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Performance measures based optimization of supply chain network resilience: A NSGA-II + Co-Kriging approach

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ABSTRACT

Increased vulnerability of supply chain networks, due to globalization of trade, has solicited attention of researchers and practitioners towards enhanced risk and disaster management. This has resulted in evolution of extant literature and new practices to construct resilient networks. Resilience is the ability of a network to regain its original state post-disaster. In this work, it is measured by the expected value of the fraction of demand that gets satisfied post-disaster. Most studies in literature capture resilience through qualitative dimensions. Even quantitative based researches, compute resilience through structural dimensions which characterize network density, complexity or excess resource availability. This has resulted in inadequate emphasis on two important performance measures of a supply chain network: the percentage of unfulfilled demand and the total transportation cost post-disaster.

This work addresses above gap through a Multi-Objective Stochastic Mixed-Integer Programming (MOS-MIP) model with above two performance measures as objective functions. To address high computational complexity of MOS-MIP model, a two stage approach of NSGA-II + Co-Kriging is adopted. NSGA-II generates initial points of Pareto frontier which form input for surrogate modelling through Co-Kriging. As compared to conventional simulation, the proposed approach is computationally cheaper and can handle multi-objective formulation effectively. Co-Kriging quickly performs interpolation to provide enriched Pareto frontier. Additionally, it provides variance plot to define degree of uncertainty or confidence associated with accuracy of prediction of each point of Pareto frontier. Subsequently, managers can make informed choices by evaluating tradeoff between objective functions through enriched Pareto frontier with associated degree of confidence of prediction accuracy.

1. Introduction

Globalization of trade has resulted in supply chain networks which comprise a wider eco-system, operating in complex, uncertain environment. These networks are susceptible to vulnerabilities which may arise due to natural catastrophes: earthquakes, hurricanes or human interventions: terrorist attacks, bombing or operational contingencies: supplier discontinuities, equipment failures, industrial accidents, labor strikes, etc. The resulting operational discontinuities may have serious financial impacts in the form of lost sales, inventory shortages and higher transportation costs. However, in spite of being aware of potential widespread negative impacts, many organizations are not yet sufficiently equipped to handle above vulnerabilities. Mitroff and Alpaslan (2003) have adjudged that in case of disruptions, about 95% of the Fortune 500 companies would be incapable of handling them.

Increased vulnerability of supply chain networks has solicited attention of researchers and practitioners towards enhanced risk and disaster management. This has resulted in evolution of extant literature and new practices to construct resilient networks. Resilience is the ability of a network to regain its original state post-disaster. Christopher and Peck (2004) conceptualized resilience of a supply chain network as its ability to reconcile to its original state or to a more desirable state post-disaster. In this work, it is measured by the expected value of fraction of demand that gets satisfied post-disaster, as in Chen and Miller-Hooks (2012). Contemporary contributions have defined and identified different characteristics of supply chain network resilience. Introduction to resilience concept in Section 2 reveals that it has received focus primarily on qualitative aspects of supply chain network characteristics like diversity, adaptability, efficiency and cohesion (Fiksel, 2003); adaptability, safety, mobility, and recovery (Murray-Tuite,

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2006); density, complexity, and node criticality and two supply chain mitigation capabilities: recovery and warning (Craighead, Blackhurst, Rungtusanatham, & Handfield, 2007). Even quantitative based researches, measure resilience through structural dimensions, which characterize network density, complexity or excess resource availability. However, increased focus on structural antecedents of resilience has mitigated researchers' emphasis on two important performance measures of any supply chain network: the percentage of unfulfilled demand and the total transportation cost post-disaster.

This work analyzes resilience of a supply chain network while addressing tradeoff between above two performance measures. We adopt Chen and Miller-Hooks (2012) as the foundation paper for quantification of network resilience and for formulation of Multi-Objective Stochastic Mixed-Integer Programming (MOS-MIP) model with minimization of percentage of unfulfilled demand post-disaster as the first objective function. Furthermore, we incorporate minimization of total transportation cost post-disaster as the second objective function, which is another important performance measure of a supply chain network. The resulting multi-objective formulation though induces higher computational complexity (addressed in Section 4), it provides an opportunity to evaluate compromising relationship between the two performance measures on Pareto frontier for better decision making. To address high computational complexity of MOS-MIP model, we adopt a two stage approach using Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and Surrogate Modeling via Co-Kriging (SMK). Multi-Objective evolutionary algorithm NSGA-II is first applied to generate initial points of Pareto frontier. These points are then fed into Co-Kriging surrogate model to interpolate Pareto frontier.

The main contributions of this work over Chen and Miller-Hooks (2012) are following. It incorporates another important performance parameter of supply chain network, the total transportation cost post-disaster, as second objective function. As compared to Monte Carlo Simulation approach of Chen and Miller-Hooks (2012), the proposed NSGA-II + Co-Kriging approach is computationally cheaper and can handle multi-objective formulation more effectively. Co-Kriging quickly performs interpolation to provide enriched Pareto frontier. Additionally, it provides variance plot to define degree of uncertainty or confidence associated with accuracy of prediction of each point of Pareto frontier. Viana, Haftka, and Steffen (2009) and Mehmani, Chowdhury, and Messac (2015) state that error measures can be used to assess the accuracy of the surrogate model in representing the actual system behavior and for quantifying the uncertainty associated with the surrogate. Subsequently, managers can make informed choices by evaluating tradeoff between objective functions through enriched Pareto frontier with associated degree of confidence of prediction accuracy.

The paper is structured as follows. Section 2 provides an understanding of the concept of network resilience. In Section 3, MOS-MIP model is formulated. Section 4 discusses basic concepts of Kriging and illustrates proposed NSGA-II + Co-Kriging methodology. Section 5 performs scenario analysis of intermodal transportation network problem adopted from Chen and Miller-Hooks (2012) and derives key insights for decision making from Pareto frontier and variance plot obtained from Co-Kriging interpolation. Finally Section 6, concludes the paper by emphasizing contributions, the advantages of proposed methodology and scope for future work.

2. Concept of resilience

This section reviews various definitions and characteristics of resilience. Further, it examines quantitative research reported in supply chain network resilience and identifies research gap.

Fiksel (2003), inspired from a broader systems thinking approach, developed a design protocol that encourages explicit consideration of resilience in engineering holistic systems. The researcher identified following characteristics of a resilient system: diversity, adaptability, efficiency and cohesion. Dalziell and McManus (2004) proposed use of the term resilience to describe an all-encompassing goal of a system to remain functional to the maximum extent achievable, when subjected to a stress. The authors defined resilience as a function of vulnerability of system and its adaptive capability. Christopher and Peck (2004) conceptualized resilience of a supply chain network as its ability to reconcile to its original state or to a more desirable state post-disaster. Sheffi (2005) opines that if certain features are engineered into a freight transportation network, its resilience can be improved significantly. Collaborative effort, among corporate entities of network to identify and manage risks, has been suggested as a preferred approach. Brabhaharan (2006) proposed that network resilience is a combination of its low degradation vulnerability in case of a hazardous event, and the minimal time within which it can be reinstated to expected levels of performance. Craighead et al. (2007) conducted an empirical research to derive insights that relate severity of supply chain disruptions to three supply chain design characteristics: density, complexity, and node criticality and two supply chain mitigation capabilities: recovery and warning. Further, Falasca, Zobel, and Cook (2008) took the three supply chain design characteristics identified by Craighead et al. (2007) as inputs, recognized complexity of modelling their relationships and suggested a simulation based decision framework. Their model investigates impact of design decisions on flow of materials as impacted by disruptive changes in environment, which propagate through physical infrastructure of supply chain. Ponomarov and Holcomb (2009) presented an integrated understanding of resilience through social, psychological, ecological, organizational and economic perspectives. The authors defined supply chain resilience as "the adaptive capability of supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function". Ta, Goodchild, and Pitera (2009) provide a definition of resilience in context of freight transportation network. It incorporates interactions between participating entities like physical and information infrastructure, infrastructure users and infrastructure managers. The authors enlist properties of resilience that contribute to overall ability of freight transportation system to recover from disruptions. Zhu and Su (2010) undertook a study on supply chain elasticity based on the Hooke's Law of physics. Shuai, Wang, and Zhao (2011) established a correspondence of cell viscoelasticity theory to resilience concept of supply chain, and defined resilience as the ability of self-adaption and self-organization of a supply chain system. Soni, Jain, and Kumar (2014) modelled relationships between major enablers of resilience using graph theory and Interpretive Structural Modeling. The numerical index obtained can be used to compare different supply chains.

Özdamar, Ekinci, and Küçükyazici (2004) developed a hybrid planning model, integrating multi-commodity network flow problem and the vehicle routing problem, to address natural disaster logistics planning. An earthquake scenario is modeled to obtain optimal mixed pick-up and delivery schedules and quantities on possible routes. Murray-Tuite (2006) introduced a quantitative measure for resilience incorporating multiple dimensions of adaptability, safety, mobility, and recovery. Holmgren, Jenelius, and Westin (2007) have presented a game-theoretic approach for an electric grid to optimally allocate resources for reinforcement in case of natural disruptions. Grenzeback and Lukman (2008) studied effects of Hurricane Katrina and Hurricane Rita on national and regional intermodal transportation facilities. Murray-Tuite