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Reliable design of an integrated supply chain with expedited shipments under disruption risks

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ABSTRACT

This paper studied the design of a two-echelon supply chain where a set of suppliers serve a set of terminals that receive uncertain customer demands. In particular, we considered probabilistic transportation disruptions that may halt product supply from certain suppliers. We formulated this problem into an integer nonlinear program to determine the optimal system design that minimizes the expected total cost. A customized solution algorithm based on Lagrangian relaxation was developed to efficiently solve this model. Several numerical examples were conducted to test the proposed model and draw managerial insights into how the key parameters affect the optimal system design.

1. Introduction

Supply chain operations are susceptible to various uncertainties such as supplier disruptions, transportation disruptions or delays, and customer demand fluctuations. As evidenced in recent catastrophic events (e.g., West Coast Lockdown (Gibson Brian et al., 2015), Sichuan Earthquake (Chan, 2008), Fukushima nuclear leak (Holt et al., 2012), and Hurricane Sandy (Blake et al., 2013)), supply chain facilities are vulnerable to various natural and anthropogenic disruption risks such as floods, earthquakes, power outages, and labor actions. Such disruptions, once happening, can choke the supply of corresponding commodities (or services) at the very source. Even if the commodities are successfully sent out from the supply facilities, they may experience extensive transportation delays, especially when they are shipped with slow transportation modes (e.g., waterways and railroads (Tseng et al., 2005; Ouyang and Li, 2010)). Such transportation delay may cause depletion of downstream stocks and loss of customer demand, particularly when customer demand is stochastic and fluctuating. To ensure customer service levels, one way is to hold a high inventory of commodities at the downstream terminals (or retailer stores), which however incurs excessive inventory holding cost. Or expedited transportation can be used to largely reduce the delivery time to avoid accumulation of unmet demand, which however may dramatically increase transportation cost. Li (2013) showed that a better way would be wisely combining inventory management and expedited transportation such that neither a high inventory nor frequent expedited services are needed. This series of uncertainties throughout these interdependent planning and operational stages, if not properly managed, may seriously damage system performance and deteriorate customer satisfaction. An integrated design methodology is needed to plan an efficient and reliable supply chain system that not only smartly balances cost tradeoffs over space and time but also robustly hedges against the unexpected uncertainties from supply, inventory, and demand.

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There have been a number of studies addressing different facets of supply chain design. On the supplier location side, one recently intensively investigated topic is reliable supplier location design. Studies on this topic basically aim to increase the expected performance of a supply chain system across various supplier disruption scenarios by adding proper redundancy to the location design. On the operational side, freight lead time uncertainties and customer demand fluctuations have been well recognized as major challenges to inventory management and customer service quality. A recent study by Li (2013) proposed an integrated methodological framework that incorporated both planning and daily operations under a stochastic setting. This framework also enhanced the reliability of the supply chain system by taking the expedited transportation service into account, where a set of terminals ordered products from a set of suppliers based on the uncertain demands and inventory levels. The mathematical model proposed in this paper mainly minimized the fixed investment involving the cost of setting up service relationships with selected suppliers, the inventory holding cost at terminals, and the operational cost involving regular and expedited shipment cost from suppliers to terminals. It provided an integrated planning paradigm that balanced all the involved decision components and yielded a more reliable logistic system.

This paper aims to bridge this research gap by proposing an integrated supply chain system design model that simultaneously determines supplier location, multi-modal transportation configuration, and inventory management decisions all together under both transportation disruption risks and operational uncertainties. This model considers a two-echelon supply chain system where a set of downstream terminals order products from a subset of candidate upstream suppliers per arriving customer demands. Each shipment from a supplier to a terminal can be delivered via either a regular transportation mode that is cheap yet has a long and uncertain lead time or an expedited transportation mode that is much more expensive yet assures timely delivery. The adoption of expedited services also affects a terminal's inventory position and the corresponding inventory holding cost. Note that the transportation disruptions mentioned in our study refer to the disasters that disrupt the regular shipment service of suppliers. Then the terminals that used to be served by this supplier have to divert to other suppliers or completely lose the service. To assure the regular service reliability, a terminal may be assigned to a sequence of suppliers such that if regular services of some of them are disrupted, the terminal can resort to the remaining according to the assignment priorities. The system design of this problem is very challenging. Not to mention the inherited NP-hardness of a location problem, the system has to face an extremely large number of possible disruption scenarios of regular shipment service that are exponential to the number of the suppliers. Further, the nested uncertainties from transportation delays and customer arrivals will complicate this problem even more. With our efforts, a compact polynomial-size mathematical programming model is proposed that integrates all these decisions components, including supplier location selections, supplier assignments to terminals, expedited transportation activation rules and inventory holding positions, so as to minimize the expected system cost from both location planning and operations under various uncertainties. The compact structure of this model formulation allows the development of an efficient Lagrangian relaxation algorithm that can efficiently solve this problem to a near-optimum solution. Numerical examples show that the proposed model can yield a supply chain system design that minimizes the impacts from probabilistic disruptions and also leverages expedited shipments and inventory management to balance tradeoffs between transportation and inventory costs.

The rest of this paper is organized as follows. Section 2 reviews related literature. Section 3 formulates the design of the studied supply chain system into an integer nonlinear programing model. Section 4 develops a customized solution algorithm based on Lagrangian relaxation. Section 5 conducts numerical studies and discusses the experiment results. Section 6 concludes this paper and briefly discusses future research directions.

2. Literature review

Studies on facility location can be traced back to about a century ago (Weber, 1929). Earlier location models focused on the single tradeoff between one-time facility investment and day-to-day transportation cost (see Daskin (1995) and Drezner (1995) for a review on these developments). These fundamental models were later extended in a number of directions that largely enriched the contents of facility location models. Spatially, the fundamental two-layer supply structures were extended to multi-layer (or multi-echelon) topologies (Şahin and Süral, 2007). Temporally, single-period stationary operations were generalized to multi-period dynamic operations (Melo et al., 2006). The system service was extended from a single commodity to multiple commodities that share the supply chain infrastructure (Klose and Drexl, 2005). Direct transportation was extended to less-than-truck-load operations that involve vehicle routing decisions (Laporte, 1987; Salhi and Petch, 2007). Most of these models assume that all components of the supply chain system behave deterministically and their actions are fully predictable.

In reality, however, uncertainties exist almost ubiquitously throughout all components in a supply chain. Studies in 1980s (Daskin, 1982, 1983; ReVelle and Hogan, 1989; Batta et al., 1989) pointed out the need for facility redundancy under stochastic demand. Later studies (Lee et al., 1997; Ouyang and Daganzo, 2006; Ouyang and Li, 2010) further recognized that demand uncertainties cause serious challenges to inventory management when transportation takes long and uncertain lead times. Ouyang and Li (2010) analyzed the bullwhip effect for general supply chains system that consists of general network topology, general linear ordering policies and various customer demands. To test the existence of the bullwhip effect, a robust formulation was proposed without the knowledge of demand process. Moreover, another formulation that characterized order streams with certain customer demand processes was also presented, which strengthened findings in Ouyang and Daganzo (2006). These formulations offered logistics planners a series of robust ordering policies and operational strategies