$, and operates under capacity constraints, $u^{\mathcal{D}}_{d}$, representing the maximum volume of waste they can handle efficiently. This capacity management is crucial for balancing operational efficiency with environmental responsibility.

Disposal centers generate added value by converting waste into usable materials sold to suppliers, $s \in \mathcal{S}$. Each unit of processed material generates revenue, $pc^{\mathcal{D}}_{ds}$, which offsets disposal costs and enhances the financial sustainability of the operation. This revenue stream incentivizes efficient and eco-friendly waste management practices.

Transportation costs significantly affect the operational expenses of disposal centers. Processed materials must be transported to suppliers if they meet quality standards. The total transportation cost depends on the distance $\vartheta^{\mathcal{D}}_{ds}$, between a disposal center, $d \in \mathcal{D}$, and a supplier $s \in \mathcal{S}$, and the unit transportation cost per disposed product, $tc^{\mathcal{D}}_{ds}$. These factors collectively influence the feasibility and profitability of incorporating disposal centers into the reverse supply chain. By aligning strategic and tactical planning, disposal centers not only mitigate environmental impacts but also contribute to the economic efficiency of the CLSC, ensuring waste is managed sustainably and resourcefully.

3. Literature review

Recently, significant attention has been directed toward developing efficient CLSC networks that incorporate sustainability criteria [6–8]. However, to the best of the author's knowledge, there is a noticeable gap in the literature regarding redesigning CLSC networks with the option to close existing facilities and open new ones. Existing CLSC models have been tailored to various industrial applications, including glass [9], tire [10], and agriculture [11] industries. In this review, this study explores recent advancements in the field and emphasizes the need for research focused on redesigning CLSC networks to address this critical gap.

One of the pioneering studies on CLSC networks was conducted by Savaskan et al. [12] in 2004, introducing the concept of CLSC where manufacturers manage the collected wastes either directly from customers or through outsourcing to third parties. Kim et al. [13] extended this framework by proposing a CLSC model that minimizes both total costs and carbon emissions associated with transportation activities. They employed a weighted sum method to address these conflicting objectives. In 2009, Dehghanian and Mansour [14] made significant contributions to the field by analyzing a multi-objective reverse logistics network. Their approach focused on simultaneously reducing both overall costs and carbon emissions, while also maximizing job creation. They utilized a multi-objective genetic algorithm to find the near-optimal solutions for this complex problem.

Amaro et al. [15] conducted one of the pioneering studies on handling uncertainty in CLSC networks, focusing on both operational and disruption-related uncertainties. Özkir et al. [16] developed a multi-objective CLSC model that aimed to maximize overall profits while enhancing the satisfaction of both traders and customers. Their approach optimized decisions related to facility locations and the distribution of facilities to minimize transportation, production, and purchasing costs. In 2014, Devika et al. [17] proposed a sustainable CLSC model that sought to minimize total costs, carbon emissions, job losses, and workdays lost, utilizing hybrid metaheuristic algorithms that combined an imperialist competitive algorithm with variable neighborhood search to tackle the problem. In a similar vein, Govindan et al. [18] designed a CLSC network featuring hybrid recovery facilities, with objectives focused on increasing profitability and social welfare while reducing carbon emissions.

Soleimani et al. [19] introduced a CLSC network that managed multiple products over several periods, using a scenario-based multi-criteria solution approach to handle uncertainties in demand and pricing. Mohammed et al. [20] applied a multi-criteria framework using the technique for order preferences by similarity to ideal solutions (TOPSIS) to rank Pareto-optimal solutions derived from the epsilon constraint method. Their work focused on minimizing costs, delivery times for meat products, and the number of transportation vehicles required in the network. In a different study, Gaur et al. [21] explored a CLSC network designed for a battery company in India, shedding light on key management strategies for waste recovery and recycling operations. In 2018, Fathollahi-Fard et al. [9] presented a stochastic multi-objective CLSC model that incorporated social factors such as job creation and reduced work absences. Their model also aimed to minimize financial risk alongside operational costs. To solve the problem, they developed innovative hybrid metaheuristic methods based on the Red Deer Algorithm (RDA) and Keshtel Algorithm (KA).

Garai et al. [22] developed a sustainable CLSC network that focused on enhancing customer satisfaction and reducing environmental pollution, employing a T-set fuzzy environment to address uncertainties. Similarly, Dutta et al. [23] proposed a CLSC model tailored for e-commerce operations, evaluating economic, environmental, and social objectives through a goal programming framework. In 2020, Fathollahi-Fard et al. [24] applied a sustainable CLSC model to an integrated water supply and wastewater management system. Their work incorporated various sustainability criteria within a scenario-based stochastic programming structure. Abdolazimi et al. [25] explored a robust optimization approach for a CLSC network, targeting cost reduction and carbon emission minimization while ensuring on-time delivery through strict scheduling constraints.

In recent years, Fathollahi-Fard et al. [26] introduced hybrid optimization techniques by combining whale optimization and red deer algorithms to tackle a dual-channel CLSC problem, which involved both online and offline distribution channels. Elfarouk et al. [27] explored a multi-product CLSC problem under demand uncertainty, utilizing a multi-objective algorithm based on a non-dominated sorting genetic algorithm to assess economic, environmental, and social factors. Soleimani et al. [28] proposed a sustainable CLSC model with a focus on energy efficiency, incorporating Lagrangian relaxation reformulations and two heuristic methods to solve the model.

In 2023, Ali et al. [2] developed a scenario-based multi-objective CLSC model, combining a weighted-sum method with the Lagrangian relaxation framework for a case study in Bangladesh. That same year, Seydanlou et al. [11] implemented a sustainable CLSC model tailored for the olive industry, using a scenario-based robust optimization approach and a multi-neighborhood tabu search algorithm for solution optimization. Edalatpour et al. [3] expanded the scope of sustainable CLSC networks in 2024 by integrating globalization aspects, applying a heuristic algorithm based on Lagrangian relaxation.

In another recent study, Hoeke et al. [29] investigated the role of tires in microplastic pollution and laid the foundation for an effective mitigation strategy by mapping the tire supply chain and quantifying microplastic emissions in the Netherlands. Their research involved stakeholder collaboration for data collection. Finally, Manupati et al. [30] developed a MIP model to minimize the total cost of an end-of-life (EOL) tire remanufacturing supply chain, employing an evolutionary algorithm-based approach. Their case study from a tire remanufacturing company showed that the modified genetic algorithm outperformed other methods in delivering cost-effective solutions for EOL tire management strategies.

The existing literature highlights significant advancements in the design and optimization of CLSC, particularly focusing on sustainability and operational efficiency. However, a notable research gap remains in the area of redesigning CLSC networks, specifically in incorporating the strategic decisions of opening new facilities and closing existing ones. This gap is critical, as many industries, including glass manufacturing, face challenges in adapting their networks to increasing demand and sustainability objectives. Additionally, the integration of both forward and reverse supply chains with effective facility location, capacity planning, and product allocation remains an area requiring further exploration.

The contributions of this research directly address these gaps by proposing an integrated decision-making framework for the redesign of CLSC networks in the glass industry. This framework, formulated as a MIP model, incorporates both forward and reverse supply chains, emphasizing facility location, capacity planning, and customer assignment. The sensitivity analysis conducted in the study provides valuable insights into how redesign costs, recycling, remanufacturing efficiencies, and disposal effectiveness impact network performance, offering a practical tool for supply chain designers in high-demand industries.

By focusing on the strategic redesign of CLSC networks, this research offers a novel approach that aligns operations with sustainability goals, contributing to a more adaptive and resilient CLSC design. Furthermore, it fills the gap by providing a comprehensive methodology that addresses both operational and sustainability challenges through an integrated, real-world case study, particularly for industries facing dynamic demand and environmental concerns.

4. Proposed model

Here, the assumptions underlying the CLSCNR problem are outlined (Section 4.1). Subsequently, an integrated decision-making framework is developed through the proposed MIP model, to address this problem (Section 4.2).

4.1. Assumptions

The proposed MIP model extends existing CLSC networks for the glass industry [5, 9, 17], introducing a novel set of assumptions that are being addressed for the first time as follows:

- Facilities are categorized into two types: existing facilities and potential candidate facilities.
- Existing facilities are currently operational, and their closure incurs a predetermined fixed cost.
- Candidate facilities represent prospective additions to the network, each associated with a specific fixed cost for opening.
- The closure cost of an existing facility is assumed to be marginally less than the cost of establishing a new facility.

The rest of the assumptions are taken according to the literature review on the CLSC networks for the glass industry as follows:

- Material flows do not occur between facilities within the same level. For instance, suppliers do not transfer materials to one another. As shown in Fig. 1, material movement is restricted to adjacent levels of the CLSC network, such as between suppliers and manufacturers.
- Each facility level operates under predefined capacity limitations. For instance, manufacturers have restrictions on the volume of glass products they can produce.
- To calculate the transportation costs, the geographic distances between facilities and the unit cost of moving glass products, raw materials, and waste items have a direct impact on these costs.
- The demand at each customer location is predetermined and remains constant.
- The goal of a network redesign process for the CLSC is to ensure that all demands must be fully satisfied, with no allowance for shortages.
- Collection centers are expected to gather only a portion of the waste and returned products from each customer location.
- Collection centers sort returned products into recyclables, remanufacturables, and non-reusable waste. High-quality items go to remanufacturing, reusable materials to recycling, and non-reusable waste to disposal.
- Remanufactured products are delivered to distribution centers for customer distribution.
- Recycled materials are sent to manufacturing centers for production.
- Disposed products meeting raw material standards are redirected to suppliers.
- Suppliers function independently and are not part of the CLSC network ownership.

4.2. Mixed-integer program (MIP)

For the proposed MIP model, the following decision variables are defined:

$y_m^{\mathcal{M}}$ 1, if manufacturing center, $m \in \mathcal{M}$, is open; otherwise, 0.

$y_n^{\mathcal{N}}$ 1, if distribution center, $n \in \mathcal{N}$, is open; otherwise, 0.

$y_c^{\mathcal{C}}$ 1, if collection center, $c \in \mathcal{C}$,, is open; otherwise, 0.

$y_r^{\mathcal{R}}$ 1, if recycling center, $r \in \mathcal{R}$, is open; otherwise, 0.

$y_j^{\mathcal{J}}$ 1, if remanufacturing center, $j \in \mathcal{J}$, is open; otherwise, 0.

$y_d^{\mathcal{D}}$ 1, if disposal center, $d \in \mathcal{D}$, is open; otherwise, 0.

$x_{sm}^{\mathcal{S}}$ Amount of raw materials transported from supplier, $s \in \mathcal{S}$, to manufacturing center, $m \in \mathcal{M}$

$x_{mn}^{\mathcal{M}}$ Amount of produced glass products transported from manufacturing center, $m \in \mathcal{M}$, to distribution center, $n \in \mathcal{N}$

$x_{nk}^{\mathcal{N}}$ Amount of distributed glass products transported from distributing center, $n \in \mathcal{N}$, to customer, $k \in \mathcal{K}$

$x_{kc}^{\mathcal{K}}$ Amount of waste and retuned glass products transported from customer, $k \in \mathcal{K}$, to collection center, $c \in \mathcal{C}$

$x_{cr}^{\mathcal{CR}}$ Amount of recyclable waste products transported from collection center, $c \in \mathcal{C}$, to recycling center, $r \in \mathcal{R}$

$x_{cd}^{\mathcal{CD}}$ Amount of non-reusable waste products transported from collection center, $c \in \mathcal{C}$, to disposal center, $d \in \mathcal{D}$

$x_{cj}^{\mathcal{CJ}}$ Amount of remanufacturable waste products transported from collection center, $c \in \mathcal{C}$, to remanufacturing center, $j \in \mathcal{J}$

$x_{rm}^{\mathcal{R}}$ Amount of recycled products transported from recycling center, $r \in \mathcal{R}$ to manufacturing center, $m \in \mathcal{M}$

$x_{ds}^{\mathcal{D}}$ Amount of disposed products transported from disposal center, $d \in \mathcal{D}$ to supplier $s \in \mathcal{S}$

$x_{jn}^{\mathcal{J}}$ Amount of remanufactured glass products transported from remanufacturing center, $j \in \mathcal{J}$ to distribution center, $n \in \mathcal{N}$

The objective function is calculated as the total cost Z, which includes several components: the fixed costs associated with facility closures $Z_{\mathcal{CF}}$, the fixed costs of establishing new facilities $Z_{\mathcal{OF}}$, the operational variable costs, $Z_{\mathcal{VC}}$, and the transportation costs, $Z_{\mathcal{TC}}$. These components collectively define the overall cost structure as outlined below.

$$\min\left(Z = Z_{\mathcal{CF}} + Z_{\mathcal{OF}} + Z_{\mathcal{VC}} + Z_{\mathcal{TC}}\right) \tag{1}$$

$$\begin{aligned} Z_{\mathcal{CF}} = & \sum_{m \in \mathcal{M}^{\mathcal{L}}} f_m^{\mathcal{ML}}\left(1 - y_m^{\mathcal{M}}\right) + \sum_{n \in \mathcal{N}^{\mathcal{L}}} f_n^{\mathcal{NL}}\left(1 - y_n^{\mathcal{N}}\right) \\ & + \sum_{c \in \mathcal{C}^{\mathcal{L}}} f_c^{\mathcal{CL}}\left(1 - y_c^{\mathcal{C}}\right) + \sum_{j \in \mathcal{J}^{\mathcal{L}}} f_j^{\mathcal{JL}}\left(1 - y_j^{\mathcal{J}}\right) \\ & + \sum_{r \in \mathcal{R}^{\mathcal{L}}} f_r^{\mathcal{RL}}\left(1 - y_r^{\mathcal{R}}\right) + \sum_{d \in \mathcal{D}^{\mathcal{L}}} f_d^{\mathcal{DL}}\left(1 - y_d^{\mathcal{D}}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} Z_{\mathcal{OF}} = & \sum_{m \in \mathcal{M}^{\mathcal{NL}}} f_m^{\mathcal{MNL}} y_m^{\mathcal{M}} + \sum_{n \in \mathcal{N}^{\mathcal{NL}}} f_n^{\mathcal{NNL}} y_n^{\mathcal{N}} \\ & + \sum_{c \in \mathcal{C}^{\mathcal{NL}}} f_c^{\mathcal{CNL}} y_c^{\mathcal{C}} + \sum_{j \in \mathcal{J}^{\mathcal{NL}}} f_j^{\mathcal{JNL}} y_j^{\mathcal{J}} \\ & + \sum_{r \in \mathcal{R}^{\mathcal{NL}}} f_r^{\mathcal{RNL}} y_r^{\mathcal{R}} + \sum_{d \in \mathcal{D}^{\mathcal{NL}}} f_d^{\mathcal{DNL}} y_d^{\mathcal{D}} \end{aligned} \tag{3}$$

$$\begin{aligned} Z_{\mathcal{VC}} = & \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} pc_s^{\mathcal{S}} x_{sm}^{\mathcal{S}} + \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} vc_m^{\mathcal{M}} x_{mn}^{\mathcal{M}} \\ & + \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} vc_n^{\mathcal{N}} x_{nk}^{\mathcal{N}} \\ & + \sum_{c \in \mathcal{C}} vc_c^{\mathcal{C}}\left(\sum_{r \in \mathcal{R}} x_{cr}^{\mathcal{CR}} + \sum_{d \in \mathcal{D}} x_{cd}^{\mathcal{CD}} + \sum_{j \in \mathcal{J}} x_{cj}^{\mathcal{CJ}}\right) \\ & + \sum_{r \in \mathcal{R}} \sum_{m \in \mathcal{M}} vc_r^{\mathcal{R}} x_{rm}^{\mathcal{R}} + \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}} vc_d^{\mathcal{D}} x_{ds}^{\mathcal{D}} \\ & + \sum_{j \in \mathcal{J}} \sum_{n \in \mathcal{N}} vc_j^{\mathcal{J}} x_{jn}^{\mathcal{J}} - \sum_{r \in \mathcal{R}} \sum_{m \in \mathcal{M}} pc_{rm}^{\mathcal{R}} x_{rm}^{\mathcal{R}} \\ & - \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}} pc_{ds}^{\mathcal{D}} x_{ds}^{\mathcal{D}} - \sum_{j \in \mathcal{J}} \sum_{n \in \mathcal{N}} pc_{jn}^{\mathcal{J}} x_{jn}^{\mathcal{J}} \end{aligned} \tag{4}$$

$$\begin{aligned} Z_{\mathcal{TC}} = & \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{M}} \vartheta_{sm}^{\mathcal{S}} tc_{sm}^{\mathcal{S}} x_{sm}^{\mathcal{S}} + \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \vartheta_{mn}^{\mathcal{M}} tc_{mn}^{\mathcal{M}} x_{mn}^{\mathcal{M}} \\ & + \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} \vartheta_{nk}^{\mathcal{N}} tc_{nk}^{\mathcal{N}} x_{nk}^{\mathcal{N}} + \sum_{k \in \mathcal{K}} \sum_{c \in \mathcal{C}} \vartheta_{kc}^{\mathcal{K}} tc_{kc}^{\mathcal{K}} x_{kc}^{\mathcal{K}} \\ & + \sum_{c \in \mathcal{C}} \sum_{r \in \mathcal{R}} \vartheta_{cr}^{\mathcal{CR}} tc_{cr}^{\mathcal{CR}} x_{cr}^{\mathcal{CR}} + \sum_{c \in \mathcal{C}} \sum_{j \in \mathcal{J}} \vartheta_{cj}^{\mathcal{CJ}} tc_{cj}^{\mathcal{CJ}} x_{cj}^{\mathcal{CJ}} \\ & + \sum_{c \in \mathcal{C}} \sum_{d \in \mathcal{D}} \vartheta_{cd}^{\mathcal{CD}} tc_{cd}^{\mathcal{CD}} x_{cd}^{\mathcal{CD}} + \sum_{r \in \mathcal{R}} \sum_{m \in \mathcal{M}} \vartheta_{rm}^{\mathcal{R}} tc_{rm}^{\mathcal{R}} x_{rm}^{\mathcal{R}} \\ & + \sum_{j \in \mathcal{J}} \sum_{n \in \mathcal{N}} \vartheta_{jn}^{\mathcal{J}} tc_{jn}^{\mathcal{J}} x_{jn}^{\mathcal{J}} + \sum_{d \in \mathcal{D}} \sum_{s \in \mathcal{S}} \vartheta_{ds}^{\mathcal{D}} tc_{ds}^{\mathcal{D}} x_{ds}^{\mathcal{D}} \end{aligned} \tag{5}$$

The objective function, represented in Eq. (1), seeks to minimize the overall cost of the redesigned CLSC network. This total cost comprises several components: fixed costs for closing and opening facilities, variable costs associated with operational activities, and transportation costs. Eq. (2) quantifies the fixed costs incurred by closing existing facilities, such as manufacturing, distribution, collection, recycling, remanufacturing, and disposal centers. Similarly, Eq. (3) addresses the fixed costs of establishing new facilities across these categories, balancing the cost implications of network adjustments.

Eq. (4) calculates the variable costs arising from key operations within the CLSC network. These include the procurement of raw materials, production of glass products, delivery to customers, collection and sorting of returned and waste products, as well as the recycling, remanufacturing, and disposal processes. Additionally, the network incorporates revenue streams generated from selling recycled materials to manufacturing centers, remanufactured products to distribution centers, and recoverable disposed materials to suppliers.

Finally, Eq. (5) assesses the transportation costs across all stages of the CLSC network. This includes the movement of raw materials from suppliers to manufacturing centers, finished products to distribution centers, and distribution to customers. It also accounts for the cost of transporting waste and returned items from customers to collection centers, as well as transferring these items to remanufacturing, recycling, or disposal centers. Additional transportation costs include moving recycled products to manufacturing centers, remanufactured items to distribution centers, and materials from disposal centers to suppliers.

The objective function defined in Eqs. (1) to (5) is governed by a series of constraints to ensure the viability of the CLSC network. Network balance constraints, outlined in Eqs. (6) to (11), ensure consistent flow between facilities. Demand satisfaction constraints, detailed in Eqs. (12) and (13), guarantee that customer demands are met and that collection centers process returned products effectively. Recycling, remanufacturing, and disposal constraints, specified in Eqs. (14) and (15), regulate the classification and allocation of waste for recycling or remanufacturing. Capacity constraints, described in Eqs. (16) to (22), enforce facility limitations. Finally, boundary constraints in Eqs. (23) to (38) define the acceptable ranges for decision variables.

- **Network balance constraints**

The network balance constraints are designed to maintain a consistent and feasible flow of materials across all levels of the CLSC network. Eq. (6) ensures that manufacturing centers receive sufficient raw materials to produce glass products, which are subsequently sent to distribution centers. Eq. (7) verifies that distribution centers appropriately allocate the glass products they receive to fulfill customer requirements. Eq. (8) governs collection centers by ensuring that all waste and returned products collected from customers are properly sorted and directed to recycling, remanufacturing, or disposal centers based on their classification as recyclable, remanufacturable, or non-reusable. Eq. (9) confirms that recycled materials are appropriately routed from recycling centers to manufacturing centers for reuse in production. Eq. (10) manages remanufacturing centers, ensuring that remanufacturable items are processed and dispatched to distribution centers as remanufactured products. Eq. (11) oversees disposal centers, ensuring that non-reusable waste is properly handled and sent to suppliers if it can be repurposed as raw material. Together, these constraints provide a structured framework to regulate material movement and ensure the efficiency of the CLSC network.

$$\sum_{s\in\mathcal{S}} x_{sm}^{\mathcal{S}} = \sum_{n\in\mathcal{N}} x_{mn}^{\mathcal{M}}, \ \forall m \in \mathcal{M} \tag{6}$$

$$\sum_{m\in\mathcal{M}} x_{mn}^{\mathcal{M}} = \sum_{k\in\mathcal{K}} x_{nk}^{\mathcal{N}}, \ \forall n \in \mathcal{N} \tag{7}$$

$$\sum_{k\in\mathcal{K}} x_{kc}^{\mathcal{K}} = \sum_{r\in\mathcal{R}} x_{cr}^{\mathcal{CR}} + \sum_{j\in\mathcal{J}} x_{cj}^{\mathcal{CJ}} + \sum_{d\in\mathcal{D}} x_{cd}^{\mathcal{CD}}, \ \forall c \in \mathcal{C} \tag{8}$$

$$\sum_{c\in\mathcal{C}} x_{cr}^{\mathcal{CR}} = \sum_{m\in\mathcal{M}} x_{rm}^{\mathcal{R}}, \ \forall r \in \mathcal{R} \tag{9}$$

$$\sum_{c\in\mathcal{C}} x_{cj}^{\mathcal{CJ}} = \sum_{n\in\mathcal{N}} x_{jn}^{\mathcal{J}}, \ \forall j \in \mathcal{J} \tag{10}$$

$$\sum_{c\in\mathcal{C}} x_{cd}^{\mathcal{CD}} = \sum_{s\in\mathcal{S}} x_{ds}^{\mathcal{D}}, \ \forall d \in \mathcal{D} \tag{11}$$

- **Demands satisfaction constraints**

Eq. (12) ensures that distribution centers meet all customer demands by delivering the required quantity of glass products, satisfying their needs entirely. Eq. (13) quantifies the proportion of customer demand that turns into waste or returned products, mandating that this fraction is collected by collection centers for appropriate processing within the CLSC network.

$$\sum_{n\in\mathcal{N}} x_{nk}^{\mathcal{N}} = q_k, \ \forall k \in \mathcal{K} \tag{12}$$

$$\sum_{c\in\mathcal{C}} x_{kc}^{\mathcal{K}} = \alpha_k q_k, \ \forall k \in \mathcal{K} \tag{13}$$

- **Recycling, and remanufacturing constraints**

Eq. (14) restricts the proportion of waste collected at collection centers that can be categorized as recyclable, based on an estimated fraction of the total collected waste. These wastes are directed to the recycling centers. Eq. (15) limits the proportion of collected waste that can be designated as remanufacturable, aligning with an estimation derived from the collected waste at the collection centers. These wastes are directed to the remanufacturing centers.

$$\sum_{r\in\mathcal{R}} x_{cr}^{\mathcal{CR}} \le \beta_c \sum_{k\in\mathcal{K}} x_{kc}^{\mathcal{K}}, \ \forall c \in \mathcal{C} \tag{14}$$

$$\sum_{j\in\mathcal{J}} x_{cj}^{\mathcal{CJ}} \le \gamma_c \sum_{k\in\mathcal{K}} x_{kc}^{\mathcal{K}}, \ \forall c \in \mathcal{C} \tag{15}$$

- **Capacity constraints**

For each CLSC network, capacity constraints are among the most complex elements of optimization models, as they ensure that the material and product flows are consistent with the operational capacities of different facilities [2, 3]. They also establish a crucial link between location decision variables and flow variables. For example, Eq. (16) defines the capacity limitation for suppliers. Eq. (17) specifies the capacity constraint for manufacturing centers. Eq. (18) imposes the capacity restriction for distribution centers. Eq. (19) addresses the capacity limits for collection centers. Eq. (20) ensures capacity compliance for recycling centers. Eq. (21) defines the capacity constraint for remanufacturing centers. Eq. (22) sets the capacity limits for disposal centers. These constraints collectively ensure that material flows within the network remain feasible and adhere to the capacity specifications of each facility.

$$\sum_{m\in\mathcal{M}} x^{\mathcal{S}}_{sm} \le u^{\mathcal{S}}_{s},\ \forall s\in\mathcal{S} \quad (16)$$

$$\sum_{n\in\mathcal{N}} x^{\mathcal{M}}_{mn} \le u^{\mathcal{M}}_{m} y^{\mathcal{M}}_{m},\ \forall m\in\mathcal{M} \quad (17)$$

$$\sum_{k\in\mathcal{K}} x^{\mathcal{N}}_{nk} \le u^{\mathcal{N}}_{n} y^{\mathcal{N}}_{n},\ \forall n\in\mathcal{N} \quad (18)$$

$$\sum_{k\in\mathcal{K}} x^{\mathcal{K}}_{kc} \le u^{\mathcal{C}}_{c} y^{\mathcal{C}}_{c},\ \forall\ c\in\mathcal{C} \quad (19)$$

$$\sum_{c\in\mathcal{C}} x^{\mathcal{CR}}_{cr} \le u^{\mathcal{R}}_{r} y^{\mathcal{R}}_{r},\ \forall r\in\mathcal{R} \quad (20)$$

$$\sum_{c\in\mathcal{C}} x^{\mathcal{CI}}_{cj} \le u^{\mathcal{J}}_{j} y^{\mathcal{J}}_{j},\ \forall j\in\mathcal{I} \quad (21)$$

$$\sum_{c\in\mathcal{C}} x^{\mathcal{CD}}_{cd} \le u^{\mathcal{D}}_{d} y^{\mathcal{D}}_{d},\ \forall d\in\mathcal{D} \quad (22)$$

- **Boundary constraints**

Eqs. (23) to (28) introduce the binary variables in the model, representing decisions related to opening or closing facilities within the CLSC network. Meanwhile, Eqs. (29) to (38) define the continuous variables, which capture material allocations, production volumes, and the flow of glass products and waste among facilities across various network levels.

$$y^{\mathcal{M}}_{m} \in \{0,1\},\ \forall m\in\mathcal{M}=\{\mathcal{M}^{\mathcal{L}}\cup\mathcal{M}^{\mathcal{NL}}\} \quad (23)$$

$$y^{\mathcal{N}}_{n} \in \{0,1\},\ \forall n\in\mathcal{N}=\{\mathcal{N}^{\mathcal{L}}\cup\mathcal{N}^{\mathcal{NL}}\} \quad (24)$$

$$y^{\mathcal{C}}_{c} \in \{0,1\},\ \forall c\in\mathcal{C}=\{\mathcal{C}^{\mathcal{L}}\cup\mathcal{C}^{\mathcal{NL}}\} \quad (25)$$

$$y^{\mathcal{R}}_{r} \in \{0,1\},\ \forall r\in\mathcal{R}=\{\mathcal{R}^{\mathcal{L}}\cup\mathcal{R}^{\mathcal{NL}}\} \quad (26)$$

$$y^{\mathcal{J}}_{j} \in \{0,1\},\ \forall j\in\mathcal{J}=\{\mathcal{R}^{\mathcal{L}}\cup\mathcal{R}^{\mathcal{NL}}\} \quad (27)$$

$$y^{\mathcal{D}}_{d} \in \{0,1\},\ \forall d\in\mathcal{D}=\{\mathcal{D}^{\mathcal{L}}\cup\mathcal{D}^{\mathcal{NL}}\} \quad (28)$$

$$x^{\mathcal{S}}_{sm} \ge 0,\ \forall\ s\in\mathcal{S},\ m\in\mathcal{M}=\{\mathcal{M}^{\mathcal{L}}\cup\mathcal{M}^{\mathcal{NL}}\} \quad (29)$$

$$x^{\mathcal{M}}_{md} \ge 0,\ \forall m\in\mathcal{M}=\{\mathcal{M}^{\mathcal{L}}\cup\mathcal{M}^{\mathcal{NL}}\},\ d\in\mathcal{D}=\{\mathcal{D}^{\mathcal{L}}\cup\mathcal{D}^{\mathcal{NL}}\} \quad (30)$$

$$x^{\mathcal{N}}_{nk} \ge 0,\ \forall n\in\mathcal{N}=\{\mathcal{N}^{\mathcal{L}}\cup\mathcal{N}^{\mathcal{NL}}\},\ k\in\mathcal{K} \quad (31)$$

$$x^{\mathcal{K}}_{kc} \ge 0,\ \forall k\in\mathcal{K},\ c\in\mathcal{C}=\{\mathcal{C}^{\mathcal{L}}\cup\mathcal{C}^{\mathcal{NL}}\} \quad (32)$$

$$x^{\mathcal{CR}}_{cr} \ge 0,\ \forall c\in\mathcal{C}=\{\mathcal{C}^{\mathcal{L}}\cup\mathcal{C}^{\mathcal{NL}}\},\ r\in\mathcal{R}=\{\mathcal{R}^{\mathcal{L}}\cup\mathcal{R}^{\mathcal{NL}}\} \quad (33)$$

$$x^{\mathcal{CD}}_{cd} \ge 0,\ \forall c\in\mathcal{C}=\{\mathcal{C}^{\mathcal{L}}\cup\mathcal{C}^{\mathcal{NL}}\},\ d\in\mathcal{D}=\{\mathcal{D}^{\mathcal{L}}\cup\mathcal{D}^{\mathcal{NL}}\} \quad (34)$$

$$x^{\mathcal{CJ}}_{cj} \ge 0,\ \forall c\in\mathcal{C}=\{\mathcal{C}^{\mathcal{L}}\cup\mathcal{C}^{\mathcal{NL}}\},\ j\in\mathcal{J}=\{\mathcal{J}^{\mathcal{L}}\cup\mathcal{J}^{\mathcal{NL}}\} \quad (35)$$

$$x^{\mathcal{R}}_{rm} \ge 0,\ \forall r\in\mathcal{R}=\{\mathcal{R}^{\mathcal{L}}\cup\mathcal{R}^{\mathcal{NL}}\},\ m\in\mathcal{M}=\{\mathcal{M}^{\mathcal{L}}\cup\mathcal{M}^{\mathcal{NL}}\} \quad (36)$$

$$x^{\mathcal{D}}_{ds} \ge 0,\ \forall d\in\mathcal{D}=\{\mathcal{D}^{\mathcal{L}}\cup\mathcal{D}^{\mathcal{NL}}\},s\in\mathcal{S} \quad (37)$$

$$x^{\mathcal{J}}_{jn} \ge 0,\ \forall j\in\mathcal{J}=\{\mathcal{J}^{\mathcal{L}}\cup\mathcal{J}^{\mathcal{NL}}\},\mathcal{N}=\{\mathcal{N}^{\mathcal{L}}\cup\mathcal{N}^{\mathcal{NL}}\} \quad (38)$$

5. Computational experiments

This section presents the results of computational experiments designed to evaluate the proposed MIP model in terms of solution quality and computational efficiency for the network redesign process in the CLSC network. Section 5.1 outlines the features of the test instances created for the experiments, which were designed to mimic real-world scenarios and ensure the relevance of the findings. Section 5.2 investigates the effects of integrating new facilities into the network during its redesign, examining how these additions impact the network's structure, cost, and overall efficiency across different instances. All experiments were carried out using GAMS 24.7.4 software with the CPLEX solver. The computations were performed on a system with an Intel(R) Core(TM) i7–10850H CPU and 32 GB of RAM.

5.1. Test instances

To evaluate the proposed MIP model comprehensively, a diverse set of test instances was created using a structured approach to parameter selection. This process drew inspiration from established methodologies in prior research, particularly by Devika et al. [17] and Fathollahi-Fard et al. [26], to ensure a robust and consistent basis for data generation.

Due to the computational limitations of the exact solver employed in this study, the focus was restricted to small-scale instances that could be solved efficiently within a reasonable time frame. Table 1 outlines the specifics of these instances. Four test instances were generated for each of the four problem sizes. For problem size P1, instances T1 through T4 were developed. Similarly, instances T5 to T8 correspond to size P2, T9 to T12 to size P3, and T13 to T16 to size P4.

The test instances summarized in Table 1 were developed using a systematic and structured

Table 1. Test instances.

Sizes	Test instances	Number of suppliers	Number of manufacturing centers		Number of collection centers		Number of disposal centers		Number of remanufacturing centers		Number of distribution centers		Number of recycling centers		Number of customers
		$\lvert\mathcal{S}\rvert$	$\lvert\mathcal{M}^{\mathcal{L}}\rvert$	$\lvert\mathcal{M}^{\mathcal{NL}}\rvert$	$\lvert\mathcal{C}^{\mathcal{L}}\rvert$	$\lvert\mathcal{C}^{\mathcal{NL}}\rvert$	$\lvert\mathcal{D}^{\mathcal{L}}\rvert$	$\lvert\mathcal{D}^{\mathcal{NL}}\rvert$	$\lvert\mathcal{J}^{\mathcal{L}}\rvert$	$\lvert\mathcal{J}^{\mathcal{NL}}\rvert$	$\lvert\mathcal{N}^{\mathcal{L}}\rvert$	$\lvert\mathcal{N}^{\mathcal{NL}}\rvert$	$\lvert\mathcal{R}^{\mathcal{L}}\rvert$	$\lvert\mathcal{R}^{\mathcal{NL}}\rvert$	$\lvert\mathcal{K}\rvert$
P1	T1, T2, T3, and T4	4	2	2	2	2	2	2	2	2	2	2	2	2	10
P2	T5, T6, T7, and T8	5	3	4	3	4	3	4	3	4	3	4	3	4	20
P3	T9, T10, T11, and T12	5	3	6	3	6	3	6	3	6	3	6	3	6	40
P4	T13, T14, T15, and T16	8	4	12	4	12	4	12	4	12	4	12	4	12	50

methodology to ensure realistic and varied scenarios for evaluating the proposed MIP model. The approach incorporated several key steps and considerations as outlined below:

- Facilities were assigned random locations on a two-dimensional coordinate plane with coordinates (x, y) uniformly distributed between 0 and 1000. These coordinates represent the geographical positioning of facilities such as suppliers, manufacturing centers, distribution centers, collection centers, recycling centers, remanufacturing centers, and disposal centers. The Euclidean distances between facilities were computed using these coordinates, forming the basis for calculating transportation costs.
- Transportation costs per unit of demand volume were randomly generated within a range of 3 to 8 units. This variability reflects differences in logistics costs due to distance, service quality, and mode of transportation such as rail, air, and
- The demand volumes for customer locations were generated randomly, ranging from 50 to 200 units. This range ensures diversity in customer requirements, simulating small-scale to mid-scale demand scenarios.
- The fixed cost of closing a facility was calculated as the total transportation costs of all potential connections to that facility, assuming the facility handles half of the total demand. For example, for a manufacturing center, this includes the transportation costs associated with connected suppliers, distribution centers, and recycling centers. In contrast, the fixed cost of opening a facility was set as double the fixed closing cost, accounting for additional expenses such as infrastructure, workforce mobilization, and initial setup.
- Raw material purchasing costs from suppliers were assigned randomly within a range of 3 to 5 units. This range reflects variability in procurement costs depending on supplier characteristics or material quality.
- For the reverse supply chain, the percentage of customer demand returned as waste or used products was estimated to range between 50% and 100%, acknowledging variability in product return rates and customer behavior.
- Facility capacities were estimated as a percentage of the total network demand, ranging from 20% to 50%.
- The proportion of waste products classified as remanufacturable was estimated to range between 10% and 30% of collected waste at each collection center. Similarly, the proportion classified as recyclable was set between 30% and 60%, with the remaining waste designated as non-reusable and sent for disposal.
- Variable costs incurred at each facility during operations, including processing and handling, were randomly assigned values between 3 and 5 units.
- The price of recycled products sent to manufacturing centers was randomly set between 3 and 5 units.
- The price of remanufactured products designated for distribution centers was assigned a range of 5 to 8 units, reflecting the added value of remanufactured products.
- The price of disposed products directed to suppliers was estimated between 1 and 3 units, acknowledging their limited utility or value.

5.2. Analyzing the redesign performance for the CLSC network

For each test instance, the CPLEX solver is used to obtain optimal solutions for the proposed MIP model. The results capture critical performance metrics, including total cost, computational time (measured in seconds), and the number of open facilities before and after optimization based on the network re-

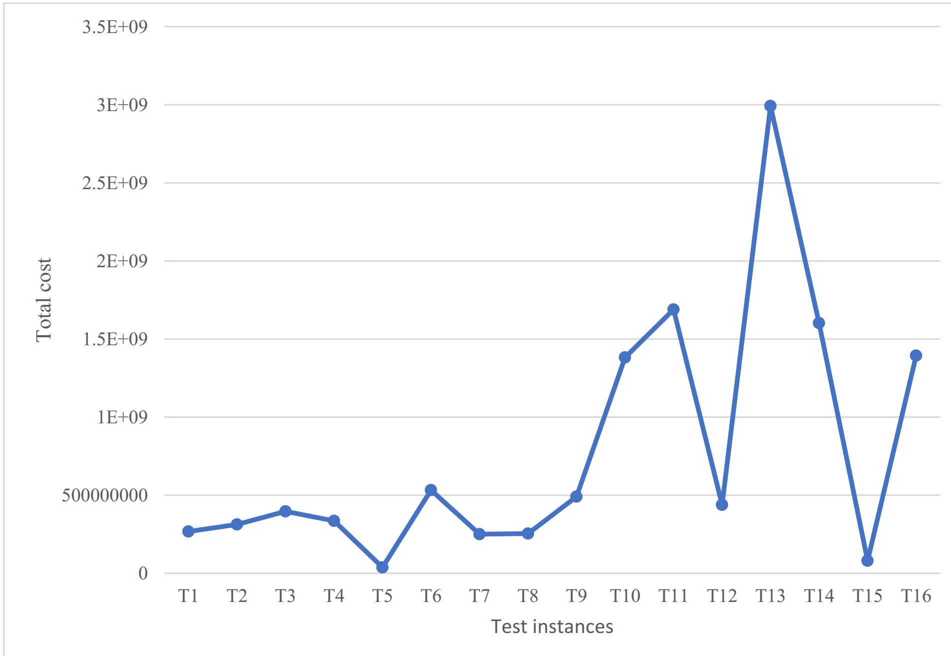

Fig. 2. Total cost per each test instance.

design process. These metrics provide insights into the efficiency of the CLSC network design and the impact of decision variables on the network's structural adjustments.

Fig. 2 illustrates the variation in total costs for each test instance, providing insights into the relationship between network size instance, and associated expenses. As the size of the network increases (from smaller test instances like T1 to larger ones like T16), there is a general rise in total costs. This increase is expected, as larger networks involve higher transportation expenses, greater facility operations, and increased material flows. The data from Table 2 reveals that the total cost is not solely dependent on the network size but is also influenced by the network redesign process. For example, instances T5, T12, and T15 exhibit notably lower total costs compared to other instances of similar size. A closer examination shows that these instances experienced minimal changes in their network redesign, specifically in the number of new facilities added. These observations suggest a direct relationship between the total cost and the number of new facilities added to the network. Instances requiring fewer new facilities often

Table 2. Computational results.

Test instances	Total cost	CPU time (seconds)	Number of open centers before network redesign	Number of open centers after network redesign
T1	267049308	28.22	12	18
T2	312582559.5	31.49	12	18
T3	396378990.8	29.2	12	20
T4	335837640	29.42	12	20
T5	37577015.67	29.13	18	19
T6	532157424	27.48	18	21
T7	250078998.5	29.01	18	20
T8	253870756.9	29.43	18	20
T9	490677280	44.17	18	20
T10	1382027945	44.85	18	21
T11	1689304995	44.85	18	21
T12	437968210.8	45.86	18	20
T13	2992831260	60.65	24	27
T14	1601832896	60.9	24	26
T15	80471143.75	60.8	24	24
T16	1393451283	62.26	24	26

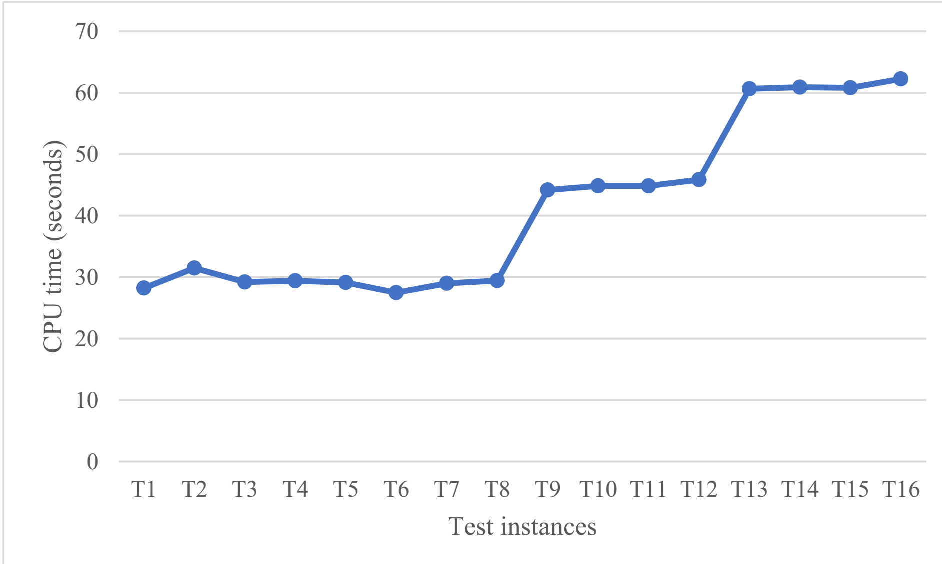

Fig. 3. Computational complexity of instances.

incur lower redesign costs, contributing to overall cost efficiency.

Fig. 3 presents the CPU time required to solve each test instance, highlighting a clear relationship between computational time and instance size. Larger instances require significantly more computational resources. For example, test instances belonging to size P4 consistently demand more CPU time than those in size P3, demonstrating the direct correlation between instance complexity and solver performance. Similarly, instances in size P3 also exhibit longer computational times compared to smaller test instances in sizes P1 and P2. The computational time grows disproportionately as the network size increases, reflecting the inherent complexity of solving the MIP for the CLSCNR problem. This emphasizes the challenges associated with scaling up the network and solving larger instances within reasonable timeframes.

Fig. 4 illustrates the number of new facilities incorporated into the network during the optimization of the CLSCNR problem. For example, in test T15,

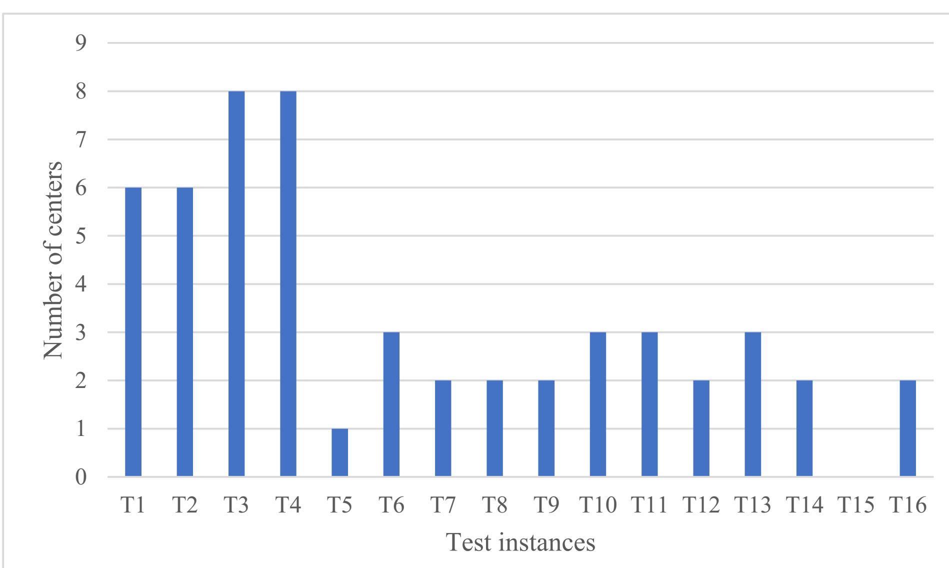

Fig. 4. Number of new centers added according to the network redesign process.

no new facilities were added. This suggests that the existing open facilities were sufficient to meet the demands, and the additional costs for transportation and variable operations did not justify the need for introducing new facilities. In contrast, only one new facility was added in T5, indicating that the existing network could handle the demands with minimal expansion. The optimization process found that adding a single new facility was sufficient to improve cost efficiency. For the remaining instances, varying numbers of new facilities were incorporated. Notably, instances T3 and T4 saw the addition of 8 new facilities, reflecting a more significant network expansion. These instances required a larger number of new facilities, likely due to higher demand, transportation costs, or variable operational costs, which made the addition of new facilities more beneficial.

6. Conclusions and perspectives

This study addresses the challenges of CLSCNR within the glass manufacturing industry, offering a novel integrated decision-making framework as a MIP model to optimize operational efficiency and sustainability. The framework incorporates key decisions such as opening new facilities, closing existing ones, and managing cost trade-offs during the redesign process. Through extensive computational experiments, this study demonstrated that the proposed MIP model effectively enhances operational efficiency and aligns supply chain operations with sustainability goals by optimizing network configurations. In doing so, this work aligns with several key Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) by promoting sustainable supply chain practices that reduce waste and enhance resource efficiency. By improving the design of reverse logistics and recycling systems, this study contributes to SDG 9 (Industry, Innovation, and Infrastructure) through the development of resilient and innovative industrial supply chain infrastructures. Furthermore, the model supports SDG 13 (Climate Action) by minimizing the environmental impact of manufacturing operations, contributing to climate mitigation efforts through optimized resource use. Lastly, this work also indirectly supports SDG 8 (Decent Work and Economic Growth), as more efficient and sustainable supply chain operations can contribute to economic growth while fostering the creation of decent jobs in green industries. Through these contributions, this paper demonstrates the critical role of optimized supply chain redesign in advancing global sustainability objectives and encourages further research into integrating sustainability goals into industrial supply chain management.

The results from the computational experiments provide valuable insights into the practical implications of CLSC network redesign. The analysis of total costs, CPU time, and the number of new facilities added during optimization illustrates that the performance of the network redesign process is not solely dependent on the network size, but also heavily influenced by the structure of the redesign itself. For example, while larger networks naturally incur higher costs due to increased transportation expenses and more complex operations, instances where fewer new facilities were added (such as T5, T12, and T15) demonstrated lower costs despite being of similar size to others. This highlights the importance of strategic facility decisions and the direct relationship between the total cost and the number of new facilities incorporated into the network.

Despite the promising results, several limitations of the proposed framework should be acknowledged. First, the computational time required for larger instances, particularly those in size P4, remains a significant challenge. As the network size increases, the MIP model becomes more computationally demanding, and solving large-scale instances within reasonable timeframes can become unfeasible. Future research could focus on developing more efficient algorithms, such as metaheuristics or hybrid optimization methods [31], to tackle larger problems and provide near-optimal solutions within practical time limits.

Second, the current model assumes that all facility parameters, such as transportation costs, fixed and variable costs, and demand volumes, are generated randomly within specified ranges. While this allows for a robust analysis, real-world data and more precise forecasting techniques could lead to more accurate parameter generation. Incorporating real data from the glass industry [32] or other relevant sectors could improve the applicability of the model and offer deeper insights into the specific challenges faced by industries in their CLSC network redesign efforts.

Lastly, the framework primarily focuses on cost efficiency in the redesign process, while environmental and social sustainability considerations are only implicitly addressed. Future research could expand the model to include a more explicit focus on sustainability metrics, such as carbon emissions [3], energy consumption [28], and waste reduction [2], providing a more holistic approach to optimizing CLSC networks.

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Data availability

The data is available upon a reasonable request from the author.

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