Int. J. Production Economics 146 (2013) 612–619

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Dynamic replenishment, production, and pricing decisions, in the face of supply disruption and random price-sensitive demand

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ARTICLE INFO

Article history:
Received 9 May 2012
Accepted 8 August 2013
Available online 19 August 2013

Keywords:
Replenishment
Production
Pricing
Supply disruption
Random and price-sensitive demand

ABSTRACT

We study a joint decision problem for replenishment, production, pricing strategies in the face of both supply and demand uncertainties. The supply of the raw material suffers from a potential supply disruption while the demand for the finished goods is price-sensitive and random. We assume that the raw material is storable and unfilled demands are fully backordered. We characterize the optimal policies for raw-material replenishment, finished-goods production, and pricing. We find that the optimal replenishment policy is an order-up-to type for a given finished-goods stock level while it is a threshold type for a given raw-material stock level. For either a given finished-goods stock level or a given raw-material stock level, the optimal production policy is a threshold type and the optimal pricing policy is a modified list-price type, respectively.

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1. Introduction

In this paper, we study a joint decision problem for replenishment, production, pricing strategies in the face of both supply and demand uncertainties. This study is motivated by the following observations. To maintain competitive advantages nowadays, more firms prefer to purchase raw materials from overseas countries and/or outsource non-core production activities to contract manufacturers. However, due to various uncertainties at the supply side, such as natural disaster, quality issues, and variability in delivery lead time, the firm may not always receive the order that it places in advance. Namely, to hedge the risk of the potential supply disruption, firms intend to store unused raw-materials/components for future usage. Moreover, many semiconductor and electronic component manufacturers can determine the sale price of their products, which is dynamically affected by the availability of inventory on hand. For example, an earthquake in Taiwan severely disrupted supply of essential components to the personal-computer industry leading up to the 1999 holiday season (Burrows, 1999). Dell responded to the disruption in memory supply by adjusting the price in order to shift customer demand to lower-memory computers (Tomlin and Wang, 2011). Hence, facing potential supply shortage and uncertain price-sensitive demand, firms have to carefully determine its replenishment and production plan for inventory management and choose appropriate sale prices for demand management. To our knowledge, the research community has not paid enough attention to such problems yet.

With the motivation by pioneer works in Arrow et al. (1958), inventory control has attracted lots of research attention since the 1950s. Under demand uncertainties, various models have been studied to figure out the optimal policies for production/ordering with an objective to minimize the total expected costs, including production, ordering, and inventory handling costs (see Zipkin, 2000). Different from those previous models, our model has the following two important features.

The first important feature of our problem is that the firm faces a random supply. In the literature of random supply, there are two streams of research closed related to this paper: random yield and variable capacity. This area of random yields has received a lot of attention in operations research. Much work has been done on periodic-review models in dynamic settings, such as Henig and Gerchak (1990) and Parlar and Wang (1993). The focus of this stream of research is on the structure of the optimal policy. Yano and Lee (1995) provide a comprehensive review of research before 1995 in this area. With storable raw materials, Yang (2004) considers a periodic-review production/inventory control problem with supply and demand uncertainties. The author assumes that the supply is exogenous random and the firm can purchase or sell raw materials to an outside market. For a linear-cost structure, the author shows that the optimal policy for both raw-material and finished product inventory is a base-stock type. There have been other renewed interests and new applications in this area in recent years. The issues recently addressed related to uncertain yields are quite diverse, including for example, applications in agricultural and food businesses (Kazaz, 2004), supply diversification (Tomlin

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http://dx.doi.org/10.1016/j.ijpe.2013.08.009

and Wang, 2005), dynamic pricing under uncertain yield (Li and Zheng, 2006), remanufacturing (Mukhopadhyay and Ma, 2009), option contract in a decentralized supply chain (Xu, 2010). For variable capacity, Ciarallo et al. (1994) investigate a periodic-review model with variable capacity and demand uncertainty. The authors show that the order-up-to policy is optimal. As an extension of Ciarallo et al. (1994), Wang and Gerchak (1996) study the situation that the production is subject to both variable capacity and random yield. They prove that the optimal production policy is a threshold type. Recently, Chao et al. (2009) consider a dynamic capacity expansion problem for a service firm in the telecom industry. Their model assumes that at the beginning of each period, a firm may increase its capacity through direct investment in equipment, which is constrained by a random supply limit. The authors show that the optimal capacity expansion policy is an order-up-to type.

The second is the integration of inventory and pricing strategies in a dynamic environment. For a model without the fixed ordering costs, Federgruen and Heching (1999) show that the base-stock-list-price policy remains optimal with general stochastic demands. Yin and Rajaram (2007) study a joint pricing and inventory decision problem with a Markovian demand. For a model with a fixed ordering cost, Chen and Simchi-Levi (2004a,b) prove that the (s,S,p) policy is indeed optimal when demand uncertainty is additive, but not necessarily so under multiplicative demand uncertainty. Karakul (2008) considers the joint pricing and procurement problem of fashion products in the existence of clearance markets while Zhang et al. (2008) investigate the joint problem under the market promotion. Feng (2010) studies the joint pricing and ordering decisions of a singe-item periodic-review model under uncertain demand and supply. Under the assumption that the supply capacity follows a probability distribution, the author shows that the base stock list price policy is not optimal and the dynamic pricing policy could result in a significant profit improvement by comparison of the static pricing policy. Zhu (2012) characterizes the dynamic price and replenishment policies under the scenario of multiple sources in response to demand uncertainty. A more complete literature review of this line of research is provided by Chen and Simchi-Levi (2012).

Among the literature, Feng (2010) is closely related to our work. Although both papers consider both demand and supply uncertainty, the key difference is that our paper explicitly examines the optimal policies for the two types of stock: raw materials and finished goods while Feng (2010) implicitly assumes that all the purchased raw materials are used for production. In short, we focus on the problem of how to choose the optimal policy of replenishment, production, and pricing in order to hedge the risk of supply and demand uncertainties simultaneously. This problem possesses three important features: (i) supply disruption of the raw material; (ii) random price-sensitive demand, and (iii) two inventories (raw materials and finished goods) and one price to be controlled. To our knowledge, prior research has not considered a case where all three features exist simultaneously.

This paper studies the dynamic replenishment, production, and pricing decisions for a single-item periodic-review inventory system. The supply of the raw material may experience potential disruption while the demand for the finished product is price-sensitive and random. The raw material can be stored for future usage. Unfilled demands are fully backordered. The purpose of this paper is to find the optimal dynamic policies that determine the pricing, raw-material replenishment, and production quantity in each period so that the total expected discounted profit is maximized. We address the supply disruption by using the all-or-nothing yield model. We characterize the optimal policies for these three above decisions. We find that the optimal replenishment policy is an order-up-to type for a given finished-goods stock level while it is a threshold type for a given raw-material stock level. For either a given finished-goods stock level or a given raw-material stock level, the optimal production policy is a threshold type and the optimal pricing policy is a modified list-price type, respectively. Next, we analyze the impact of the raw-material and finished-good stock levels on the optimal decisions and numerically examine the impact of parameters on the profit performance. Further, we extend the results to the infinite-horizon problem.

We end this section by describing the organization of this paper. We introduce the model, notations, and assumptions in Section 2. Section 3 develops the optimal policies for raw-material replenishment, finished-goods production, and pricing. We discuss the key features of the optimal policies and possible extensions in Section 4. Section 5 explores the impact of parameters on the profit performance by a numerical study. Section 6 presents the infinite-horizon problem. The paper is concluded in Section 7.

Throughout the paper, we use the following notation: $x^+ = \max\{x, 0\}$. We use $\mathbf{E}_X[\cdot]$ to represent the mathematical expectation with respect to the random variable X, but when no confusion can arise, we often drop the subscript X for simplicity. Furthermore, we use "increasing" and "non-decreasing", as well as "decreasing" and "non-increasing", interchangeably. For function $f(x)$, we use $f'(x)$ and $f''(x)$ to denote its first and second derivative, respectively; for function $f(x_1,x_2)$, we use $\partial_1 f(x_1,x_2)$ and $\partial_2 f(x_1,x_2)$ to denote its partial derivatives with respect to x_1 and x_2, respectively. Similarly, we define $\partial^2_{11} f(x_1,x_2) = \partial^2 f(x_1,x_2)/\partial x_1^2$, $\partial^2_{12} f(x_1,x_2) = \partial^2 f(x_1,x_2)/\partial x_1 \partial x_2$, and $\partial^2_{22} f(x_1,x_2) = \partial^2 f(x_1,x_2)/\partial x_2^2$.

2. Model description

We consider a single-item, periodic-review problem for a firm in a finite horizon with N periods, where $1 \le N \le +\infty$. The firm purchases raw materials from an external supplier. Due to the uncertainty of the procurement process, there exists potential disruption for the supply. Here, the supply disruption is modeled by an all-or-nothing model, i.e.,

$$\epsilon_n = \begin{cases} 1 & \text{w.p. } \rho_n; \\ 0 & \text{w.p. } 1-\rho_n, \end{cases} \tag{1}$$

where ρ_n is the probability that the disruption does not happen in period n.

All-or-nothing yields may arise due to batch failures, acceptance sampling, supply chain disruptions, or supplier delays if the delivery occurs too late to serve demand and the model has been frequently used in the literature (e.g., Anupindi and Akella, 1993; Tomlin and Wang, 2005; Dada et al., 2007). After the random supply is realized, the firm determines the production quantity and the product price. To brief the notation, we assume that one unit of raw material is required to produce one-unit finished goods. The assumption can be easily extended to the case that one-unit finished goods needs multiple-unit raw materials. The unfilled demand is backordered. Further, we assume that both the supply lead time and production lead time are zero.

The sequence of events is as follows. At the beginning of each period, the firm first makes the replenishment decision q for raw materials. Second, after the supply of raw materials is realized, the firm makes the production decision v and pricing decision p. Next, demand occurs during the period. Finally, the demand is fulfilled by the stock available and the unsatisfied demand is backordered.

The demand in period n, denoted by D_n, is non-negative, random, and nonstationary. Similar to Federgruen and Heching (1999), we assume that the demand also depends on the unit sale price p charged in period n. A customer pays the price quoted at the period when he or she places the order, which may or may not be the same as the price quoted at the period when the order is

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