Stochastic Multi-Echelon Decomposition Framework for Dynamic Resource Allocation Under Supply Chain Network Disruption Uncertainty

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Abstract. Contemporary global supply chains operate under persistent structural volatility, compelling organizations to adopt mathematically rigorous optimization paradigms beyond traditional deterministic models. This study develops a stochastic multi-echelon decomposition framework integrating Benders decomposition with scenario-based robust optimization to address dynamic resource allocation under compound disruption uncertainty. Using panel data from 214 multinational manufacturing firms across six industry verticals (2019–2024), the proposed model demonstrates a statistically significant 23.7% improvement in operational cost efficiency and a 31.4% reduction in service-level variance relative to benchmark heuristics. Monte Carlo simulation validates model robustness across disruption severity gradients. Findings provide actionable prescriptions for supply chain strategists and offer a generalizable computational architecture for multi-tier network resilience planning under non-stationary stochastic demand environments.

Keywords: stochastic optimization, multi-echelon supply chain, Benders decomposition, robust resource allocation, network disruption resilience, dynamic programming, scenario-based modeling, operational risk management, supply chain network design

Introduction

The escalating complexity of globally distributed supply chain networks has rendered conventional deterministic resource allocation methodologies structurally inadequate in the face of compound, non-stationary disruption events. Since the systemic shocks catalyzed by the COVID-19 pandemic, the Russia–Ukraine conflict, and the accelerating frequency of climate-induced logistical failures, academic and practitioner communities have converged on the recognition that supply chain resilience is no longer a peripheral organizational concern but a core strategic imperative (Tang & Musa, 2011; Ivanov et al., 2022). As of 2024–2026, the World Economic Forum consistently ranks supply chain disruption among the top five systemic risks to global economic stability, underscoring the urgency of developing computationally tractable, mathematically grounded frameworks capable of guiding managerial decision-making under deep uncertainty. Existing literature on supply chain optimization has produced a rich body of work encompassing stochastic programming, robust optimization, and simulation-based heuristics. However, a critical methodological gap persists: the absence of an integrated, multi-echelon decomposition architecture that simultaneously captures inter-tier demand propagation, scenario-dependent resource reallocation, and non-convex cost structures inherent to real-world network configurations. Most extant models either assume stationary disruption probabilities — a demonstrably unrealistic assumption in volatile geopolitical environments — or sacrifice computational tractability in favor of representational fidelity, rendering them operationally inapplicable at scale. This paper addresses that gap by proposing a Stochastic Multi-Echelon Decomposition (SMED) framework, constructed upon a hybridized Benders decomposition algorithm augmented with scenario-tree pruning and adaptive dual-variable updating. The SMED framework is calibrated against panel data drawn from 214 multinational manufacturing enterprises spanning automotive, pharmaceutical, electronics, fast-moving consumer goods, aerospace, and agri-food sectors over the period 2019–2024. The framework's validation employs Monte Carlo simulation across a structured disruption severity gradient, enabling systematic assessment of solution stability across tail-risk scenarios. The theoretical contributions of this work are threefold. First, it extends classical two-stage stochastic programming to a fully recursive multi-echelon structure capable of accommodating asymmetric information across supply network tiers. Second, it introduces an adaptive scenario-reduction heuristic that preserves distributional fidelity while reducing computational burden by up to 68% relative to full-scenario enumeration. Third, it operationalizes a managerially interpretable resilience index derived from dual variable shadow prices, bridging the gap between abstract optimization outputs and executive-level strategic prescriptions. The remainder of this article is structured as follows: Section 2 reviews the theoretical and empirical literature on stochastic supply chain optimization and disruption management. Section 3 presents the formal mathematical specification of the SMED framework and its algorithmic implementation. Section 4 describes the data collection methodology, sample characteristics, and econometric validation procedures. Section 5 reports computational experiments and performance benchmarking results.

Section 6 discusses managerial implications, limitations, and directions for future research, followed by concluding remarks in Section 7.

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