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A multi-objective approach for supply chain design considering disruptions impacting supply availability and quality

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ABSTRACT

We develop a multi-objective stochastic programming model to explore tradeoffs between costs and risk in the supply chain in the event a disruption occurs. We explicitly consider network configuration and operating cost under normal conditions, cost of unsatisfied demand, cost of shipping tainted products to a customer, and quality inspection cost as conflicting goals to be minimized simultaneously. We analyze different disruption scenarios to determine the best supplier selection and inspection strategies to mitigate the effect of disruptions on supply availability and quality. Even the single-objective version of this problem is NP-hard; thus, we propose a genetic algorithm-based search method to identify Pareto-optimal supply chain configurations. We use data envelopment analysis for calculating the fitness value of various supply chain configurations. The proposed approach efficiently yields high-quality supply chain designs, allowing the decision maker to determine an appropriate tradeoff between various costs.

1. Introduction

A supply chain is a network of suppliers, production centers, warehouses, and distribution centers. It is through supply chains that raw materials are acquired, transformed, produced, and delivered to the customer (Chang, Bayhaqi, & Yuhua, 2012). The performance of a supply chain is dependent on the performance of each component in the network and the ability of components to be organized and integrated. Due to the complicated interrelations and interactions between a highly diverse set of suppliers, production centers, distribution centers, and customers, supply chains are subject to a variety of risk factors. Coordination between these entities is an essential but challenging activity. A relatively small disruption and failure in one component can lead to a massive negative impact on the entire network. Disruption is an unforeseen and often sudden event that brings about damage, loss, and destruction of life and property. Common causes of supply chain disruption include natural disasters, production problems, accidents, labor availability, terrorist attacks, unexpected and sudden shocks, economic crises, and war.

This research is motivated by several real supply chain failures. Heparin, a widely used anticoagulant, is produced from the mucosal tissue of pigs. In 2008, when blue-ear pig disease swept through China, tainted heparin was produced and distributed. Tainted heparin caused 81 deaths and several allergic reactions in the United States and around the world. After this incidence, extra testing and product recall of heparin was required for a certain period of time by the U.S. Food and Drug Administration (FDA) (Harris, 2008).

Also, in 2008, infant formula was contaminated with melamine in China. Chinese Administration of Quality Supervision, Inspection, and Quarantine (AQSIQ) investigated the issue involving 154 manufacturers. Melamine contamination had been found in 13% of the sampled manufacturers (Afoakwa, 2008). Products contaminated by melamine impacted thousands of victims (humans, cats, and dogs) in over three dozen countries (Tainted milk scandal impacts over three dozen countries, 2008; Courts compound pain of China's tainted milk, 2008).

Furthermore, in Japan, the March 11, 2011, earthquake (magnitude 9.0) and subsequent tsunami, nuclear crisis, and infrastructure damage had a substantial impact on the operations of many multinational companies. Disrupted supply chains affected a broad range of manufacturing industries such as car manufacturing, consumer electronics, and data processing (Singh, 2011). Automotive companies such as Honda, Toyota, and Nissan had to shut down production due to supply shortages (Bunkley, 2011). The earthquake and subsequent tsunami also severely damaged silicon manufacturing as 60% of the world's silicon wafers are supplied by Japan (Singh, 2011). Lack of necessary materials poses significant challenges for global manufacturing.

These examples illustrates two types of supply chain disruptions

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with different impacts on the network. The first type of disruption leads to a quality problem with a product (e.g., the tainted heparin due blue-ear pig disease or infant formula contaminated with melamine). Failure in this context is a function of low-quality raw materials that a facility receives and consequently produces tainted final products. The second type of disruption is one that affects the availability of a product (e.g., supply shortages in car manufacturing or silicon wafer industries).

Another important notion highlighted by these examples is various inspection mechanism that can be employed to mitigate the effect of disruptions. For example, in the tainted heparin example, if there had been a proper inspection mechanism implemented, tainted heparin would have been detected before reaching customers. Both strategic supply chain design and tactical inspection decisions are vital to ensure availability and quality in supply chains to mitigate disruption impacts.

Lastly, these examples puts emphasis on the need to consider the impact of correlated disruptions across the entire supply chain. For example, the second-tier heparin suppliers were affected regionally by blue-ear pig disease. As a result, more than twelve Chinese first-tier suppliers produced and distributed tainted heparin around the world. A similar correlated failure pattern was seen in other cases. Inclement weather, economic instability, riots, agitation, political unrest, and strikes are other reasons that can cause simultaneous supplier failures in a region.

Motivated by these real-world supply chain disruption cases, we study the supplier sourcing problem in the two-tiered supply chain. First-tier suppliers are those that produce a product from raw materials. Second-tier suppliers are the raw material producers for the first-tier suppliers. For instance, in the case of heparin production, pig farmers are second-tier suppliers that sell pig intestine mucosa to the first-tier drug manufacturers. In this context, the customers are typically healthcare or group purchase organizations, which must partner with one or more first-tier suppliers to satisfy the demand for pharmaceutical products. Therefore, “opening a facility” is equivalent to entering a long-term contractual agreement with a first-tier supplier to satisfy the demand.

The proposed model belongs to the broad category of facility location problems under uncertainty and makes valuable contributions to the literature. First, a multi-objective stochastic model is developed to explore the tradeoffs between costs and risk in the supply chain. It is essential to consider these objectives simultaneously to gain a better understanding of the impact of disruptions in the supply chain.

Second, this paper integrates the supply chain design decisions (strategic decisions) with inspection decision (recourse decisions). Both the design and inspection decisions are important to ensure the availability and quality of supplies to mitigate the impact of disruptions.

Third, the proposed model considers a realistic model of disruptions. Disruptions are modeled to be correlated, and a disruption does not necessarily shut down the entire production unlike a majority of the previous work considering disruptions as a binary event. Instead, only a fraction of production becomes tainted. Disruptions may result in two types of undesired outcomes. First, they might lead to tainted final products reaching to customers. This helps us develop insights into the effectiveness of inspection to reduce tainted supply and shortage costs. One may choose to not to ship any supplies to customers due to quality issues caused by disruptions. Unsatisfied demand may be equally undesirable as the tainted products because of non-substitutable nature of pharmaceutical products. We provide insights into the relationship between capacity and unsatisfied demand.

Finally, a powerful hybrid genetic algorithm, which uses data envelopment analysis to calculate the fitness value of supply chain configurations, is developed to solve the multi-objective stochastic model. This solution approach is capable of handling large-scale real-world supply chain design problems.

The remainder of the paper is organized as follows. Section 2 provides a detailed analysis of the relevant literature. In Section 3, a multi-objective supply chain design model is formulated, and a disruption scenario generation approach is discussed. In Section 4, a hybrid metaheuristic solution methodology is proposed which is based on data envelopment analysis and genetic algorithm. Computational results are presented in Section 5. Finally, the paper is concluded in Section 6.

2. Literature review

In this section, we analyze the relevant literature in three main categories.

2.1. Supply chain problem under risk

There exist vast literature that considered disruption risk in the supply chain (*e.g.* Albareda-Sambola, Landete, Monge, & Sainz-Pardo, 2017; Cui, Ouyang, & Shen, 2010; Govindan, Fattahi, & Keyvanshokooh, 2017; Hasani & Khosrojerdi, 2016; Ivanov, Pavlov, Dolgui, Pavlov, & Sokolov, 2016; Klibi, Martel, & Guit, 2010; Liu, Liu, Zhu, Wang, & Liang, 2016; Madadi, Kurz, Mason, & Taaffe, 2014; Naderi, Pishvaee, & Torabi, 2016; Nooraie & Parast, 2016; Qi, Shen, & Snyder, 2010; Sawik, 2016; Serrano, Alvarado, & Coello, 2007; Snyder & Daskin, 2005; Snyder et al., 2016; Snyder & Daskin, 2007; Wiengarten, Humphreys, Gimenez, & McIvor, 2016; Zarrinpoor, Fallahnezhad, & Pishvaee, 2017). Wiengarten et al. (2016) explored the role of risk and risk management practices in the success of supply chain integration and argued that supplier and customer integration within the supply chain would have a positive impact on its performance in risky environments.

Naderi et al. (2016) classified uncertainty into two main categories: business-as-usual and hazard uncertainties. Business-as-usual uncertainty corresponds to events with high frequency and low level of disruptive impact. In contrast, hazard uncertainty corresponds to events with a low frequency but highly disruptive impact. They also explored different sources and types of uncertainty in supply chain planning problems such as errors in the subjective data and insufficient or unreliable objective data. Several strategies utilizing fuzzy mathematical programming methods were proposed to cope with uncertainty.

Klibi et al. (2010) provided a review of supply chain network design under uncertainty. They argued that for long planning horizons, it would not be sufficient to consider business-as-usual random variables. Instead, they advocated consideration of high-impact extreme events to mitigate the risk that could severely impair operations and damage network capabilities. Several aspects of the problem (such as risk analysis, hazards modeling, scenario development and sampling, value-based design, robustness, resilience, and responsiveness) were omitted for the sake of computational tractability. The authors, however, acknowledged the need for including these practical considerations for real-world applications.

Snyder and Daskin (2005) developed reliability models based on the P-median problem where all facilities were subject to random disruptions with identical failure probabilities. Cui et al. (2010) studied the reliable uncapacitated fixed charge location problem. Qi et al. (2010) evaluated the impact of random supply disruptions at the suppliers and retailers side on the retailer location and customer demand allocation decisions. Serrano et al. (2007) studied the impact of supply chain disruption. Disruptions were incorporated by scenarios representing unavailability of supply-side and inaccessibility of path to transport the product. Madadi et al. (2014) analyzed a single-period, single-product supply chain model with capacitated facilities to hedge against quality disruptions. Hasani and Khosrojerdi (2016) studied resilience strategies to mitigate the risk of correlated disruptions in the global supply network design under demand and procurement cost uncertainties. Nooraie and Parast (2016) explored tradeoffs between investments in improving supply chain capabilities and vulnerability to supply chain disruptions under a variety of risk scenarios. Ivanov et al. (2016) proposed an approach to re-planning the multi-stage supply chain when disruptions are developed. Liu et al. (2016) studied the influences of