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Simulation-Based Analysis of Disruptions and Recovery Strategies in Closed-Loop lithium-ion Battery Supply Chains

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Abstract
Managing disruptions in reverse supply chains is critical with the growing demand for electric vehicles and lithium-ion battery recycling. Fires and other risks pose significant challenges, yet the impact of recovery policies remains underexplored. This study uses discrete event simulation to examine disruptions in closed-loop supply chains and evaluates three resilience strategies, including reconstruction, inventory capacity expansion, and backup suppliers. Applied to a case study in Iran, the analysis assesses profitability, responsiveness, and environmental sustainability under disruption scenarios. Findings show that while a backup supplier improves service levels, it increases sourcing costs and CO_2 emissions, leading to environmental trade-offs. The results highlight the complexities of recovery policies in disrupted supply chains and the need to consider economic and environmental factors when designing long-term resilience strategies.

Keywords: Discrete event simulation, Supply chain resilience, anyLogistix, Sustainability, Disruption management

1. Introduction and literature review

Sustainability and resilience are two of the most significant dimensions of a viable supply chain. As evidenced by the literature on the subject, many models and proposals have been developed over the past twenty years to improve and examine this concept in depth in line with research data [1]. Combining these concepts can create a viable closed-loop supply chain [2]. A closed-loop supply chain is designed, controlled, and operated to maximize value creation through dynamic value recovery of multiple sources and outputs throughout the product life cycle. It faces a variety of risks that are generally divided into two categories: operational risks (such as demand fluctuation) and disruption risks (such as facility shutdown) [3], [4].

In this study, the focus will be on both risks, which appear in the reverse flow in a multilayer closed-loop supply chain. Lithium-ion batteries, while essential for modern technology, pose significant challenges throughout their life cycle, from supply chain risks to end-of-life management. The improper disposal of used lithium-ion batteries (LIBs) can lead to ecological disasters, as highlighted in a study emphasising the dangers of mishandling these batteries [5]. Furthermore, harmful substances may be released during the recycling process, potentially causing environmental pollution; burning LIB waste might even result in the emission of toxic gases [6].

Keeping extensive inventories of lithium-ion batteries also presents substantial risks due to the inherent instability of these energy storage devices. For instance, thermal runaway—a self-sustaining exothermic reaction—can cause fires or explosions, posing severe safety hazards in storage facilities and transportation [7]. Such incidents endanger human lives, inflict financial losses, and disrupt supply chains. On the other hand, recycling lithium-ion batteries is crucial for mitigating these risks and promoting sustainability within the circular economy framework. Recycling allows for the recovery of valuable materials from spent LIB streams, helping to reduce reliance on newly mined resources and thus addressing issues related to resource scarcity [8]. Additionally, proper recycling prevents hazardous components, including heavy metals and toxic substances, from entering the environment, thereby protecting ecosystems and public health [9]. Efficient recycling processes are continuously being developed to address technological challenges and improve material recovery rates, ensuring that lithium-ion batteries contribute positively to a sustainable future rather

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than becoming a source of disaster [10].

Fires within the layers of a closed-loop lithium battery supply chain are an unavoidable risk, making resilience a critical necessity. However, selecting the most effective strategy to enhance supply chain resilience is a complex decision that requires careful evaluation. This study aims to identify and analyse the most effective resilience strategy by implementing discrete event simulation in a closed-loop lithium battery supply chain. To achieve this, we address the following research question:

RQ1: How does a disruption in the reverse flow of a closed-loop supply chain affect its key performance indicators?

To address this question, we analyze various resilient recovery policies in response to a fire disruption scenario within our case study. Using discrete event simulation, we compare the outcomes of different scenarios across key supply chain performance indicators, including total profit, CO_2 emissions, and service level. Additionally, this methodology is adaptable and can be applied to other types of disruptions and supply chains. By answering RQ1, we gain insights into how disruptions impact profitability, environmental sustainability, and operational performance. Specifically, the simulation allows us to assess changes in profit levels, carbon emissions, service quality, and inventory availability, providing a comprehensive understanding of disruption effects and resilience strategies.

This study makes several key contributions to the field of closed-loop supply chain resilience and sustainability.

First, it addresses disruptions in the reverse flow of the lithium-ion battery supply chain, a critical yet often overlooked aspect of supply chain resilience. While previous studies primarily focus on disruptions in the forward supply chain, this research highlights the vulnerabilities and cascading effects caused by interruptions in battery recycling and material recovery processes. By incorporating various recovery strategies, the study provides actionable insights for mitigating reverse logistics disruptions in resource-dependent industries.

Second, this research implements a Material Requirements Planning (MRP) inventory policy within a discrete event simulation model, an approach not previously explored in similar studies. The integration of MRP with resilience analysis enhances the accuracy of demand-driven inventory management while evaluating its effectiveness in maintaining stability during supply chain disruptions. This contribution is particularly valuable for industries dealing with volatile demand and critical material shortages, such as lithium-ion battery manufacturing.

Furthermore, the study provides a comprehensive comparative analysis of resilience strategies, considering financial, operational, and environmental trade-offs. The findings offer a quantitative framework for decision-makers to balance cost efficiency, service level, and sustainability when designing disruption recovery policies. By evaluating profitability, service performance, lead time variations, and CO_2 emissions, this research contributes to the growing need for sustainable and resilient supply chain planning in the lithium-ion battery sector.

2. Problem and case statement

Figure 1 illustrates the network structure of the lithium-ion battery supply chain in Iran. The forward supply chain consists of three raw material suppliers for lithium, cobalt, and nickel in Hamedan, Mashhad, and Kerman. Lithium is available from two sources: lithium derived from mines, and lithium derived from battery recycling centers. A manufacturing plant in Tehran processes these materials into batteries, which are distributed through two distribution centers in Tehran and Zanjan. These centers serve seven customer hubs in Tehran, Tabriz, Mashhad, Sari, Kermanshah, Birjand, and Ahvaz. Raw materials are transported to the plant using small trucks with a 100 kilograms capacity. Finished batteries are shipped to distribution centers in large trucks with a 150 kilograms capacity. The final delivery to customers is assumed to follows a less-than-truckload (LTL) transportation policy to optimize distribution efficiency.

The reverse logistics chain includes two collection centers, two recycling centers, and a waste disposal facility. Used batteries collected from customers are sent to recycling centers, where pure lithium is extracted and redirected to production. Non-recyclable waste is transported to the disposal facility. Lithium supply is primarily sourced from a key supplier and supplemented by the two recycling centers. An (s, S) inventory control policy is applied across all facilities except distributors, which use Material Requirements Planning (MRP) based on customer demand forecasts.

A major challenge in this process is the fire hazard posed by lithium batteries at recycling centers, which can significantly disrupt operations. To mitigate risks, supply chain managers seek recovery strategies that are economically viable, environmentally sustainable, resilient, and responsive. This study defines, analyzes, and compares various recovery scenarios using anyLogistix 3.0.1, a simulation and optimization software designed for supply chain management [11]. One of its key features is the ability to model risks as discrete events and conduct comparative experiments to evaluate the performance of different resilience strategies. The details of the supply chain facilities are described in Figure 2.

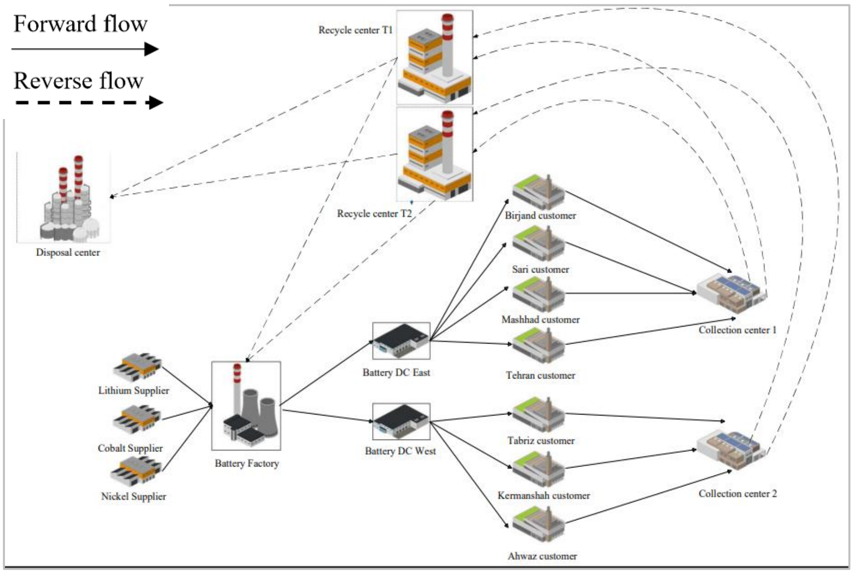

Figure 1. Overview of the supply chain case study network structure

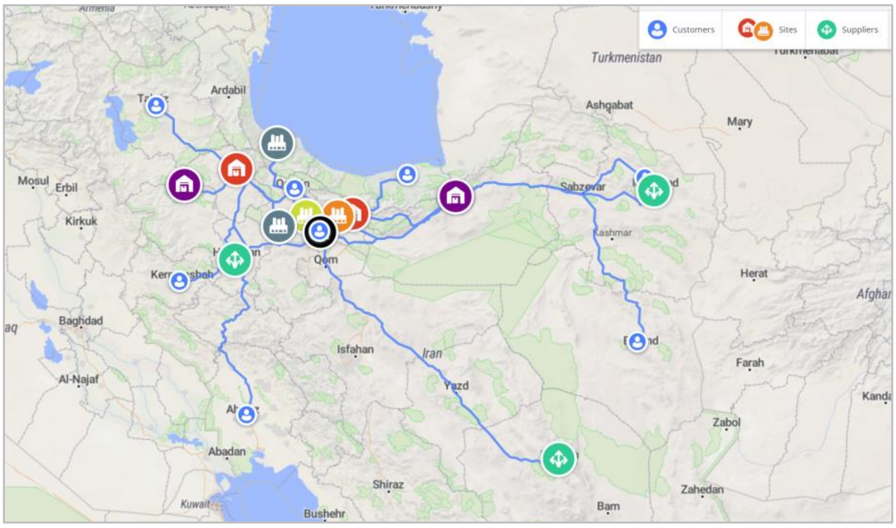

Figure 2. Location of facilities

2.1. Simulation model input parameters and assumptions

This section presents the input parameters of the simulation model, and the key assumptions as follows:

2.1.1 Demand

Table 1 presents the details of customer-related parameters. Customer demand follows a uniform distribution and occurs on a weekly basis.

Table 1. Demand table

Customer	location	product	Parameters	Revenue ($)	Lead time (day)
Customer 01	Tehran	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5
Customer 02	Tabriz	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5
Customer 03	Birjand	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5
Customer 04	Sari	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5
Customer 05	Kermanshah	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5
Customer 06	Ahwaz	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5
Customer 07	Mashhad	Lithium Battery	Order interval: 7, Quantity: Uniform(35;45), First occurrence: First day	50	5

2.1.2 Paths

The simulated supply chain includes eighteen routes. There are three routes from suppliers to the factory, two from the factory to the west and east distribution centers, and seven from distribution centers to customers. Additionally, there are two routes from collection centers to recycling centers, two from recycling centers to the battery manufacturing plant, and two from recycling centers to the disposal center, as shown in Figure 2. The transportation cost is $0.2 per kilometer, and vehicles produce 1 unit of CO_2 per kilometer. The GIS capabilities of anyLogistix software are utilized to accurately calculate transportation costs and transit times.

2.1.3 Production and Bills of Materials

Table 2 presents the details of production rates. The details of Bills of Materials (BOMs) are provided in Appendix A.

Table 2. Production-related parameters

Site	Product	Production rate (minutes)	Production cost ($)
Battery Factory	Lithium Battery	30	4
Recycle center T1	Lithium	60	10
Recycle center T2	Lithium	60	10

2.1.4 Inventories

This supply chain operates under an (s, S) inventory control policy at all facilities, except for the East and West distribution centers according to Table 3. In this policy, s represents the reorder point, while S denotes the maximum inventory level to which stock is replenished when orders are placed. For the East and West distribution centers, Material Requirements Planning (MRP) is used instead. This approach orders the required number of batteries based on demand forecasts, optimizing inventory costs and reducing excess stock. The specific details of the MRP policy are provided in Appendix B.

Table 3. Inventory policies and parameters

Facility	Product	Inventory policy	Parameters
Battery Factory	Nickel	Min Max (s,S)	s=150, S=250
Disposal center	Trash	Min Max (s,S)	s=130, S=300
Disposal center	Dispose	Min Max (s,S)	s=400, S=700
Recycle center 2	Recycle Battery	Min Max (s,S)	s=150, S=250
Recycle center 2	Lithium	Min Max (s,S)	s=150, S=250
Recycle center 2	Trash	Min Max (s,S)	s=150, S=200
Recycle center 1	Recycle Battery	Min Max (s,S)	s=150, S=250
Recycle center 1	Lithium	Min Max (s,S)	s=150, S=250
Recycle center 1	Trash	Min Max (s,S)	s=150, S=250
Battery Factory	Lithium	Min Max (s,S)	s=250, S=350

Battery Factory	Cobalt	Min Max (s,S)	s=150, S=250
Battery Factory	Lithium Battery	Min Max (s,S)	s=350, S=550
Collection center 1	Used Lithium Battery	Min Max (s,S)	s=200, S=300
Collection center 2	Used Lithium Battery	Min Max (s,S)	s=150, S=250
Battery DC East	Lithium Battery	MRP	Appendix B
Battery DC West	Lithium Battery	MRP	Appendix B

2.3 Simulation scenarios

If a disruption occurs at one of the recycling centers, the supply of lithium for battery production will be affected, potentially leading to production delays and supply chain inefficiencies. To address this challenge, we define and compare five different scenarios, including three resilience strategies designed to mitigate the negative impact of disruptions. These strategies aim to enhance supply chain stability by ensuring a continuous lithium supply and minimizing operational risks. The details of these scenarios are outlined in the following subsection.

2.3.1. Business as usual scenario

In this scenario, the simulation runs using all previously defined data, serving as a baseline for comparison. The model operates from January 1, 2024, to December 31, 2025, representing normal supply chain conditions without disruptions. This scenario is essential for validating the effectiveness of recovery policies by providing a benchmark for performance assessment. By comparing the results of disruption scenarios against this baseline, we can evaluate the impact of resilience strategies on profitability, service level, and environmental sustainability.

2.3.2. Disruption with no recovery policy scenario

In this scenario, a disruption occurs at Recycling Center 1 starting at the beginning of the third month and persists until the end of the simulation period. No recovery strategies are implemented, allowing us to observe the full impact of disruption on lithium supply, production continuity, and overall supply chain performance. This scenario serves as a benchmark to assess the effectiveness of resilience strategies by highlighting operational, financial, and environmental consequences in the absence of mitigation measures.

2.3.3. Reconstruction scenario

In this scenario, a disruption occurs at Recycling Center 1 at the beginning of the third month and lasts until the facility is fully restored. Reconstruction is carried out at a fixed cost and takes five months to complete. Once the renovation is finished, the recycling process resumes at the center, restoring lithium recovery and supply chain stability. This scenario evaluates the financial, operational, and environmental trade-offs of investing in reconstruction as a resilience strategy. The results, including total recovery time, cost implications, and impact on supply chain performance, are analyzed and compared to other recovery strategies.

2.3.4. Capacity expansion scenario

In this scenario, a disruption occurs at Recycling Center 1 at the beginning of the third month. To compensate for the lost capacity, the processing capability of Recycling Center 2 is immediately increased by 50% for each product. Since Recycling Center 2 remains operational, this expansion helps sustain lithium recovery and maintain supply chain continuity. This strategy assesses the feasibility of leveraging existing infrastructure to absorb disruptions while avoiding the costs and delays associated with reconstruction. The results evaluate the impact on processing efficiency, supply chain responsiveness, operational costs, and environmental performance compared to other recovery strategies.

2.3.5. Backup supplier scenario

In this scenario, a disruption occurs at Recycling Center 1 at the beginning of the third month, prompting the activation of a backup lithium supplier in China. To ensure a continuous supply, lithium is transported by air cargo using 500 Kilograms capacity aircraft under a Full Truckload (FTL) shipment policy. To optimize transportation costs and reduce customs tariffs, the FTL regulation is enforced with a minimum capacity utilization threshold of 90%. This ensures that shipments are cost-effective while maintaining a stable lithium supply for battery production. This strategy examines the trade-offs between supply chain resilience, cost efficiency, and environmental impact, as air transport significantly increases operational expenses and CO_2 emissions. The results assess the feasibility of international sourcing as a contingency measure compared to other recovery strategies.

3. Results and discussion

Identifying the appropriate key performance indicators is essential for evaluating business performance and making data-driven decisions [12], [13]. This study assesses the effectiveness of different recovery scenarios using a set of performance indicators that capture financial, operational, and environmental aspects. The evaluation considers profit, inventory levels, service level, expected lead time service level, and total CO_2 emissions. Each KPI is analysed in its respective section to provide a detailed understanding of how different recovery strategies impact supply chain resilience, efficiency, and sustainability.

3.1. Profit analysis

Table 4 shows the comparison experiment results of overall supply chain profit. The simulation results reveal that disruptions in the reverse supply chain significantly impact profitability. In the no recovery scenario, where no resilience strategy is applied, total profit declines by 46%, dropping from $552,483.86 to $297,803.57. This severe loss highlights the critical need for implementing recovery strategies to mitigate financial risks. Among the resilient recovery strategies, the reconstruction scenario proves to be the most effective in preserving profitability. By restoring operations with minimal adjustments, it recovers 45% of the lost profit, resulting in a total profit of $544,424.26, just 1% below the business-as-usual scenario. This suggests that rebuilding the affected facility is a cost-effective approach that minimizes long-term financial losses.

The capacity expansion scenario, where the processing capacity of the unaffected recycling center is increased by 50%, recovers 36% of the lost profit, bringing total earnings to $498,930.50. While this approach offers a faster response compared to reconstruction, the additional investment in expansion and operational adjustments results in a 10% overall profit reduction compared to the normal state. The backup supplier scenario, which involves sourcing lithium from China and using air transport, recovers 32% of the lost profit, with total earnings reaching $474,611.88. However, this approach incurs higher transportation and customs costs, leading to the lowest profitability among the resilience strategies, with a 14% reduction compared to business as usual. Despite its lower profit retention, this scenario provides a rapid solution for supply chain disruptions, making it a viable option when immediate recovery is prioritized over cost efficiency.

Overall, the results indicate that reconstruction is the most effective strategy for preserving profitability, given its low cost and strong recovery performance. Capacity expansion also offers a viable alternative, especially when reconstruction is not feasible in the short term. The backup supplier approach, while effective in maintaining operations, comes with significant financial and environmental trade-offs due to the reliance on air transport.

Table 4. Profit comparison analyses details.

Scenarios	**Value ($)**	**Difference (%)**
Business as usual	552,483.86	0%
No recovery	297,803.57	-46%
Resilient scenario 1- Reconstruction	544,424.26	-1%
Resilient scenario 2- Capacity expansion	498,930.50	-10%
Resilient scenario 3- Backup supplier	474,611.88	-14%

3.2. ***Available inventory analysis***

This section looks at the availability of lithium batteries in business as usual and No Recovery, Reconstruction, Capacity expansion, and Backup Supplier scenarios. According to the figure, it can be seen that in the business as usual scenario (blue line), there is a standard level of inventory, and in the No Recovery scenario (green line), the available inventory decreases sharply during a disruption. In the reconstruction scenario (purple line), the available inventory also decreases when a disruption occurs, and after repair, the inventory in the supply chain increases. However, in the second scenario (pink line), which is capacity expansion, the available inventory in the supply chain seeks to maintain more goods than in the other scenarios due to the increase in capacity. The last scenario (red line), which is the backup supplier, seeks to receive lithium from China when a fire occurs in the recycling center. It increases lithium battery storage according to customs tariffs and figure 3. shows this section.

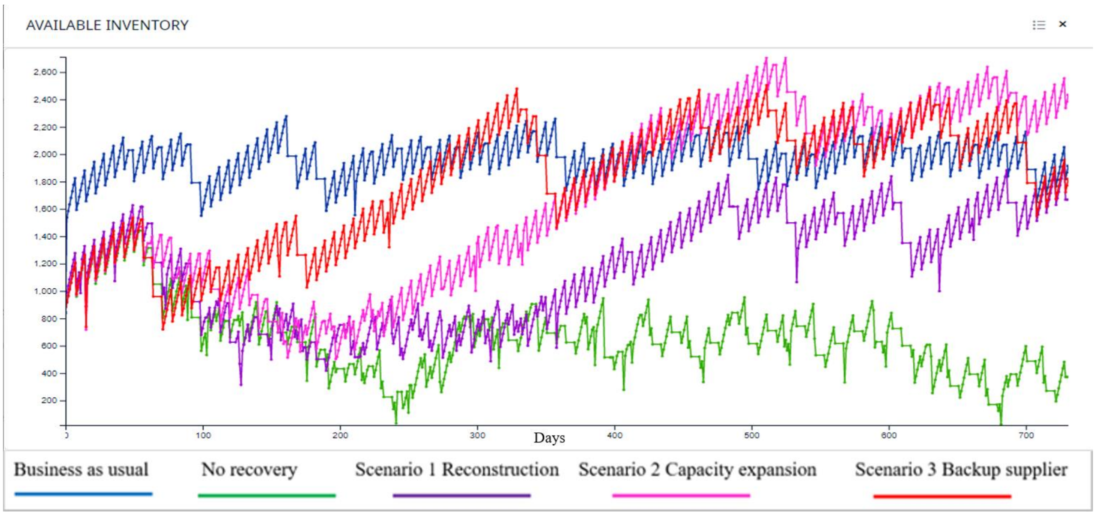

Figure 3. Available inventory graph

3.3. *Service level and ELT Service level analysis*

Figure 4 shows the supply chain demand responsiveness for each scenario. Accordingly, the Business-as-Usual and Backup Supplier scenarios maintain a 100% service level throughout the simulation, demonstrating either uninterrupted operations or successful mitigation through strategic reliance on an external supplier. The Backup Supplier scenario highlights the role of global supplier diversification in ensuring supply chain continuity despite disruptions. In contrast, the No Recovery scenario experiences a steep decline to 55%, exposing severe operational vulnerabilities when no resilience strategies are in place. This scenario underscores the urgent need for contingency planning, as the disruption significantly deteriorates service levels over time.

Intermediate strategies offer varying degrees of resilience. The Reconstruction and Capacity Expansion scenarios achieve service levels between 65% and 95%, indicating partial mitigation of disruptions. These approaches demonstrate that investing in infrastructure restoration or capacity upgrades can significantly improve supply chain performance, though they may require longer recovery times or additional operational costs. The ELT service level trends mirror these findings, reinforcing the importance of hybrid resilience strategies that combine capacity expansion, supplier diversification, and infrastructure recovery to safeguard lithium battery supply chains against disruptions.

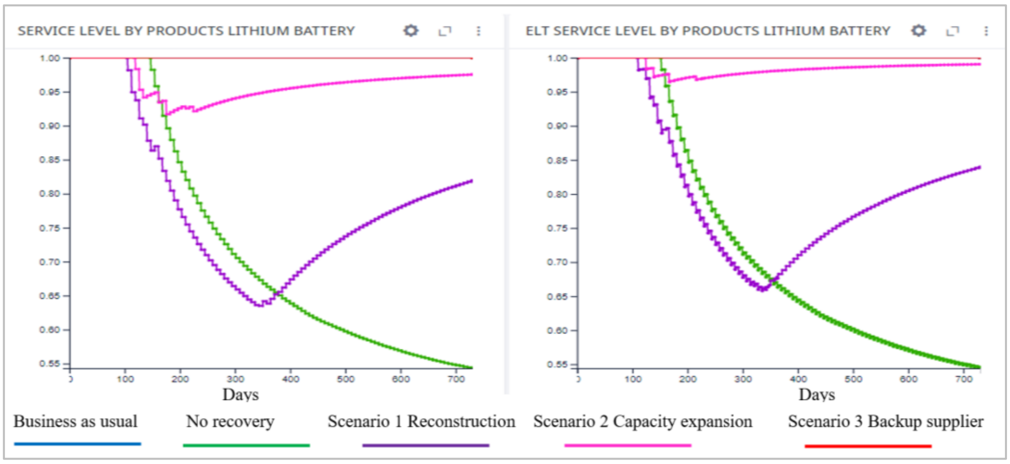

Figure 4. Service level and ELT service level comparisons

3.4. *CO_2 emission analysis*

Figure 5 shows the amount of CO_2 emitted for each scenario. Accordingly, the simulation results reveal significant differences in total CO_2 emissions across the scenarios, highlighting the environmental trade-offs of various resilience strategies. The Backup Supplier scenario generates the highest emissions, surpassing all other strategies. This is primarily due to the reliance on air transportation for lithium shipments from China to Iran, which significantly increases the supply chain's carbon footprint. While this approach ensures uninterrupted production and high service levels, it comes at a considerable environmental cost. In contrast, the Business-as-Usual scenario maintains moderate CO_2

emissions, as it operates without disruptions or the need for high-emission recovery actions. The No Recovery scenario results in similar emissions since production is heavily restricted due to the disruption, reducing overall transportation and processing activities.

The Reconstruction and Capacity Expansion scenarios exhibit higher emissions than the No Recovery scenario but significantly lower than the Backup Supplier approach. Reconstruction involves infrastructure repairs and resumes operations at the original facility, contributing to a controlled increase in emissions. Capacity expansion leads to additional energy and resource consumption at the operational recycling center, but without the extreme CO_2 burden of air transport. These results emphasize the need for sustainable resilience planning. While outsourcing lithium supply mitigates operational risks, its environmental impact underscores the importance of alternative strategies such as local supplier diversification, improved logistics efficiency, and investments in lower-emission transport options. Future resilience strategies must balance environmental sustainability with operational continuity to ensure a more sustainable and resilient closed-loop lithium battery supply chain.

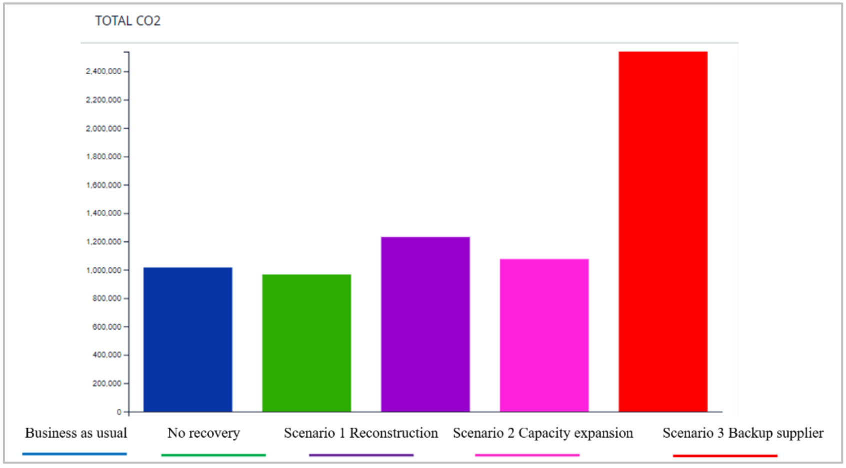

Figure 5. Comparison experiment for CO_2 emission

4. Managerial Insights

This study underscores the critical need for resilient supply chain strategies in lithium-ion battery recycling centers, particularly in response to disruptions such as fires. By simulating multiple resilience strategies, the findings reveal that rebuilding a damaged facility, expanding the capacity of an operational recycling center, or sourcing lithium from a foreign supplier can all serve as viable recovery approaches. The results highlight key trade-offs between financial recovery, operational continuity, and environmental sustainability. While capacity expansion and outsourcing help mitigate profit losses and sustain service levels, they significantly increase carbon emissions due to additional transportation requirements. In contrast, rebuilding disrupted facilities offers a cost-effective and sustainable solution, ensuring long-term resilience without the high environmental costs associated with air transport.

Managers should adopt a flexible, hybrid approach to supply chain resilience, integrating local recovery strategies with diversified sourcing options to reduce vulnerability while maintaining environmental responsibility. The study also suggests that evaluating alternative transportation modes for backup supplier policies can reduce emissions and operational costs while preserving supply chain flexibility [12], [13]. Furthermore, the use of advanced simulation tools like anyLogistix is essential for decision-making. By leveraging scenario-based analysis, organizations can anticipate potential disruptions, optimize recovery strategies, and balance profitability, service performance, and sustainability in lithium battery recycling supply chains.

5. Conclusion

This study provides a detailed analysis of resilience strategies to mitigate disruptions, such as fires, in the closed-loop supply chain for lithium-ion batteries. By evaluating three approaches including rebuilding a damaged facility, increasing the capacity of an operational recycling center, and sourcing lithium from a foreign supplier, the results show that reconstruction is the most cost-effective strategy for minimizing disruptions while maintaining profitability. The findings also highlight the environmental impact of different recovery strategies. Outsourcing lithium supply through air transport increases CO_2 emissions, making it the least sustainable option. In contrast, expanding local recycling capacity offers a more balanced approach by reducing reliance on high-emission transportation while maintaining supply chain stability. This study reinforces the need for flexibility, sustainability, and risk management in supply chain planning to ensure operational efficiency without compromising environmental responsibility. Future research can explore the application of these resilience strategies in other industries, such as electronic waste management and high-risk manufacturing. Investigating the use of technologies like blockchain and the Internet of Things could enhance real-time risk monitoring and improve adaptability in supply chains. Additionally, further studies can apply multi-attribute and multi-objective decision-making tools to better evaluate financial and environmental trade-offs, enriching the insights gained from discrete event simulation.

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Appendix A. BOM

Table 5. BOM details

BOM	*End product (ratio)*	*Components (ratio)*

BOM 01	Lithium Battery (1)	Cobalt (0.25)-Lithium (0.5)-Nickel (0.25)
BOM 02	Lithium (0.5)	Recycle Battery (1)

Appendix B. MRP inventory parameters

Table 6. MRP policy for Battery DCs West and East

Distribution center	***Days for report creation***	***Min order quntity***	***Mult order quantity***	***Max order qunatity***	***Period of supply***	***Aggreation period, days***	***Expected lead time***	***Safety stuck quantity***
East	7	450	200	700	7	10	7	800
West	7	200	100	450	7	10	7	450

Table 7. Demand forcast

Facility	***Product***	***Type***	***Parameters***
Battery DC East Battery DC West	Lithium Battery	Periodic demand	Order interval: 7, Quantity: 40, First occurrence: First day