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Sub-supply chain coordination in a three-layer chain under demand uncertainty and random yield in production

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ABSTRACT

One of the major objectives of modern supply chain management is to deal with the growing decentralization among the involved entities and hence minimizing the double marginalization effect inside the chain, especially when the end-customers' demand is not deterministic. To address this, a three-layer supply chain with one raw-material supplier, one manufacturer and one retailer is developed and studied in this paper. Effects of both supply chain coordination as well as sub-supply chain coordination are examined. Optimal order and production quantities are obtained for the centralized system which depicts the scenario under coordination. Optimal order quantities and expected profits of the individual channel actors are maximized locally in the decentralized system under commonly used price-only contract. Semi-integrated models are also studied under price only contract. The optimal strategies under different power structures are compared, and the effects of the channel parameters on the optimal strategies are also examined. Numerical example is given to illustrate the developed model.

1. Introduction

In competitive industrial environment, the integration of entities in the supply chain has become very much essential to obtain an optimal production or inventory policy. A centralized control policy involves the existence of a unique decision-maker who possesses all the information relevant to make decisions as well as has the contractual power to implement such decisions so as to maximize the total profit of the chain rather than looking at the profit of individual entity. In absence of centralized information or risk sharing among channel members, each member would naturally try to maximize its own profit without looking at the others (decentralized system). This sub-optimization reduces the total profit of the chain, which is better known as double marginalization effect. To get rid of such an effect, several contract mechanisms (revenue sharing, buyback, price discount, two-part tariff, to name a few) between the acting entities have been proposed and studied by a large number of researchers over a long period of time. However, all of these contracts are designed to share information and risks between two adjacent members, thus preventing sub-optimization between them only. Todays real world business supply chains have no longer been restricted into a local area or state; on the contrary, the global competition has been enforcing companies to spread its business chain over the continents for availability of raw materials, cheaper labor cost, easy taxation policy, and of course, potential customers. Clearly, such a supply chain comprises of more than two echelons. Available contract mechanisms, which are designed to coordinate two adjacent entities only, are then needed to be extended so that they become able to encompass all the members. However, as pointed out by Kanda and Deshmukh (2008), many difficulties remain when it comes to implementing suitable coordination schemes for all supply chain members, as constraints like geographical distances, additional administrative burdens, performance measurement and incentives at individual firms based on a local perspective, dynamically interchanging products, etc are hard to overcome. The next best choice for the manager of a retail firm or a manufacturing industry would then be to coordinate with at least one of its adjacent members. Semi integration within a supply chain takes place when two or more adjacent channel members (but not all members) come under a contract to enhance their profits. In fact, from a broader perspective, all the available coordination mechanisms to coordinate two-echelon supply chains are meant for semi-integration, as no supply chain really consists of only two echelons. This sub-supply chain coordination will perform at least better than the decentralized model with no mutual information sharing. Moreover, different game theoretic strategies may be established in two or higher echelon supply chain models, typically models with competitive/cooperative horizontal entities (Huang and Huang (2010)), where some strategies are proved to produce better results than compared to others.

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The profit of the acting entities in a supply chain mainly depends on the market demand. Several policies are being adopted by the companies to anticipate the acceptance of the product among the customers before launching a new product. However, the market demand cannot be anticipated exactly until it arrives. This uncertainty plays a vital role while deciding optimal strategies. Though earlier works were based on deterministic market demand (constant or dependent on certain parameters), because of the high risk involved in production and business operations in a chain, how to realize the negative impact of retail-market demand uncertainty became an important topic of research soon. Hadley and Whitin (1963) first extended the classical EOQ inventory model to the stochastic model. Assuming the retail price and wholesale price to be fixed and retailers order quantity to be the only decision variable, Iyer and Bergen (1997) studied the effect of demand uncertainty in a manufacturer-retailer channel. Mantrala and Raman (1999) studied non-cooperative (i.e., leader-follower) relationship between manufacturer(s) and retail(s), in which manufacturer is the leader and retailer is the follower. Li et al. (1996), Chen and Xu (2001) studied conflict and coordination of a manufacturer and a retailer in a supply channel for single-period products, and provided ways of reducing negative impacts of demand uncertainty on the supply channel. Lau and Lau (2002) considered a non-cooperative game between a manufacturer and a retailer for a single-period product under manufacturer-stackelberg game strategy. Li et al. (2002) utilized chance-constrained game theory to investigate the interaction relationship between a manufacturer and a retailer considering the market demand to satisfy normal distribution. He and Zhao (2012) studied a three-echelon supply chain under supply and demand uncertainty. Hu et al. (2013), Guler and Keskin (2013), Giri and Bardhan (2014), Gao et al. (2014), Bicer (2015), Mateen et al. (2015), Alhaj et al. (2016), Moshtagh and Taleizadeh (2017) etc have also enriched existing literature by considering random demand under different market scenarios.

In the practical industrial scenario, it may not always be possible for a manufacturer to produce the exact amount he/she plans to. Phenomena such as machine breakdown, not up-to-the quality raw material, labor problems, natural calamities affecting the production or any kind of such chaos affects the production and compels the produced quantity to be less than the planned one. Though earlier researchers assumed the produced quantity to be deterministic to make the model simple, modern competitive market strongly requires random yield to be taken into account. The effect of random yield has been studied extensively by many researchers over the last two decades. Henig and Gerchak (1990) showed that if the production level of unreliable supplier is endogenous, then the optimal order level for the newsvendor would be greater than that in the base case. Anupindi and Akella (1993) considered the operational issue of quantity allocation between two uncertain suppliers. Ciarallo et al. (1994) considered the aggregate planning problem for a single product with random demand and random capacity and showed that if the production level is independent of order level, the optimal order quantity for the newsvendor does not change. Jones et al. (2001) considered a production problem with yield uncertainty. Kazaz (2004) studied a single period two-stage decision-making problem under random yield in production and demand uncertainty and determined the optimal production quantity as well as the optimal resource order where the retail price is yield dependent. Considering the problem of a newsvendor with multiple suppliers where a supplier is defined to be either perfectly reliable or unreliable, Dada et al. (2007) showed that a supplier will be selected only if all less-expensive suppliers are selected, regardless of the suppliers reliability. Hsieh and Wu (2008) studied coordinated decisions in a decentralized supply chain with uncertainties on both the demand and supply sides. Wang (2009) studied a decentralized supply chain comprising a single manufacturer and a single distributor for a short life-cycle product with random yield and uncertain demand. Xu (2010) studied 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. Yeo and Yuan (2011) developed a periodic review model in which the firm manages its inventory under supply uncertainty and demand cancelation. Schmitt and Snyder (2012) considered 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. Xiang et al. (2014), Bollapragada et al. (2015), Giri and Bardhan (2015), Li et al. (2015), Yin and Ma (2015), Eskandarzadeh et al. (2016) are to name a few who have made recent contributions in this field.

In this paper, we study a three-echelon supply chain with one raw-material supplier, one manufacturer and one retailer over a single period of time. Although research articles are available which address business management problem in multi-echelon supply chains (Hwang et al., 2013; Ventura et al., 2013; Omar et al., 2013; Almeder et al., 2015; Modak et al., 2015; Giri et al., 2016; Hu et al., 2016; Zhao et al., 2016), almost all of them considered deterministic demand pattern. We have assumed the market demand to be completely stochastic in nature. Moreover, randomness is involved in each stage of production. Different power structures are studied under three major scenarios, namely, centralized or coordinated, decentralized or non-coordinated, and semi-integrated. Optimal results are analyzed to show the acceptability of one power structure over another. The contribution of this paper in the area of supply chain literature is two-fold. Firstly, we consider a three-echelon supply chain with stochastic demand in which both the productions of the raw-material supplier as well as the manufacturer are subject to random yield. To the best of our knowledge, there is no work till date that addresses a three-echelon supply chain with uncertainty at every stage. The most general work till date is that of He and Zhao (2012) that considered uncertainty at demand as well as at the production of the raw-material supplier. However, they assumed production of the manufacturer to be deterministic which we have allowed to be subject to random yield. In that sense, our work is a generalization of theirs. Secondly, we exhibited the effect of coordination between two adjacent entities on the other entities present in the chain. A semi-integration within two members may be achieved through suitable choice of contracts and numerous work has been done towards this direction, but the effect of coordination on the decisions (such as ordering, production, and supply planning) of other channel members who stay outside the range of contract has not been addressed so far. The underlying behaviors of the optimal strategies under semi-integrated channels are compared to show how the channels performance may be enhanced. Recently Seifert et al. (2012) studied sub-supply chain coordination in a three-echelon supply chain; however, randomness in production of finished goods has not been considered by them. In that sense, our work is the most general work towards studying both three echelon supply chain considering randomness as well as sub-supply chain coordination, and thus contributing to the existing literature.

The rest of the paper is arranged as follows: Section 2 presents notations and a brief description of the problem under consideration. The centralized model is provided as a benchmark case depicting the situation under coordination in Section 3. The decentralized model is studied under two different power structures in Section 4. The semi-integrated models with different power structures are studied in Section 5. A numerical example is given and the optimal results are analyzed in Section 6. Finally, Section 7 draws the conclusion and indicates the way to future research.

2. Problem description and notations

The notations used in the paper are provided in Table 1. We consider a three-echelon supply chain of single item consisting of one raw-material supplier, one manufacturer and one retailer. The market demand is assumed to be completely stochastic in nature. Productions of raw-material as well as final product are subject to random yield. For a given wholesale price, the retailer decides his optimal order quantity D units of finished product and places the order to the manufacturer. The