# RESILIENCE AND RESPONSIVENESS IN CLOSED – LOOP SUPPLY CHAIN WITH MULTI-STREAM RECYCLING POLICY UNDER DISRUPTIONS

By

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I, Izma Abdus Saboor declare that this Masters degree's thesis entitled "Resilience and Responsiveness in Closed Loop Supply Chains with Multi-Stream Recycling Policy under Disruptions" submitted to NUST Business School for the degree of Masters in Logistics and Supply Chain Management is the result of my own hard work and dedication. I have acknowledged all the material sources utilized in this research.

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# Abstract

With increasing environmental hazards and governmental concerns over limited resources, special attention is being paid to closed-loop supply chain (CLSC) networks design having resilience and responsiveness in wake of disruptions. This research provides a multi-objective mixed integer linear programming (MILP) model for optimizing a CLSC during disruptions while taking resilience and responsiveness into account. Total cost function considering sustainable dimensions (economic, environmental, and social) along with resilience and responsiveness is studied. The concept of multi-stream recycling (MSR) is suggested to maintain a smooth flow of CLSC thereby increasing return rate and reducing the disposal rates. This study will contribute towards the CLSC literature while enriching it with integrated concepts of resilience-responsiveness-sustainability under disruption scenarios. Solution methodology known as interactive multi-objective fuzzy programming is used for the optimization of mathematical model. The proposed model and methods are used to solve the case of float glass industry for further investigation and validation. Data is collected from a float glass industry of Pakistan and findings are applied to the real case to provide fruitful results regarding CLSC decisions. The results showed that any rise in the percentage of interruptions will result in additional expenses, mostly because of delays/shortages and increased capacity interruptions of the primary player result in a decline in the responsiveness of the CLSC, which increases the deviation from the target value. Additionally, the notion of MSR must be implemented in order to lower the contamination levels and decrease waste fractions. Moreover, raising the degree of responsiveness will result in additional expenses and raise the levels of departure from the predetermined objectives.

**Keywords:** Closed Loop Supply Chain (CLSC); Multi-Stream Recycling (MSR); Sustainability; Responsiveness; Resilience; Disruptions; Interactive Multi-Objective Fuzzy Programming

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# Chapter 1: Introduction

In recent years, there has been a growing awareness and concern among researchers and governments about the depletion of scarce natural resources and environmental degradation. As the world grapples with these challenges, CLSC has emerged as a critical strategy to address these pressing issues. The concept of CLSC aligns closely with the broader goal of achieving sustainability and realizing a circular economy. One of the primary objectives of CLSC is to minimize resource input and reduce emissions across the entire product life cycle. This approach encompasses a range of practices, including maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. By integrating these practices into supply chain operations, organizations can significantly reduce their environmental footprint. For instance, remanufacturing and refurbishing allow products to be restored to their original condition, extending their lifespan, and reducing the need for new resources. Recycling ensures that materials are used efficiently, and that waste is minimized. Central to the concept of CLSC is the idea of a circular economy. In a circular economy, products and materials are kept in circulation for as long as possible, with waste and environmental impacts minimized. CLSC achieves this by combining forward and reverse flows in the supply chain. The forward flow represents the traditional movement of products from manufacturers to consumers, while the reverse flow involves products being collected and returned at the end of their life cycle for recycling or other forms of recovery as depicted in figure 1.1. This closed-loop approach not only conserves resources but also reduces the disposal of waste in landfills.

While the economic aspect of supply chains remains undeniable, there is a growing recognition of the importance of environmental and social considerations. In an era of heightened environmental awareness and increased social responsibility, organizations are realizing that focusing solely on economic factors is no longer sufficient. To gain a competitive advantage and maintain a positive public image, companies are striving to achieve a "triple bottom line" that takes into account economic, environmental, and social aspects  (Nayeri et al. 2020; Gholizadeh et al. 2021).. This multifaceted approach to supply chain management is not only ethical but also aligns with consumer expectations and regulatory requirements.

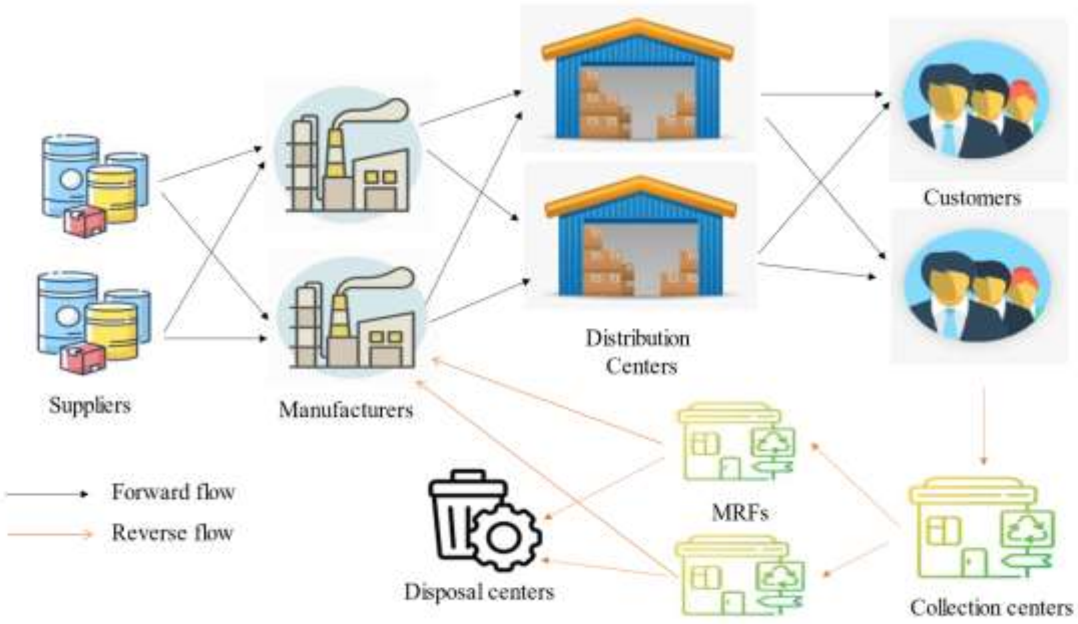

**Figure 1-1: Closed Loop Supply Chain Network design**

The complexity of supply chains has intensified in recent years due to globalization, rapid technological innovation, and fluctuations in demand and supply. However, this complexity also makes supply chains more vulnerable to disruption risks. Disruptions can be triggered by a wide range of factors, including natural disasters, epidemics, political instability, or regulatory changes. Such disruptions can have significant adverse effects on supply chain performance. To mitigate the impact of disruptions, organizations are increasingly focused on building resilient supply chains (Cardoso et al. 2015; Jabbarzadeh, Fahimnia, and Sabouhi 2018). Resilience in this context refers to a supply chain network's ability to recover and adapt swiftly after an interruption. Resilient supply chains are better equipped to withstand shocks and disruptions, ensuring that critical operations continue with minimal disruption to customers and stakeholders. In addition to resilience, responsiveness is another critical aspect of supply chain management. Responsiveness involves the network's ability to meet and satisfy consumer needs within predefined timeframes (Nayeri et al. 2020). This agility is crucial in a fast-paced and dynamic business environment, where customer expectations are constantly evolving.

CLSC has received significant attention in the literature, emphasizing its potential to contribute to sustainability goals. However, the convergence of CLSC with dimensions such as sustainability, resilience, and responsiveness remain relatively unexplored. While the economic aspects of supply chain management have traditionally dominated research, there is a growing recognition of the need to address environmental and social considerations. One notable observation is that within the field of Supply Chain and Network Design (SCND), researchers have often prioritized cost reduction as a response to disruption threats. This singular focus on cost containment has sometimes led to neglecting the broader environmental and social aspects of supply chain management (Jabbarzadeh, Haughton, and Khosrojerdi 2018). This gap in research highlights the need for a more comprehensive approach that considers not only cost efficiencies but also sustainability and resilience in the face of disruptions. In particular, CLSC, despite its critical role in sustainability, has been somewhat overlooked when it comes to resilience and disruptions. Supply chains are susceptible to various risks, including natural disasters, geopolitical instability, and global health crises. Integrating CLSC principles with resilience strategies could help organizations better prepare for and recover from such disruptions while also advancing sustainability goals. This holistic approach recognizes that supply chains must be adaptable and robust in the face of adversity, not just cost-effective.

Moreover, the emergence of Multi-Stream Recycling (MSR) represents a novel and promising development in the realm of supply chain sustainability. MSR concept has gained momentum due to its potential to reduce contamination levels in recyclable materials, lower the costs associated with sorting centers, and contribute to a greener environment by reducing the reliance on landfills. Despite its potential benefits, the concept of MSR and its application within supply chains remains relatively unexplored in the current body of knowledge.

## 1.1. Significance of Study

This groundbreaking research endeavor addresses critical issues in the context of global supply chains, which are increasingly vulnerable to disruptions and grappling with the challenges of resource scarcity. The primary aim of this research is to introduce and elucidate the concept of MSR within the framework of CLSC network designs. It seeks to achieve an innovative integration of responsiveness, resilience, and sustainability considerations within CLSC, especially in the face of disruption threats. To facilitate a comprehensive analysis and decision-making process, the research employs a multi-objective mixed-integer linear programming model. This model provides a valuable tool for decision-makers to conduct trade-off analyses among various critical aspects of supply chain management. Specifically, it allows decision-makers to balance the competing objectives of responsiveness, resilience, and sustainability in the context of CLSC network design.

The proposed Closed-Loop Supply Chain Network (CLSCN) in this research comprises seven distinct echelons, each playing a unique role in the supply chain ecosystem. These echelons include potential suppliers, manufacturing units, potential distribution centers, client zones, potential collection centers, potential material recovery facilities, and disposal centers. This comprehensive representation of the supply chain reflects the intricate web of interactions involved in the movement of materials and products. The material flow within this CLSCN commences with the procurement of raw materials, and it progresses through various stages. Notably, the reverse flow component of the supply chain is a pivotal element. It encompasses the recycling of used products facilitated by MSR. Products are collected, processed through material recovery facilities, and then directed back to manufacturing sites. If products are deemed unusable, they are routed to disposal centers. This closed-loop approach not only conserves resources but also minimizes waste and environmental impact.

In the context of Pakistan, the outcomes and decisions resulting from this optimization model hold significant implications. Pakistan took a pioneering step in 2016 by becoming the first country to include the Sustainable Development Goals (SDGs) in its national development plan. By incorporating these global objectives into its national policies and strategies, Pakistan has made commendable progress toward achieving these SDGs. Of particular importance is SDG Goal 12, which pertains to "responsible consumption and production." The optimization decisions stemming from this research align closely with the targets under this SDG goal. By optimizing CLSCN designs to enhance sustainability, minimize waste, and promote responsible consumption and production, Pakistan can make substantial strides toward achieving more sustainable patterns by 2030. This not only benefits Pakistan but also contributes to global sustainability efforts.

The proposed research methodology adopts an interactive multi-objective fuzzy programming approach as a strategic tool to effectively tackle the multi-objective model at hand. This approach presents an innovative and systematic framework for addressing complex decision-making scenarios, where multiple objectives need to be optimized simultaneously, while taking into account the inherent uncertainty and vagueness often encountered in real-world situations. The core principle of this approach revolves around the sequential optimization of individual goal functions within the multi-objective model. To elaborate further, the process begins by isolating one of the objectives and solving it to obtain its corresponding value. This value is then utilized as a constraint when optimizing the next objective in line. This stepwise optimization continues until all objectives have been addressed, resulting in a pay-off table that provides a comprehensive overview of the extreme function values associated with each goal.

What sets this approach apart is its ability to ensure the fulfillment of limits and constraints throughout the optimization process. This is achieved by leveraging the capabilities of mixed-integer linear programming to establish boundaries for the function values. As a result, the methodology maintains a high degree of practicality and feasibility, as the final solutions will inherently adhere to all specified constraints, which is crucial for real-world applicability. To put this methodology into practice and validate its effectiveness, a real-world case study focusing on the float glass industry of Pakistan is included. Notably, this case study is a unique contribution to the field, as no prior research has explored this specific industry within the context of the proposed multi-objective model to the best of our knowledge. By applying the model and solutions to a real-world scenario, the research aims to demonstrate the practical utility and relevance of the developed approach. Furthermore, the examination of the float glass industry in Pakistan allows for a thorough validation of the model's capabilities and its potential to generate meaningful insights and recommendations in a specific industrial context.

The research undertaken in this study follows a well-structured framework consisting of four distinct phases. These phases are thoughtfully designed to ensure a systematic and comprehensive approach to addressing the research problem at hand as shown in figure 1.2.

### Phase 1 - Problem Identification and Gap Analysis

In the initial phase of this research, the primary focus is on precisely defining the problem that the study aims to solve. This step is crucial as it sets the foundation for the entire research endeavor. It involves a thorough examination of the current state of knowledge, identifying gaps in existing literature, and pinpointing areas where further investigation is needed. By clearly defining the research problem and conducting a comprehensive gap analysis, the study establishes its relevance and provides a context for subsequent phases.

### Phase 2 - Literature Review

Building upon the problem definition and gap analysis, Phase 2 involves an extensive literature review. This phase is pivotal in gaining a deep understanding of the existing body of knowledge related to the research topic. Researchers explore academic papers, articles, books, and relevant sources to gather insights, theories, and empirical evidence that inform the research. The literature review not only helps identify prior research findings but also highlights methodologies and approaches that have been used in similar studies. It serves as the scholarly backdrop against which the research can be contextualized.

### Phase 3 - Model Design (Multi-Objective Mixed Integer Linear Programming - MOMILP)

With a solid understanding of the problem and insights gathered from the literature review, Phase 3 is dedicated to the design of the research model. In this case, the study adopts a Multi-Objective Mixed Integer Linear Programming (MOMILP) model. This phase involves the formulation of mathematical equations and algorithms that represent the complexities of the problem. The MOMILP model is crafted to accommodate multiple objectives, reflecting the multi-faceted nature of the research problem. It is in this phase that the study's theoretical framework is established, paving the way for empirical testing and analysis.

### Phase 4 - Case Study and Verification

The final phase of the research involves the application of the developed MOMILP model to a real-world case study. This case study serves as a practical validation of the model and its ability to yield meaningful results. By utilizing the model to address specific challenges within the context of the chosen case study (in this instance, the float glass industry of Pakistan), the research demonstrates the model's applicability and relevance to actual industrial scenarios. The outcomes of this phase help verify the effectiveness of the model in generating solutions and insights that can be applied in practical settings.

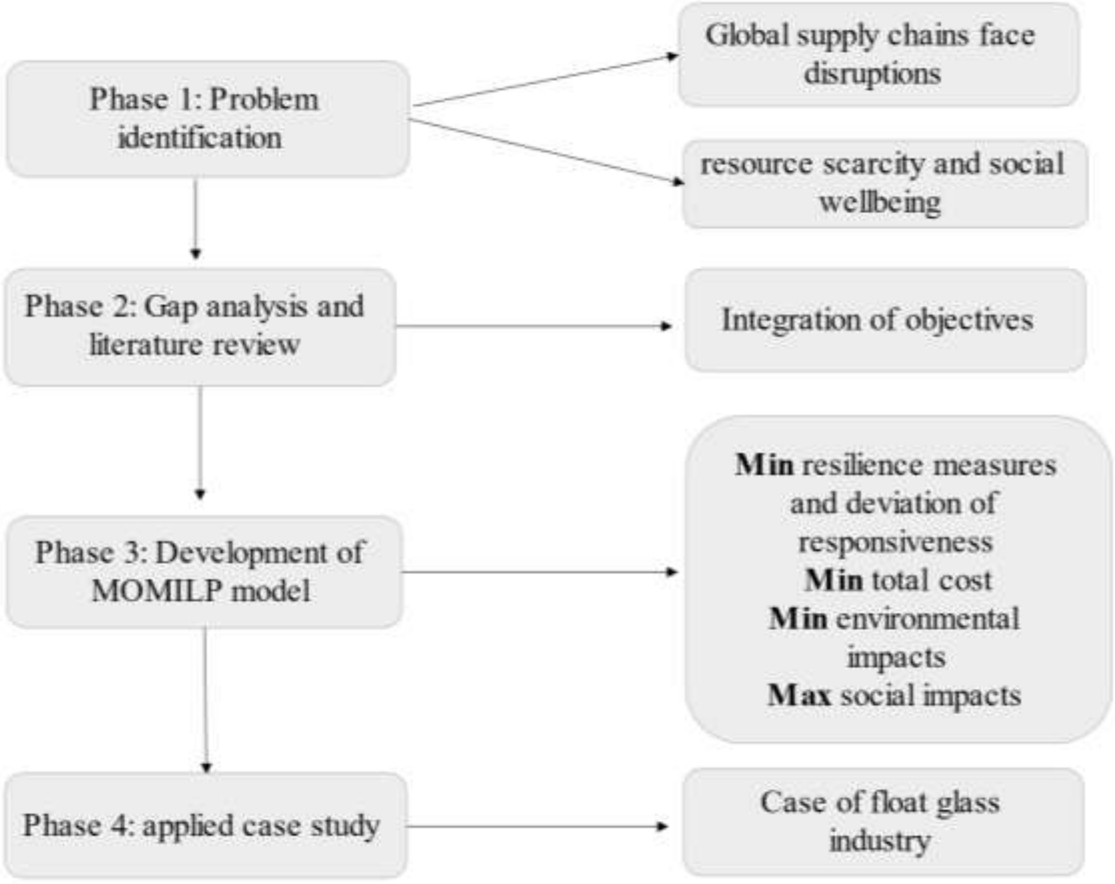

**Figure 1-2: Phases of research**

## 1.2. Problem Statement

The pressing challenges of resource scarcity, environmental conservation through green initiatives, and the promotion of social well-being have significantly elevated the importance of CLSC and sustainability within the contemporary business landscape. These challenges underscore the necessity for innovative approaches that not only optimize resource utilization but also reduce waste and mitigate environmental impacts. CLSC, with its emphasis on practices such as recycling, remanufacturing, and reuse, aligns perfectly with these imperatives by offering a holistic framework for sustainable supply chain management. In parallel, modern supply chains have embraced efficiency-driven methodologies like Lean and Just-in-Time (JIT) inventory management. These strategies, coupled with the increasing complexity driven by globalization, have, paradoxically, heightened the vulnerability of supply chains to disruptions. The interconnectedness of global supply networks means that disruptions can propagate swiftly across borders and industries, affecting businesses' abilities to meet customer demand and maintain operational continuity. Therefore, there's a growing recognition of the need for resilience and responsiveness in supply chains.

Despite these apparent challenges and the critical need for supply chain resilience and responsiveness, the research landscape in these areas remains relatively limited. The dearth of comprehensive studies that integrate CLSC, sustainability, resilience, and responsiveness present a notable gap in the literature. This gap signifies a significant opportunity for researchers to undertake an optimized, integrated study that systematically explores trade-offs among these dimensions and provides valuable insights for viable investment decisions. Figure 1.3, as depicted in the research, offers a pictorial representation of the multifaceted problem at hand. It serves as a visual aid that encapsulates the intricate interplay between resource scarcity, green initiatives, social well-being, CLSC, and the imperative for supply chain resilience and responsiveness. This visual representation highlights the complexity and interconnectedness of these factors, emphasizing the need for a holistic approach to address the challenges and opportunities they present.

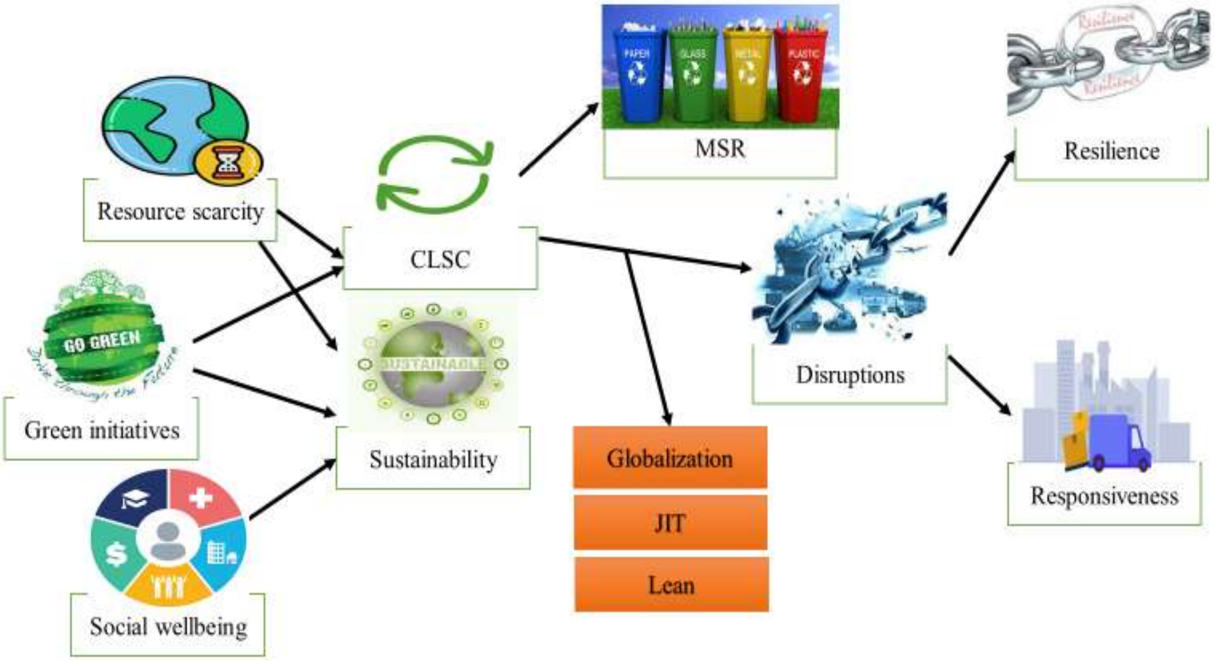

Figure 1-3: Problem Statement of the CLSC

## 1.3. Aims and Objectives

To address the stated problem, following aims and objectives will be the focus of the research:

- To increase the responsiveness of CLSC
- To maximize the resilience of CLSC
- To reduce the total cost
- To reduce the environmental impact
- To increase the social impact

These aims and objectives together form a structured roadmap for the research, encompassing exploration, model development, analysis, decision support, and practical validation. The research's systematic approach ensures that it contributes valuable insights and tools to address the complex challenges of integrating sustainability, resilience, and responsiveness in CLSC.

## 1.4. Research Questions

This study will be able to answer the following research questions:

**Research Question 1**: What could be the possible numbers and locations of facilities?

**Research Question 2**: How much quantity flow will there be in forward and reverse flows?

**Research Question 3**: What will be the possible tradeoffs between costs, responsiveness, sustainability, and resilience measures?

**Research Question 4**: How responsiveness and resilience of CLSC will be affected in disruption scenarios?

**Research Question 5**: What effect will MSR have on the CLSCN in terms of return rate and disposal rate?

This study aims to address a series of critical research questions. Firstly, it will explore potential numbers and locations for facilities within a CLSC network. Secondly, it will analyze the quantity and direction of product flows, both forward and reverse. Thirdly, the study will investigate the tradeoffs between various factors such as costs, responsiveness, sustainability, and resilience measures within the CLSC. Additionally, the research will examine how disruptions impact the responsiveness and resilience of the CLSC. Finally, the study will assess the impact of MSR on the CLSC network, particularly in terms of return and disposal rates. These research questions collectively seek to provide comprehensive insights into the design, operation, and sustainability of a CLSC network.

## 1.5. Chapter summary

The introduction chapter explains that contemporary supply chain management has evolved to emphasize sustainability principles, the adoption of a triple bottom line approach, and a focus on resilience and responsiveness. These strategies not only mitigate environmental impacts but also enhance the long-term viability and competitiveness of supply chains. The increasing importance of CLSC due to resource scarcity and disruption being inevitable makes it necessary to study resilience and responsiveness in the network. Furthermore, the intersection of CLSC with sustainability, resilience, and responsiveness presents an exciting area for further research and exploration within the field. This offers opportunities for scholars and practitioners to advance our understanding of how these critical dimensions can be integrated to create more environmentally and socially responsible supply chains that are also resilient in the face of disruptions. Additionally, emerging concepts as MSR introduce new possibilities for enhancing sustainability within supply chains, offering valuable avenues for future investigation and development. This chapter comprises of four subsections. The first section gives the significance of our study. The second section entails the problem that this study aims to optimize. Then in third section aims and objectives of the study are given then finally the research questions are listed that this study aims to answer.

# Chapter 2: Literature Review

This chapter elaborates an extensive literature review on resilience and responsiveness in Closed-Loop Supply Chains (CLSC) with a focus on multi-stream recycling policy under disruption scenarios. Contribution table given at the end of chapter entails the gaps and contribution of our study.

Considering the scarce natural resources, government legislations and environmental concerns CLSC proves its necessity (Ghomi-Avili, Khosrojerdi, and Tavakkoli-Moghaddam, 2019). Industry owners are now more focused on waste reduction and the green supply chain thanks to the growing circular economy idea. The circular economy is the foundation of the closed-loop supply chain, that seeks to boost productivity and profitability by consuming less energy and trash (Govindan et al., 2023). A CLSC network considering multi-product, multi echelon, multi-period model was created by a hybrid algorithm: the genetic algorithm (GA) and particle swarm optimization (PSO) using MATLAB and CPLEX software applied to hospital furniture manufacturer as case study (Soleimani and Kannan, 2015). The study has single objective of total cost reduction considering design and planning decision level without considering sustainable dimensions or grading of products in reverse flow. Zhang et al., (2019) studied and developed multi-objective multi echelon CLSC network design under uncertainty including all three sustainable dimensions.

Operational uncertainty regarding demand and remanufacturing rate are studied by applying robust optimization method and uncertainty of missed days due to social impact are studied using fuzzy membership theories using ILOG CPLEX software (Pishvaee, Rabbani, and Torabi, 2011) presented a robust optimization model considering inherent ambiguity of the source data in a CLSC network design problem. A MILP model is generated considering both push and pull supply systems solved using ILOG CPLEX 10.1 optimization software considering single product. Ahmed et al., (2020) studied a multi-objective MILP mathematical model aiming at reducing costs and CO2 emissions for CLSC which is environmentally sustainable. This study applied the epsilon constraint method and genetic algorithm optimization method while considering assembly, disassembly, transportation, handling, and remanufacturing sectors for CO2 emissions with single mode of transport.

According to Gaur, Amini, and Rao (2017), firms focus on forward supply chains for new and existing products while simultaneously engaging in reverse supply chain activities such as remanufacturing rejected products. This study uses CLSC to create a single objective multi-period mixed-integer non-linear programming (MINLP) model that includes production and sales planning for both new and reconditioned products throughout their life cycles, inventory levels at each stage, and stage selection. To solve the suggested model, this work employs the Outer Approximation/Equality Relaxation/Augmented Penalty (OA/ER/AP) strategy to analyze the developed framework and applied it to a battery manufacturing case study. Golara et al., (2012) proposed a multi-period, multi-product, MILP model involving CLSC with profit maximization as single objective while considering strategic and tactical planning decisions including acquisition, manufacturing, storage, distribution, take-back, reconditioning, reuse, and recycling however they didn't consider the uncertainty of the parameters involved. Case study of beverage supply chain involving glass containers is further investigated using GAMS software with CPLEX solver showing return rate and acquisition costs as detrimental drivers.

The goal of supply chain sustainability is to inculcate environmental and social factors into traditional cost-oriented supply chain management (SCM) procedures. Nayeri et al., (2020) proposed a multi-objective mixed integer (MOMIP) mathematical model to set up the sustainable close loop supply chains (SCLSC) network by applying the model to water tank supply networks while discussing sustainability in all three aspects: economic, environmental, and social. Given uncertainty in SCLSC networks, a fuzzy robust optimization (FRO) method in the study. The model is resolved via goal programming. The study considers transport modes, carbon policy and supplier selection. Pourjavad and Mayorga 2018 proposed a multi objective, mixed integer, multi echelon, and multi period CLSC that reduces costs and environmental impacts while increasing social benefits. The non-dominated sorting genetic (NSGAII) algorithm was found to be an appropriate tool for analyzing the multi-objective CLSC network design problem proposed in the study.

Rezaei and Maihami (2020) presented a better new gaming structure (Stackelberg, a Nash game and novel bargaining structure) in a multi-echelon CLSC involving sustainable decisions considering first and second markets with centralized and decentralized scenarios over two-period planning showing better performance of decentralized scenario. Yun, Chuluunsukh, and Gen

(2020) studied a multi-objective optimization problem of sustainable CLSC by reducing costs and CO2 emissions from product manufacturing and shipping, as well as enhancing societal influence. Three distribution channels (normal delivery, direct delivery, and direct shipment) are explored for effective/efficient distribution and can be solved utilizing pareto optimum solutions. A hybrid genetic algorithm (pro-HGA) approach is applied to developed model. Gholizadeh et al., (2021) proposed a multi period multi product MILP model for sustainable closed loop supply chain (SCLSC) applied to the case of dairy industry with some uncertain parameters. The work uses robust optimization and heuristics to supplement the epsilon-constraint technique with linearization.

In the present quickly evolving climate, Supply networks are more vulnerable to risks due to a variety of causes like expanded globalization, higher customer expectations, climate unpredictability, and the internal/external risks. The researchers underline the need of risk and disruption management in supply chains for businesses to compete in today's increasingly turbulent and uncertain economy. Cardoso et al. (2015) showed complex supply chains that are more prone to disruptions because of operating in global market among which the CLSC boost operational indicator and resilience indicator. The approach reinforces a more resilient supply chain by establishing a more flexible network with diverse node links. The study used multi product multi period single objective MILP model to decide the design and planning by using CPLEX 12.0 a European supply chain is considered to apply the methodology and research shows that CLSC network gives higher ENPV (expected net present value) while being most resilient. They also showed that less mitigation methods are required to deal with interruptions in a network structure that is more resilient from scratch. Considering resilience to disruptions and sustainability Jabbarzadeh, Fahimnia, and Sabouhi (2018) built a stochastic bi-objective optimization model using the fuzzy e-means clustering technique while implementing resilience tactics and outsourcing choices to reduce overall costs. They consider disruption at factories and suppliers by applying it to the case study of plastic pipe industry while excluding transportation disruptions. To deal with disruption risks several resilience strategies are applied using two stage stochastic programing thereby concluding that resilient strategies reduce loses (Vali-Siar, Roghanian, and Jabbarzadeh, 2022). Gholizadeh and Fazlollahtabar (2020) studied environmental aspect of sustainability for CLSC using the case study of melting industry by applying robust optimization and modified genetic algorithms using LINGO software. Decision-making at the tactical and operational levels is combined to configure the CLSC capturing additional value using return processes. Sundarakani, Pereira, and Ishizaka (2020) studied the facility location problems for modern supply chains that are resilient and sustainable at the same time.

A robust optimization and mixed integer linear programming method (ROMILP) is used and applied to the case of apparel industry. Ghomi-Avili, Khosrojerdi, and Tavakkoli-Moghaddam, (2019) showed supply chains get gain from the lateral transshipment approach for mitigating the risk of interruption used various transportation ways to meet customer demand by collecting return items from direct consumers. They developed CLSC design using multi objectives of cost minimization profit maximization and minimization of total flow using a compromise programming method of Lp-metric and thereby suggesting robust optimization method for the given uncertainty in the model. Hamidieh, Arshadi Khamseh, and Naderi, (2018) presented a new model of responsive resilient supply chain network consisting of reactive and preventive resilient strategies to deal with parametric uncertainties using a hybrid possible distinct possibilistic robust programming method applied to the case of polyethylene industry. Most work turn on supply chain resilience, responsiveness and disruptions are qualitative studies for instance (Duminy and Grosser, 2018) studied shortages in critical consumer goods production supply chains making resilience as a basis of sustainability. de Arquer, Ponte, and Pino, (2021) examined the closed loop supply chain's resilience and efficiency trade-off where demand of customers can be satisfied by both new and manufactured products thereby considering inventory performance production smoothness by measuring bullwhip effect and investigating resilience to demand volatility. A systematic literature review and disruption in supply chain is done by Kochan and Nowicki, (2018); Parast and Shekarian, (2019); Negri et al., (2021). Nayeri et al., (2021) designed an integrated model for sustainable resilient responsive supply chain network using a fuzzy robust stochastic approach having multiple objectives and applied to water heater industry is one of the closest studies found in literature that relates to our research. A closed-loop supply chain network with bi objective is created while accounting for discounts, uncertainties, and environmental factors by Javid et.al., (2020). Three multi-objective decision-making techniques are used to first solve the deterministic chain model. Then, using decision-making techniques, a robust optimization model is presented and solved. This is based on real-world uncertainty associated with some of the parameters. In the end, based on the displaced ideal solution, the most deterministic and reliable models are chosen.

Waste producers get separate containers from MSR to separate recyclables, and it entails retrieving recyclables after waste pickup. Studies have explored the impact of multi-stream recycling policies on supply chain operations, emphasizing the need for supply chains to adapt to evolving recycling regulations. Multi-stream recycling policies often require supply chains to segregate and manage various recyclable materials separately, which can affect supply chain design and operations. Bafail and Abdulaal (2021) showed that MSR is the most recommended of the alternative although it has higher cost, but MSR had a lower rate of recovery and residual rate factor as reflected in overall cost allowing high quality and preventing additional costs associated with getting rid of low-quality materials overall and reducing landfills impacting environment. They used a case study of paper and pulp industry to verify findings using AHP and TOPSIS. Effects of MSR are not discussed in respect to supply chain optimization.

The findings of a life cycle analysis (LCA) research comparing the most widely used construction materials with eco-materials utilizing three distinct effect categories are presented by Bribián et al. in 2020. The objective is to have a deeper understanding of the energy and environmental requirements for construction materials. Environmental impacts of float glass are taken from their study. Dahl et.al., (2020) identified actors, waste sources, and applications for recycled flat glass and included all in the CLSC model of flat glass. In addition, they proposed a cost structure of a flat glass CLSC. Flat glass may be used to make float glass, container glass, and glass wool, among other things. The price range for flat glass splits cost aspects into the three phases of a flat glass CLSC and six supply chain cost categories including production cost, distribution cost, warehousing cost, administration cost, capital cost, and installation cost. Souviran rt.al., (2021) for the first time studied a long-term time series on architectural glass manufacture. The results highlight two key issues: first, despite the tightening of European environmental policies, since the 1990s, efforts to improve energy efficiency have been less effective.; second, the demand for architectural glass in the EU continues to be particularly high, leading to a production rate that consumes a lot of energy and raw materials. The absolute decoupling of environmental costs from industrial expansion does not appear to have occurred, despite the relative decoupling of energy and CO2 intensities having passed a threshold.

One of the most effective and simple methods for reducing greenhouse gas emissions is carbon pricing, which is universally accepted (GHG). As a result, an increasing number of nations have created or are currently creating carbon pricing instruments as one of the strategies to assist the implementation of Nationally Determined Contributions (NDCs). Although Pakistan's NDC does not specifically include carbon price, various policy papers lay the groundwork for its implementation. For instance, a carbon tax is included in the National Climate Change Policy (2012) as one of the mitigation strategies that might help the energy sector reduce its GHG emissions. Additionally, the creation of incentive programs to aid mitigation efforts is included in both the National Climate Change Policy and its implementation framework (2013). Carbon pricing approaches consist of two options: carbon taxation (or “direct pricing”) and the establishment of an emissions trading system (ETS). A carbon tax is, in theory, the most practical tool for implementation in any given jurisdiction from a technological perspective. It has simple economic principles, often involves modest implementation costs, and allows for extensive coverage of emissions. According to the report by institute of global environmental strategies (IGES) and government of Pakistan on carbon pricing instruments in Pakistan a carbon tax often receives little legislative support, and neither do business organizations or the general people. Their study's findings and consultations clearly imply that Pakistan might experience a similar situation. According to their study, Pakistan has a lot of potential for the implementation of an emissions trading system (ETS). First off, this is a choice that offers policymakers and covered organizations considerably more freedom than a carbon tax does. This flexibility may take the form of allowing enterprises to choose how to meet their emissions quota (for instance, by reducing their own GHG emissions or by purchasing emission units from other participants). When selling their excess allowance, the least polluting organizations could be able to make money. The ability of the national government to customize an ETS is another benefit. By issuing "free emission permits," it can protect industrial sectors that are vulnerable to worldwide competition in particular. Additionally, it has the authority to determine the total level of work needed of ETS members as well as the proportionate contributions of the various sectors. Pakistan is an adherent to the Paris Agreement and has pledged in its Nationally Determined Contribution (NDC), subject to funding availability, to reduce 20% of its greenhouse gas (GHG) emissions by 2030. This is the emission reduction goal, and not the more ambitious one of 50% in October 2021.

Modified interactive fuzzy programming, which defines the satisfaction level of each objective, is proposed to address this multi-objective, multi-period supply chain problem. Although Paksoy and Pehlivan used this method to a multi-stage supply chain network problem, in their instance, expert judgment was given the same weight regardless of their level of expertise. Imran et. al., (2021) also used the modified interactive fuzzy programming to solve its multi-objectives. Interactive fuzzy programming approach method for solving the linear programming was proposed by Zimmermann (Zimmermann 1978) showing the linear vector maximum issue is applied with fuzzy linear programming techniques. It demonstrates that outcomes of fuzzy linear programming are consistently effective outcomes. Additionally, it illustrates the effects of selecting an "optimal" compromise solution by merging many individual objective functions.

The literature on resilience and responsiveness in CLSC with multi-stream recycling policy underscores the importance of integrating these dimensions to meet sustainability goals and effectively manage disruptions. Decision-makers face the challenge of finding the right balance between sustainability objectives, supply chain resilience, and responsiveness while adapting to evolving recycling regulations. Research in this area provides valuable insights, optimization models, and industry-specific case studies that can inform the design and management of CLSCs under multi-stream recycling policies. Table 2.1 shows the contribution of this research in literature with respect to most relevant research.

Table 2-1: Literature Contribution Table for Resilient and Responsive CLSC

| Articles | Network Design | Mathematical Model | Sustainability | Responsiveness | Resilience | Disruptions | Multi-Stream Recycling | Case Study | Solving Method |
|---|---|---|---|---|---|---|---|---|---|
| Cardoso et al., (2015) | CLSC | SOMILP | | | ✓ | ✓ | | | CPLEX 12.0 |
| Jabberzadeh et al., (2018) | forward SC | BOMIP | ✓ | | ✓ | ✓ | | plastic pipe | fuzzy e-means clustering |
| Hamidieh et al., (2018) | forward SC | SOMILP | | ✓ | ✓ | ✓ | | polyethylene | possibilistic robust programming |
| Nayeri et al., (2020) | CLSC | MOMIP | ✓ | | | | | water tank | fuzzy robust optimization (FRO) |
| Sundarakani et al., (2020) | forward SC | SOMILP | ✓ | | ✓ | | | apparel industry | robust optimization |
| Gholizadeh et al., (2021) | CLSC | BOMILP | ✓ | | | | | dairy industry | robust optimization |

Table 2-2: Literature Contribution Table for Resilient and Responsive CLSC (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Nayeri et al., (2021) | forward SC | MOMIP | ✓ | ✓ | ✓ | | | water heater | fuzzy robust stochastic (FRS) |
| Jabbarzadeh et al., (2022) | CLSC | SOMILP | | | ✓ | ✓ | | | Improved particle swarm optimization (IPSO) |
| Govindan et al., (2023) | CLSC | BOMILP | ✓ | | | | | Cable and wire industry | Epsilon constraint method |
| Our study | CLSC | MOMILP | ✓ | ✓ | ✓ | ✓ | ✓ | Float glass | interactive multi-objective fuzzy programming approach |

## 2.1. Research Gap

It is evident from literature that researchers have stressed on closed-loop supply chain network design CLSC and sustainability whereas literature on responsiveness, resilience, and supply chain disruptions is very scarce. Most work done quantitatively encompasses CLSC network design and sustainability whereas resilience in face of supply chain disruptions and responsiveness are studied qualitatively. Our study presents quantitative research using mathematical modeling and optimization methods by integrating three main dimensions of closed loop supply chain that are resilience- responsiveness- sustainability by considering disruptions and inculcating MSR policy.

### 2.1.1. Proposed framework

To fill in the gaps identified through literature review, a MOMILP model is proposed for the CLSC networks that will serve as a decision-making tool for resilient responsive CLSC. The proposed model is based on the objectives of cost minimization, minimization of environmental impacts maximizing social impacts and minimizing the deviation of responsiveness and resilience. The proposed model is optimized using interactive multi-objective fuzzy programming. Figure 2.1 shows the framework of study.

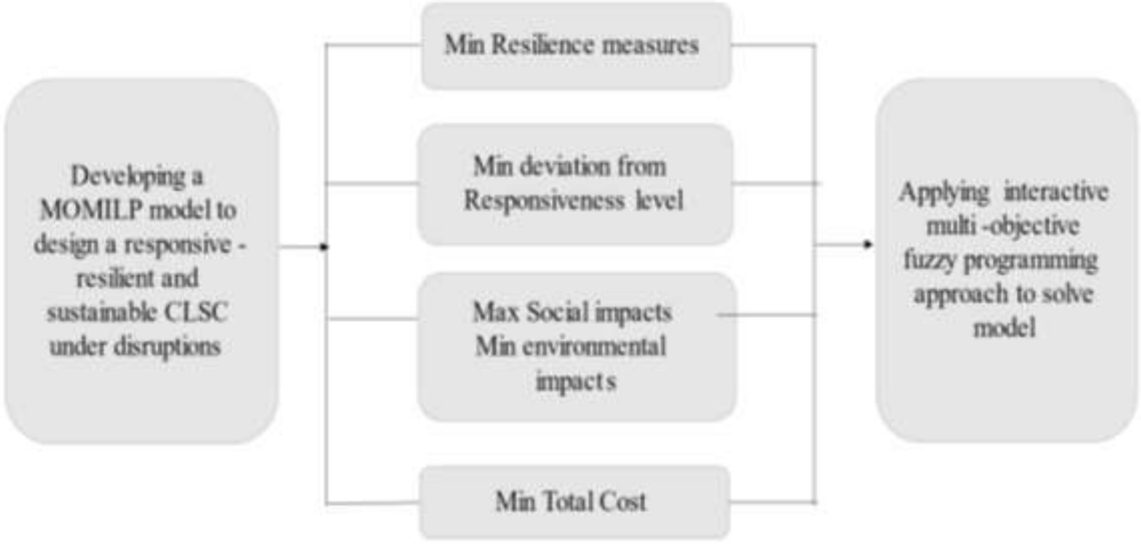

Figure 2-1: Framework of the study

## 2.2. Chapter summary

Chapter 2 describes the previous literature to identify the research gap for this study. There is a need to transition from forward supply chains towards Closed-loop supply chains mainly due to resource scarcity and to protect the environment. Most literature consists of qualitative studies on resilience and responsiveness in supply chains. Moreover, closed loop supply chain is still a topic that needs more exploration in terms of quantitative studies. Optimization models integrating different aspects of closed loop supply chains with multiple objectives cease to exist. Also, MSR bearing such an importance is not integrated in the supply chain models even merely as a concept although very limited qualitative studies on MSR do exist.

# Chapter 3: Development of Mathematical Model

This section delineates the proposed mathematical model showing a comprehensive and in-depth exploration of the model's structural components, including the elucidation of notations, the definition of decision variables, the specification of parameters, the formulation of objective functions, and the establishment of constraints. This extensive detailing serves the purpose of providing a clear and holistic understanding of the mathematical framework that underpins the optimization problem at hand.

## 3.1. Problem description

This research aims at optimizing a sustainable, resilient, and responsive closed-loop supply chain under disruptions. This proposed CLSCN model includes seven echelons involving potential suppliers, potential manufacturers, potential distribution centers, customer zones, potential collection centers, potential MRF and potential disposal centers. Forward Material flow is started by procuring required raw materials from supplier. After this the products are manufactured in the manufacturing unit and transported to customer zones through distribution centers. Then in reverse flow the products are recycled according to a return rate and collected at waste collection centers then sent to Material recovery facility. At MRF the products are further divided into two parts and sent to disposal centers and manufacturing sites according to a specific percentage thereby forming a closed-loop supply chain. It should be emphasized that shortfall is also permitted, thus the business is not required to completely satisfy every customer's needs. On the other hand, we have considered different transportation vehicles with different capacities and emissions. Figure 3.1 depicts the CLSC network under consideration.

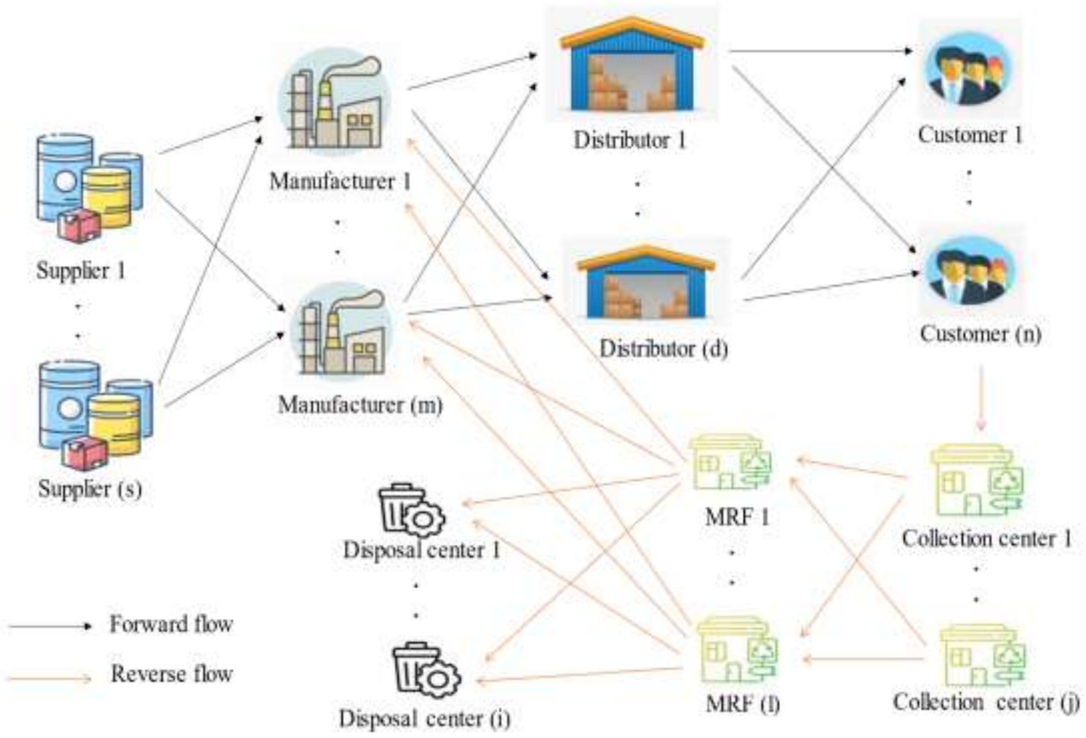

Figure 3-1: The proposed CLSC network under consideration

To design the above mentioned CLSC network, The primary goal function seeks to reduce the overall costs related to facility creation and operation. The next objective function maximizes the environmental effects while considering sustainability. There are two parts to the third objective function. The first section seeks to reduce the resilience measure, while the second section seeks to reduce the anticipated departure from the CLSC responsiveness level. The fourth objective function considers the third sustainable dimension and optimizes the social impacts. The sustainability modeling portion of this study also takes the carbon cap-and-trade program into account. This policy states that the CLSC permits the generation of a specific quantity of carbon in its network, known as the carbon cap. The CLSC may sell any extra carbon credits it has if the amount of carbon it produces falls below the carbon cap. On the other hand, if the amount of carbon required to meet consumer needs exceeds the carbon quota, the CLSC can purchase additional carbon credits from the market. (Mohammed et al. 2017; Nayeri et al. 2020).

We specify how to include sustainability, responsiveness, and resilience metrics in this research in the sections that follow. Three pillars have been used to evaluate sustainability: (a)

Economic (i.e., minimizing the total costs of CLSCN), (b) Environmental (i.e., minimizing the environmental damages), and (c) Social (i.e., maximizing the social impacts) (Fathollahi-Fard, Ahmadi, and Al-e-Hashem 2020; Nayeri et al. 2020; Soleimani and Kannan 2015). Whereas the CLSCN's responsiveness level is determined by dividing the entire amount of satisfied demand by the total amount of unmet demand. The approach seeks to reduce the anticipated responsiveness level's departure from a goal value established by experts. (Nayeri et al. 2021). In terms of resilience, the suggested model seeks to reduce node complexity as a metric of the CLSCN's resilience. (Zahiri, Zhuang, and Mohammadi 2017; Nayeri et al. 2021). Another indicator of resilience is how interruption situations affect the capabilities of the facilities. (Jabbarzadeh, Fahimnia, and Sabouhi 2018; Torabi et al. 2016). For detailed explanation, the dimensions (i.e., measures) of responsiveness, resilience, and sustainability in the CLSCN under consideration are depicted in Figure 3.2.

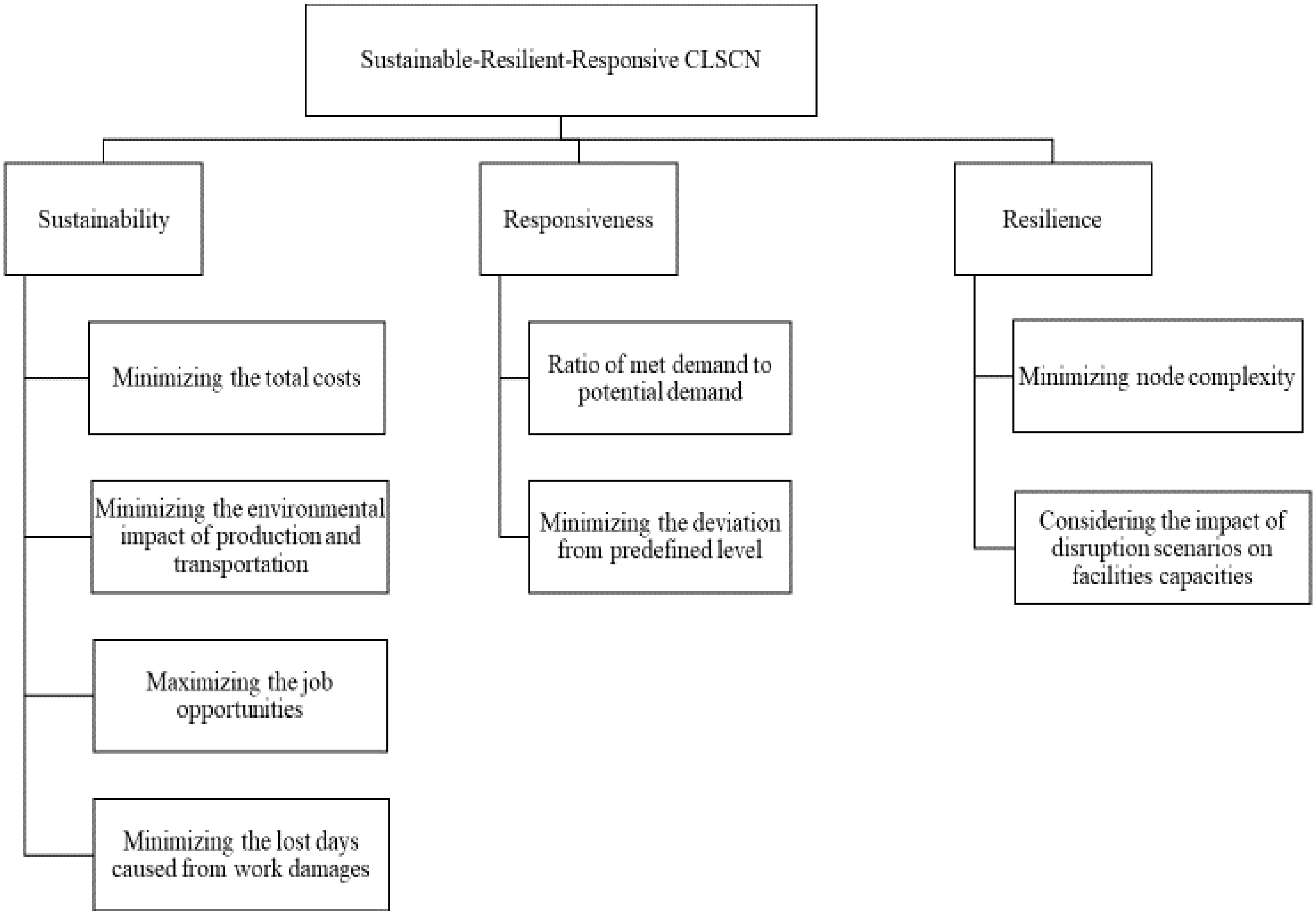

Figure 3-2: Attributes of proposed CLSC network

## 3.2. Model assumptions

The following model assumptions are taken into account to formulate the problem:

1. Facilities of the closed-loop supply chain (i.e., suppliers, manufacturers, distributors, collection centers and material recovery facilities) have limited capacities (Nayeri et al. 2020).
2. Predetermined candidate locations are there for possible facilities (Nayeri et al. 2020).
3. The model is investigated under the carbon cap-and-trade legislation to create a trade-off amongst costs and environmental emissions (which was attributed to transportation and manufacturing activities). (Nayeri et al. 2021).
4. All of the social, environmental, and economic factors are taken into consideration while discussing the sustainability dimension. Different costs are assessed as economic measurements for this. Additionally, "carbon emission" is taken into account as an environmental metric, whilst “job opportunities" are taken into account as CLSCN's social consequences. Notably, expanding work options helps to raise the local employment rate and discourages unwelcome migration. However, safety plays a crucial part in the wellbeing of the workforce. (Fathollahi-Fard, Ahmadi, and Al-e-Hashem 2020; Lotfi et al. 2021; Nayeri et al. 2021).
5. Similar to (Govindan and Fattahi 2017; Nayeri et al. 2021), we evaluate the ratio of the met demand to the total potential demand as the level of SC responsiveness.
6. In the resilience dimension, we take facility capacity and disruption situations into consideration. Similar to (Zahiri, Zhuang, and Mohammadi 2017; Cardoso et al. 2015), we aim to reduce the resilience measure of node complexity at the network level.
7. The weights assigned to various elements in this study are only assumed to be equal. AHP and BWM are two pair-wise comparison-based MADM techniques that might be utilized, nonetheless, for a more precise weight estimation. (Rezaei and Maihami 2020).
8. Multi stream recycling policy is considered to maintain a smooth flow of closed loop supply chain (Zhang et al. 2021).

## 3.3. Model Notations

This section presents the necessary notations used followed by parameters and decision variables of the proposed MOMIP model.

### 3.3.1. Sets

| | |
|---|---|
| $S$ | Set of Suppliers indexed by $s$ |
| $M$ | Set of Potential Manufacturers indexed by $m$ |
| $D$ | Set of Potential Distributors indexed by $d$ |
| $N$ | Set of Customers indexed by $n$ |
| $J$ | Set of Potential Collection centers indexed by $j$ |
| $I$ | Set of Disposal centers indexed by $i$ |
| $L$ | Set of Potential material recovery facilities indexed by $l$ |
| $P$ | Set of Products indexed by $p$ |
| $R$ | Set of Raw materials indexed by $r$ |
| $T$ | Set of Available transportation vehicles indexed by $t$ |
| $K$ | Set of Disruption scenarios indexed by $k$ |

### 3.3.2. Parameters

| | |
|---|---|
| $FM_m$ | Fixed cost of opening manufacturing site $m$ (\$) |
| $FD_d$ | Fixed cost of opening distribution center $d$ (\$) |
| $FC_j$ | Fixed cost of opening collection center $j$ (\$) |
| $FR_l$ | Fixed cost of opening material recovery facility $l$ (\$) |
| $FS_s$ | Fixed cost of contracting a supplier $s$ under disruption scenario $k$ (\$) |
| $UR_{rs}$ | Unit cost of purchasing raw material $r$ from supplier $s$ (\$) |
| $MC_{pmk}$ | Unit manufacturing cost of product $p$ produced in manufacturing site $m$ under disruption scenario $k$ (\$) |

| | |
|---|---|
| $OD_{dpk}$ | Unit operational cost of distributor $d$ for product $p$ under disruption scenario $k$ ($) |
| $OC_{jpk}$ | Unit operational cost of collection centers $j$ for product $p$ under disruption scenario $k$ ($) |
| $OR_{lpk}$ | Unit operational cost of material recovery facilities $l$ for product $p$ under disruption scenario $k$ ($) |
| $SC_{pnk}$ | Unit shortage cost of product $p$ for customers $n$ under disruption scenario $k$ ($) |
| $f$ | Fuel price ($/liter) |
| $fcr$ | Fuel consumption rate (liter/km) |
| $CRB$ | Unit cost of buying/selling carbon ($) |
| $DIS_{sm}$ | Distance between supplier $s$ and manufacturer $m$ (km) |
| $DIS_{md}$ | Distance between manufacturer $m$ and distributor $d$ (km) |
| $DIS_{dn}$ | Distance between distributor $d$ and customer zones $n$ (km) |
| $DIS_{nj}$ | Distance between customer $n$ and collection centers $j$ (km) |
| $DIS_{ji}$ | Distance between collection centers $j$ and disposal centers $i$ (km) |
| $DIS_{jm}$ | Distance between collection centers $j$ and manufacturer $m$ (km) |
| $DIS_{jl}$ | Distance between collection centers $j$ and recovery facility $l$ (km) |
| $DIS_{ji}$ | Distance between material recovery facility $l$ and disposal centers $i$ (km) |
| $DIS_{jm}$ | Distance between material recovery facility $l$ and manufacturer $m$ (km) |
| $DEM_{npk}$ | Demand of customer $n$ for product $p$ under disruption scenario $k$ (ton) |
| $CNSP_{rp}$ | Consumption of raw materials $r$ in a unit of product $p$ |
| $CPS_{sr}$ | Supplier $s$ capacity for raw materials $r$ (ton) |
| $CPM_{mp}$ | Maximum capacity of manufacturer $m$ for product $p$ (ton) |

| | |
|---|---|
| $CPD_{dp}$ | Maximum capacity of distributor $d$ for product $p$ (ton) |
| $CPJ_{jp}$ | Maximum capacity of collection center $j$ for recycled product $p$ (ton) |
| $CPL_{lp}$ | Maximum capacity of MRF $l$ for recycled product $p$ (ton) |
| $CPT_t$ | Capacity of transportation mode $t$ used (units/vehicle) |
| $CC$ | Carbon cap over the entire planning horizon (allowable emissions in ton) |
| $WR_r$ | Weight of raw materials $r$ (tons) |
| $WP_p$ | Weight of products $p$ (tons) |
| $PC_{sk}$ | Percentage of capacity of suppliers $s$ disrupted under disruption scenario $k$ |
| $PC_{mk}$ | Percentage of capacity of manufacturer $m$ disrupted under disruption scenario $k$ |
| $PC_{jk}$ | Percentage of capacity of collection centers $j$ disrupted under disruption scenario $k$ |
| $PC_{lk}$ | Percentage of capacity of material recovery facility $l$ disrupted under disruption scenario $k$ |
| $PC_{dk}$ | Percentage of capacity of distributors $d$ disrupted under disruption scenario $k$ |
| $EI_p$ | Environmental impacts of producing product $p$ |
| $TEI_{tp}$ | Environmental impacts of transportation vehicle $t$ used for shipping products $p$ |
| $JS_s$ | No. of fixed job opportunities created if supplier $s$ is selected |
| $JM_m$ | No. of fixed job opportunities created if manufacturer $m$ is opened |
| $JD_d$ | No. of fixed job opportunities created if distributor $d$ is selected |
| $JJ_j$ | No. of fixed job opportunities created if collection center $j$ is selected |
| $JL_l$ | No. of fixed job opportunities created if material recovery facility $l$ is selected |

| | |
|---|---|
| $REP$ | Amount of target considered for supply chain responsiveness level |
| $QR_{pnk}$ | Quantity of product p returned from customers $n$ under scenario $k$ |
| $DF_{pk}$ | Disposal fraction of product $p$ under scenario k |
| $PK_k$ | Possibility occurrence of disruption scenario $k$ |
| $\beta_s$ | Penalty coefficient for node complexity of supplier $s$ |
| $\beta_m$ | Penalty coefficient for node complexity of manufacturer $m$ |
| $\beta_d$ | Penalty coefficient for node complexity of distributor $d$ |
| $\beta_j$ | Penalty coefficient for node complexity of collection center $j$ |
| $\beta_l$ | Penalty coefficient for node complexity of material recovery facility $l$ |
| $WJ$ | Weight of job opportunities created |
| $WEI$ | Weight of environmental impacts |
| $WSI$ | Weight of social impacts |
| $WREP$ | Weight of responsiveness level |
| $WRE$ | Weight of resilience level |

### 3.3.3. Decision variables

| | |
|---|---|
| $SS_s$ | $\begin{cases}1\\0\end{cases}$ If supplier $s$ is selected then 1, otherwise 0 |
| $SM_m$ | $\begin{cases}1\\0\end{cases}$ If manufacturing site $m$ is selected then 1, otherwise 0 |
| $SD_d$ | $\begin{cases}1\\0\end{cases}$ If distributor $d$ is selected then 1, otherwise 0 |
| $SJ_j$ | $\begin{cases}1\\0\end{cases}$ If collection center $j$ is selected then 1, otherwise 0 |

| | |
|---|---|
| $SL_l$ | $\begin{cases}1\\0\end{cases}$ If material recovery facility $l$ is selected then 1, otherwise 0 |
| $T_{smt}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between suppliers $s$ and manufacturers $m$ then 1, otherwise 0 |
| $T_{mdt}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between manufacturers $m$ and distributors $d$ then 1, otherwise 0 |
| $T_{dnt}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between distributor $d$ and customer $n$ then 1, otherwise 0 |
| $T_{njt}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between customer $n$ and collection center $j$ then 1, otherwise 0 |
| $T_{jlt}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between collection center $j$ and material recovery facility $l$ then 1, otherwise 0 |
| $T_{lmt}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between material recovery facility $l$ and manufacturer site $m$ then 1, otherwise 0 |
| $T_{lit}$ | $\begin{cases}1\\0\end{cases}$ If transportation mode $t$ is selected between material recovery facility $l$ and disposal center $i$ then 1, otherwise 0 |
| $QR^k_{rsmt}$ | Quantity of raw material $r$ purchased from supplier $s$ and shipped to manufacturer $m$ using transportation mode $t$ under disruption scenario $k$ |
| $QP^k_{pmdt}$ | Quantity of product $p$ produced by manufacturer $m$ and shipped to distributor $d$ using transportation mode $t$ under disruption scenario $k$ |
| $QD^k_{pdnt}$ | Quantity of product $p$ moved from distributor $d$ to customer $n$ using transportation mode $t$ under disruption scenario $k$ |

| | |
|---|---|
| $QN^{k}_{pnjt}$ | Quantity of product $p$ moved from customer $n$ to collection center $j$ using transportation mode $t$ under disruption scenario $k$ |
| $QL^{k}_{pjlt}$ | Quantity of recycled product $p$ moved from collection center $j$ to material recovery facility $l$ using transportation mode $t$ under disruption scenario $k$ |
| $QI^{k}_{plit}$ | Quantity of recycled product $p$ moved from material recovery facility $l$ to disposal center $i$ using transportation mode $t$ under disruption scenario $k$ |
| $QM^{k}_{plmt}$ | Quantity of recycled product $p$ moved from material recovery facility $l$ to manufacturer $m$ using transportation mode $t$ under disruption scenario $k$ |
| $QPC_{k}$ | Quantity of carbon credit purchased under disruption scenario $k$ |
| $QSC_{k}$ | Quantity of carbon credit sold under disruption scenario $k$ |
| $QSH_{pnk}$ | Quantity of shortage for product $p$ in customer zone $n$ under disruption scenario $k$ |
| $REP_{nk}$ | Responsiveness level of closed loop supply chain for customers $n$ under disruption scenario $k$ |
| $DR_{k}$ | Deviation amount of responsiveness from predefined target under disruption scenario $k$ |

## 3.4. Mathematical Model

Before presenting the mathematical model, it is important to define the measures of sustainability, resilience and responsiveness used in the below mentioned model.

**The sustainability measures**

In this study, a comprehensive approach to sustainability measures is adopted, recognizing and addressing the three fundamental facets of sustainability: economic, environmental, and social. Each of these facets plays a crucial role in shaping the overall sustainability profile of a supply chain system, and this study endeavors to balance and optimize them for the most sustainable outcomes.

- Minimizing Total Costs

One of the key economic objectives in sustainable supply chain management is minimizing total costs. This encompasses various cost components, including the fixed costs associated with establishing supply chain facilities, the operational costs related to opening and processing these facilities, transportation costs for moving goods, and the expenses incurred in the buying and selling of carbon emissions. By carefully managing and optimizing these cost elements, supply chains can not only enhance their economic efficiency but also contribute to overall sustainability by reducing resource consumption and waste.

Minimizing the total costs = fixed costs of establishing facilities + opening and processing costs + transportation costs + buying/selling cost of carbon emissions

- Minimizing Environmental Impacts

The environmental dimension of sustainability is a paramount concern, and this study acknowledges its significance. To minimize environmental impacts, the study specifically focuses on reducing the carbon emissions associated with the supply chain. This includes emissions stemming from the production process and those resulting from the transportation network. The study recognizes that carbon emissions are a major contributor to climate change and environmental degradation. Therefore, by striving to minimize these emissions, supply chains can make substantial strides towards environmental sustainability.

Minimizing the environmental impacts = carbon emitted by production process + carbon emitted by transportation network

- Maximizing Social Impacts

Social sustainability is another crucial aspect considered in this study. Maximizing social impacts involves creating fixed job opportunities within the supply chain network. The emphasis here is on generating employment opportunities that provide stability and livelihoods for individuals and communities. By creating fixed job opportunities, supply chains can contribute positively to local economies, enhance the well-being of the workforce, and foster stronger social cohesion within the regions where they operate.

### The responsiveness measures

The ratio of met demand to the prospective demand of the consumers is how we characterized the level of CLSC responsiveness in this study. The CLSC responsiveness level is also taken into account, with a preset goal value taken into account (based on the recommendations of the experts). Reducing the CLSC responsiveness level's deviation from this established target value is the goal. According to the aforementioned formulations, equation 3.1 and 3.2 establish the responsiveness level and related deviation of the CLSCN respectively. It has to be stressed that the model aims to lower the expected deviance.

$$REP_{nk} \leq \frac{\sum_{pdn} QD_{pndtk}}{\sum_{p} Dem_{npk}} \qquad \forall \; n,k \tag{3.1}$$

$$\sum_{k} w_n \cdot REP_{nk} + DR_k \geq REP \qquad \forall \; n,k \tag{3.2}$$

### The resilience measures

Graph theory is one of the most often used methods for establishing a connection between a supply chain network (SCN) and its level of resiliency. According to graph theory, the SCN's facilities are represented by certain nodes, and their connections are made by arcs, or travel routes. This viewpoint is helpful for understanding how different SCN architectures impact a SCN's resilience as well as for determining how resilient a SCN is (Cardoso et al. 2015). This study uses the node complexity as a measure to determine resilience. The node complexity of a network is determined by the total number of active nodes. In other words, complexity increases as the number of active nodes increases.(Zahiri, Zhuang, and Mohammadi 2017; Cardoso et al. 2015). This criterion is measured by the equation 3.3.

$$X = \sum_{s} SS_s + \sum_{m} SM_m + \sum_{d} SD_d + \sum_{j} SJ_j + \sum_{l} SL_l \tag{3.3}$$

## Objective functions

The proposed model consists of four objective functions as explained below.

### 3.4.1. Objective 1: Minimize Cost of CLSC network

The first objective function as shown in equation 3.4 aims at reducing the total cost of closed-loop supply chain. The costs of the CLSC network comprises of establishment costs of facilities, supplier related costs, production costs, distribution costs, collection and disposal costs, shortage costs of products, transportation costs for all facilities and cost of purchasing carbon credit. It is important to state that revenue from the sale of carbon credit is subtracted from costs. Also, transportation costs are calculated using fuel consumption rate by vehicles along the distance covered.

TC = fixed cost of established facilities + opening and processing costs + transportation costs + carbon emission from production and transportation

$$
\begin{aligned}
Min\ Z_1 = {} & \sum_{m} FM_m \times SM_m + \sum_{d} FD_d \times SD_d + \sum_{j} FC_j \times SJ_j + \sum_{l} FR_l \times SL_l + \sum_{s} FS_s \times SS_s + \\
& \sum_{k} PK_k \Big( \sum_{rsmt} UR_{rs} \times QR^k_{rsmt} + \sum_{pmdt} MC_{pmk} \times QP^k_{pmdt} + \sum_{dpnt} OD_{dpk} \times QD^k_{pdnt} + \sum_{jplt} OC_{jpk} \times QL^k_{pjlt} + \\
& \sum_{lpit} OR_{lpk} \times QI^k_{plit} + \sum_{lpmt} OR_{lpt} \times QM^k_{plmt} + \sum_{pn} SC_{pnk} \times QSH_{pnk} + \sum_{rsmt} DIS_{sm} \times \left( QR^k_{rsmt} / CPT_t \right) \times f \times fcr + \\
& \sum_{pmdt} DIS_{md} \times \left( QP^k_{pmdt} / CPT_t \right) \times f \times fcr + \sum_{pdnt} DIS_{dn} \times ( QD^k_{pdnt} / CPT_t ) \times f \times fcr + \\
& \sum_{pnjt} DIS_{nj} \times \left( QN^k_{pnjt} / CPT_t \right) \times f \times fcr + \sum_{pjlt} DIS_{jl} \times \left( QL^k_{pdnt} / CPT_t \right) \times f \times fcr + \\
& \sum_{plit} DIS_{li} \times \left( QI^k_{plit} / CPT_t \right) \times f \times fcr + \sum_{plmt} DIS_{lm} \times \left( QM^k_{plmt} / CPT_t \right) \times f \times fcr + \sum CRB \times QPC_k - \\
& \sum CRB \times QSC_k \Big)
\end{aligned} \tag{3.4}
$$

### 3.4.2. Objective 2: Minimize the Environmental Impacts from Production and Transportation

The second objective function as shown in equation 3.5, with its emphasis on curtailing environmental impacts from both production and transportation processes, represents a pivotal facet of sustainable closed loop supply chain management. It epitomizes a commitment to responsible environmental practices and aligns with the broader global imperatives of reducing carbon footprints and safeguarding the planet's ecological well-being. As organizations increasingly embrace sustainability as a core value, this objective function takes on even greater significance in shaping the future of supply chain management.

Environmental impact = environmental impact of production + environmental impact of transportation vehicles

$$Min\,Z_2 =$$

$$WEI\left(\sum_k PK\left(\sum EI_p QP_{p\,\mathrm{mdtk}} + \sum TEI_{pt}\begin{pmatrix} DIS_{sm}(QR_{rsmtk}/CPT_t) + DIS_{md}(QP_{pmdtk}/CPT_t) \\ +\ DIS_{dn}(QD_{pdntk}/CPT_t) \\ + DIS_{nj}(QN_{pnjtk}/CPT_t) + DIS_{jl}(QL_{pjltk}/CPT_t) \\ + DIS_{li}(QI_{plitk}/CPT_t) + DIS_{lm}(QM_{plmtk}/CPT_t) \end{pmatrix}\right)\right) \tag{3.5}$$

### 3.4.3. Objective 3: Minimize deviation from Resilience and Responsiveness

The third objective function, elegantly articulated in Equation 3.6, assumes a pivotal role within the optimization model, embarking on a dual mission of paramount importance. This objective strives to achieve two distinct yet interrelated goals: first, to reduce the level of deviation of responsiveness from the carefully predefined target; and second, to minimize the measures of resilience. This objective function encapsulates the essence of responsive and resilient supply chain management. It addresses the intricate interplay between meeting customer demands promptly and enhancing the supply chain's ability to withstand disruptions. This dual mission reflects the adaptive and customer-centric nature of modern supply chain operations, where the optimization process aims to harmonize these critical dimensions for sustained success and competitiveness.

$$Min\, Z_4 \;=$$

$$WRE\left(\sum \beta_s SS_s + \sum \beta_m SM_m + \sum \beta_d SD_d + \sum \beta_j SJ_j + \sum \beta_l SL_l\right) + WREP\left(\sum_k PK_k \cdot DR_k\right) \qquad (3.6)$$

### 3.4.4. Objective 4: Maximize the Social Impacts of CLSC Network

The fourth objective function, elegantly expressed in Equation 3.7, embarks on a noble mission of paramount significance within the realm of supply chain network design. It aims to maximize the social impacts emanating from the closed-loop supply chain (CLSC) network configuration. This objective function exemplifies the imperative for supply chain managers to consider the broader societal implications of their decisions. By striving to maximize social impacts, organizations not only contribute to local communities' well-being but also bolster their own sustainability and competitiveness.

Maximizing the social impacts = Created job opportunities

$$Max\ Z_3 =$$

$$WSI\left(Wj\left(\sum JS_s SS_s + \sum JM_m SM_m + \sum JD_d SD_d + \sum JJ_j SJ_j + \sum JL_l SL_l\right)\right) \qquad (3.7)$$

### 3.4.5. Constraints

The amount of raw material bought from supplier is calculated using equation 3.8.

$$\sum_r QR_{rsmtk} = \sum_p CNSP_{rp} \cdot QP_{pmdtk} \qquad \forall s, m, d, t, k \qquad (3.8)$$

The capacity constraint of supplier is given in equation 3.9.

$$\sum_s QR_{rsmtk} \le \left(1 - PC_{sk}\right) \cdot CPS_{sr} \cdot SS_s \qquad \forall r, m, t, k \qquad (3.9)$$

Equations 3.10 till equation 12 explain the transshipment constraints of the CLSC network model. Equation 3.10 ensures that the quantity of product produced equals the quantity of recycled product and available raw materials. Equation 3.11 and 3.12 shows the number of products sent from the producer to the distributor. equals the quantity of product which is sent from distributors to customers and the quantity sent from customer to collection centers is equal to the quantity shipped from collection centers to MRF respectively. Equation 3.13 shows that the quantity shipped from collection centers to MRF is equal to the quantity of product sent from MRF to disposal centers and MRF to manufacturers.

$$\sum_{m} QM_{plmtk} + \sum_{m} QR_{rsmtk} = \sum_{d} QP_{pmdtk} \qquad \forall p,r,t,k \tag{3.10}$$

$$\sum_{m} QP_{pmdtk} = \sum_{d} QD_{pdntk} \qquad \forall p,n,t,k \tag{3.11}$$

$$\sum_{j} QN_{pnjtk} = \sum_{l} QL_{pjltk} \qquad \forall p,n,t,k \tag{3.12}$$

$$\sum_{j} QL_{pjltk} = \sum_{l} QI_{plitk} + \sum_{m} QM_{plmtk} \qquad \forall p,t,k \tag{3.13}$$

Equation 3.14 gives the capacity limitation of manufacturer.

$$\sum QP_{pmdtk} \leq \sum \left(1 - PC_{mk}\right) \cdot CPM_{mp} \cdot SM_{m} \qquad \forall m,p,t,k \tag{3.14}$$

Equation 3.15 calculates the capacity limitation of distributors.

$$\sum QD_{pdntk} \leq \sum \left(1 - PC_{dk}\right) \cdot CPD_{dp} \cdot SD_{d} \qquad \forall d,p,t,k \tag{3.15}$$

Capacity limitation of collection centers is given in equation 3.16.

$$\sum QL_{pjltk} \leq \sum \left(1 - PC_{jk}\right) \cdot CPJ_{jp} \cdot SJ_{j} \qquad \forall j,p,k,t \tag{3.16}$$

Equation 3.17 gives the capacity limitation of material recovery facilities.

$$\sum QI_{plitk} + \sum QM_{plmtk} \leq \sum \left(1 - PC_{lk}\right) \cdot CPL_{lp} \cdot SL_{l} \qquad \forall l,p,t,k \tag{3.17}$$

Capacity constraints for transportation vehicles are calculated using equations 3.18 to 3.24. The quantity transported multiplied by its weight should be less than or equal to the capacity of the transportation vehicle selected.

$$\sum_{r} QR_{rsmtk} \cdot WR_{r} \leq CPT_{t} \cdot T_{smt} \qquad \forall s,m,t,k \tag{3.18}$$

$$\sum_{p} QP_{pmdtk} \cdot WP_{p} \leq CPT_{t} \cdot T_{mdt} \qquad \forall m,d,t,k \tag{3.19}$$

$$\sum_{p} QD_{pdntk} \cdot WP_{p} \leq CPT_{t} \cdot T_{dnt} \qquad \forall d,n,t,k \tag{3.20}$$

$$\sum_{p} QN_{pdntk} \cdot WP_{p} \leq CPT_{t} \cdot T_{njt} \qquad \forall d,n,t,k \tag{3.21}$$

$$\sum_{p} QL_{pjltk} \cdot WP_{p} \leq CPT_{t} \cdot T_{jlt} \qquad \forall j,l,t,k \tag{3.22}$$

$$\sum_{p} QI_{plitk} \cdot WP_{p} \leq CPT_{t} \cdot T_{lit} \qquad \forall l,i,t,k \tag{3.23}$$

$$\sum_{p} QM_{plmtk} \cdot WP_{p} \leq CPT_{t} \cdot T_{lmt} \qquad \forall m,l,t,k \tag{3.24}$$

Equation 3.25 deals with the carbon cap and trade policy.

$$\sum EI_{p} QP_{pmdtk} + TEI_{tp} \begin{pmatrix} DIS_{sm} QR_{rsmtk} + DIS_{md} QP_{pmdtk} + \\ DIS_{dn} QD_{pdntk} + DIS_{nj} QN_{pnjtk} \\ + DIS_{jl} QL_{pjltk} + DIS_{li} QI_{plitk} + DIS_{lm} QM_{plmtk} \end{pmatrix} + QSC_{k} \leq CCP + QPC_{k} \tag{3.25}$$

Equation 3.26 determines the amount of items sent to demand locations and the amount of shortfall.

$$\sum_{n} QD_{pdntk} + \sum_{n} QSH_{pnk} \geq Demd \qquad \forall p,t,k \tag{3.26}$$

Equations 3.27 to 3.29 calculates the return rate and disposal fractions respectively in the CLSC.

$$\sum_{n} QN_{pnjtk} \geq \sum Demd * RR \qquad \forall p,t,k \tag{3.27}$$

$$\sum_{l} QM_{plmtk} = \sum_{j} \left(1 - DF_{pk}\right) \cdot QL_{pjltk} \qquad \forall p,t,k \tag{3.28}$$

$$\sum_{i} QI_{plitk} = \sum DF_{pk}\left(QL_{pjltk}\right) \qquad \forall p,t,k \tag{3.29}$$

Equation 3.30 and 3.31 gives the responsiveness measures. Responsiveness is calculated as ratio of met demand to potential demand and deviation plus the responsiveness level achieved should be more than the predefined target.

$$REP_{nk} \le \frac{\sum_{pdn} QD_{pndtk}}{\sum_{p} Dem_{npk}} \qquad \forall n,k \tag{3.30}$$

$$\sum_{k} w_n \cdot REP_{nk} + DR_k \ge REP \qquad \forall n,k \tag{3.31}$$

Network level resilience measures of node complexity is used and given in constraint 3.32.

1. Node complexity

$$X = \sum_{s} SS_s + \sum_{m} SM_m + \sum_{d} SD_d + \sum_{j} SJ_j + \sum_{l} SL_l \tag{3.32}$$

Binary constraints are given in equation 3.33.

$$SS_s, SM_m, \mathrm{SD}_d, SJ_j, SL_l, T_{smt}, T_{mdt}, T_{dnt}, T_{njt}, T_{jlt}, T_{lmt}, T_{lit} \in \{0,1\} \tag{3.33}$$

Non-negativity constraints are given in equation 3.34.

$$\begin{aligned} &QR_{rsmtk}, QP_{pmdtk}, QD_{pdntk}, QN_{pnjtk}, QJ_{pjitk}, QC_{pjmtk}, QL_{pjltk}, QI_{plitk}, QM_{plmtk}, \\ &QPC_k, QSC_k, QSH_{pnk}, REP_{nk}, DR_k \ge 0 \end{aligned} \tag{3.34}$$

## 3.5. Chapter summary

This chapter is divided into four subparts. The first section explains the problem that the model aims to optimize. The second section gives the model assumptions that are used to solve the model. Third section shows the notations used in mathematical model. Its sub sections explain sets, parameters, and decision variables respectively. The last section explains the mathematical model developed. The MOMILP model consists of four objectives that are to be optimized. The first objective targets total cost reduction of CLSCN. The second objective aims at reducing the environmental impacts of production and transportation. The third objective deals with resilience measures and level of deviation of responsiveness. Finally, the last objective function considers the social impacts of CLSCN and aims at maximizing them. Lastly, the constraints of the developed MOMILP closed-loop supply chain network model are explained in detail.

# Chapter 4: Development of Solution Methodology

The multi-objective approaches are of two types.

The 1st approach uses aggregation function like goal programming, weighted sum approaches, lexicographic ordering, e-constraint method, interactive fuzzy programming, weighted min-max approach. These methods don't come up with pareto optimal front (a set of solutions). But it provides an exact solution that is global optimum.

The 2$^{nd}$ approach to solve multi-objective function is evolutionary heuristics that generate pareto front. These techniques include multi-objective GA (genetic algorithms), multi-objective particle swarm algorithms, NSGA-II (Non-Dominated sorting). In this method all objectives are evaluated simultaneously and plot pareto optimal front that give a solution to the objective functions and satisfy all constraints.

These heuristic-based approaches never guarantee global optimum solution as sometimes they get trapped into local optimums. Moreover, these approaches are good for NP-hard problems and Non-linear programming with multi objectives. In this study the solution approach adopted is interactive multi-objective fuzzy programming. Since the problem is linear and includes four objective functions. As the total cost of transportation, cost relates to different environment levels at points of this transshipment model, resilience and responsiveness and the social impacts are all important objective functions. So, in this case interactive multi-objective fuzzy programming is more beneficial. This method for solving the linear programming was proposed by Zimmermann (Zimmermann 1978).

## Interactive Fuzzy programming approach

Interactive multi-objective fuzzy programming (IMOFP) is a decision-making and optimization technique that combines multiple objectives, uncertainty, and stakeholder preferences to find optimal solutions in complex, real-world problems. This approach is particularly useful when dealing with problems where objectives may conflict, data is uncertain, or there is a need to involve multiple decision-makers or stakeholders in the decision-making process. Fuzzy logic allows for the representation of uncertainty and vagueness in the decision-making process. Instead of using crisp values, fuzzy sets and linguistic terms are employed to describe uncertain parameters and preferences (Imran et al., 2021). Unlike traditional optimization methods, IMOFP is interactive. It involves stakeholders, decision-makers, or experts in the optimization process. They provide feedback and adjust preferences during the optimization to arrive at a solution that aligns with their goals and preferences. IMOFP typically aims to find solutions on the Pareto front. These are solutions that cannot be improved in one objective without worsening another. The interactive process helps decision-makers explore and select solutions along this efficient frontier. The interactive nature of IMOFP allows decision-makers to analyze trade-offs between different objectives. They can assess how changes in one objective affect the others and make informed decisions based on these trade-offs.

Steps For Solution methodology are:

## 4.1. α−extreme solutions

There are two different approaches to find α-extreme solution:

1. In this first approach the decision taker already knows the maximum and minimum values of all objective functions. These maximum and minimum values of every objective function act as upper and lower bound values for them. Every objective function gets solved within those bounds and within the set of constraints that leads to finally obtaining a pay-off table. This payoff table is then linearized and utilized to create a single objective function in its final form. In this approach the upper and lower bound set by decision takers may violate the constraint set and the objectives. So, the solution may be feasible, but the optimality of the solution is not confirmed.
2. In the 2nd approach, to get α-extreme values, each objective function is solved separately at a time and the values are noted. Then the solved objective acts as a constraint so the 2nd objective is optimized individually. This particular method is repeated again for the other objective functions. Finally with this process a payoff table Is obtained that contains α-extreme values for each objective function. In this methodology mixed integer linear programming is implemented to get the bounds of objective function values. So, the other constraints and bounds are always satisfied during optimization. Thus, in this study we have used this strategy to ensure global optimal solution.

## 4.2. Linearization using the fuzzy membership function

The second strategy, which was covered in Section 4.1, is the one we apply in our suggested technique. The objectives are linearized using a fuzzy membership function. The goal functions are linearized using a triangle membership function. Equation 4.1 demonstrates the triangular membership function in its general form.

$$u_o = \left\{ \begin{array}{ll} 0 & if\ f \geq f_o^{a-lb} \\ \dfrac{f_o^{a-ub} - f}{f_o^{a-ub} - f_o^{a-lb}} & if\ f_o^{a-lb} < f < f_o^{a-ub} \\ 1 & if\ f \leq f_o^{a-ub} \end{array} \right\} \tag{4.1}$$

$f_o^{a-lb}$ and $f_o^{a-ub}$ are the extreme function values of function "o".

Determination of satisfaction level and formulation of single objective is done by combining all the objective functions using a payoff table. An interactive process starts when weights are assigned, and optimization model is solved till the decision maker gets the required satisfaction levels for the results.

## 4.3. Chapter summary

This chapter explains the solution methodology used to optimize the model. The interactive fuzzy programming approach is used as solution methodology. This approach involves solving one objective function at a time, recording its value, and using it as a constraint when optimizing subsequent objectives one at a time. The other objectives are then subjected to the same method until a pay-off table with the extreme function values for each aim is attained. In this approach, boundaries and other restrictions are always satisfied since the function values' bounds are determined using mixed integer linear programming.

# Chapter 5: Case Study

This section implements the model created in chapter 4 on a realistic case study. To validate the proposed mathematical model the case of float glass industry is taken into consideration. In Pakistan there are only two big producers of float glass one is Ghani glass and the other one is Tariq glass limited. This study takes into consideration Tariq Glass limited as a case and the proposed mathematical model is applied to their closed-loop supply chain and results are analyzed. Limited data is obtained from them whereas some data is collected from market research and some data sets of similar problem size from literature are used. The raw materials of flat glass (figure 5.1) are silica sand, lime, and soda (statista.com). Flat glass has two important properties: durability and transparency. Flat glass is preferred over other transparent materials like plastics because of its great temperature and corrosion resistance. The use of flat glass is essential in our constructed world. Its manufacturing results in the release of pollutants like CO2 and involves the mining of raw materials and the burning of fossil fuels. ( Souviron and Khan 2021; Dahl, Lu, and Thill 2021).

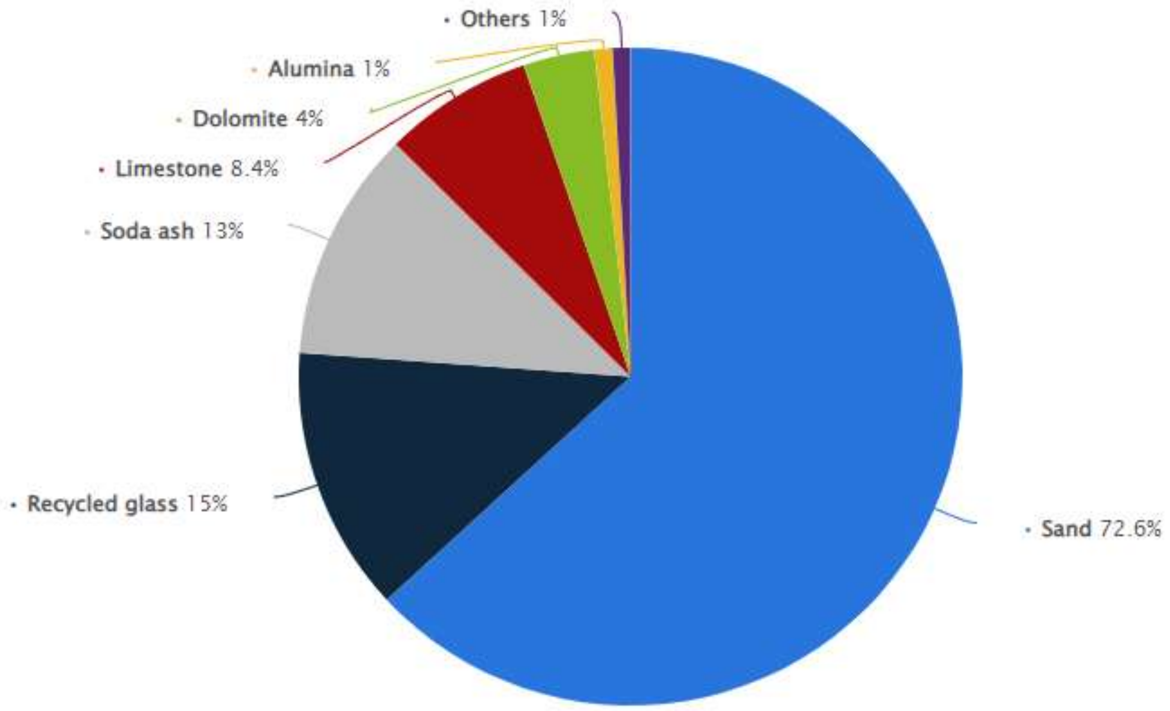

Figure 5-1: Raw materials of flat glass

Tariq Float Glass, Tariq Glass Industries Limited's (TGL) newest endeavor, was introduced in 2013. and is located in Sheikhupura, Punjab, Pakistan. A cutting-edge facility with a 550 ton per day manufacturing capacity has swiftly built brand awareness both in Pakistan and on global markets. This facility can produce clear float glass in thicknesses between 2 and 12 mm, colored glass that is reflective and can be coated online, sandblasted glass, and aluminum-coated mirrors. Their clear glass is ideally used for windows, display cases, appliances, shelves, partitions, furniture, frames, automobiles, buildings etc. This study specifically considers their clear glass as a product for model application due to limitations of data availability. A square meter of 8mm clear glass is considered as product.

## 5.1. Problem description

The closed-loop supply chain network for Tariq Float Glass consists of seven echelons consisting of four potential suppliers, one manufacturer (Tariq Glass), eleven potential distribution centers, fifteen customer zones, seven potential collection centers, three potential MRF and one disposal center. Forward Material flow is started by procuring required raw materials from supplier. Then the products are manufactured in the manufacturing unit and transported to customer zones through distribution centers. Then in reverse flow the products are returned according to a return rate considering MSR and collected at waste collection centers then sent to Material recovery facility. At MRF the products are further divided into two parts and sent to disposal centers and manufacturing sites according to a specific percentage thereby forming a closed-loop supply chain. It is emphasized that shortfall is also permitted thus the business is not required to completely satisfy every customer's needs. On the other hand, we have considered three different transportation vehicles with different capacities and emissions. The following figure 5.2 shows the CLSCN for the underlying case study.

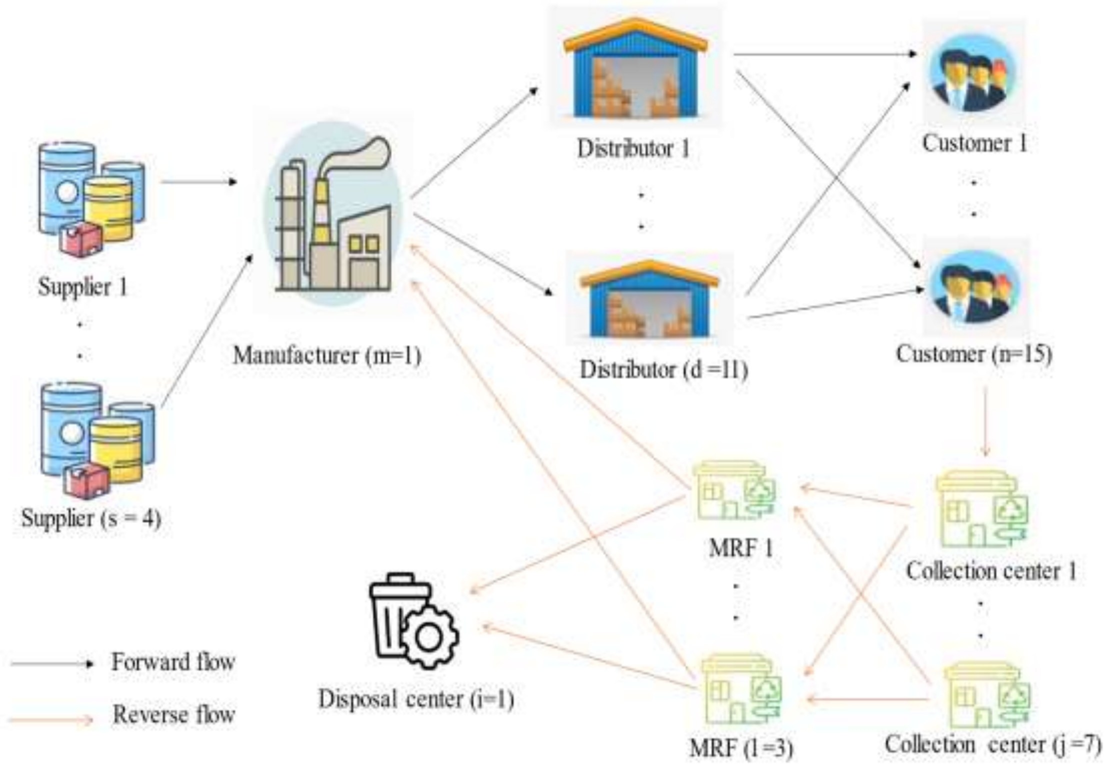

Figure 5-2: CLSC network for case study

For the purpose of case study primary data regarding customer demand and list of suppliers, distributors, customers, collection centers, material recovery facilities and disposal centers is collected from the Tariq glass industry. Secondary data is collected using market research such as costs, exact location of facilities. The remaining data sets are used from the studies of Govindan 2021. All the data sets used in the formulation of mathematical model are given in appendix.

## 5.2. Results of the case

The numerical results were derived using MATLAB (R2022b) on a personal computer with 8 GB RAM and Intel(R) Core (TM) 1.61 GHz processor. The branch and bound algorithm are used for the solution. The solution of the case study consists of the following steps.

1. For all of the objectives, the crisp model is solved to get the payoff values shown in table 5.1. Through the use of mixed integer linear programming, the bounds of each target were determined. Table 5.1 is the result of individually optimizing each goal function, setting the

equality constraint, and then optimizing the other objective turn-wise. For instance, the value in first row and column of table 5.1 is the optimal value of the following function:

- **Step 1**: Minimize cost F1

  Subject to constraints given in equation 3.8 to equation 3.34

  Once the optimal value is obtained, we set this function as a constraint and optimized the second objective. The value second objective (F2) of $CO_2$ emissions is obtained using the following problem formulation.

- **Step 2:** Minimize environmental impact F2

  Subject to constraints given in equation 3.8 to equation 3.34 and
  F1 = 1,328,832.42.

  Similarly, in the third column and first row of table 5.1, we obtain the value of resilience and responsiveness by optimizing the following case:

- **Step 3:** Minimize resilience measures and level of deviation from responsiveness F3

  Subject to constraints given in equation 3.8 to equation 3.34 and
  F1 = 1,328,832.42.

  Likewise, in the fourth column and first row of table 5.1, we obtain the value of social impact by optimizing the following case:

- **Step 4:** Maximize social impacts F4

  Subject to constraints given in equation 3.8 to equation 3.34 and
  F1 = 1,328,832.42.

These four steps are repeated for all the objectives until the payoff table was finally obtained as shown in table 5.1. The selection of facilities for the CLSC network design under study are depicted in figure 5.3.

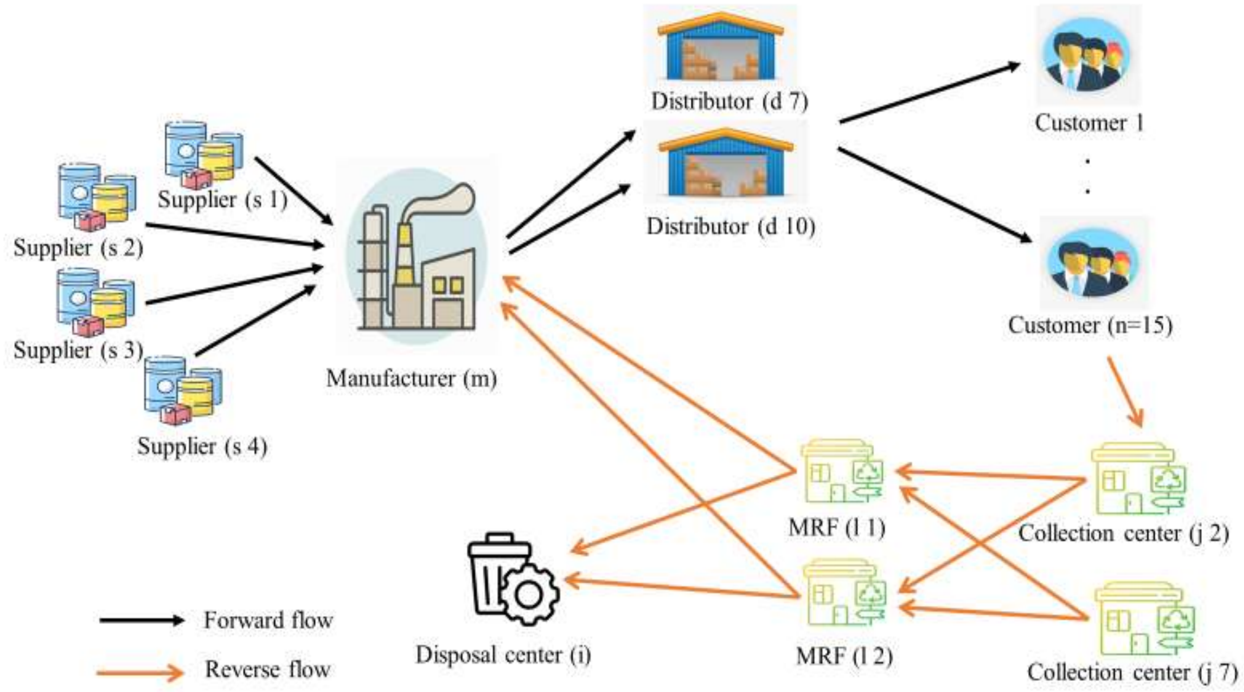

Figure 5-3: Selection of nodes for CLSC network of case study

Table 5-1: Payoff Table

| | **OF1** (Cost in $) | **OF2** (Tons of $CO_2$) | **OF3** (Resilience & Responsiveness) | **OF4** (Jobs) |
|---|---|---|---|---|
| F1- Cost | 1,328,832.42 | 6,258.33 | 569.78 | 5,490.00 |
| F2- Environmental impact | 54,306,500.71 | 6,258.33 | 569.18 | 5,490.00 |
| F3 – Resilience and Responsiveness | 52,715,195.91 | 8,716.14 | 345.38 | 5,777.00 |
| F4 – Social impact | 56,937,957.86 | 6,413.70 | 1,539.53 | 20,070.00 |

2. To determine satisfaction level, the next step is to create fuzzy membership functions for each objective. The fuzzy membership is calculated using the equation (4.1) mentioned in methodology section (chapter 4). Below given equations (5.1) to (5.4) are the satisfaction of the cost, emissions, resilience and responsiveness and social impact respectively. Note that equal weight is given to all the objective functions. Results are shown in.

$$\mu_1 = \left\{ \begin{array}{l|l} 0 & F1 \geq 1,328,832.24 \\ \dfrac{56,937,957.86 - F1}{56,937,957.86 - 1,328,832.24} & 1,328,832.24 < F1 < 56,937,957.86 \\ 1 & F1 \leq 56,937,957.86 \end{array} \right\} \tag{5.1}$$

$$\mu_2 = \left\{ \begin{array}{l|l} 0 & F2 \geq 6,258.33 \\ \dfrac{8,716.14 - F2}{8,716.14 - 6,258.33} & 6,258.33 < F2 < 8,716.14 \\ 1 & F2 \leq 8,716.14 \end{array} \right\} \tag{5.2}$$

$$\mu_3 = \left\{ \begin{array}{l|l} 0 & F3 \geq 345.38 \\ \dfrac{1,539.52 - F3}{1,539.52 - 345.38} & 345.38 < F3 < 1,539.52 \\ 1 & F3 \leq 1,539.52 \end{array} \right\} \tag{5.3}$$

$$\mu_4 = \left\{ \begin{array}{l|l} 0 & F4 \geq 5490 \\ \dfrac{20,070 - F4}{20,070 - 5490} & 5490 < F4 < 20,070 \\ 1 & F4 \leq 20,070 \end{array} \right\} \tag{5.4}$$

$$Maximize \ f = w_1 \times \mu_1 + w_2 \times \mu_2 + w_3 \times \mu_3 + w_4 \times \mu_4 \qquad (5.5)$$

Table 5-2: Optimal OF value with satisfaction level

| **Objectives** | **Satisfaction level** | **Objective function value** |
|---|---|---|
| Cost ($) | 99.9% | 1,478,947.94 |
| Environmental impact ($CO_2$) | 97.79% | 6,305.52 |
| Resilience and responsiveness | 99.48% | 379.02 |
| Social impact | 100% | 5,310 |

## 5.3. Chapter summary

This chapter describes the case study used to validate the proposed model. The case of closed-loop supply chain network of Tariq Float glass is explored. There are seven echelons in the network with four suppliers, one manufacturer, eleven distributors, fifteen customers, seven collection centers, three material recovery facilities and one disposal center. The results showed that one supplier, one manufacturer, one distributor, two collection centers and two material recovery facilities are selected to provide us with a final solution where satisfaction level for all the objective functions and constraints is achieved. Results tables are provided in the appendix.

# Chapter 6: Results and Discussion

To resolve the case study, multi-objective interactive fuzzy programming is employed. In this method, multi-objective problems are linearized and assigned weights, which represent their relative importance. By doing so, the problem is simplified into a single objective optimization problem, making it more manageable and facilitating decision-making. This transformation enables decision-makers to balance different objectives according to their priorities. The case study involves various types of variables, including binary and continuous variables. Continuous variables can take any value within a specified range, while binary variables can only assume the values of zero or one. These different variable types allow for a more nuanced representation of decision variables, catering to real-world scenarios where certain factors may be discrete (binary) while others are continuous (Krzanowski, 1975). Table 5.2 provides essential information on each objective's optimum function values and the degree of satisfaction associated with them. This table plays a crucial role in the decision-making process as it allows decision-makers to evaluate the trade-offs and satisfaction levels associated with different solutions. It serves as a reference point for determining the most suitable solution based on the objectives' optimization and stakeholders' preferences.

## 6.1. Disruption scenarios

The sensitivity analysis conducted on our optimization model against various disruption scenarios has yielded some critical insights. Specifically, it has revealed a noteworthy pattern: when the capacity of any single player within the CLSC is disrupted or compromised, the consequences are far-reaching and substantial.

- Significance of Capacity Disruptions

The analysis highlights the critical role played by each participant or entity within the CLSC network. Whether it's a manufacturer, distributor, collection center, or any other player, their capacity and operational capabilities are integral to the smooth functioning of the entire supply chain.

- Economic and Sustainable Costs

Disrupting the capacity of any key player within the CLSC has a cascading effect on both economic and sustainable costs. This disruption can lead to increased costs due to inefficiencies, delays, and a breakdown in the circular flow of materials and products. Higher costs can erode profitability and hinder the achievement of sustainability goals.

- Deviation from Responsiveness Levels

Another significant impact of capacity disruptions is the deviation from predefined responsiveness levels. Responsiveness is essential for meeting customer demands promptly and efficiently. When capacity disruptions occur, the supply chain may struggle to maintain these responsiveness levels, potentially leading to customer dissatisfaction and lost opportunities.

- Node Complexity

Capacity disruptions also introduce complexity into the nodes of the CLSC. Nodes represent different points in the supply chain, such as collection centers, manufacturing units, or distribution hubs. When capacity disruptions occur, these nodes may need to adapt, change their roles, or handle unexpected bottlenecks, adding complexity to their operations.

- Interconnectedness of CLSC Players

The findings underscore the interconnectedness of CLSC players and their interdependencies. Disruptions in one part of the network can ripple through the entire system, affecting other players and processes. This highlights the need for a holistic and integrated approach to supply chain management.

- Importance of Resilience

In light of these sensitivity analysis results, building resilience in the CLSC becomes paramount. Resilience involves the ability to absorb disruptions and recover quickly. Organizations should invest in strategies and technologies that enhance supply chain resilience to minimize the impact of capacity disruptions.

- Strategic Planning and Risk Mitigation

The insights gained from this analysis can inform strategic planning and risk mitigation efforts. Supply chain managers and decision-makers should identify critical players and nodes and develop contingency plans to address potential capacity disruptions. This may involve redundancy, alternative sourcing, or capacity buffer strategies.

During the sensitivity analysis of our optimization model against disruption scenarios it is seen that disrupting the capacity of any one CLSC player will significantly increase the economic and sustainable costs and deviation from responsiveness levels thereby increasing the node complexity. The increase in costs is mainly due to the selection of new nodes in order to make the CLSC more responsive. Possibility occurrence of the scenarios are taken from literature (Negri et al., 2021). Table 6.1 to table 6.5 show the effect of disrupted capacities of different CLSC players and their effect on the objective functions of our MOMILP model for the case study.

Table 6-1 : Disruption scenario 1 where 10% of suppliers' capacity is disrupted

| **Disruption 1** | **Pk** | **OF1 ($)** | **OF2 (Tons of $CO_2$)** | **OF3** | **OF4 (Jobs)** |
|---|---|---|---|---|---|
| **10% of suppliers' capacity is decreased** | 0.05 | 89,788,039.20 | 325.29 | 358.02 | 5,278.00 |
| | 0.3 | 150,820,791.47 | 1,943.88 | 348.09 | 5,277.00 |
| | 0.6 | 250,182,290.01 | 3,787.29 | 375.68 | 5,308.00 |

In table 6.1 it can be seen that if 10% of the supplier's capacity is decreased, economical plus sustainable costs are increased greatly thereby increasing the possibility occurrence of this scenario. Similar analysis goes for other scenarios however, it is evident from the given tables that disrupting suppliers and manufacturers capacity results in massive operational costs of the CLSC making them the critical players. As far as resilience and responsiveness is concerned out of all the CLSC players suppliers, manufacturers and distributors play a major role.

Table 6-2: Disruption scenario 2 where 30% of manufacturers capacity is disrupted

| **Disruption 2** | **Pk** | **OF1 ($)** | **OF2 (Tons of $CO_2$)** | **OF3** | **OF4 (Jobs)** |
|---|---|---|---|---|---|
| **30% of manufacturers capacity is decreased** | 0.05 | 25,000,027.50 | 354.13 | 348.02 | 5,277 |
| | 0.3 | 90,008,451.90 | 1,951.84 | 357.09 | 5,278 |
| | 0.6 | 150,000,081.35 | 3,787.29 | 375.68 | 5,308 |

Table 6-3: Disruption scenario 3 where 80% of distributers capacity is disrupted

| **Disruption 3** | **Pk** | **OF1 ($)** | **OF2 (Tons of $CO_2$)** | **OF3** | **OF4 (Jobs)** |
|---|---|---|---|---|---|
| **80% of distributers capacity is decreased** | 0.05 | 15,818,438.86 | 325.91 | 352.09 | 5,276.00 |
| | 0.3 | 25,481,555.76 | 1,939.86 | 359.52 | 5,278.00 |
| | 0.6 | 88,646,717.88 | 3,782.91 | 379.68 | 5,310.00 |

Table 6-4 : Disruption scenario 4 where 30% of collection centers capacity is disrupted

| **Disruption 4** | **Pk** | **OF1 ($)** | **OF2 (Tons of $CO_2$)** | **OF3** | **OF4 (Jobs)** |
|---|---|---|---|---|---|
| **30% of collection centers capacity is decreased** | 0.05 | 10,144,766.89 | 323.95 | 348.02 | 5,277.00 |
| | 0.3 | 60,546,301.33 | 1,943.52 | 348.09 | 5,277.00 |
| | 0.6 | 120,795,889.95 | 3,887.04 | 358.18 | 5,277.00 |

Table 6-5: Disruption scenario 5 where 30% of MRFs capacity is disrupted

| **Disruption 5** | **Pk** | **OF1 ($)** | **OF2 (Tons of $CO_2$)** | **OF3** | **OF4 (Jobs)** |
|---|---|---|---|---|---|
| **30% of MRF capacity is decreased** | 0.05 | 20,496,350.58 | 943.36 | 348.09 | 5,277 |
| | 0.3 | 60,496,350.58 | 1,943.36 | 348.09 | 5,277 |
| | 0.6 | 120,958,592.90 | 3,886.85 | 348.18 | 5,277 |

### 6.1.1. Resilience vs Disruptions

The analysis of the optimization model's response to increased disrupted capacity percentages and the likelihood of disruption scenarios reveals a compelling trend—one that underscores the dynamic and adaptive nature of the CLSC. As these disruptive events become more prevalent or severe, the model exhibits a strategic inclination towards selecting a greater number of facilities. This deliberate choice results in the emergence of a more intricate and multifaceted CLSC network, characterized by heightened node complexity.

- Network Resilience and Adaptability

The phenomenon observed in Figure 6.1 speaks to the CLSC's innate resilience and adaptability in the face of disruptions. As the magnitude or probability of disruptions escalates, the model's response is not merely reactive but strategic. It proactively selects additional facilities to counteract the potential disruptions, ensuring that supply chain operations can continue effectively.

- Facility Redundancy

The inclination to select more facilities can be seen as a form of facility redundancy. Redundancy is a strategic approach that organizations employ to mitigate risks and enhance system reliability. By having multiple facilities capable of performing similar functions, the CLSC becomes less susceptible to disruptions at any single point, thereby enhancing overall robustness.

- Demand Satisfaction

One of the driving factors behind the selection of additional facilities is the imperative to meet demand and maintain high satisfaction levels. The model's objective is not only to minimize costs or environmental impact but also to ensure that customers' needs are met promptly and efficiently, even in the face of disruptions.

- Node Complexity

The consequence of this strategic response is an increase in node complexity within the CLSC network. More facilities translate into a richer and more intricate network structure, characterized by additional nodes, connections, and interdependencies. While this complexity may present challenges, it also offers opportunities for increased resilience and responsiveness.

- Flexibility and Responsiveness

The selection of multiple facilities in response to disruptions enhances the CLSC's ability to adapt and respond swiftly. This flexibility is a valuable asset in a dynamic and uncertain business environment, where disruptions can arise from various sources, including natural disasters, supply chain volatility, or unexpected demand fluctuations.

- Optimized Decision-Making

It's important to note that the MOMILP model's selection of multiple facilities is a result of rigorous optimization. The model makes these decisions based on a careful evaluation of cost, environmental impact, and the ability to meet demand while considering the disruptions' potential consequences.

In essence, the trend observed in the model's response underscores the strategic foresight embedded in modern supply chain management. By selecting additional facilities in anticipation of disruptions, the CLSC strives not only to minimize operational disruptions but also to maintain high levels of customer satisfaction and adaptability. This strategic approach, while leading to increased node complexity, ultimately positions the CLSC to thrive in an environment marked by uncertainty and change. It is evident from figure 6.1 that in the understudy case the most resilient echelon is that of distributors against the maximum disruption of 80% followed by supplier and manufacturer.

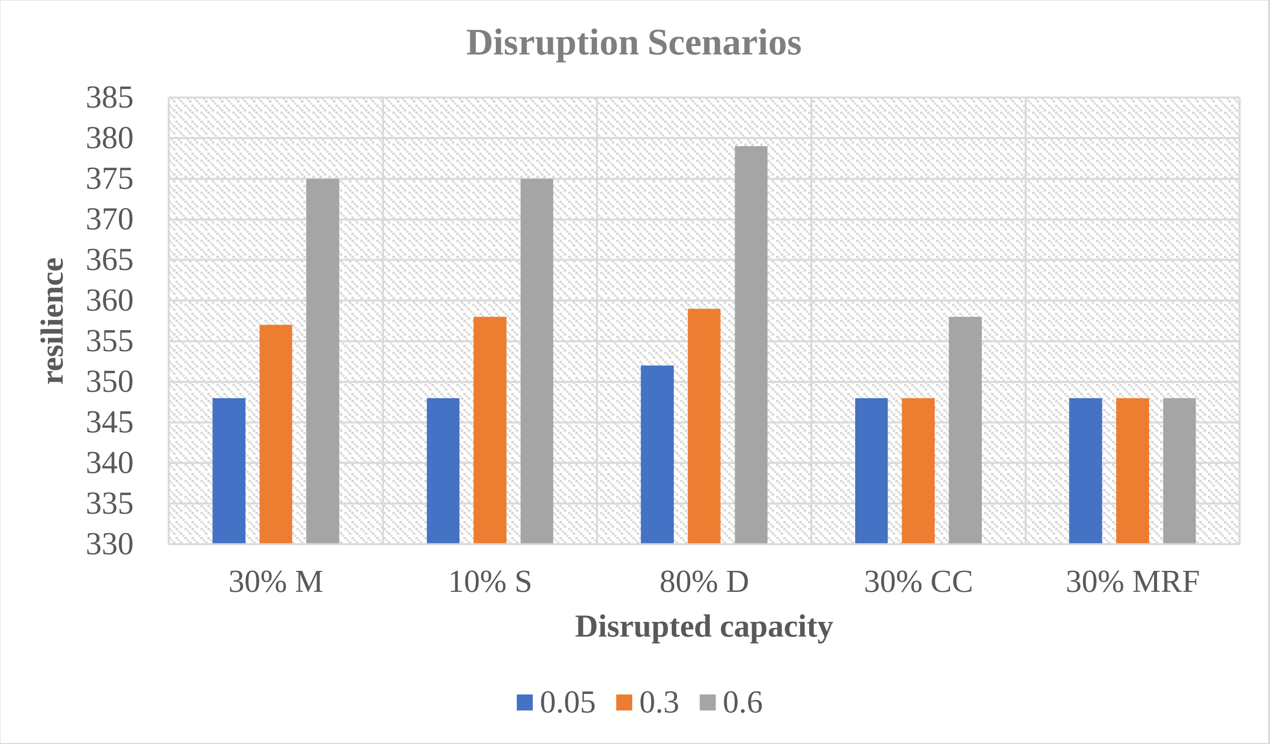

Figure 6-1: Disruption vs Resilience in CLSC network

### 6.1.2. Responsiveness deviation vs Disruption

The observed relationship between an escalation in the percentage of disrupted capacity among facilities and the consequent increase in the deviation from the target responsiveness level highlights a critical dynamic within the CLSCN. This phenomenon underscores the intricate interplay between disruptions and the network's ability to meet responsiveness goals, with notable implications evident in Figure 6.2.

- Responsiveness as a Key Performance Indicator

Responsiveness serves as a pivotal Key Performance Indicator (KPI) in supply chain management. It reflects the network's capacity to meet customer demands promptly and efficiently. Deviations from target responsiveness levels are indicative of the network's ability to adapt to disruptions while ensuring customer satisfaction.

- Disruption Impact on Critical Players

Figure 6.2 underscores that disruptions affecting critical players within the CLSCN, such as manufacturers, suppliers, and distributors, have a disproportionately significant impact on responsiveness levels. These entities play pivotal roles in the supply chain ecosystem, and disruptions affecting them ripple through the network. Disruptions affecting any of these nodes can disrupt the entire supply chain's rhythm.

- Variability in Deviation

The observed variability in the deviation from responsiveness targets highlights the dynamic nature of disruptions. Depending on which nodes within the network are affected and to what extent, the impact on responsiveness can vary significantly. This variability underscores the need for a nuanced and adaptive response to disruptions.

- Risk Mitigation and Resilience

This trend underscores the imperative for supply chain managers to prioritize risk mitigation and resilience strategies, particularly for manufacturers, suppliers, and distributors. These strategies may include redundancy in sourcing, diversified supplier networks, and agile manufacturing processes to enhance adaptability.

- Supply Chain Contingency Planning

The findings highlight the importance of robust supply chain contingency planning. Developing and implementing contingency plans that address disruptions to critical nodes can help mitigate the impact on responsiveness and ensure a more seamless response to unexpected events.

- Data-Driven Decision-Making

To effectively manage disruptions and their impact on responsiveness, supply chain managers can employ data-driven decision-making. Utilizing real-time data and predictive analytics can enable more agile responses to disruptions as they occur.

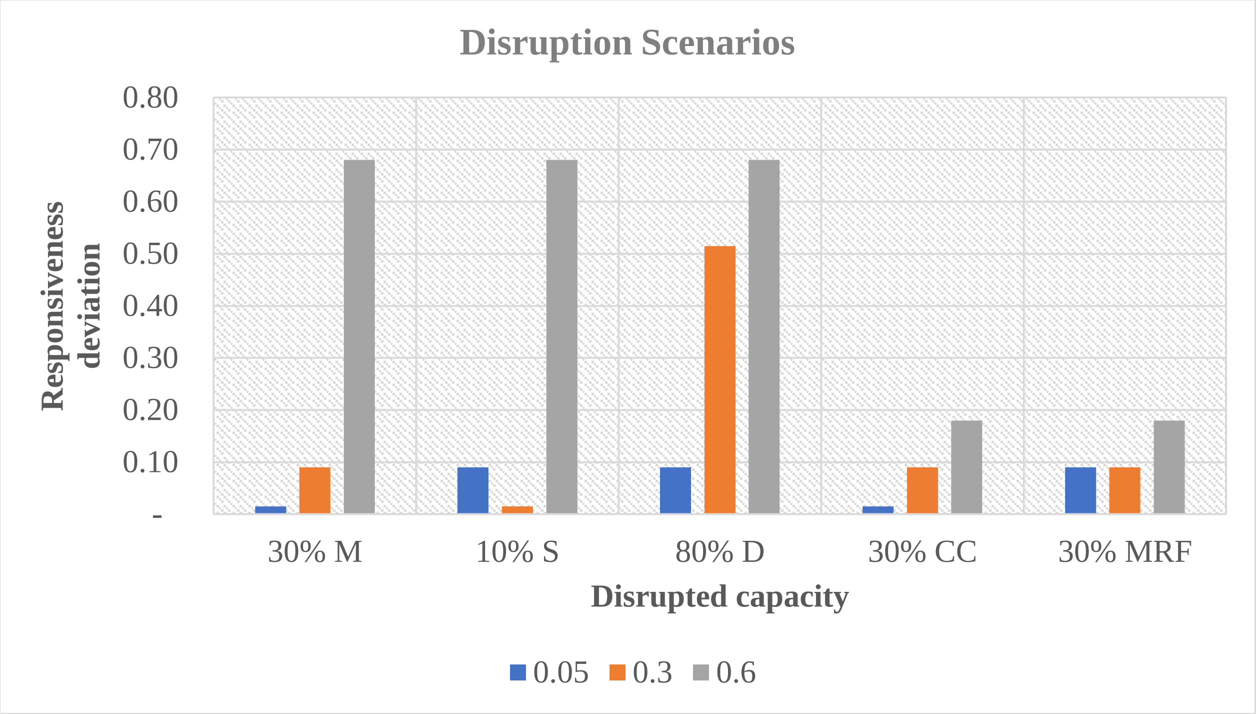

Figure 6-2: Disruption vs Responsiveness for CLSC network

## 6.2. Manufacturers capacity

The most crucial player in the closed-loop supply chain is the manufacturer in our case study as it is singlehandedly managing all the demand. Doing sensitivity analysis on the manufacturer's capacity showed that the model remains resilient for a maximum disruption of 30% after this if the capacity of manufacturer is disrupted further due to any reason the model solution becomes infeasible. It can be seen from the figure 6.3 shown below that the total cost of the closed-loop supply chain increases with increased disruption in capacity of the important player whereas the deviation of responsiveness level from a predefined target also increases.

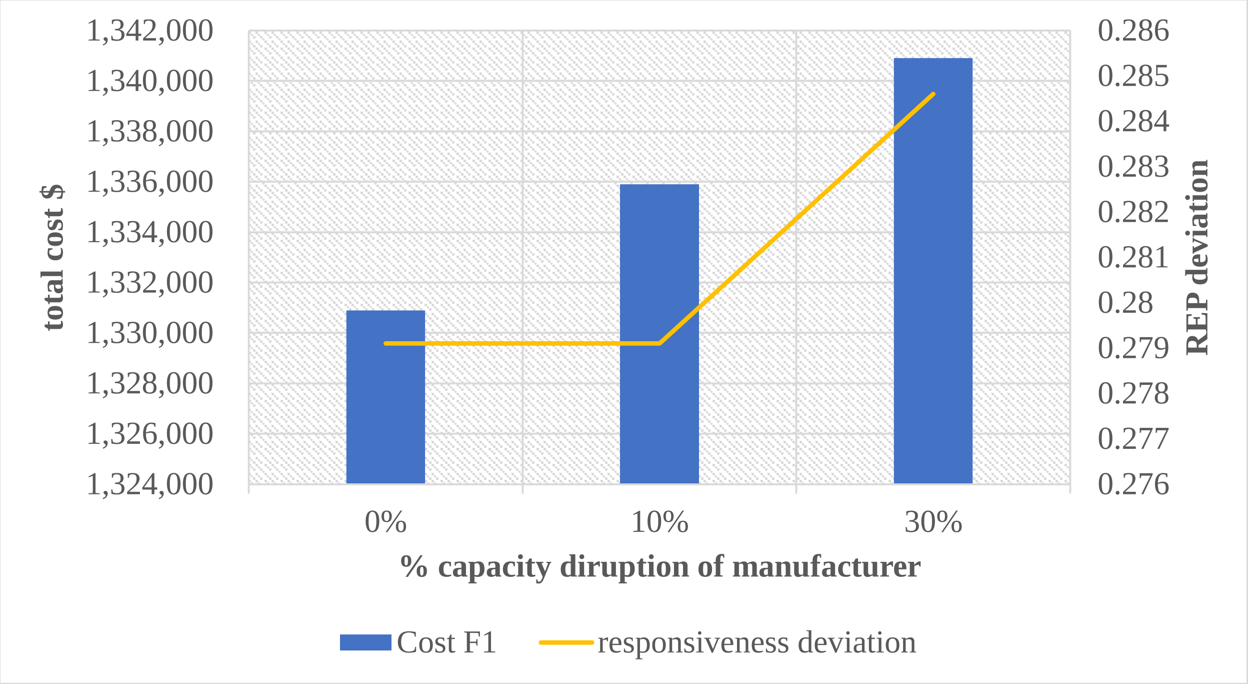

Figure 6-3: Impact of % capacity disruption of manufacturer

## 6.3. Recycling rate

This study delves into the intriguing concept of Multi-Stream Recycling (MSR), an innovative approach to waste management that advocates for the segregation of waste into distinct bins by customers at the point of disposal. This practice holds the promise of significantly reducing contamination levels within the waste stream, thereby rendering recycling processes more streamlined and efficient. However, it's worth noting that the adoption of MSR comes with its own set of challenges, particularly in terms of cost implications. One of the primary cost-related considerations in the context of MSR is the requirement for separate recycling bins. These bins, tailored to accommodate different types of recyclable materials, represent an initial investment for both households and organizations. Additionally, there are costs associated with educating individuals about the proper use of these bins and the segregation of waste. These costs, while essential for effective MSR implementation, are indeed higher when compared to the more traditional single-stream recycling approach.

It's pertinent to highlight that existing literature predominantly offers qualitative insights into the concept of MSR. While these qualitative studies shed light on the potential benefits and challenges of MSR, there's a noticeable gap when it comes to the quantitative integration of MSR within Supply Chain (SC) models. This study aims to bridge this gap by conducting a rigorous sensitivity analysis focused on cost factors. To unravel the cost dynamics of MSR, our study introduces sensitivity analysis that explores various scenarios, encompassing different return rates and disposal rates as depicted in figure 6.4. By doing so, we aim to provide a data-driven perspective on the cost implications associated with MSR adoption. This quantitative approach empowers us to assess the feasibility and economic viability of MSR within the context of supply chains, offering valuable insights that extend beyond qualitative discussions. Most literature has used ranges from 0.1 to 0.6 as return rates and 0.1 o 0.5 as disposal rates (Dahl, Lu, and Thill 2021) (Jabbarzadeh, Haughton, and Khosrojerdi 2018) (Fu et al. 2021).

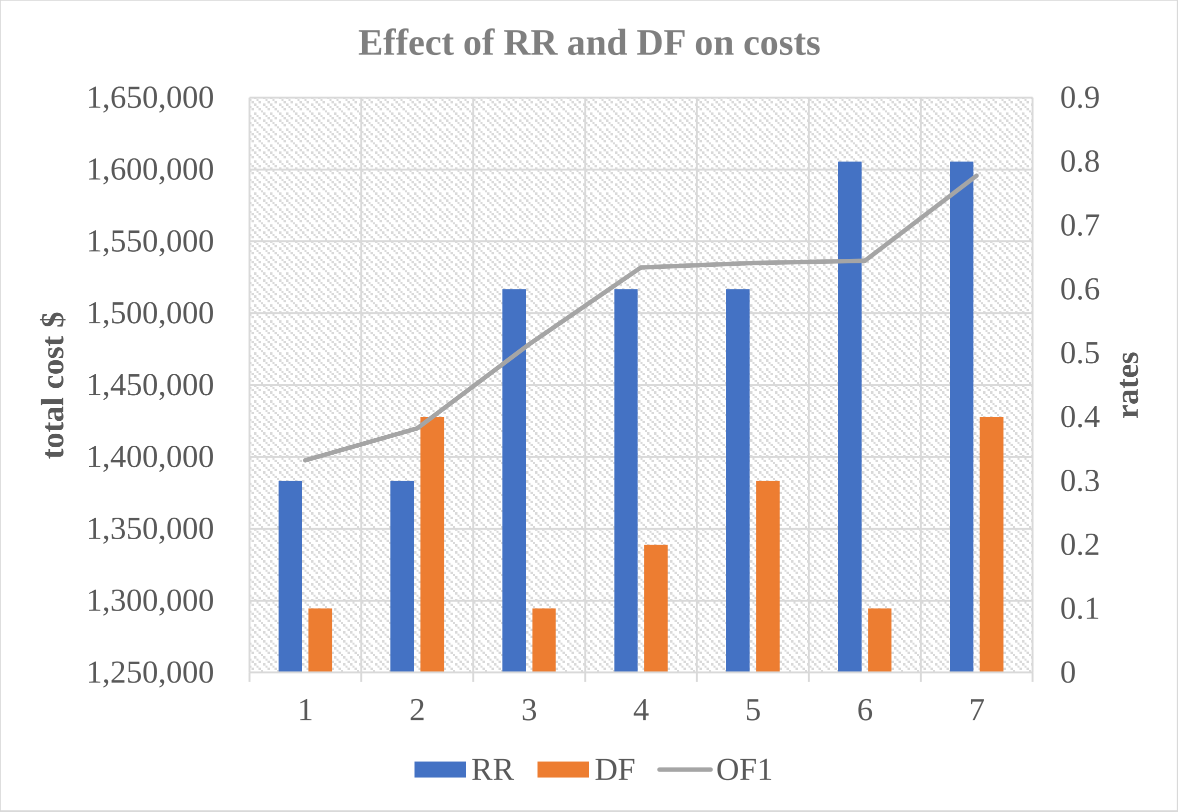

Figure 6-4: Effect of return rate and disposal fractions on costs

It can be clearly seen from the above figure 6.4 that if the return rate is kept constant and disposal rates are reduced due to MSR there is a significant decrease in the costs however if the return rates are lower and disposal rates are significantly high due to contamination levels the total cost incurred will drastically be increased.

## 6.4. Responsiveness target

Doing sensitivity analysis on the cost and deviation level of responsiveness by changing the predefined target shows that any slight increase in the target will increase the deviation amount from the target incurring additional cost. Although a slight change in cost can be observed for our case of closed loop supply chain network whereas increased target makes it difficult to satisfy the responsiveness level completely.

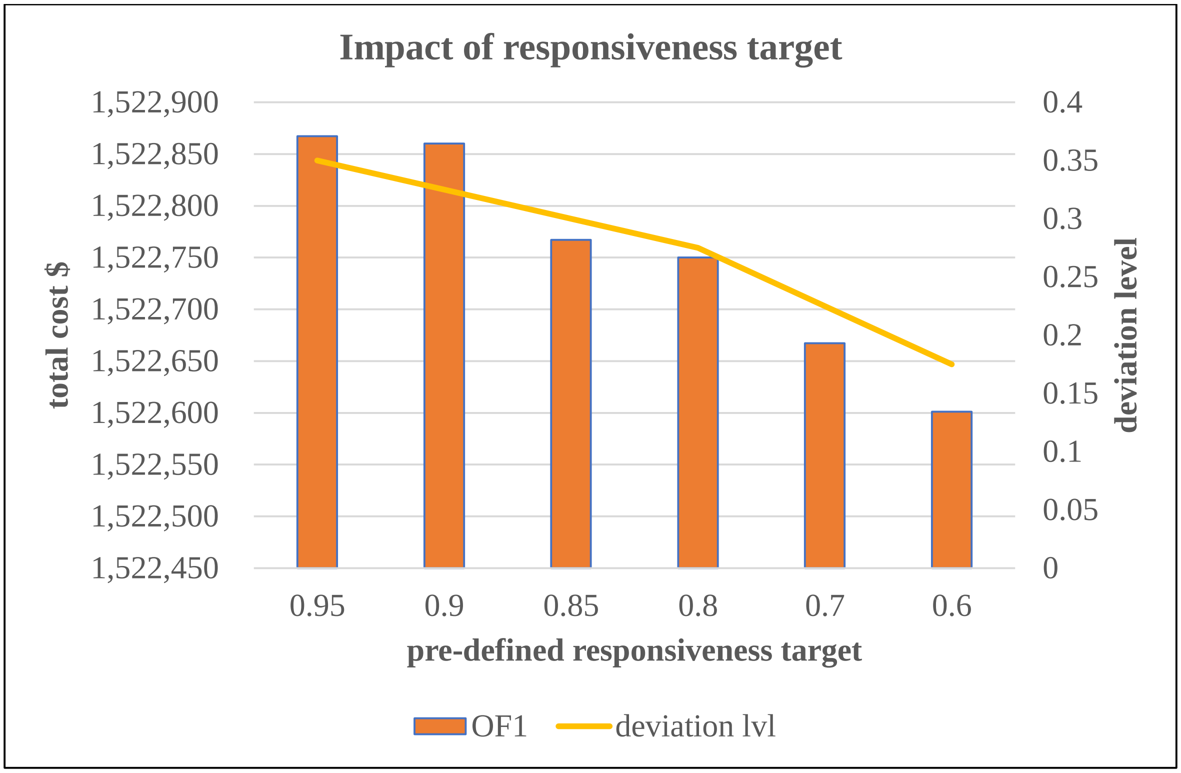

Figure 6-5: Impact of responsiveness target of CLSC network

It can be clearly seen from figure 6.5 that optimal responsiveness target seems to be 88% where the costs and deviation from target are low. Before this point the responsiveness level is kept low which is not always desirable although it costs less and after this point the costs increase while also increasing the deviation levels from the predefined targets.

## 6.5. Managerial insights

Based on the collected numerical data, we will provide some insightful management information in this section.

- This study proposed a MOMILP model to design a sustainable-resilient-responsive CLSCN that will provide managers with a good perspective to manage closed loop supply chain network.
- Concerning the impact of disruptions on total costs. Figure 6.3 showed that the increase in percentage disruptions will lead towards extra costs mainly due to shortages and delays. The underlying case study showed that up to 30% capacity disruption on the manufacturer could be handled by the network if the capacity is disrupted more than that then the solution becomes infeasible.
- Considering the impact of capacity disruption on responsiveness level of closed loop supply chain network it can be seen from figure 6.3 that with increased capacity disruptions of the main player the responsiveness level of the closed loop supply chain decreases there by increasing the deviation from the predefined target value.
- Based on the sensitivity analysis it can be seen that decreasing disposal fractions will lead towards decreased closed loop supply chain costs. Disposal fractions can be reduced only if the concept of MSR is used thereby reducing contamination levels. Figure 10 also shows that decreased return rates with increased disposal fractions will increase the overall closed loop supply chain costs.
- Considering the analysis shown in figure 6.5 it can be clearly seen that increasing the level of responsiveness will incur extra costs and will also increase the deviation levels from the predefined targets whereas reduced responsiveness targets will have less costs but that is not a desirable situation in supply chains.

## 6.6. Theoretical implications

The theoretical ramifications of this investigation are covered in this section. Following is a summary of this paper's key theoretical contributions:

- In this study, a closed-loop supply chain network is designed by simultaneously taking into account three crucial factors: sustainability, resilience, and responsiveness (i.e., adhering to the LARG paradigm). In this sense, economic, environmental, and social aspects are used to establish the sustainability measure, and resilience is added by taking node complexity into account while accounting for disruption scenarios. Additionally, responsiveness is determined by the percentage of the demand that the CLSCN is able to meet. Additionally, many sensitivity studies are carried out to evaluate the relationship between these characteristics.

- This study has incorporated the concept of MSR into the closed loop supply chain network design. MSR supplies waste producers with separate containers to sort recyclables, and it entails retrieving recyclables after waste pickup. Consistent with the results of (Nayeri et al. 2021) our study showed that MSR is the most recommended of the alternative as the residual rate factor were lower in MSR as reflected in overall cost allowing high quality and avoiding extra overall cost linked with disposing of low-quality materials and reducing landfills impacting environment.

## 6.7. Chapter summary

This chapter consists of the results obtained from solving the closed loop supply chain model using case study of Tariq float glass limited. This chapter is further divided into five subsections. The first section explains the effect of capacity disruption on overall cost and responsiveness level showing that increased disruptions lead to reduced responsiveness levels. The second section explains the effect of multiteam recycling by considering the return and disposal rates showing a decrease in overall cost due to reduced landfills. Section three explains the responsiveness levels achieved and a slight increase in the targets may increase the deviation levels from the predefined targets thereby incurring costs. The fourth section provides the decision makes with useful insights obtained from model and last section gives the theoretical implications of our proposed model.

## Chapter 7: Conclusion

In an era marked by the escalating significance of CLSC, driven by the imperatives of resource scarcity and the inescapable reality of disruptions, there emerges a compelling and imperative need for a comprehensive exploration of resilience and responsiveness within these intricate networks. Within this context, this study undertakes the formidable challenge of optimizing a multi-objective, sustainable, resilient, and responsive closed-loop supply chain network, all under the shadow of potential disruptions, while embracing the innovative Multi-Stream Recycling (MSR) policy.

At its heart, this research endeavor is motivated by a trifold mission. First and foremost, it seeks to meticulously unravel the intricate fabric of the CLSCN, with an overarching goal of reducing its overall cost structure. This cost-centric perspective aligns seamlessly with the prevailing economic imperatives, ensuring that CLSC efficiency remains at the forefront of considerations. Simultaneously, this study casts a discerning eye on the environmental implications ingrained within the CLSCN. Notably, the specter of carbon emissions looms large in this regard. The imperative to reduce these environmental footprints, stemming from both production and transportation processes, serves as a guiding light for the research, underscoring the commitment to ecological sustainability.

Equally vital is the emphasis placed on optimizing social impacts within the CLSCN. Central to this endeavor is the laudable goal of creating job opportunities, with a keen focus on enriching the social fabric of the communities intertwined with the supply chain network. In so doing, the study acknowledges that supply chain management transcends mere economic considerations, wielding profound societal implications. The assessment of resilience within the CLSCN is executed through the prism of node complexity, serving as a robust measure of the network's capacity to weather disruptions and swiftly rebound. Responsiveness, on the other hand, is quantified through the ratio of met demand to potential demand, ensuring that customer satisfaction remains a paramount concern.

This research, being first of its kind, aims at describing the concept of MSR in CLSC network designs, integrating responsive-resilient-sustainable close-loop supply chain (CLSC) under disruption threats. A multi-objective mixed integer linear programming model is created to present a tradeoff analysis of the mentioned aspects for decision makers. The proposed CLSCN consists of seven echelons having potential suppliers, manufacturing units, potential distribution centers, client zones, potential collection centers, potential material recovery facilities, and disposal centers. Material flow is started from procuring raw materials and onwards while reverse flow accounts for recycling of used products through MSR and going to collection centers, material recovery facilities and then back to manufacturing sites or otherwise if not usable to disposal centers.

To solve the proposed multi-objective model an interactive multi-objective fuzzy programming approach will be used. This approach involves solving one goal function at a time, recording its value, and using it as a constraint while optimizing the other objectives. The other objectives are then subjected to the same method until a pay-off table with the extreme function values for each aim is attained. In this approach, boundaries and other restrictions are always satisfied since the function values' bounds are determined using mixed integer linear programming. Finally, a real-world case study of float glass industry of Pakistan is provided that is not previously studied as to our knowledge to validate the model and solutions. It can be concluded that an increase in percentage disruptions will lead towards extra costs mainly due to shortages and delays. Increase in the capacity disruptions of the main player the responsiveness level of the closed loop supply chain decreases there by increasing the deviation from the predefined target value. Also, disposal fractions can be reduced only if the concept of MSR is used thereby reducing the contamination levels. Moreover, increasing the level of responsiveness will incur extra costs and will also increase the deviation levels from the predefined targets.

Sustainable supply chains are now a concern for researchers and governments alike due to environmental, social, and economic concerns. As we understand we are left with limited resources and must save them for coming generations we need to be careful with their usage, for this purpose CLSC needs to be studied so that minimum resources are used and tied up in the system. Moreover, decisions impacting CO2 emissions and social wellbeing of employees will be fruitful for society. In terms of Pakistan the decisions resulting from optimization might help in achievement of SDGs that are of paramount importance to the world. Some targets under SGD goal 12 “responsible consumptions and production” will be fulfilled helping Pakistan to move towards more sustainable patterns by 2030.

## 7.1. Limitations and future research

The comprehensive results and insightful discussions stemming from this case study are poised to provide invaluable guidance to decision-makers navigating the intricate landscape of supply chain network design. These findings offer a nuanced understanding of the trade-offs that organizations may need to consider, setting the stage for informed and strategic planning. However, the horizons of future research beckon with intriguing possibilities, offering opportunities for more detailed exploration and expansion of the current framework.

- Delving Deeper into Multi-Stream Recycling

Future research endeavors could delve deeper into the concept of Multi-Stream Recycling (MSR), examining its nuances and variations. Exploring factors such as waste composition, treatment methods, and the integration of MSR into supply chain models can shed more light on its practical implementation and benefits.

- Expanding the Disruption Landscape

While this study primarily focused on capacity disruptions, there exists a rich tapestry of disruption scenarios that can be explored within the context of the proposed model. Future research could venture into disruptions arising from various sources, including natural disasters, geopolitical shifts, or global supply chain volatility, providing organizations with a broader spectrum of solutions.

- Enhancing Resilience and Responsiveness Measures

The current study employed specific measures for resilience and responsiveness. Future research endeavors could consider incorporating a more diverse array of measures, reflecting the multifaceted nature of these dimensions. This would enable organizations to fine-tune their strategies and optimize results in alignment with their unique goals and challenges.

- Application Beyond the Case Study

The proposed mathematical model, with its capacity to balance sustainability, resilience, and responsiveness, holds promise beyond the specific case study at hand. Industries beyond the glass sector, such as textiles, plastics, and other domains with closed-loop supply chains, can readily apply this model to investigate their own processes and uncover valuable trade-offs.

- Continuous Improvement and Adaptation

Supply chain management is an ever-evolving field, and as such, the proposed model can serve as a dynamic tool for continuous improvement and adaptation. Organizations can revisit and optimize their supply chain configurations as circumstances change, ensuring that they remain agile and resilient in an evolving business landscape.

In essence, this study represents a significant milestone in the journey toward more sustainable, responsive, and resilient supply chains. It sets the stage for future research to push the boundaries of knowledge, exploring new dimensions of supply chain optimization, and offering innovative solutions to the multifaceted challenges faced by industries worldwide. As the global landscape continues to evolve, this research paves the way for CLSC to not only adapt but thrive in the face of change and uncertainty.

# Refences

.

Ahmed, Md, SM Salauddin Iqbal, Tazrin Jahan Priyanka, Mohammad Arani, Mohsen Momenitabar, and Md Billal. 2020. "An environmentally sustainable closed-loop supply chain network design under uncertainty: Application of optimization." In International Online Conference on Intelligent Decision Science, 343-58.

Bafail, Omer A, and Reda MS Abdulaal. 2021. 'New approach for selecting a suitable recycling collection program for recovered paper and pulp recyclables using AHP-TOPSIS techniques', Waste Management & Research, 39: 1406-13.

Cardoso, Sónia R, Ana Paula Barbosa-Póvoa, Susana Relvas, and Augusto Q Novais. 2015. 'Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty', Omega, 56: 53-73.

Dahl, Thor Lobekk, Yichang Lu, and Sidney Carina Thill. 2021. "Sustainability of Construction and Demolition Waste: A Closed-loop Supply Chain for Flat Glass."

de Arquer, María, Borja Ponte, and Raúl Pino. 2021. 'Examining the balance between efficiency and resilience in closed-loop supply chains', Central European Journal of Operations Research: 1-30.

Duminy, Lize, and Stefan N Grosser. 2018. 'Resilience as basis for sustainability: Shortages in production supply chains for essential consumer goods.' in, Innovative solutions for sustainable supply chains.

Fathollahi-Fard, Amir Mohammad, Abbas Ahmadi, and SMJ Mirzapour Al-e-Hashem. 2020. 'Sustainable closed-loop supply chain network for an integrated water supply and wastewater collection system under uncertainty', Journal of Environmental Management, 275: 111277.

Fu, Rong, Qiang Patrick Qiang, Ke Ke, and Zuqing Huang. 2021. 'Closed-loop supply chain network with interaction of forward and reverse logistics', Sustainable production and consumption, 27: 737-52.

Gaur, Jighyasu, Mehdi Amini, and AK Rao. 2017. 'Closed-loop supply chain configuration for new and reconditioned products: An integrated optimization model', Omega, 66: 212-23.

Gholizadeh, Hadi, and Hamed Fazlollahtabar. 2020. 'Robust optimization and modified genetic algorithm for a closed loop green supply chain under uncertainty: Case study in melting industry', Computers & Industrial Engineering, 147: 106653.

Gholizadeh, Hadi, Hamed Jahani, Ahmad Abareshi, and Mark Goh. 2021. 'Sustainable closed-loop supply chain for dairy industry with robust and heuristic optimization', Computers & Industrial Engineering, 157: 107324.

Ghomi-Avili, Morteza, Amir Khosrojerdi, and Reza Tavakkoli-Moghaddam. 2019. 'A multi-objective model for the closed-loop supply chain network design with a price-dependent demand, shortage and disruption', Journal of Intelligent & Fuzzy Systems, 36: 5261-72.

Golara, Sina, Nasim Mousavi, Mohammad Jafar Tarokh, and Mostafa Hosseinzadeh. 2012. 'Closed-loop supply chain network design with recovery of glass containers', International Journal of Strategic Decision Sciences (IJSDS), 3: 1-26.

Govindan, Kannan, and Mohammad Fattahi. 2017. 'Investigating risk and robustness measures for supply chain network design under demand uncertainty: A case study of glass supply chain', International Journal of Production Economics, 183: 680-99.

Govindan, Kannan, Farhad Salehian, Hadi Kian, Seyed Teimoor Hosseini, and Hassan Mina. 2023. 'A location-inventory-routing problem to design a circular closed-loop supply chain network with carbon tax policy for achieving circular economy: An augmented epsilon-constraint approach', International Journal of Production Economics, 257: 108771.

Hamidieh, Alireza, Alireza Arshadi Khamseh, and Bahman Naderi. 2018. 'A resilient supply chain network design model with a novel fuzzy programming method under uncertainty and disruptions: a real industrial approach', Journal of Quality Engineering and Production Optimization, 3: 27-50.

Jabbarzadeh, Armin, Behnam Fahimnia, and Fatemeh Sabouhi. 2018. 'Resilient and sustainable supply chain design: sustainability analysis under disruption risks', International Journal of Production Research, 56: 5945-68.

Jabbarzadeh, Armin, Michael Haughton, and Amir Khosrojerdi. 2018. 'Closed-loop supply chain network design under disruption risks: A robust approach with real world application', Computers & Industrial Engineering, 116: 178-91.

Kochan, Cigdem Gonul, and David R Nowicki. 2018. 'Supply chain resilience: a systematic literature review and typological framework', International Journal of Physical Distribution & Logistics Management.

Lotfi, Reza, Yahia Zare Mehrjerdi, Mir Saman Pishvaee, Ahmad Sadeghieh, and Gerhard-Wilhelm Weber. 2021. 'A robust optimization model for sustainable and resilient closed-loop supply chain network design considering conditional value at risk', Numerical algebra, control & optimization, 11: 221.

Mohammed, Fareeduddin, Shokri Z Selim, Adnan Hassan, and Mujahid Naqeebuddin Syed. 2017. 'Multi-period planning of closed-loop supply chain with carbon policies under uncertainty', Transportation Research Part D: Transport and Environment, 51: 146-72.

Nayeri, Sina, Mohammad Mahdi Paydar, Ebarhim Asadi-Gangraj, and Saeed Emami. 2020. 'Multi-objective fuzzy robust optimization approach to sustainable closed-loop supply chain network design', Computers & Industrial Engineering, 148: 106716.

Nayeri, Sina, S Ali Torabi, Mahdieh Tavakoli, and Zeinab Sazvar. 2021. 'A multi-objective fuzzy robust stochastic model for designing a sustainable-resilient-responsive supply chain network', Journal of Cleaner Production, 311: 127691.

Negri, Marta, Enrico Cagno, Claudia Colicchia, and Joseph Sarkis. 2021. 'Integrating sustainability and resilience in the supply chain: A systematic literature review and a research agenda', Business Strategy and the environment, 30: 2858-86.

Parast, Mahour M, and Mansoor Shekarian. 2019. 'The impact of supply chain disruptions on organizational performance: a literature review', Revisiting supply chain risk: 367-89.

Pishvaee, Mir Saman, Masoud Rabbani, and Seyed Ali Torabi. 2011. 'A robust optimization approach to closed-loop supply chain network design under uncertainty', Applied mathematical modelling, 35: 637-49.

Pourjavad, E, and RV Mayorga. 2018. 'Optimization of a sustainable closed loop supply chain network design under uncertainty using multi-objective evolutionary algorithms', Advances in Production Engineering & Management, 13: 216-28.

Rezaei, Saeid, and Reza Maihami. 2020. 'Optimizing the sustainable decisions in a multi-echelon closed-loop supply chain of the manufacturing/remanufacturing products with a competitive environment', Environment, Development and Sustainability, 22: 6445-71.

Soleimani, Hamed, and Govindan Kannan. 2015. 'A hybrid particle swarm optimization and genetic algorithm for closed-loop supply chain network design in large-scale networks', Applied mathematical modelling, 39: 3990-4012.

Souviron, Jean, and Ahmed Z Khan. 2021. 'The materiality of transparency: An environmental analysis of the architectural flat glass industry since 1945 in Europe, France and Belgium', Resources, Conservation and Recycling, 174: 105779.

Sundarakani, Balan, Vijay Pereira, and Alessio Ishizaka. 2020. 'Robust facility location decisions for resilient sustainable supply chain performance in the face of disruptions', The International Journal of Logistics Management.

Torabi, SA, J Namdar, SM Hatefi, and F Jolai. 2016. 'An enhanced possibilistic programming approach for reliable closed-loop supply chain network design', International Journal of Production Research, 54: 1358-87.

Vali-Siar, Mohammad Mahdi, Emad Roghanian, and Armin Jabbarzadeh. 2022. 'Resilient mixed open and closed-loop supply chain network design under operational and disruption risks considering competition: A case study', Computers & Industrial Engineering, 172: 108513.

Yun, YoungSu, Anudari Chuluunsukh, and Mitsuo Gen. 2020. 'Sustainable closed-loop supply chain design problem: A hybrid genetic algorithm approach', Mathematics, 8: 84.

Zahiri, Behzad, Jun Zhuang, and Mehrdad Mohammadi. 2017. 'Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study', Transportation Research Part E: Logistics and Transportation Review, 103: 109-42.

Zhang, Abraham, Jason X Wang, Muhammad Farooque, Yulan Wang, and Tsan-Ming Choi. 2021. 'Multi-dimensional circular supply chain management: A comparative review of the state-of-the-art practices and research', Transportation Research Part E: Logistics and Transportation Review, 155: 102509.

Zhang, Xin, Gang Zhao, Yingxiu Qi, and Botang Li. 2019. 'A robust fuzzy optimization model for closed-loop supply chain networks considering sustainability', Sustainability, 11: 5726.

Zimmermann, H-J. 1978. 'Fuzzy programming and linear programming with several objective functions', Fuzzy sets and systems, 1: 45-55.

## Appendix

Following are the name/location of the facilities provided by the company (Tariq Glass) and their notations used in the proposed model case study.

### Suppliers

1. Kamar Mishani (s1)
2. Jhangera (s2)
3. Khewra (s3)
4. Lahore (s4)

### Manufacturer

1. Tariq Float Glass Limited (m1)

### Distributors

1. Model Town B, Bahawalpur, Punjab (d1)
2. Madina Abad Faisalabad, Punjab (d2)
3. Rasheed Colony, Gujranwala, Punjab (d3)
4. Zafar Colony, Gujrat, Punjab 50700 (d4)
5. Islamabad Capital Territory 44000 (d5)
6. Sultan Pura, Gujrat, Punjab (d6)
7. Gulberg III, Lahore, Punjab (d7)
8. Defense Rd, Lahore, Punjab (d8)
9. Humayun Rd, Multan, Punjab (d9)
10. Rawat Industrial Estate, Islamabad, Rawalpindi, Punjab (d10)
11. Lahore - Sheikhupura, Punjab (d11)

### Customer Zones

1. Bahawalnagar (n1)
2. Bahawalpur (n2)
3. Dera Ghazi Khan (n3)
4. Faisalabad (n4)
5. Gujranwala (n5)

6. Gujrat (n6)
7. Islamabad (n7)
8. Lahore (n8)
9. Multan (n9)
10. Rahim Yar Khan (n10)
11. Rawat (n11)
12. Rawalpindi (n12)
13. Sahiwal (n13)
14. Sargodha (n14)
15. Sheikhupura (n15)

**Collection centers**

1. Rawalpindi waste management company (j1)
2. Lahore waste management company (j2)
3. Faisalabad waste management company (j3)
4. Gujranwala waste management company (j4)
5. Sialkot waste management company (j5)
6. Multan waste management company (j6)
7. Bahawalpur waste management company (j7)

**Disposal center**

1. Lakhodair Landfill, Lahore Punjab (i1)

The following tables show that distances calculated using the supply chain add in (log-hub) of MS Excel and the values of parameters obtained from the data collected from the industry plus some market research. Some data sets were used from the literature having same problem size.

Table A-1: Distance from supplier to manufacturer

| Suppliers | Manufacturer (km) |
|---|---|
| S 1 | 411.36 |
| S 2 | 390.91 |
| S 3 | 195.96 |
| S 4 | 39.78 |

Table A-2: Distance from manufacturer to distributors

| Distributors | Manufacturer (km) |
|---|---|
| D 1 | 408.21 |
| D 2 | 103.54 |
| D 3 | 85.15 |
| D 4 | 133.06 |
| D 5 | 285.18 |
| D 6 | 152.97 |
| D 7 | 46.41 |
| D 8 | 53 |
| D 9 | 47.05 |
| D 10 | 277.35 |
| D 11 | 29.53 |

Table A-3: Distance from distributors to customer zones

| Distributor /customer (km) | N 1 | N 2 | N 3 | N 4 | N 5 | N 6 | N 7 | N 8 | N 9 | N 10 | N 11 | N 12 | N 13 | N 14 | N 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D 1 | 246.53 | 7.86 | 181.75 | 298.77 | 462.2 | 476.87 | 607.52 | 402.85 | 96.4 | 193.49 | 581.61 | 601.75 | 238.7 | 382.51 | 405.49 |
| D 2 | 182.83 | 302.26 | 319.1 | 3.52 | 189.27 | 190.24 | 319.72 | 139.18 | 221.33 | 474.18 | 293.81 | 313.95 | 93.77 | 94.71 | 100.82 |
| D 3 | 332.24 | 469.09 | 485.93 | 186.55 | 0.72 | 52.1 | 218.24 | 68.03 | 388.16 | 641.01 | 193.36 | 209.75 | 235.12 | 197.47 | 86.17 |
| D 4 | 380.15 | 480.66 | 497.5 | 185.87 | 49.45 | 2.93 | 169.03 | 115.93 | 399.73 | 652.59 | 144.15 | 160.54 | 283.03 | 182.8 | 134.08 |
| D 5 | 532.27 | 593.99 | 581.95 | 298.59 | 201.58 | 152.28 | 24.19 | 268.05 | 513.06 | 765.92 | 9.55 | 11.99 | 435.15 | 224.41 | 286.2 |
| D 6 | 400.06 | 500.57 | 517.42 | 205.78 | 69.37 | 19.06 | 184.68 | 135.84 | 419.65 | 672.5 | 159.81 | 176.19 | 302.94 | 202.71 | 153.99 |
| D 7 | 266.41 | 411.89 | 432.9 | 144.74 | 74.68 | 126.23 | 292.37 | 7.53 | 335.13 | 587.99 | 267.5 | 283.89 | 169.29 | 189.35 | 46.22 |
| D 8 | 251.95 | 412.1 | 436.12 | 151.33 | 82.09 | 133.64 | 299.78 | 15.44 | 338.35 | 591.2 | 274.9 | 291.29 | 169.5 | 192.56 | 52.81 |
| D 9 | 267.31 | 412.78 | 433.8 | 145.37 | 75.32 | 126.87 | 293.01 | 8.17 | 336.03 | 588.88 | 268.13 | 284.52 | 170.18 | 190.24 | 46.85 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D 10 | 524.44 | 586.16 | 569.9 | 290.76 | 193.75 | 144.45 | 26.6 | 260.22 | 505.23 | 758.09 | 1.72 | 18.11 | 427.32 | 216.58 | 278.37 |
| D 11 | 280.25 | 411.89 | 428.74 | 127.86 | 68.1 | 119.65 | 285.79 | 14.75 | 330.97 | 583.82 | 260.92 | 277.3 | 183.13 | 170.65 | 29.34 |

Table A-4: Distance from customers to collection centers

| Collection Centers/customers (km) | N 1 | N 2 | N 3 | N 4 | N 5 | N 6 | N 7 | N 8 | N 9 | N 10 | N 11 | N 12 | N 13 | N 14 | N 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J 1 | 547.71 | 602.58 | 575.61 | 312.21 | 215.2 | 165.9 | 8.31 | 281.68 | 526.68 | 779.54 | 23.17 | 6.03 | 448.77 | 238.03 | 299.82 |
| J 2 | 271.29 | 409.36 | 431.23 | 139.49 | 69.44 | 120.99 | 287.13 | 2.62 | 333.46 | 586.31 | 262.26 | 278.65 | 172.35 | 182.29 | 40.98 |
| J 3 | 187.01 | 299.15 | 321.03 | 1.65 | 187.67 | 187.66 | 317.14 | 137.58 | 223.26 | 476.11 | 291.23 | 311.37 | 96.13 | 92.13 | 99.22 |
| J 4 | 335.91 | 465.9 | 487.78 | 188.4 | 3.39 | 49.37 | 215.51 | 69.87 | 390.01 | 642.86 | 190.63 | 207.02 | 236.97 | 194.74 | 88.02 |
| J 5 | 394 | 501.15 | 523.02 | 211.39 | 57.26 | 59.89 | 226.04 | 120.47 | 425.25 | 678.11 | 201.16 | 217.55 | 287.56 | 208.31 | 138.07 |
| J 6 | 215.5 | 96.93 | 100.15 | 224.51 | 387.95 | 402.61 | 533.26 | 328.59 | 2.28 | 263.34 | 507.35 | 527.49 | 177.09 | 308.25 | 331.23 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J 7 | 251.65 | 0.96 | 185.07 | 302.08 | 465.52 | 480.19 | 610.83 | 406.16 | 99.72 | 193.55 | 584.92 | 605.07 | 242.01 | 385.82 | 408.8 |

Table A-5: Demand and shortage cost for customers

| Customers | N 1 | N 2 | N 3 | N 4 | N 5 | N 6 | N 7 | N 8 | N 9 | N 10 | N 11 | N 12 | N 13 | N 14 | N 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Demand (units) | 58 | 108 | 459 | 288 | 314 | 259 | 3553 | 9992 | 494 | 280 | 1686 | 2305 | 190 | 442 | 133 |
| Unit shortage cost ($) | 3.5 | 3.5 | 3.5 | 4 | 3.5 | 3.5 | 3.5 | 4 | 4 | 3.5 | 3.5 | 4 | 3.5 | 3.5 | 4 |

Table A-6: Distance from collection centers to MRFs

| Collection Centers/MRF (km) | MRF 1 | MRF 2 | MRF 3 |
|---|---|---|---|
| J 1 | 298.01 | 301.33 | 297.86 |
| J 2 | 17.83 | 18.93 | 17.68 |
| J 3 | 151.02 | 152.98 | 150.87 |
| J 4 | 86.21 | 89.52 | 86.05 |
| J 5 | 144.69 | 145.79 | 144.54 |
| J 6 | 335.13 | 337.09 | 334.98 |
| J 7 | 407.02 | 402 | 406.87 |

Table A-7: Distance from MRFs to manufacturer

| Collection Center/manufacturer (km) | Manufacturer 1 |
|---|---|
| J 1 | 299.52 |
| J 2 | 41 |
| J 3 | 100.12 |
| J 4 | 87.71 |
| J 5 | 137.76 |
| J 6 | 332.13 |
| J 7 | 409.7 |

Table A-8: Distance from collection centers to disposal center

| Collection Center/landfill (km) | I 1 |
|---|---|
| J 1 | 292.22 |
| J 2 | 17.12 |
| J 3 | 148.12 |
| J 4 | 80.42 |
| J 5 | 119.37 |
| J 6 | 344.98 |
| J 7 | 422.56 |

Table A-9: Distance from MRFs to disposal center

| landfill/MRF (km) | MRF 1 | MRF 2 | MRF 3 |
|---|---|---|---|
| I 1 | 29.29 | 31.18 | 29.11 |

Table A-10: Distance from MRFs to manufacturer

| MRF/manufacturer (km) | MRF 1 | MRF 2 | MRF 3 |
|---|---|---|---|

| | | | |
|---|---|---|---|
| M 1 | 50.89 | 53.07 | 50.72 |

Table A-11: Unit cost of raw materials

| Suppliers (unit cost $) | R 1 | R 2 | R 3 | R 4 | R 5 |
|---|---|---|---|---|---|
| S 1 | 127 | 75 | 250 | 300 | 50 |
| S 2 | 127 | 75 | 250 | 300 | 50 |
| S 3 | 127 | 75 | 250 | 300 | 50 |
| S 4 | 127 | 75 | 250 | 300 | 50 |

Table A-12: Consumption rate of raw materials

| Suppliers (unit consumption rate %) | R 1 | R 2 | R 3 | R 4 | R 5 |
|---|---|---|---|---|---|
| S 1 | 0.726 | 0.04 | 0.13 | 0.01 | 0.084 |
| S 2 | 0.726 | 0.04 | 0.13 | 0.01 | 0.084 |
| S 3 | 0.726 | 0.04 | 0.13 | 0.01 | 0.084 |
| S 4 | 0.726 | 0.04 | 0.13 | 0.01 | 0.084 |

Table A-13: Capacity of suppliers

| Suppliers/ raw materials (ton/month) | R 1 | R 2 | R 3 | R 4 | R 5 |
|---|---|---|---|---|---|
| S 1 | 40000 | 40000 | 40000 | 40000 | 40000 |
| S 2 | 40000 | 40000 | 40000 | 40000 | 40000 |
| S 3 | 40000 | 40000 | 40000 | 40000 | 40000 |
| S 4 | 40000 | 40000 | 40000 | 40000 | 40000 |

Table A-14: Capacity of distributors

| Distributors | Capacity (ton/month) |
|---|---|
| D 1 | 50000 |
| D 2 | 20000 |
| D 3 | 30000 |
| D 4 | 55000 |
| D 5 | 60000 |
| D 6 | 30000 |
| D 7 | 70000 |
| D 8 | 22000 |
| D 9 | 45000 |
| D 10 | 66000 |
| D 11 | 70000 |

Table A-15: Capacity of collection centers

| Collection centers | Capacity (ton/month) |
|---|---|
| J 1 | 100000 |
| J 2 | 120000 |
| J 3 | 100000 |
| J 4 | 100000 |
| J 5 | 100000 |
| J 6 | 120000 |

| | |
|---|---|
| J 7 | 100000 |

Table A-16: Capacity of MRFs

| Material Recovery Facility | MRF1 | MRF2 | MRF3 |
|---|---|---|---|
| Capacity (ton/month) | 10000 | 12000 | 10000 |

Table A-17: Fixed costs of suppliers

| Suppliers fixed cost ($) | R 1 | R 2 | R 3 | R 4 | R 5 |
|---|---|---|---|---|---|
| S 1 | 7500 | 6700 | 5300 | 7300 | 6000 |
| S 2 | 7300 | 7300 | 7400 | 7400 | 5900 |
| S 3 | 5400 | 7600 | 6400 | 6200 | 7500 |
| S 4 | 7700 | 5200 | 7200 | 7200 | 6700 |

Table A-18: Fixed and operational cost of distributors

| Distributors | Fixed costs ($) | Operational costs ($) |
|---|---|---|
| D 1 | 3500 | 2 |
| D 2 | 5800 | 1.2 |
| D 3 | 5100 | 1.5 |
| D 4 | 4000 | 3 |
| D 5 | 5400 | 2 |
| D 6 | 4100 | 2.5 |
| D 7 | 5100 | 1 |
| D 8 | 2900 | 2 |
| D 9 | 4900 | 1.2 |

| | | |
|---|---|---|
| D 10 | 6700 | 1.5 |
| D 11 | 6400 | 1 |

Table A-19: Fixed and operational costs of collection centers

| Collection centers | Fixed costs ($) | Operational costs ($) |
|---|---|---|
| J 1 | 3400 | 2 |
| J 2 | 3900 | 3.5 |
| J 3 | 4900 | 2 |
| J 4 | 5300 | 3.2 |
| J 5 | 4400 | 3 |
| J 6 | 3700 | 3.5 |
| J 7 | 7400 | 2 |

Table A-20: Fixed and operational costs of MRFs

| MRF | MRF 1 | MRF 2 | MRF 3 |
|---|---|---|---|
| Fixed costs ($) | 7000 | 5300 | 6200 |
| Operational costs ($) | 5 | 5.5 | 4 |

Table A-21: Fixed cost of manufacturer

| Manufacturer | Fixed cost ($) |
|---|---|
| M1 | 20000 |

Table A-22: jobs created of supplier for raw material 1

| Suppliers for R1 | Jobs |
|---|---|
| S 1 | 125 |
| S 2 | 120 |
| S 3 | 125 |
| S 4 | 120 |

Table A-23: Jobs created of supplier for raw material 2

| Suppliers for R2 | Jobs |
|---|---|
| S 1 | 120 |
| S 2 | 125 |
| S 3 | 120 |
| S 4 | 125 |

Table A-24: Jobs created of supplier for raw material 3

| Suppliers for R3 | Jobs |
|---|---|
| S 1 | 120 |
| S 2 | 125 |
| S 3 | 120 |
| S 4 | 125 |

Table A-25: Jobs created of supplier for raw material 4

| Suppliers for R4 | Jobs |
|---|---|
| S 1 | 125 |
| S 2 | 120 |
| S 3 | 125 |
| S 4 | 120 |

Table A-26: Jobs created of supplier for raw material 5

| Suppliers for R5 | Jobs |
|---|---|
| S 1 | 125 |
| S 2 | 120 |
| S 3 | 125 |
| S 4 | 125 |

Table A-27: Jobs created for collection centers

| Collection centers | Jobs |
|---|---|
| J 1 | 10000 |
| J 2 | 12000 |
| J 3 | 10000 |
| J 4 | 12000 |
| J 5 | 12000 |
| J 6 | 10000 |
| J 7 | 10000 |

Table A-28: Jobs created for distributors

| Distributors | Jobs |
|---|---|
| D 1 | 125 |
| D 2 | 120 |
| D 3 | 125 |
| D 4 | 120 |
| D 5 | 110 |
| D 6 | 110 |
| D 7 | 125 |
| D 8 | 120 |

| | |
|---|---|
| D 9 | 125 |
| D 10 | 125 |
| D 11 | 120 |

Table A-29: Jobs created for MRFs

| MRF | MRF 1 | MRF 2 | MRF 3 |
|---|---|---|---|
| Jobs | 125 | 120 | 125 |

Table A-30: Jobs created for manufacturer

| Manufacturer | Jobs |
|---|---|
| M1 | 600 |

Table A-31: Suppliers’ penalty coefficient for complexity

| Suppliers’ penalty coefficient for complexity | R 1 | R 2 | R 3 | R 4 | R 5 |
|---|---|---|---|---|---|
| S 1 | 100 | 90 | 80 | 100 | 100 |
| S 2 | 90 | 100 | 90 | 95 | 100 |
| S 3 | 80 | 90 | 100 | 85 | 90 |
| S 4 | 100 | 80 | 100 | 90 | 100 |

Table A-32: Distributors’ penalty coefficient for complexity

| Distributors | Penalty coefficient for complexity |
|---|---|
| D 1 | 60 |
| D 2 | 50 |
| D 3 | 45 |
| D 4 | 55 |
| D 5 | 60 |
| D 6 | 65 |

| | |
|---|---|
| D 7 | 44 |
| D 8 | 36 |
| D 9 | 70 |
| D 10 | 55 |
| D 11 | 60 |

Table A-33: Collection centers’ penalty coefficient for complexity

| Collection centers | Penalty coefficient for complexity |
|---|---|
| J 1 | 60 |
| J 2 | 65 |
| J 3 | 50 |
| J 4 | 60 |
| J 5 | 55 |
| J 6 | 62 |
| J 7 | 60 |

Table A-34: MRFs’ penalty coefficient for complexity

| MRF | MRF 1 | MRF 2 | MRF 3 |
|---|---|---|---|
| Penalty coefficient for complexity | 60 | 65 | 70 |

Table A-35: Manufacturers’ penalty coefficient for complexity

| Manufacturer | Penalty coefficient for complexity |
|---|---|
| M1 | 125 |

Table A-36: Quantity flow from distributor to customer

| Qd (units) | N 1 | N 2 | N 3 | N 4 | N 5 | N 6 | N 7 | N 8 | N 9 | N 10 | N 11 | N 12 | N 13 | N 14 | N 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 8 | 29 | 54 | 229.5 | 144 | 157 | 129.5 | 0 | 4996 | 247 | 140 | 0 | 0 | 95 | 221 | 66.5 |
| D 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D 10 | 0 | 0 | 0 | 0 | 0 | 0 | 1777 | 0 | 0 | 0 | 843 | 1152 | 0 | 0 | 0 |
| D 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table A-37: Quantity flow from customer to collection centers

| Qn (units) | N 1 | N 2 | N 3 | N 4 | N 5 | N 6 | N 7 | N 8 | N 9 | N 10 | N 11 | N 12 | N 13 | N 14 | N 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| J 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| J 3 | 0 | 0 | 0 | 336 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| J 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| J 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| J 7 | 0 | 12000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table A-38: Quantity flow from MRF to disposal center

| Qi (units) | MRF1 | MRF2 | MRF3 |
|---|---|---|---|
| Landfill (i1) | 2467 | 2466 | 0 |

Table A-39: Quantity flow from MRF to manufacturer

| Qm (units) | MRF1 | MRF2 | MRF3 |
|---|---|---|---|
| Manufacturer (m1) | 7402 | 0 | 0 |

Table A-40: Shortage quantity for customers

| Qsh (units) | N 1 | N 2 | N 3 | N 4 | N 5 | N 6 | N 7 | N 8 | N 9 | N 10 | N 11 | N 12 | N 13 | N 14 | N 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shortage units | 29 | 54 | 229 | 144 | 157 | 129 | 1776 | 4996 | 247 | 140 | 843 | 1152 | 95 | 221 | 66 |

Table A-41: Values of carbon, complexity, and deviation

| | |
|---|---|
| Qsc | 1,000,000.00 ton |
| Qpc | 99,970.17 ton |
| NCX | 12 nodes |
| Drep | 0.35 |
| Rep | 0.5 |

Table A-42: Quantity flow from collection centers to MRF

| Ql (units) | MRF1 | MRF2 | MRF3 |
|---|---|---|---|
| J 1 | 0 | 0 | 0 |
| J 2 | 0 | 0 | 0 |
| J 3 | 10,000 | 0 | 0 |
| J 4 | 0 | 0 | 0 |
| J 5 | 0 | 0 | 0 |
| J 6 | 0 | 0 | 0 |
| J 7 | 0 | 2336 | 0 |

Table A-43: Quantity flow from manufacturer to distributor

| Qp (units) | Manufacturer (m1) |
|---|---|
| D 1 | 0 |
| D 2 | 0 |
| D 3 | 0 |
| D 4 | 0 |
| D 5 | 0 |
| D 6 | 0 |
| D 7 | 0 |
| D 8 | 6508 |
| D 9 | 0 |

| | |
|---|---|
| D 10 | 3772 |
| D 11 | 0 |

Table A-44: Quantity flow from supplier to manufacturer for raw material 1

| Qr (RM1) units | Manufacturer (m1) |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 1 |
| S 4 | 0 |

Table A-45: Quantity flow from supplier to manufacturer for raw material 2

| Qr (RM2) units | Manufacturer (m1) |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 0 |
| S 4 | 24000 |

Table A-46: Quantity flow from supplier to manufacturer for raw material 3

| Qr (RM3) units | Manufacturer (m1) |
|---|---|
| S 1 | 1 |
| S 2 | 0 |
| S 3 | 0 |
| S 4 | 0 |

Table A-47: Quantity flow from supplier to manufacturer for raw material 4

| Qr (RM4) units | Manufacturer (m1) |
|---|---|
| S 1 | 0 |

| | |
|---|---|
| S 2 | 0 |
| S 3 | 1 |
| S 4 | 0 |

Table A-48: Quantity flow from supplier to manufacturer for raw material 5

| Qr (RM5) units | Manufacturer (m1) |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 0 |
| S 4 | 9305 |

Table A-49: Selection of distributors

| Sd | Distributors Selection |
|---|---|
| D 1 | 0 |
| D 2 | 0 |
| D 3 | 0 |
| D 4 | 0 |
| D 5 | 0 |
| D 6 | 0 |
| D 7 | 0 |
| D 8 | 1 |
| D 9 | 0 |
| D 10 | 1 |
| D 11 | 0 |

Table A-50: Selection of collection centers

| Sj | Collection center selection |
|---|---|
| J 1 | 0 |

| | |
|---|---|
| J 2 | 0 |
| J 3 | 1 |
| J 4 | 0 |
| J 5 | 0 |
| J 6 | 0 |
| J 7 | 1 |

Table A-51: Selection of supplier for raw material 1

| ss (RM1) | Selection |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 1 |
| S 4 | 0 |

Table A-52: Selection of supplier for raw material 2

| ss (RM2) | Selection |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 0 |
| S 4 | 1 |

Table A-53: Selection of supplier for raw material 3

| ss (RM3) | Selection |
|---|---|
| S 1 | 1 |
| S 2 | 0 |
| S 3 | 0 |
| S 4 | 0 |

Table A-54: Selection of supplier for raw material 4

| ss (RM4) | Selection |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 1 |
| S 4 | 0 |

Table A-55: Selection of supplier for raw material 5

| ss (RM5) | Selection |
|---|---|
| S 1 | 0 |
| S 2 | 0 |
| S 3 | 0 |
| S 4 | 1 |

Table A-56: Selection of MRF

| Sl | MRF1 | MRF2 | MRF3 |
|---|---|---|---|
|  | 1 | 1 | 0 |