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Coordination in multi-echelon supply chain under supply and demand uncertainty

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ABSTRACT

The main purpose of this paper is to study the inventory, production, and contracting decisions of a multi-echelon supply chain with both demand and supply uncertainty. We find that the commonly used wholesale price contracts used by both up-stream and downstream supply-chain members cannot coordinate the system. We then propose a returns policy used by the manufacturer and the retailer, combined with the wholesale price contract used by the raw-material supplier and the manufacturer, which can perfectly coordinate the supply chain. Through Nash bargaining analysis, we further provide contract terms that lead to win–win situation. We also investigate the impact of the supplier's risk attitude on the decisions, as well as the impact of spot market price for raw material on the performance of the entire supply chain.

1. Introduction

This paper studies the supplier's raw-material production-planning decision, the retailer's replenishment decision, and the choice of contract for a three-tier supply chain with uncertainty about both demand and raw-material yield. The main purpose is to investigate contract terms that coordinate raw-material planning and replenishment decisions and achieve the most efficient performance of the entire supply chain. This paper differs from traditional random-yield and contracting papers in several ways: (1) Instead of focusing on a two-level supply chain that involves manufacturers and retailers, we study a three-level supply chain that includes a raw-material supplier that provides basic components and faces random yields, a manufacturer that is responsible for production, and a retailer that sells to the stochastic demand. Jaber and Goyal (2008) also consider channel coordination in a three-level supply chain; however, in contrast, they assume that both demand and supply are certain. (2) We also examine the contract terms (set by the supplier and the manufacturer respectively) in order to optimize the performance of the total supply chain. Most contract literature has focused on supply chain (systems) with perfect supply and on a two-level supply chain (Cachon, 2003). This paper examines the equilibrium inventory and supply decisions and contract decisions of the decentralized supply chain, and provides optimal contract prices that achieve the best performance of the supply chain with both yield and demand uncertainty. (3) We further investigate how a risk-averse supplier makes the production decision and compare it with that of a risk-natural supplier. To our knowledge, there is still no reference for the production-decision problem for a risk-averse supplier who faces supply uncertainty.

Because of long lead times, complicated production processes, and unpredictable factors like weather and environment, the yield of a raw-material manufacturer is often lower than the initial production quantity. The central question of this paper is: what happens to a three-level supply chain that involves both demand and raw-material yield uncertainty? We consider a Stackelberg game in which the supplier plans production for raw materials by anticipating the retailer's order quantity and the realized yield follows a general probability distribution. What would the equilibrium order quantity and raw-material production quantity decisions be? Can simple wholesale-price contracts coordinate the three-level supply chain in the world of stochastic yields? How about the returns policy?

To address these questions, we develop a single-period, one-supplier/one manufacturer/one-retailer supply-chain model that focuses on three major issues: replenishment, raw-material production planning, and contract prices for supply chains under both supply and demand uncertainty. In this model, the supplier and the manufacturer first propose contract terms for raw materials and finished products, respectively. The supplier is responsible for determining raw-material production quantity before the production season, and the retailer determines replenishment quantity before the demand is known. The manufacturer,

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which has deterministic yield, will purchase raw materials from the supplier at an amount that fulfils the retailer's order. In the case that the supplier does not yield enough raw materials to satisfy the manufacturer, it will purchase the difference from a spot market. The manufacturer then produces the same amount as the retailer's order quantity and the products are delivered to the retailer. Finally, demand is observed, revenues are collected, and profits are earned.

This paper makes four main contributions. First, we provide insights for production, replenishment, and pricing decisions for a multi-echelon supply chain that involves both demand and supply uncertainty. We characterize the production decision of the supplier and the inventory replenishment decision of the retailer in such a system. Second, we investigate the efficiencies of wholesale price contracts and returns policy and provide contract terms that effectively coordinate the supply chain. We use Nash bargaining solution to provide contract terms that lead to a win–win situation. Third, we examine the impact of spot market on such a supply-chain system. We find that a high spot-market price for raw materials deteriorates the profit of the supply chain. In the extension, we investigate how a risk-averse and uncertain supplier makes the production decision, and we find that the more risk-averse the supplier is, the more the supplier plans to produce.

The paper proceeds as follows. In Section 2, we discuss related literature and then in Section 3 we provide a description of the model, including notations and assumptions, and we study the integrated supply-chain problem. In Section 4, we investigate decentralized supply chain under wholesale price contracts, and in Section 5, we examine the decentralized supply-chain system where the manufacturer uses a returns policy instead of a wholesale price contract. Section 6 presents numerical examples to illustrate further insights. Section 7 extends the model to a risk-averse supplier and Section 8 presents conclusions, insights, and directions for future research.

2. Related literature

This paper touches on two areas of research: research on random yield and research on contracting in a supply chain with demand uncertainty. There is extensive literature in the first area; for example, Henig and Gerchak (1990) show that if the production level of unreliable supplier is endogenous then the optimal order level for the newsvendor would be greater than the base case. Anupindi and Akella (1993) consider the operational issue of quantity allocation between two uncertain suppliers. They introduce three models for the supply process based on the type of delivery contract a buyer has with the suppliers. Ciarallo et al. (1994) consider the aggregate planning problem for a single product with random demand and random capacity. They show that if the production level is exogenous, that is, independent of order level, the optimal order quantity for the newsvendor does not change. Dada et al. (2007) consider the problem of a newsvendor that is served by multiple suppliers, where a supplier is defined to be either perfectly reliable or unreliable. They show that in the optimal solution a supplier will be selected only if all less-expensive suppliers are selected, regardless of the supplier's reliability. Jones et al. (2001) consider a hybrid seed-corn production problem with yield uncertainty. They assume that there are two sequential production periods, and they analyze strategies for determining the number of production acres for each period. Kazaz (2004) also studies a two-stage decision-making problem under yield and demand uncertainty, in the olive oil industry, and determines the optimal production quantity of olives as well as the optimal recourse order where the retail price is yield dependent. Hsieh and Wu (2008) consider coordinated decisions in a decentralized supply chain with uncertainties on both the demand and supply sides. They find that coordinating with the original equipment manufacturer (OEM) improves the manufacturer's expected profit and the probability of meeting downstream demand, yet coordinating with the manufacturer is not necessarily beneficial to the OEM when downstream coordination between the manufacturer and the distributor is lacking. Wang (2009) studies a decentralized supply chain comprising a single manufacturer and a single distributor for a short life-cycle product with random yield and uncertain demand. By assuming the manufacturer acts as a price-taker and the wholesale price is exogenous, he analyzes two alternatives for doing business. One is the traditional supply-chain arrangement; the other is a Vendor-Managed-Inventory (VMI) arrangement. Xu (2010) also studies the management problems of production and procurement in a decentralized supply chain consisting of one supplier with random yield and one manufacturer with stochastic demand. He demonstrates that both the supplier and the manufacturer can be better off with the introduction of option contracts. Schmitt and Snyder (2010) consider an inventory system that faces both yield uncertainty and the risk of complete supply disruptions, and they demonstrate the importance of analyzing a sufficiently long time horizon when modeling inventory systems subject to supply disruptions. Yeo and Yuan (2011) develop a periodic review model in which the firm manages its inventory under supply uncertainty and demand cancellation. They show that the optimal inventory policy with supply uncertainty features structural properties similar to that with supply certainty for both the finite horizon case and the infinite horizon case. Gerchak et al. (1988), Henig and Gerchak (1990), Yano and Lee (1995), and Wang and Gerchak (1996) provide detailed reviews and discussions in this field.

There is a vast amount of literature about contracting in decentralized supply chains. How to sell to a downstream supply-chain partner, a foundation to address more complicated supply-chain problems, has attracted extensive attention from academics. Without a properly designed contract, there is the problem of double marginalization (Spengler, 1950) because the downstream retailer does not have an incentive to order enough inventories to maximize the total supply-chain profit. Under the assumptions of deterministic production yields and a two-level supply chain, Lariviere and Porteus (2001) show that the simple wholesale-price-only contract is unable to coordinate the supply chain; and Pasternack (1985) shows that a returns policy, when the parameters are properly chosen, can coordinate the supply chain. Cachon (2003) provides a detailed review of this literature.

Because the simple wholesale-price-only contract cannot coordinate the supply chain, researchers have been focusing on designs of contracts to coordinate a supply chain; for example, quantity flexibility contracts (Tsay, 1999; Wang and Tsao, 2006), revenue sharing contracts (Cachon and Lariviere, 2005; Bellantuono et al., 2009), quantity discounts (Weng, 1995; Li and Liu, 2006), sales rebate contracts (Taylor, 2002; Wong et al., 2009), and returns policy or buyback contracts (Pasternack, 1985; Emmons and Gilbert, 1998; Xiao et al., 2010). Returns policy is one of the most commonly studied coordination contracts in literature, under many complicated situations. For example, Choi et al. (2008) carry out a mean-variance analysis of supply chains and illustrate that a returns policy can simultaneously achieve channel coordination and risk control. He et al. (2009) consider a condition in which the stochastic market demand is sensitive to both retail price and sales effort. They show that coordination is achieved by using a properly designed returns policy with a sales rebate and penalty (SRP) contract. Chen and Bell (2011) investigate a channel that consists of a manufacturer and a retailer where the retailer simultaneously