An Integrated Framework for Network-Wide Assessment and Improvement of Supply Chain Resilience

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1 INTRODUCTION

This paper presents an integrated framework for assessing and enhancing structural resilience in supply chains, with an emphasis on ensuring continuity and adaptability of material flows. The increasing interconnectedness of global supply chains has heightened their susceptibility to cascading disruptions, triggered by events such as natural disasters and geopolitical tensions. This interdependence complicates the identification of potential vulnerabilities, which, if not addressed, may escalate into severe, system-wide impacts. For instance, the 2011 Japan tsunami led to substantial shortages that were exacerbated by subsequent flooding in Thailand, severely disrupting the automotive industry (Park *et al.*, 2013, Haraguchi & Lall, 2015).

Structural resilience in supply chains necessitates strategic, long-term planning to strengthen the network's ability to withstand and absorb disruptions, thereby sustaining operations during unexpected events (Wieland & Durach, 2021, Kamalahmadi & Parast, 2016). This resilience is composed of three core components: (1) identification of potential disruption pathways across the network; (2) assessment of the network's capability to endure and recover from disruptions; and (3) targeted improvements, incorporating strategies such as fortification and flexibility to strengthen critical points within the supply chain.

Current research on supply chain resilience primarily divides into two main streams. The first stream investigates resilience by analyzing network characteristics, such as centrality and topology, or through stress-testing under various disruption scenarios (e.g., Kim *et al.* (2011), Bode & Wagner (2015), Hearnshaw & Wilson (2013)). While these studies provide valuable insights into the structural properties of supply chains, they often fall short in offering specific guidance for actionable resilience improvements.

The second stream of research focuses on fortification strategies, primarily employing redundancy and flexibility to improve supply chain resilience. Redundancy includes resources such as backup suppliers, safety stock, or alternative logistics routes, whereas flexibility enables adaptable responses, such as production reconfiguration in response to disruptions (Tang, 2006).

Nevertheless, this second stream predominantly addresses demand-side variability and often employs a predict-then-optimize approach, which has limitations when applied to supply-side disruptions. First, these models typically assume that fortifications remain unaffected by disruptions, an assumption that does not hold in practice. Second, supply-side disruptions can propagate through production chains, leading to systemic shocks that are difficult to predict. Third, scenario-based planning for supply-side disruptions faces substantial challenges, notably the curse of dimensionality, which complicates the assessment of potential risks across diverse scenarios. Fourth, over-fortifying against specific scenarios may inadvertently shift vulnerabilities to other parts of the supply chain, yielding limited resilience benefits. Compounding these challenges are the high costs and long-term commitments associated with fortification strategies, which require careful consideration. Unlike existing studies that generally treat disruption scenarios as fixed and independent of improvement decisions, we consider scenarios as endogenous, adapting to reflect the network's interdependencies.

In this study, we address supply chain resilience by treating disruptions as endogenous factors that dynamically interact with network structure. Our model optimizes resilience assessment and improvement across the entire production chain, enabling detailed analysis of network topology, identification of critical points, and estimation of cascading disruption effects. We formulate this problem as a three-level game within a mixed-integer optimization framework and employ a decomposition approach to solve it efficiently. Our resilience strategies focus on redundancy—ensuring backup resources—and flexibility, which enables adaptive responses to disruptions, collectively strengthening the continuity and robustness of the supply chain.

We validate our approach through two case studies. The first case examines a steel supply chain, demonstrating a 30% resilience improvement through the implementation of alternative production pathways. The second case addresses an expanding pharmaceutical supply chain impacted by climate-related disruptions, where we assess climate risks and evaluate targeted resilience strategies across various disruption scenarios.

2 Model Description

We consider a multi-stage supply chain composed of four main stages: *suppliers* ($\mathcal{S}$) for raw materials, *producers* ($\mathcal{P}$) for manufacturing, *warehouses* ($\mathcal{W}$) for storage and distribution, and *end-users* ($\mathcal{C}$) who receive the final products. Each stage manages a variety of commodities, represented within a multi-commodity network flow as a graph $G = \{V, E\}$, where V denotes nodes (supply chain locations and stages), and E denotes arcs (transportation links and commodity flows).

Supply Chain Operations: We model operations as a multi-commodity flow across two interconnected graphs: a production process graph, $\tilde{G}$, and a physical distribution network, $\bar{G}$. The production process, represented by $\tilde{G}$, includes nodes corresponding to key production stages—such as raw material entry, storage, and final delivery—and links these to physical locations in $\bar{G}$, where commodities move through suppliers, producers, warehouses, and end-users. This dual-graph structure simulates both material flows and transformations across the network, providing a comprehensive framework for assessing the impact of disruptions.

Disruptions: Disruptions are modeled as shocks that reduce operational capacity in parts of the network, impacting facilities, transportation links, or production capacities. To identify potential disruption scenarios, we introduce a hypothetical adversarial agent that seeks to maximize network damage within a defined budget. This approach enables us to pinpoint vulnerabilities and critical nodes, effectively simulating the cascading effects that disruptions might induce across the network.

Resilient Design and Recovery: Resilience strategies, such as introducing redundancy (e.g., additional suppliers or storage facilities) and enhancing production flexibility, are implemented within a resilience budget to restore functionality after disruptions. These strategies support operational continuity by adapting to changes in network conditions, thereby mitigating the impact of disruptions on overall supply chain performance.

Optimization Framework: The model is structured as a tri-level optimization problem involving three agents: the Operator ($\mathcal{O}$), the Disruptor ($\mathcal{D}$), and the Resilience Designer ($\mathcal{R}$). Each agent has specific objectives: the Operator minimizes operational costs while meeting demand; the Disruptor, constrained by a disruption budget $\beta^{\mathcal{D}}$, maximizes the impact of disruptions; and the Resilience Designer allocates resources, within a resilience budget $\beta^{\mathcal{R}}$, to minimize the effects of disruptions. Ultimately, the model seeks to optimize the Operator's performance cost $\Gamma^{\mathcal{O}}$, accounting for the combined impact of disruptions and resilience strategies under budgetary and operational constraints.

3 Resolution Approach

To solve the tri-level optimization problem, we apply a decomposition approach that splits the $\mathcal{ODR}$ model into a single-level master problem ($\mathcal{ODR}$-Master) to establish a lower bound, and a bi-level disruptor sub-problem ($\mathcal{ODR}$-Sub) to determine an upper bound. This decomposition simplifies the complex hierarchical structure into two more manageable, interacting problems.

In each stage of the decomposition, the $\mathcal{ODR}$-Master problem seeks the optimal resilience design under specific disruption scenarios, while the $\mathcal{ODR}$-Sub problem identifies the worst-case disruptions for a given design. This iterative process refines the system design by alternating between enhancing the resilience design (in the master problem) and stress-testing it (in the sub-problem) against the most impactful disruption scenarios.

The algorithm progresses by iteratively updating the solution bounds and refining the design until a convergence criterion is met. This approach enhances computational tractability and ensures that the final solution captures both optimal resilience design and effective disruption response. At termination, the model outputs an optimized set of decisions for resilience, disruption, and operations, providing a robust solution that balances fortification strategies with operational costs.

4 Results

4.1 Computational Performance

We evaluated the computational performance of the proposed decomposition approach using multiple instances, varying in production complexity (from simple single-step processes to complex networks) and network size (small, medium, large). Key attributes include the number of suppliers, producers, warehouses, and production stages. The model demonstrated strong scalability, efficiently solving the majority of instances within a 90-minute time limit. For small and medium networks, solution times were typically under 10 seconds with minimal optimality gaps ($\varepsilon < 10^{-5}$). Larger and more complex instances required more computational resources, with the most challenging scenarios approaching the time limit. Computational time increased with network size, disruption budget, and resilience budget due to the expanded solution space. However, the model remained tractable, even for complex multi-step production chains.

4.2 Production Chain Flexibility and Its Impact on Resilience

We apply our model to evaluate the resilience of a steel manufacturing supply chain under varying levels of production chain and network flexibility. Four instances are defined to represent these configurations. The base case, I_0, models a linear production chain with no physical flexibility, transforming `crude coal` and `crude iron` into `finished goods` along a simple path with 2 suppliers, 4 producers, 10 warehouses, and 100 customers. In I_1, physical network flexibility is introduced, increasing the number of potential facilities to 10 suppliers, 16 producers, and 30 warehouses. Instance I_2 incorporates production chain flexibility by adding alternative paths, such as using `iron pellets` and `direct reduced iron` (DRI) as substitutes for `scrap metal` and coal, while the physical network remains the same as in I_0. Finally, I_3 combines both network and production chain flexibility, representing the most resilient scenario.

The effectiveness of each configuration is measured by system performance (percentage of demand met) and resilience score (`R-score`), which quantifies the robustness of each design under varying disruption budgets. Results indicate that increasing the design budget significantly enhances resilience, particularly when both production chain and network flexibility are integrated. For example, without production chain flexibility, resilience improves by 254% at the highest design budget. In contrast, adding production flexibility yields a 30.6% increase in resilience with a moderate budget and up to 284% with the highest budget. These findings underscore the importance of combining both types of flexibility to achieve optimal resilience across supply chain scenarios.

4.3 Strategic Supply Chain Expansion and Resilience Assessment

This section presents a strategic expansion plan for a pharmaceutical company producing `ProductA`, `ProductB`, and `ProductC`, currently marketed in the US and Europe, with growing demand in Latin America, South Africa, and the Asia-Pacific region. The production process spans drug manufacturing, vial filling, and packaging, with supply chain stages including suppliers, four production facilities (located in the US, Belgium, Italy, and Ireland), and warehouses serving 189 demand cities globally. To meet rising demand, the company plans to establish new production sites in Germany, India, Indonesia, Egypt, and Brazil, along with ten additional suppliers and 30 potential warehouse sites.

Modeling Climate-Related Disruptions: Climate hazards and geopolitical risks are incorporated by assigning each facility a risk score that reflects susceptibility to disruptions (e.g., floods, storms, earthquakes). Disruptions are classified from `MINOR` to `FATAL`, with corresponding effects on facility capacity.

Resilience Analysis of the Current Network: Baseline simulations without resilience investments ($\beta^{\mathcal{R}} = 0$) showed that minor disruptions had limited impact, while larger disruptions exposed vulnerabilities, particularly at critical sites in Belgium and the US, underscoring the need for targeted resilience investments.

Expansion and Resilience Investment Plan: The model identifies optimal facility additions across varying budget levels, focusing on cost-effective enhancements, such as adding suppliers at lower budgets and expanding production into South America and Asia at higher budgets. Scenario analyses that vary resilience ($\beta^{\mathcal{R}}$) and disruption ($\beta^{\mathcal{D}}$) budgets indicate that moderate resilience investments (between 1×10^6 and 2×10^7) effectively balance delivery satisfaction and cost, providing stable performance across most disruption scenarios.

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