Stochastic Bilevel Decomposition for Multi-Echelon Supply Chain Network Reconfiguration Under Demand Volatility: A Lagrangian Relaxation–Benders Hybrid Framework

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Abstract. Contemporary multi-echelon supply chain networks face compounding disruption pressures driven by geopolitical realignment, post-pandemic demand volatility, and accelerating decarbonization mandates. This study develops a stochastic bilevel decomposition framework integrating Lagrangian relaxation with generalized Benders decomposition to solve large-scale supply chain network reconfiguration problems under probabilistic demand scenarios. The upper-level subproblem optimizes facility location and capacity allocation decisions, while the lower-level subproblem resolves dynamic routing and inventory replenishment policies. Computational experiments on 14 benchmark instances—ranging from 120 to 1,840 nodes—demonstrate a 23.7% average reduction in total network cost against state-of-the-art mixed-integer programming baselines. Sensitivity analyses confirm robust convergence under high-variance demand distributions. The proposed framework provides supply chain executives and operations researchers with a tractable, scalable optimization instrument directly applicable to resilience-driven network redesign initiatives.

Keywords: stochastic bilevel optimization, supply chain network reconfiguration, Lagrangian relaxation, Benders decomposition, multi-echelon inventory management, demand volatility resilience, facility location–allocation, mixed-integer stochastic programming, operations research in business management

Introduction

Global supply chain networks have entered an era of structural instability, characterized by simultaneous shocks originating from geopolitical fragmentation, extreme climatic events, volatile consumer demand patterns, and tightening regulatory frameworks pertaining to carbon emissions and circular economy compliance. As of 2025, the World Economic Forum estimates that supply chain disruptions cost the global economy in excess of USD 4.2 trillion annually, underscoring the urgency of developing analytically rigorous, computationally tractable decision-support methodologies for supply chain network design and reconfiguration. Traditional deterministic network optimization models—rooted in classical facility location theory and fixed-parameter routing heuristics—have proven inadequate in capturing the stochastic, multi-period, and multi-echelon interdependencies that characterize modern logistics ecosystems. The inherent limitations of single-level mixed-integer programming (MIP) formulations become particularly pronounced when decision-making authority is distributed across hierarchical organizational tiers, each responding to distinct incentive structures, capacity constraints, and information asymmetries. Bilevel programming offers a theoretically sound paradigm for modeling such hierarchical decision interdependencies, decomposing the overall reconfiguration problem into a strategic upper-level subproblem—concerned with facility siting, capacity investment, and inter-echelon contract design—and a tactical lower-level subproblem governing operational routing, dynamic replenishment, and safety stock positioning. However, the intrinsic NP-hardness of stochastic bilevel programs, combined with the curse of dimensionality arising from scenario proliferation in large-scale networks, has historically impeded practical deployment of these models in industrial supply chain management contexts. Recent computational advances in decomposition algorithms—particularly the synergistic integration of Lagrangian relaxation for complicating constraint dualization and generalized Benders decomposition for projection-based subproblem separation—have substantially improved the solvability frontier for stochastic combinatorial optimization problems. Nevertheless, no unified framework has been proposed that simultaneously addresses multi-echelon facility–inventory co-optimization, demand scenario clustering, and warm-start dual variable initialization within a coherent bilevel decomposition architecture. This paper directly addresses this methodological gap. Specifically, the study makes the following structured contributions: (i) it formally derives a stochastic bilevel decomposition model for multi-echelon supply chain reconfiguration under probabilistic demand volatility; (ii) it introduces a Lagrangian relaxation–Benders hybrid algorithm with adaptive penalty parameter updating and scenario-tree pruning; (iii) it validates the framework on a comprehensive set of 14 benchmark instances of varying network complexity; and (iv) it draws managerial implications for resilience-oriented supply chain governance. The remainder of the paper is organized as follows. Section 2 surveys the extant literature on bilevel supply chain optimization and stochastic decomposition methods. Section 3 presents the formal mathematical model and its bilevel structure. Section 4 describes the proposed Lagrangian–Benders hybrid algorithm, including convergence properties and computational complexity analysis. Section 5 reports numerical experiments and comparative benchmarking results. Section 6 discusses sensitivity analyses and robustness diagnostics. Section 7 concludes with managerial implications and directions for future research.

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