Stochastic Dynamic Programming Framework for Multi-Echelon Supply Chain Resilience Optimization Under Compound Demand Uncertainty

Nico Roberts
Professor
Technical University of Munich
Arcisstraße 21, 80333 Munich, Bavaria, Germany

Casey Campbell
Associate Professor
Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

Jordan Jones
PhD
Erasmus University Rotterdam
Burgemeester Oudlaan 50, 3062 PA Rotterdam, Netherlands

Ashley Edwards
D.Sc
University of Toronto
27 King's College Circle, Toronto, Ontario M5S 1A1, Canada

Abstract. Contemporary multi-echelon supply chains exhibit compounding vulnerabilities to demand-side stochasticity and systemic disruption cascades, rendering conventional linear optimization paradigms structurally insufficient. This study develops a stochastic dynamic programming (SDP) framework integrating Markov decision processes with robust scenario-tree decomposition to optimize resilience allocation across distributed supply network nodes. Employing a mixed-integer nonlinear programming (MINLP) formulation calibrated against panel data from 214 manufacturing firms across six economies (2019–2023), the model yields Pareto-optimal trade-off frontiers between operational cost minimization and disruption-recovery velocity. Empirical validation demonstrates a 23.4% improvement in mean-time-to-recovery metrics relative to deterministic baseline models. The findings offer prescriptive decision support for supply chain executives navigating post-pandemic structural volatility, geopolitical fragmentation, and nearshoring reconfiguration pressures.

Keywords: stochastic dynamic programming, multi-echelon supply chain resilience, Markov decision process, robust optimization, mixed-integer nonlinear programming, demand uncertainty, disruption recovery, Pareto-optimal frontier, nearshoring reconfiguration

Introduction

Global supply chain architectures have entered an era of structural fragility unprecedented in post-war economic history. The convergence of geopolitical decoupling, climate-induced logistical disruptions, and post-pandemic demand volatility has fundamentally destabilized the assumptions underpinning classical supply chain management (SCM) theory. As of 2024–2025, multinational enterprises face compounding risks arising from multi-tier supplier concentration, cross-border regulatory asymmetries, and the accelerating reconfiguration of global value chains toward regionalized and nearshored structures. Conventional deterministic optimization models—predominantly rooted in Economic Order Quantity (EOQ) extensions and static linear programming—demonstrably fail to capture the non-stationary stochastic dynamics governing real-world disruption propagation across network echelons. This gap between theoretical modeling sophistication and practical decision-support efficacy has become a critical liability for operations managers and C-suite executives charged with sustaining competitive service levels under structural uncertainty. The concept of supply chain resilience (SCRes) has evolved considerably since its initial formalization by Christopher and Peck (2004), yet quantitative operationalization remains methodologically fragmented. Extant literature bifurcates broadly into simulation-based approaches—agent-based modeling, discrete-event simulation—and analytical optimization frameworks, with limited integration of the two paradigms under a unified stochastic decision-theoretic scaffold. Markov decision processes (MDPs) and stochastic dynamic programming (SDP) offer theoretically robust instruments for sequentially adaptive decision-making under uncertainty; however, their application to multi-echelon network topology with heterogeneous disruption distributions remains nascent, particularly at the intersection of robust scenario-tree decomposition and MINLP formulations. This paper addresses the aforementioned methodological lacuna by proposing a novel SDP-MINLP hybrid framework explicitly designed for resilience resource allocation across multi-echelon supply networks subject to compound demand uncertainty. The framework is empirically grounded in panel data spanning 214 manufacturing firms across six national economies over the 2019–2023 observation window, enabling cross-sectoral and cross-regional generalizability of parametric estimates. Key contributions include the derivation of Pareto-optimal trade-off frontiers between cost efficiency and disruption-recovery velocity, the identification of critical echelon-specific vulnerability coefficients, and the formal integration of nearshoring pressure variables as exogenous stochastic drivers within the MDP state-space representation. Structurally, the remainder of this article is organized as follows. Section 2 reviews the extant SCRes optimization literature, delineating the theoretical gap addressed herein. Section 3 presents the formal stochastic dynamic programming and MINLP model specification, including state-space definition, transition probability estimation, and objective function construction. Section 4 details the data collection protocol, firm-level panel structure, and econometric calibration procedure. Section 5 reports empirical results, including sensitivity analyses and Pareto frontier visualizations. Section 6 discusses managerial implications for nearshoring strategy and resilience investment prioritization. Section 7 concludes with theoretical contributions, practical limitations, and directions for future research.

This is a preliminary version. To read the full version of the article, please purchase a subscription.

References

1. Ola, M. H. Financing mix and Financial Performance: Evidence from listed Consumer and Industrial Goods Sector in Nigeria.
2. оглу Рагимов, Э. Р., & оглу Искендерзаде, Э. Б. (2023). ЭФФЕКТИВНЫЕ МЕТРОЛОГИЧЕСКИЕ АСПЕКТЫ ПРИМЕНЕНИЯ НАНОТЕХНОЛОГИЧЕСКОЙ ПРОДУКЦИИ В ТРАНСПОРТНОЙ СФЕРЕ. Сетевое издание «Нефтегазовое дело», (1), 126-142.
3. Rahimov, E., Rahimov, C., & Davudova, S. A. Determining the optimal relationship between speed and acceleration of a vehicle to minimize pollutant emissions into the atmosphere.
4. Рагимов, Дж. Эффективные метрологические аспекты применения нанотехнологической продукции в транспортной сфере / Дж. Рагимов, Э. Рагимов, Э. Искендерзаде // Сетевое издание «Нефтегазовое дело». — 2023. — № 1. — С. 126–142.
5. Kyfyak, V., & Todoriko, I. (2021). Імплементація зарубіжного досвіду мотивації праці у діяльність українських підприємств.
6. Afgan, T. O. (2023). IMPACT OF THE COVID-19 CRISIS ON FINANCIAL STABILITY. Foundations and Trends in Modern Learning, (1).
7. Talibzade, O. A. (2023). Industry-based multiplier tables for cost of equity calculation (example of Azerbaijan). İqtisadi Artım Və İctimai Rifah, 4, 150–157.
8. Talibzadə, O. (2023). NATURE OF BUDGET PROCESS AND ANALYSIS OF BUDGET INDICATORS IN AZER-BAIJAN BANKING SYSTEM. Social and Technical Sciences Series, 3, 82–86.
9. Talibzade, O. (2022). Organization of expenses in budget management, enterprises and organizations. Geostrategy, 71 (5), 112–114.
10. Talibzade, O. (2022). Organization of expenses in budget management, enterprises and organizations. Geostrategy, 71(5), 112–114.