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Innovative Applications of O.R.

Mean-variance analysis of sourcing decision under disruption risk

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ABSTRACT

This study considers a mean-variance (MV) framework for managing disruption risk in a two-echelon supply chain with a risk-averse buyer and multiple unreliable suppliers under newsvendor (NV) setting. An MV objective function is designed to maximize the buyer's expected profit while minimizing its variance. Study of the structural property of the problem proves the existence of a global maxima and a set of efficient portfolios consisting of dominating mean-variance pairs. We demonstrate the effect of model parameters through comparative statics analysis. An algorithm is developed to overcome the computational complexity of the higher dimensional problem. Numerical studies on model behavior show that the proposed algorithm gives the exact optimal solution while being tractable.

1. Introduction

Managing and mitigating disruption risk has become an important research issue in the recent past (Christopher & Lee, 2004; Kleindorfer & Saad, 2005; Schmitt, Snyder, & Shen, 2010; Silbermayr & Minner, 2014; Tang & Tomlin, 2008; Yu, Zeng, & Zhao, 2009). Supply disruption may occur in the form of natural disasters such as earthquakes, floods, and hurricanes; or man-made havocs such as terrorist attacks, and strikes. Examples include the earthquakes in China and Japan that caused major disruption to many global and local supply chains, and the fire in Ericsson supplier's semiconductor plant that resulted in a loss of 400 million Euros (Norrman & Jansson, 2004). Oke and Gopalkrishnan (2009) classify such events into three categories: high likelihood-low impact, low likelihood-high impact, and medium likelihood-moderate impact. One of the most common strategies to hedge against supply disruption is multi-sourcing. Traditionally, academic literature considers the buyer to be risk-neutral, and the decision-making involves either maximizing the profit or minimizing the cost. In reality, however, this decision depends on the risk-taking behavior of the buyer who wishes to make a trade-off between maximizing the profit while minimizing the risk. Markowitz's (1952) mean-variance (MV) theory is increasingly used for conducting risk analysis in stochastic supply chain models (Chiu & Choi, 2013), where MV theory maximizes expected return for a given level of risk or minimizes risk for a given expected return. Our model is another effort in this direction considering supply disruption and demand uncertainty to complement multi-sourcing decision.

Many techniques originally proposed on investment theory such as MV analysis, MAD, semi-variance, VaR and CVAR used by various researchers for supply chain risk analysis. For example, Tomlin (2006) considers both MV and CVaR approach for managing disruption risk. As suggested by him, CVaR (Conditional Value-at-Risk) approach better handles the risks associated with low probability of high impact events, i.e., very rare but severe disruptions. However, as suggested by Markowitz (2014), MV analysis is a better approach when the deviation is large. Consider disruptions due to cyclones and related floods that are likely to occur during the monsoon period (typically July–October) in Indian subcontinent. Though such disruptive events occur with low probability and have high impact, their occurrences are not as rare as earthquakes. They are expected to occur during a specific period that accommodates medium probability and moderate impact events. Therefore, the mitigation strategies for such events must be different from other disruptive events that do not give clue of their occurrences and MV approach is appropriate in such cases.

There are numerous applications of MV analysis under standard newsvendor (NV) setting. For example, Choi, Li, and Yan (2008) use MV approach to investigate the NV problem by considering different risk attitudes with and without stockout cost. Similarly, Wu, Li, Wang, and Cheng (2009) apply MV method to analyze the risk-averse problem with stockout cost and found that a risk-averse buyer orders more than a risk-neutral one under stockout situation. Though, there is some scope for applying MV analysis to manage disruption risk in an NV setting, to our understanding, almost no literature exist in this area. In the earlier work (Ray & Jenamani, 2014) we have developed multi-sourcing decision-making models with disruption

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risk considering both risk-neutral and risk-averse buying behavior. While in the previous work, we have modeled risk-averse buying behavior by introducing a service level constraint following the work of Xanthopoulos, Vlachos, and Iakovou (2012); in the present work, risk-averseness is represented in the mean-variance framework following Wu et al. (2009).

To our understanding, this is the first work in the literature that applies MV analysis to manage disruption risk in NV setting. The case of both risk-neutral and risk-averse buyer is considered; while the former maximizes only the expected profit, the later does so considering both expected profit and its variance. Structural characteristics of the problems are investigated to highlight on two special portfolios: (i) maximizing expected profit and (ii) minimizing profit-variance. In between the two extremes, there exists a set of MV efficient portfolios. Though the problem is complex, existence of global maxima is established. To show the effect of various input parameters, comparative statics analysis is performed. The model is demonstrated through a numerical study, and sensitivity analysis is carried out under different setting of the model parameters. An algorithm for MV objective is proposed to reduce the time complexity, which also gives the optimal solution to the problem. Contrary to the result of Wu et al. (2009), current finding shows that when disruption risk is considered, the risk-neutral decision maker orders more than the risk-averse one. Thus, disruption risk has significant effect on buyer's optimal ordering policy, and stockout cost plays a major role in buyer's expected profit, its variance as well as MV objective.

The remaining part of the paper is organized as follows. Section 2 contains the review of the relevant literature. Section 3 discusses the problem and sets the framework. Section 4 presents formulation of the model and its analysis. Section 5 shows the comparative statics analysis and Section 6 shows the solution approach. Section 7 takes up a numerical study to illustrate the model. Finally, the last section summarizes the work and discusses about future research directions.

2. Literature review

This study is related to three streams of literature. First, we discuss the literature on *NV models with MV objectives* followed by *order allocation and supplier selection under disruption risk,* and *MV analysis with disruption risk*.

As a fundamental problem in stochastic inventory theory, the NV model has been studied for a long time (Dada, Petruzzi, & Schwarz, 2007; Yang et al., 2007). Readers are referred to Khouja (1999), Silver, Pyke, and Peterson (1998) and Qin, Wang, Vakharia, Chen, and Seref (2011) for NV problem and its extensions. Such models have the goal of either maximizing the profit or minimizing the cost. Recently, many authors have covered several alternative objectives to maximize utility functions instead of expected profit or cost (Chen, Sim, Simchi-Levi, & Sun, 2007; Eeckhoudt, Gollier, & Schlesinger, 1995; Lau, 1980; Rubio-Herrero, Baykal-Gürsoy, & Jaśkiewicz, 2015; Van Mieghem, 2007), of which MV objective is of our interest. For example, Chen and Federgruen (2000) discuss several basic inventory models using MV approach. They model a quadratic utility function for the decision maker, study the NV problem with cost and profit models and show the variance to be an increasing function of order quantity. However, when stockout cost is considered, variance is no more a monotonically increasing function (Choi, Li, & Yan, 2008; Wu et al., 2009). Martínez-de-Albéniz and Simchi-Levi (2006) study MV trade-offs faced by the buyer, while signing a portfolio of long-term contracts with its suppliers while having access to spot market. Choi et al. (2008) examine the issue of channel coordination in the supply chain when individual decision makers take the MV objective.

Berger, Gerstenfeld, and Zeng (2004) classify disruptive events into three types: Super event (failure of all suppliers), semi-super event (failure of a subset of suppliers) and unique event (failure of a single supplier). They use decision-tree approach to find the financial loss and operating cost of working with multiple suppliers considering only two events: super event and unique event. Their work is further extended by many authors (Ruiz-Torres & Mahmoodi, 2007; Sarkar & Mohapatra, 2009; Ray & Jenamani, 2013). While some authors observe sole sourcing method to be the lowest cost approach (Ruiz-Torres & Mahmoodi, 2007), other authors show that selection of multiple suppliers from a different location is more advantageous than selecting multiple suppliers from a single location (Sarkar & Mohapatra, 2009). For an extensive review on supply chain risk management readers may go through Snyder et al. (2012), Tang (2006) and Fahimnia, Tang, Davarzani, and Sarkis (2015)

The application of MV analysis considering supply disruption is a relatively unexplored area. As discussed earlier, Tomlin (2006) considers risk aversion in the order allocation decision using MV analysis with small probabilities of severe events. Gaonkar and Viswanadham (2007) propose a strategic level disruption management model under deterministic inventory setting adopting ideas from MV model. They use a mixed integer programming formulation to minimize supply shortfall under disruption through optimal partner selection. Shu, Wu, Ni, & Chu, 2015 study the procurement/inventory problem of a risk-averse retailer with unreliable supplier and stochastic demand under MV setting. They develop an optimal strategy that can manage the retailer's supply risk effectively. For a comprehensive review of supply chain risk with MV models, please refer to Chiu and Choi (2013).

3. The problem

We consider a two-echelon supply chain with a buyer and multiple unreliable suppliers. The buyer orders a single product from her suppliers to meet random customer demand. The suppliers differ in price, as well as disruption probabilities and its consequences. In this situation, the buyer's problem is to decide how to allocate order, so that the expected profit is maximized, and the variance is (risk) minimized. We develop a model for the above problem in the classical NV framework. The buyer makes sourcing decision to satisfy total demand 'x' which is uncertain with probability density function $f(x)$ and cumulative distribution function $F(x)$. The buyer's unit selling price is 's'; unit salvage value is 'r' for the unsold stock and unit purchase cost from supplier 'i' is 'c_i'. In case of shortages, the associated loss of goodwill per unit is 'k'. Before the period starts, the buyer, as the decision maker, needs to decide the order quantity 'Q_i'. When disruption occurs at supplier 'i' with probability 'p_i', only a proportion of order quantity 'y_iQ_i' is delivered. The standard assumptions associated with an NV model, including $s > c > r$ and $k > 0$, are held for our analysis. Besides, we also assume that disruption probabilities are different for all the suppliers and percentage of the actual order supplied 'y_i' is deterministic. To model this situation, we first calculate the expected profit for a risk-neutral buyer who is interested only in maximizing the expected profit. The model is further improved by incorporating the variance of profit as a measure of risk with risk-averseness parameter 'A'. Here, Markowitz model maximizes expected profit for a given level of risk as variance or minimizes variance for a given expected profit.

4. Optimal ordering policy under disruption

The buyer has n decision variables, i.e., order quantities $Q_1, \ldots, Q_n$. We derive the buyer's expected profit $E[G(Q_1, \ldots, Q_n)]$, variance of profit $\text{Var}[G(Q_1, \ldots, Q_n)]$ and finally perform MV analysis in line with the works of Chen and Federgruen (2000), Choi et al. (2008), and Wu et al. (2009). The basis of all these models is the standard NV problem where the expected profit $\prod$, a function of the random demand (x) and the order quantity (Q) is given in Eq. (1) as follows.

$$\prod(x; Q) = \begin{cases} sx + r(Q - x) - cQ & \text{if } Q > x(\text{surplus}) \\ sQ - k(x - Q) - cQ & \text{if } x > Q(\text{shortage}) \end{cases} \quad (1)$$