Stochastic Multi-Tier Supply Chain Resilience Optimization via Adaptive Dynamic Programming and Bayesian Demand Signal Decomposition

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Abstract. Contemporary global supply chains operate under compounding systemic disruptions, rendering traditional deterministic optimization frameworks structurally inadequate. This study proposes a hybrid stochastic optimization model integrating Adaptive Dynamic Programming (ADP) with Bayesian demand signal decomposition to enhance multi-tier supply chain resilience under uncertainty. Empirical validation is conducted using longitudinal operational datasets from manufacturing firms across three industry verticals over a 48-month horizon. The model demonstrates a statistically significant 23.7% improvement in disruption recovery velocity and a 17.4% reduction in total landed cost variance compared to conventional safety-stock and scenario-planning benchmarks. Furthermore, the framework introduces a novel resilience elasticity coefficient enabling real-time reconfiguration of sourcing node hierarchies. Findings carry substantive implications for operations executives and strategic procurement leaders navigating post-pandemic and geopolitical volatility contexts.

Keywords: supply chain resilience optimization, adaptive dynamic programming, Bayesian demand decomposition, stochastic supply chain modeling, multi-tier procurement networks, disruption recovery velocity, resilience elasticity coefficient, operational risk management, dynamic sourcing reconfiguration

Introduction

The structural fragility of global multi-tier supply chains has emerged as one of the most pressing operational management challenges of the mid-2020s. Successive disruptions — from the COVID-19 pandemic-induced logistics collapse, to the Red Sea shipping corridor instability of 2024, and escalating geopolitical decoupling pressures between major trading blocs — have conclusively demonstrated that legacy supply chain optimization paradigms grounded in deterministic linear programming or static scenario planning are fundamentally ill-equipped to absorb, adapt to, and recover from systemic shocks at scale. The urgency of this problem is underscored by data from the World Economic Forum's 2024 Global Risks Report, which ranked supply chain disruption among the top five most impactful near-term risks to global economic stability, with estimated annual losses to manufacturing sectors exceeding USD 1.8 trillion. Contemporary operations research has explored various probabilistic and simulation-based approaches to supply chain risk mitigation, including Monte Carlo simulation frameworks, robust optimization under interval uncertainty, and agent-based network modeling. However, these methodologies share a critical limitation: they treat disruption as an exogenous shock rather than an endogenously manageable dynamic process. The consequence is a systematic underestimation of the adaptive capacity latent within multi-tier procurement hierarchies when subjected to real-time decision intelligence. This gap constitutes the primary motivating problem of the present study. Adaptive Dynamic Programming (ADP), a class of approximate reinforcement learning-adjacent methods, offers a theoretically compelling mechanism for sequential decision-making under non-stationary stochastic environments. When coupled with Bayesian hierarchical demand signal decomposition — which enables the recursive updating of demand priors across supply tiers in response to incoming market signals — the resulting hybrid framework can operationalize what this paper terms a resilience elasticity coefficient: a quantifiable, tier-sensitive measure of a supply network's capacity to reconfigure sourcing node hierarchies without sustaining prohibitive cost penalties. The present study makes three principal contributions to the business management and operations science literature. First, it formalizes a mathematically rigorous ADP-Bayesian hybrid optimization architecture applicable to multi-tier supply chain topologies. Second, it introduces and empirically validates the resilience elasticity coefficient as a decision-support metric for C-suite and supply chain officers. Third, it benchmarks model performance against established deterministic and stochastic baselines using real-world longitudinal data from diversified manufacturing sectors, offering high external validity. The remainder of this paper is organized as follows. Section 2 provides a critical review of extant supply chain resilience literature and identifies the theoretical gap addressed herein. Section 3 presents the formal mathematical specification of the ADP-Bayesian optimization model. Section 4 describes the empirical dataset, variable operationalization, and estimation methodology. Section 5 reports and interprets quantitative findings, including comparative benchmark analyses. Section 6 discusses managerial implications, model boundary conditions, and directions for future research. Section 7 concludes with synthesized recommendations for practitioners and policymakers operating in high-volatility procurement environments.

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