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Centralization versus decentralization: Risk pooling, risk diversification, and supply chain disruptions ☆

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ABSTRACT

We investigate optimal system design in a multi-location system in which supply is subject to disruptions. We examine the expected costs and cost variances of the system in both a centralized and a decentralized inventory system. We show that, when demand is deterministic and supply may be disrupted, using a decentralized inventory design reduces cost variance through the risk diversification effect, and therefore a decentralized inventory system is optimal. This is in contrast to the classical result that when supply is deterministic and demand is stochastic, centralization is optimal due to the risk-pooling effect. When both supply may be disrupted and demand is stochastic, we demonstrate that a risk-averse firm should typically choose a decentralized inventory system design.

1. Introduction

As supply chains expand globally, supply risk increases. Classical inventory models have generally focused on demand uncertainty and established best practices to mitigate demand risk. However, supply risk can have very different impacts on the optimal inventory management policies and can even reverse what is known about best practices for system design.

In this paper, we focus on the impact of supply uncertainty on a multi-location system and compare two policies: centralization (stocking inventory only at a central warehouse) and decentralization (stocking inventory at multiple warehouses). Our analysis is a special case of One-Warehouse Multiple-Retailer (OWMR) system analysis; while most research on the OWMR model allows inventory to be held at both echelons, we allow inventory to be held at only one echelon in order to consider two opposing effects that can occur: risk pooling and risk diversification. The *risk pooling* effect occurs when inventory is held at a central location, which allows the demand variance at each retailer to be combined, resulting in a lower expected cost [14]. The *risk diversification* effect occurs when inventory is held at a decentralized set of locations, which allows the impact of each disruption to be reduced, resulting in a lower cost variance [25]. Whereas the risk-pooling effect reduces the expected cost but (as we prove) not the cost variance, the risk-diversification effect reduces the variance of cost but not the expected cost.

We prove that the risk diversification effect occurs in systems with supply disruptions. We also consider systems with both supply and demand uncertainty, in which both risk pooling and risk diversification have some impact, and numerically examine the tradeoff between the two. The risk mitigated through risk diversification is disruption risk or supply risk, whereas the risk mitigated through risk pooling is demand risk. We employ a risk-averse objective to minimize both risk sources and determine which effect dominates the system and drives the choice for optimal inventory system design.

Specifically, comparing centralized and decentralized inventory policies, we contribute the following:

- The exact relationship between optimal costs and inventory levels when demand is deterministic and supply is subject to disruption.
- The exact relationship between optimal cost variances when:
  - Demand is deterministic and supply is subject to disruption.
  - Demand is stochastic and supply is deterministic.
- Formulations of the expected cost and cost variance when demand is stochastic and supply is subject to disruption.
- Evidence that decentralization is usually optimal under risk-averse objectives.

The remainder of the paper is organized as follows. In Section 2 we review the relevant literature. In Section 3 we analyze the risk-diversification effect in a multi-location system with deterministic

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demand and disrupted supply. We consider stochastic demand and deterministic supply in Section 4. In Section 5 we consider both demand uncertainty and supply disruption and again compare inventory strategies using a risk-averse objective to choose the optimal inventory design. We summarize our conclusions in Section 6. Proofs for all propositions and theorems are given in the Appendix.

2. Literature review

Supply chain risk management has been widely studied ever since the concept of uncertainty was introduced into inventory theory. Uncertainty in supply chains is usually classified as either demand uncertainty or supply uncertainty. A simple model with demand uncertainty is the newsvendor problem, which determines the optimal order quantity or inventory level to minimize the expected cost under stochastic demand in a single period for a single location. Eppen [14] extends the newsvendor problem to a multiple-location model and shows that under demand uncertainty, a centralized inventory strategy provides risk-pooling benefits and reduces expected cost versus a decentralized strategy. Demand pooling is now a familiar idea in operations management and serves as a major instrument to protect against demand uncertainty. Corbett and Rajaram [10] generalize Eppen's work to the case of non-normal, dependent demand and show that the magnitude of the risk-pooling effect increases when the demands are less positively dependent. Berman et al. [7] analyze the benefit of inventory pooling in a multi-location newsvendor framework and show that the absolute benefit of risk pooling increases with demand variability.

There are several ways to implement demand pooling, including transshipments, postponement, and product substitution. Yang and Schrage [34] explore the conditions that cause risk pooling to increase inventory under the setting of product substitution. Paterson et al. [17] review the literature on transshipments as an analogue of inventory pooling. Alptekinoglu et al. [1] propose a model of inventory pooling to meet differentiated service levels for multiple customers. In general, these forms of pooling leverage centralization so as to diminish the impact of demand uncertainty on supply chain performance, which can be thought of as a generalization of the risk-pooling effect studied by Eppen [14] and by this paper. On the other hand, our work deviates from this stream of literature by considering supply uncertainty as well.

Supply uncertainty has been considered in several settings, including newsvendor (e.g., [11,30]) and EOQ (e.g., [6,16,23]) systems. The two most commonly considered forms of supply uncertainty are supply disruptions (in which supply is halted entirely for a stochastic amount of time) and yield uncertainty (in which the quantity delivered from the supplier is random). Chopra et al. [9] and Schmitt and Snyder [21] consider systems that have both supply disruptions and yield uncertainty. The literature on single-echelon (newsvendor) systems with both of these types of supply uncertainty is extensive, and we omit an exhaustive review here. The reader is referred to Atan and Snyder [2] and Snyder et al. [27] for reviews of the literature on inventory models with supply disruptions and Yano and Lee [37] for a discussion of the literature on single-echelon systems with yield uncertainty. Multi-period models with stochastic demand and supply have been considered by Schmitt et al. [22] and Tomlin [29], among others, and we rely on several of their results in this paper. Schmitt et al. develop a closed-form approximate solution for the optimal base-stock level in the face of disruptions and stochastic demand. Tomlin investigates multiple strategies for coping with disruptions, including acceptance (doing nothing proactively), sourcing (using multiple suppliers), and inventory policies. These papers provide a foundation for our analysis, but our application to the OWMR model provides new insights on the impact of supply disruptions in complex systems.

Regarding the management of supply risk, Aydin et al. [4] point out that decentralization, a common approach to mitigate supply risk, creates a misalignment of incentives between suppliers and buyers, competition among suppliers, competition among buyers, and asymmetric information among the supply chain parties, while Ellis et al. [13] discuss the implementation of supply disruption risk research. Interested readers are referred to Babich et al. [5], Yang et al. [35,36] and Tang and Kouvelis [28] for a closer discussion of competition versus diversification. Decentralization also provides flexibility for decision makers at the strategic level. For example, Yu et al. [38] consides the effects of supply disruptions on the decision of whether to single- or dual-source. Wang et al. [33] compare dual sourcing and process improvement to mitigate supply risk. Sawik [19,20] and Qi [18] discuss supplier selection when the supply is subject to disruptions.

Decentralization may be deployed not only occur among suppliers, but also in the inventory systems themselves. Snyder and Shen [25] use simulation to study multiple complex inventory systems, including the OWMR system with supply uncertainty with inventory at a single echelon. Their simulation results show that, under supply disruptions, expected costs are equal for centralized and decentralized systems, but the variance of the cost is higher in centralized systems. They call this the *risk-diversification* effect and suggest that it occurs because a disruption in a centralized system affects every retailer and causes more drastic cost variability. They conclude that risk diversification increases the appeal of inventory decentralization in a system with disruptions. In the context of multi-location inventory management, decentralization or diversification is leveraged to achieve lower cost variance instead of the expected cost, as in, e.g., Schmitt and Snyder [21] and Tomlin [29].

In this paper we consider supply and demand uncertainty in a multiple-demand-point system where inventory may be held at a centralized warehouse to mitigate the demand risk or at multiple warehouses to mitigate the supply risk. We assume that inventory may be held at only a single echelon in order to draw clear conclusions regarding centralization versus decentralization. We explore the implications of the risk diversification effect by developing an analytical model for the expected cost and cost variance of a multi-location system subject to supply uncertainty. We analytically prove the presence of risk diversification in this system, discuss its impact, and examine the system under uncertainty in both supply and demand. When demand is deterministic and supply is subject to disruptions, we determine the optimal inventory levels and costs. For that case and the case in which demand is stochastic and supply is deterministic, we quantify the cost variance. We combine supply disruptions and stochastic demand in a subsequent model and formulate the expected costs and cost variances. To consider the effect of cost variances in the decision making process, we adopt a risk-averse objective to incorporate the cost variance with the expected cost at the same time.

In the latter part of this paper, we consider risk-averse objectives for inventory optimization. Risk-aversion, a topic which is gaining momentum in the operations literature, has been considered in newsvendor models to mitigate demand uncertainty. For example, Eeckhoudt et al. [12] show that order quantities decrease with increasing risk-aversion. Van Meighem [32] considers resource diversification in newsvendor models with risk-averse objectives, advocating diversifying resource availability to protect against risk. Tomlin and Wang [31] consider a single-period newsvendor setting with supply disruptions; they model loss-averse and conditional value-at-risk (CVaR) objectives when deciding between single- and dual-sourcing and between dedicated and flexible resource availability. Chen