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Production planning and pricing policy in a make-to-stock system with uncertain demand subject to machine breakdowns

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A B S T R A C T

We consider a make-to-stock system served by an unreliable machine that produces one type of product, which is sold to customers at one of two possible prices depending on the inventory level at the time when a customer arrives (i.e., the decision point). The system manager must determine the production level and selling price at each decision point. We first show that the optimal production and pricing policy is a threshold control, which is characterized by three threshold parameters under both the long-run discounted profit and long-run average profit criteria. We then establish the structural relationships among the three threshold parameters that production is off when inventory is above the threshold, and that the optimal selling price should be low when inventory is above the threshold under the scenario where the machine is down or up. Finally we provide some numerical examples to illustrate the analytical results and gain additional insights.

Introduction

Manufacturing systems normally experience random failures and recoveries during their operation. This issue of machine unreliability and its impact present great challenges to manufacturing organizations and operations. These challenges have become increasingly significant in the context of just-in-time manufacturing (JIT-M), which is widely applied in the manufacturing industry. JIT-M is susceptible to disruptions due to machine (or part) failures, labor strikes, and unavailability of raw materials, among other causes. Such disruptions will reduce the system's effective capacity and may result in high operational costs. Examples of the negative impact of process disruptions on firms' operations can be found in the automobile and semiconductor manufacturing industries (see, e.g., Stern, 1994; Hamilton, 1993; Parlar & Berkin., 1991). On the other hand, facing an increasingly complex marketing environment, how to match supply with demand has become a crucial issue for firms to address. In the real world, adjusting prices is an effective means to mitigate the demand–supply mismatch. Making joint production and pricing decisions is quite common in some industries such as electronic product manufacturing. For example, production expansion plans in the liquid crystal display (LCD) and LED panel manufacturing industries typically extend to over two years. On the one hand, the expansion plan needs to acquire reliable capacity to cater for the booming market trend. On the other hand, there is a risk of over-supply. While it is difficult to solve the over-supply problem in the short term, firms can use pricing to match demand with desirable inventory levels.

Motivated by industrial observations, we investigate the impact of random disruptions in a bottleneck production facility in this paper. Besides supply management, the system manager also adopts dynamic pricing to adjust customer demand. Formulating the problem as a Markovian decision process, we consider the joint management of production and the demand process in the setting of a manufacturing system served by a failure-prone machine. The production process is random with a changeable mean production rate and the machine may break down at any time. The demand process is stochastic with a changeable mean demand rate, which depends on the product selling price being high or low. The problem is to maximize either the long-run discounted profit or the long-run average profit where the production rate and the unit selling price are random variables. At each decision point, we first decide how to dynamically adjust the production rate when the machine is up, then determine to apply the high or low price according to the current production rate and the status of the machine.

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We review two streams of research pertinent to the two research questions under study as follows: Failure-prone manufacturing systems have been extensively studied in the last two decades (see, e.g., the recent works of Cai, Wu, & Zhou, 2009, 2011). Buzacott and Shanthikumar (1993) classified the related literature into two groups. The first group is based on the "fluid flow model", where production is modeled as a continuous process and the analysis often assumes constant demand and processing times. It has been shown that the optimal policy under such a model is a hedging point control if unmet demands are completely backlogged (see, e.g., Akella & Kumar, 1986; Bielecki & Kumar, 1988). These results were extended to systems without backlogging by Hu (1995) and Mohebbi (2006) or bounded backlogging by Martinelli and Valigi (2004). A comprehensive list of works in this group of studies can be found in Gershwin (1994) and Sethi and Sethi (1990). The second group is based on the "discrete part manufacturing system", where parts are produced in discrete mode. This group takes into account the extra randomness in the production times and demand arrivals. With the assumption that unmet demands are fully backlogged, Song and Sun (1999), Feng and Yan (2000), Feng and Xiao (2002), Song (2006) and Chiu (2008) established the optimality of a hedging point policy in failure-prone manufacturing systems and provided the explicit forms of the discounted cost and the average cost under a threshold policy. Focusing on production decision making, these studies seldom discuss the pricing decision issue.

We consider in this paper both the production issue and dynamic pricing strategies in the setting of a failure-prone manufacturing system. In view of the fact that dynamic pricing strategies are widely adopted in various industries, Elmaghraby and Keskinocak (2003) characterized the market environments in which dynamic pricing is adopted in practice. Chen, Feng, and Ou (2006) considered the joint management of production and the demand process for a random production system with inventory replenishments. Feng, Ou, and Pang (2008) studied the optimal control of an assemble-to-order system with multiple make-to-stock components and a variable pricing policy. The interested readers may refer to Chen, Chen, and Pang (2011), Keblis and Feng (2012) and Pang, Chen, and Feng (2012) for more discussions of the dynamic inventory-pricing control problem.

There are studies on the impact of production time variability on the optimal inventory control policy with stochastic demand based on numerical analysis (see Sanajian, 2009). Another stream of research considers the joint management of capacity and inventory with stochastic demand in the make-to-order (MTO) system (Mayorga, Ahn, & Shanthikumar (2006), Gayon, de Vricourt, & Karaesmen (2009) and Mayorga & Ahn (2011)). The customer classes are defined by the backorder cost, rather than being differentiated by the pricing policy as in our work. Li and Womer (2012) address issues similar to ours in the MTO system.

Our setting differs from these studies in that our production system is unreliable under the make-to-stock (MTS) scenario, i.e., the machine may break down at any time. In reality, it is reasonable for a manufacturer to make joint production and pricing decisions to cope with the difficulties caused by limited resource capacity and various uncertainties such as random demand arrivals, unreliable machines, and stochastic processing times.

Our study was inspired by Ha (1997, 1997), which apply the Markov decision process approach presented in Porteus (1982). Focusing on cost parameters, the former two papers study a scheduling problem with two products and a stock rationing problem with several demand classes, respectively. However, we consider a different model setting from that in Ha (1997, 1997), whereby we focus on the pricing policy in a failure-prone manufacturing system.

Combining production control and price switching control into an integrated policy in this paper, we show that the production and pricing policy is a threshold control, which can be characterized by three threshold parameters. The first one is the production policy, which is the base-stock type, so production is off when inventory is above a certain level. The other two thresholds are the optimal control of the selling price under the scenarios where the machine is down and up, respectively. The decision maker will sell the product at a high price when inventory is low, and vice versa. The result that the optimal control policy is a threshold control characterized by three parameters holds true for both the discounted profit and long-run average profit cases. We establish the structural relationships among the three threshold parameters. Our findings imply that the manufacturer should not presume an extremely high repair rate because the related cost is high and the effect of dynamic pricing becomes weak as a result.

This paper is organized as follows: We formulate the problem as an event-driven Markov decision process in section 'The model'. We show the optimality of a threshold control for the discounted profit and the average profit cases in section 'Structure of the optimal policy'. We present a numerical example to illustrate the analytical results and gain additional insights in section 'Numerical analysis'. section 'Conclusions' concludes the paper with a summary of the results and a discussion of possible extensions of this study.

The model

There is a manufacturer that produces a single product to stock using an unreliable machine. The product is sold to customers at one of two possible prices depending on the inventory level at the time when a customer arrives. It follows that the underlying make-to-order system is subject to random machine breakdowns. When the machine is up, the system produces the product at a unit production cost c and its unit production time is exponentially distributed with a rate μ, where μ is adjustable within the range $\mu \in [0, r]$ and r is the maximum production rate. When the machine is down, the system produces nothing and the machine is sent to repair immediately. The production interrupted by machine breakdowns is resumed once the machine is repaired. Due to the memoryless property of the exponential processing time, the remaining processing time is stochastically equivalent to initiating production from scratch. Following Bielecki and Kumar (1988) and Posner and Berg (1989), we assume that the machine operating time until breakdown (i.e., machine up time) is exponentially distributed with an average failure rate q_0 and the machine repair time is exponentially distributed with an average repair rate q_1, where the average failure rate of the machine is the inverse of the mean time to failure (MTTF) and the average repair rate of the machine is the inverse of the mean time to repair (MTTR), i.e., $q_0 = \frac{1}{MTTF}$ and $q_1 = \frac{1}{MTTR}$.

Following Chen et al. (2006) and Feng et al. (2008), we model the product demand as a non-homogeneous Poisson process with a mean rate dependent on the selling price at the time when a customer arrives (i.e., the decision point). For the price setting problem, it is not always feasible to change prices every day or period because (1) it is difficult and expensive to update demand forecasting and pricing decisions and (2) frequently changed prices are not acceptable to downstream members of the supply chain. Although flexible pricing may maximize profit for the manufacturer, a simple pricing policy is often used in the real world whereby a high price is imposed in the peak demand season while a low price is adopted to spur demand. According to the latest *2013 Global Sapphire Substrate Market Report*, LED chip manufacturers apply a relatively stable pricing policy in recent years (see Fig. 1). From