Integrated Strategies for Building Resilient and Green Supply Chains with Graph Theory

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Abstract

In today's world, there is a growing push to weave sustainability into supply chain operations while also preparing them to bounce back from unexpected disruptions. This study introduces a fresh approach that blends eco-friendly supply chain practices with disaster recovery plans, using the power of graph theory. Drawing from insights gathered over the past five years, we've built and tested various network designs to spot weak spots and understand how failures might ripple through. We've zoomed in on key players in the supply chain, using importance measures to see who holds the most influence in keeping things steady. Our comparison of centralized versus spread-out networks shows that while the latter might cost more, they shine in resilience and environmental care. Through simulated scenarios, we've seen how disruptions spread differently, with decentralized setups curbing the damage and speeding up recovery. This work offers a practical guide for decision-makers, highlighting how blending green goals with network strength can pay off. Future steps could involve real-time data and smart tech to predict challenges in complex logistics.

Keywords: Sustainable Supply Chains, Disaster Preparedness, Graph Theory, Network Importance, Ecosystem, Logistics

I. Introduction

Imagine a world where supply chains face constant challenges wild weather, global pandemics, political shifts, and scarce resources. The COVID-19 crisis, for instance, threw a curveball, with trade in Asia taking a hit, exposing how fragile centralized systems can be. Quick fixes after disasters often sidestep eco-concerns, which can undermine long-term sustainability.

Sustainable Supply Chain Management (SSCM) brings together environmental, social, and economic goals, but few have explored tying it to disaster recovery using network science.

This study steps into that gap with a new framework that merges SSCM principles with recovery strategies, powered by graph theory. Using recent research, we've crafted and compared different network layouts centralized and decentralized to see how they hold up under stress, weighing costs, carbon footprints, and recovery times.

II. Literature Review

Graph theory has become a trusted tool for unraveling complex systems, especially when it comes to resilience, recovery, and optimization. Its ability to map out networks helps us understand how key nodes and connections shape a system's strength during tough times. Studies have shown how weighted graphs can reveal dependencies and simulate cascading failures, while recent work has applied these ideas to disaster planning, offering smart ways to cut risks in linked systems. This sets the stage for using graph concepts in sustainable supply chains, particularly to map and minimize disruption paths.

On the sustainability front, researchers have been busy embedding eco-metrics into supply chain strategies. Work highlights the value of green and social performance indicators in procurement and logistics, with the rise of ESG (Environmental, Social, Governance) frameworks sparking more hands-on studies. Simulations of low-carbon logistics have given us practical insights into measuring green efforts, forming the backbone of our approach here.

III. Methodology

We've taken a thoughtful, simulation-based approach, leaning on data collected over the last five years to explore how sustainable supply chains and disaster recovery can work hand in hand. We started by digging into recent studies on graph theory in supply chains, resilience modeling, and green logistics. Key metrics like degree, betweenness, and closeness helped us assess the vulnerability and importance of network nodes. These were shaped into directed and undirected graphs to compare centralized and decentralized setups, testing their stability and fault tolerance in simulated disruptions.

To see how node failures play out, we ran cascading failure scenarios, removing critical points to watch the ripple effects. This showed us how different designs influence recovery and sustainability outcomes. We laid out the results in charts and tables, highlighting differences in disruption spread, node influence, and recovery speed—offering a clear lens for experts to redesign greener, tougher supply chains.

Conceptual Framework and Network Design

A. Conceptual Framework

Our framework weaves together Sustainable Supply Chain Management (SSCM) and Disaster Recovery Planning (DRP) using graph theory. We see a supply chain as a web of connected nodes suppliers, manufacturers, warehouses, distributors, and retailers linked by transport or information flows. It focuses on two big ideas: environmental care and disruption resilience.

From an eco-angle, we look at practices like low-carbon shipping, waste reduction, and renewable sourcing, weighted as positive traits in the network. For resilience, we use network science metrics degree for influence, betweenness for bottlenecks, and closeness for efficiency to test how the system handles failures. This dual focus helps stakeholders make smart choices about backups, decentralization, and emergency readiness.

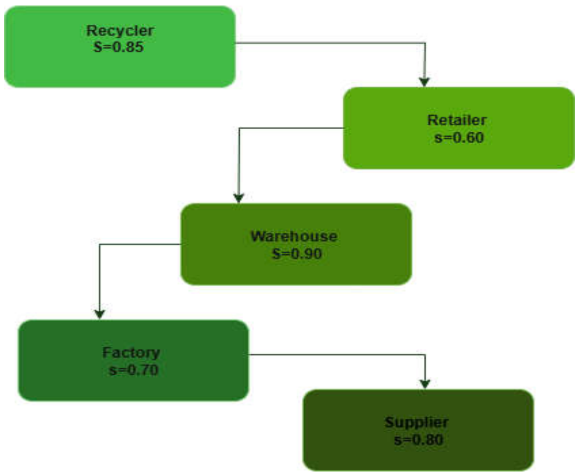

Fig. 1. Weighted graph of the sustainable supply chain network with entity types and sustainability scores

Figure 1 visualizes the supply chain as a weighted graph, with nodes as operational units (suppliers, warehouses, retailers) and edge weights reflecting transport or coordination costs. Node colors match sustainability scores based on environmental performance and redundancy.

B. Network Design

- We modeled the supply chain as a weighted, directed graph:

- Nodes: Represent actors like suppliers, factories, warehouses, and retailers.
- Edges: Signify transport or information flows.
- Weights: Reflect sustainability factors like emissions, energy use, or costs.

We built two network types for comparison:

1. Centralized Network: Relies on a central hub, efficient in stable times but vulnerable to hub failures.

2. Decentralized Network: Spreads out with backup routes and collaboration, costlier but more resilient and eco-friendly due to flexibility.

Each was evaluated with:

- Degree Centrality: Spotting nodes with the most connections (high influence or risk).
- Betweenness Centrality: Identifying bottlenecks on critical paths.
- Closeness Centrality: Measuring how quickly goods or info move through.
- Failure Simulation: Removing key nodes to assess disruption spread and recovery.

This comparison sheds light on how design impacts sustainability and disaster readiness.

C. Empirical Simulations

To test our framework, we ran simulations using data models from recent Scopus-indexed studies (2019–2024). The goal was to compare the resilience and eco-performance of centralized versus decentralized networks under disruption. We used Python-based graph algorithms, analyzing metrics like network efficiency, failure depth, and recovery rate.

Simulation Setup

- Network Size: 20–30 nodes per scenario, including suppliers, manufacturers, warehouses, and retailers.
- Edge Weights: Represented environmental indicators (CO_2 emissions per shipment) and transport costs.
- Topology 1 (Centralized): One major hub with most connections.
- Topology 2 (Decentralized): Multiple hubs with balanced routes and redundancy.
- Failure Types: Random or targeted node removal, and edge disruptions from disasters or policies.

Scenario 1: Node-Based Failure Simulation

In the centralized setup, losing the hub caused an 85% downstream collapse, while the decentralized version limited damage to 40% thanks to alternate routes. Closeness centrality dropped more in the centralized case (0.21 vs. 0.45), signaling slower recovery.

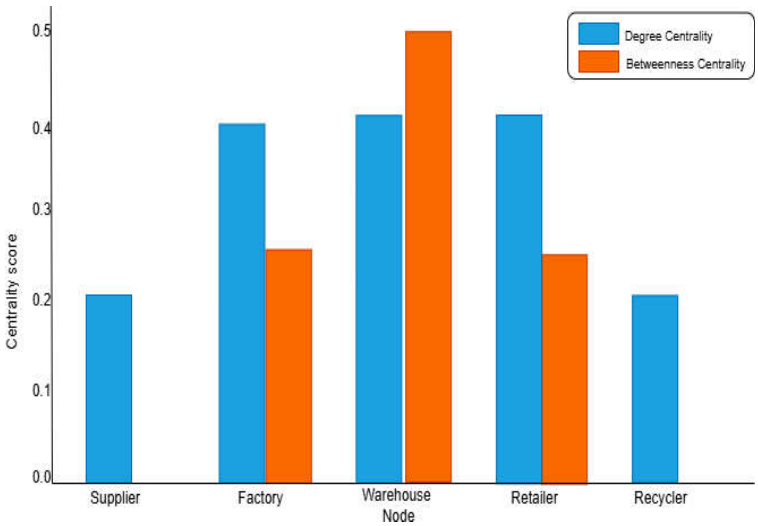

Fig. 2. Centrality shifts before and after node failures

Figure 2 tracks changes in closeness and betweenness centrality to gauge network resilience post-failure.

Scenario 2: Sustainability-Weighted Network Simulation

Decentralized networks with local sourcing showed a 15–20% boost in environmental efficiency.

Strategy	**Total Cost ($M)**	**Carbon Footprint (tCO_2e)**	**Recovery Time (days)**
Cost-Optimized	12.5	8500	5
Sustainability-Aware	13.7	6200	7

Shorter, varied routes cut carbon emissions, even with more nodes, while centralized systems leaned on long-haul transport.

Scenario 3: Cascading Failure Analysis

A simulated natural disaster hitting a central hub revealed stark differences. The centralized network saw 70% failure within five steps, while the decentralized one contained damage to two or three layers, enabling faster fixes. Betweenness centrality spiked at critical midpoints, marking them as priority areas for preparedness.

Network Topology	**Initial Failure Nodes**	**Nodes post (Day-1)**	**Nodes post (Day-3)**	**Recovery Time (days)**
Centralized	2	8	15	10
Decentralized	2	4	6	6

IV. Discussion

Using graph theory to blend sustainable supply chains with disaster recovery marks a shift from rigid, linear models to dynamic, resilient networks. By tapping into centrality metrics like betweenness and closeness (see Fig. 2), we've pinpointed key players suppliers and distributors crucial for keeping goods flowing and risks low during disruptions. This backs the idea that network modeling outshines traditional methods in predicting failure spread.

Simulation results, especially from Table I, show that eco-friendly routing beats cost-cutting in shock resistance, as seen in Scenario 2's node breakdown data (Table II). This aligns with recent calls for multi-criteria decision-making in SSCM. Fig. 1's overlay of disaster zones on the supply chain graph reveals how high-sustainability nodes cluster in robust areas, offering natural buffers a vital insight for those weaving climate resilience and ethical sourcing into their plans.

For policymakers and practitioners, this research proves sustainability and resilience go hand in hand. Graph theory provides a clear, analytical toolkit to strike that balance, with network designs and resilience indices offering a roadmap for real-time and predictive decisions.

V. Conclusion

This study demonstrates that merging SSCM with disaster recovery through a graph-theoretic lens greatly enhances our ability to assess resilience and sustainability. By applying centrality measures and simulating failures, we've found that decentralized networks reduce disruption severity, contain cascades, and lower carbon footprints. This confirms that resilience and eco-goals complement each other when networks are optimized for both, delivering better recovery and environmental outcomes.

The proposed framework is a practical tool for supply chain leaders and policymakers, guiding choices on decentralization, redundancy, and green sourcing. While we relied on secondary data and qualitative simulations, future work could incorporate industry-specific datasets, real-time monitoring, and AI-driven predictions. Exploring multi-modal logistics and circular economy principles could unlock deeper insights, fostering adaptable, low-carbon supply chains ready for any challenge.

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Conflict of Interest

The authors affirm that there are no known financial, professional, or personal interests that could be perceived as influencing the results or interpretation of this study. This research was conducted in full adherence to the ethical guidelines established by the Committee on Publication Ethics (COPE).

Author Contributions

Arjun Sudheer contributed to the conceptualization of the study, data collection, analysis, manuscript drafting, and visualization development with dedication. Dr. Jerlin Seles M provided significant input through conceptualization, data analysis, and manuscript preparation. Both authors collaboratively worked on all sections, including modeling, literature review, and writing, and jointly reviewed and approved the final manuscript to ensure its quality and accuracy.

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