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The effects of contractual agreements on the economic production quantity model with machine breakdown

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ABSTRACT

This paper develops a production-inventory model which is subject to breakdowns, and studies the influence of outsourcing on the expected total cost and the fill rate in case of any failure in the production facility. To avoid shortages and aim at a higher fill rate when there are random breakdowns, the manufacturer has the option to purchase some quantities from an external supplier while repairing the production facility. In this paper, this transaction is formulated through different settings. First, the manufacturer has the option to purchase the items from an available supplier in the market. The manufacturer is also given the option to procure the required items from a predetermined supplier based on a contractual agreement. These scenarios are then compared with the setting in which the manufacturer keeps safety stock in case of breakdown. The results of this study show that using an external supplier, when the machine is prone to failures, improves the performance of the system. We have also shown that it is more beneficial for the manufacturer to collaborate with an external supplier rather than keep safety stock. The analysis is further elaborated using several numerical experiments.

1. Introduction

In a competitive market where end-users are offered a large variety of substitute items, an out of stock situation may swiftly result in losing the margins that a business could have gained had it met the demand. The costs of shortages may extend to negatively affecting the future demand of the firm. The importance of goodwill, in a highly competitive market, forces firms to adopt strategies which will not only meet the demand they receive but also increase their market share. To avoid or minimize unplanned stock-outs in an inventory system, when defining the economic order quantity (EOQ), companies normally take proactive measures, such as diversifying the supplier portfolio or considering safety stock, as a hedge against supply disruptions.

In the production sector, factors such as unpredictable breakdowns in the production machinery, failure in transportation, and low-quality raw material may disrupt the planned supply flow. What if a manufacturer encounters a breakdown in the manufacturing process? How long would the customers wait for their items? What if these breakdowns are unavoidable due to the characteristics of the process? In a production-inventory system when a manufacturer sets their economic production quantity (EPQ), they should always take into account the reliability of the system. Since breakdowns are inevitable, a manufacturing firm should always have a contingency plan to deal with such situations. This issue has been addressed by the research community in recent decades. In addition to corrective maintenance, it has been suggested that a preventive maintenance plan, safety stock and inspection/rework operation, either individually or in combination, could be used to mitigate the effects of a disrupted production process.

The term "emergency replenishment" has been used in the inventory management literature to address an inventory system with constant supply flow (without disruptions) and stochastic demand (see, e.g., Axsäter, 2014; Johansen and Thorstenson, 2014). In such models, when there is a leap in the demand rate, researchers suggest the use of an emergency order that has a shorter lead time but incurs higher costs

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compared with ordinary orders. In this paper, we consider such a replenishment as an option for the manufacturer who replenishes his/her stock by ordering from an available supplier. We also examine other scenarios in which the manufacturer purchases some quantities from a specific supplier by long-term agreement. For example, items such as printed boxes, plastic bottles or computer chips could be produced by other manufacturers after they had made minor adjustments to their production facilities. Although buying items from an external supplier would result in some loss in the margins, it could compensate for part of the overhead cost, protect the manufacturer's reputation, and ensure future demand. The findings of this paper confirm that using an external supplier, by a contractual agreement, to meet the demand while the machine is being repaired, is beneficial.

The contribution of this research work is twofold. First, we introduce a new alternative solution to be considered when breakdowns are common in a business. The solution is more suitable for those production environments in which machine failure is frequent (e.g. relatively old machinery but not too old to be replaced) and when it is less economical in the long term to receive emergency replenishments from available suppliers. Second, the paper provides a tool to analyze and formulate the collaboration settings ensuring that both parties benefit from the joint venture.

The remainder of the paper is structured as follows: Section 2 presents an overview of the relevant literature; Section 3 describes the system as well as the mathematical model; and Section 4 presents the mathematical analysis of the system under different scenarios. Section 5 summarizes the safety stock policy introduced in the literature, followed by numerical analyses in Section 6. Finally, conclusions and insights are summarized in Section 7.

2. Literature review

Machine failure is a widespread incident in a manufacturing environment, and this has motivated the research community to address such problems. Researchers have modeled machine unreliability and its outcomes in different ways. In this section, we give an overview of the literature which focuses on these problems and on the model introduced in this paper.

One of the first papers to conceptualize random breakdowns was published by Kimemia and Gershwin (1981) in which they introduced a flexible manufacturing system (FMS) designed to produce a group of items with similar production requirements. The FMS consists of a set of machinery with an adjustment to the production plan which allows the rest of the machines to continue production while a faulty machine is undergoing repairs. Akella and Kumar (1986) introduced a similar model in which the production rate is optimized as a function of on-hand inventory. Bielecki and Kumar (1988) analyzed a particular case of Kimemia and Gershwin (1981) and showed that zero-inventory policies resulted in optimality for the systems with uncertainties.

Posner and Berg (1989) considered a machine with a constant production rate that produces an item for which the demand follows a Poisson distribution. They showed that operation time before failure and repair time both follow an exponential distribution. Groenevelt et al. (1992b) studied two different production policies under the condition of an unreliable machine. The researchers assumed that after the machine was fixed the firm could either continue the previous lot or start a new one. Berg et al. (1994) analyzed a system with multiple machines whose operating time before failure had an exponential distribution. The demand rate was considered to be based on a Poisson distribution, and any unmet demand lost. They obtained the distribution of the inventory level at the production-inventory system and used that to evaluate the performance of the process.

Glock (2013) considered the assumptions made in the literature for unreliable manufacturing systems and demonstrated that some models needed adjustments to avoid irrational results, e.g., a decrease in the total cost caused by breakdowns. He divided papers on machine breakdown into three different categories, based on what happens to the functionality of the machine and on the quality of the item produced: 1) the machine remains in operation, however, a proportion of the items produced are defective (see Section 2.3); 2) the condition of the machine lies between fully functional and not functional, hence its output is reduced; and 3) the machine is not functional. Although our study falls into Glock's third category, we have used a different system of categorization because we are interested in what measures should be taken when a production system is unreliable.

2.1. Preventive maintenance

There is a vast literature on preventive maintenance plans for the production sector in which researchers combine lot-sizing decisions with maintenance planning. In such systems, the production facility is (mostly) shut down to perform the planned preventive maintenance. In an early study, Kamien and Schwartz (1971) developed an optimal maintenance plan for a machine and suggested an appropriate time-to-sell for the machine before it started to fail frequently.

Groenevelt et al. (1992a) suggested that a fraction of the production should be stored as safety stock when the machinery was operating. The authors, simultaneously found the optimal plan for the preventive maintenance operation. Cheung and Hausman (1997) optimized preventive maintenance and safety stock with a general time-to -failure distribution function, assuming that there is a possibility of machine breakdown. By relaxing some assumptions, Dohi et al. (2001) analyzed the model introduced by Cheung and Hausman (1997) with a more precise expected cost function. Giri et al. (2005) considered production rate as a decision variable to optimize the system while time-to-breakdown and repair time are stochastic. It was also assumed that the failure rate of the machine was linked to the production rate since the stress level on the machine changes with the production rate. Aghezzaf et al. (2007) analyzed a multiple-item production system subject to random breakdowns that aimed to meet the demands of all items over a finite planning horizon and eventually suggested a joint production and maintenance planning model. El-Ferik (2008) examined a production system with age-based maintenance policy and an increasing failure rate. The researcher suggested a preventive maintenance cycle, and if the machine stops before these time points, the maintenance operations immediately start. Kazaz and Sloan (2013) assumed that a process deteriorates over time, its functionality existing somewhere on the spectrum between its best and worst state. Moreover, this process produces multiple items that can be treated with different maintenance plans. Zhang et al. (2014) used a dynamic method for estimating the size of production lots which took machine failures into account, and minimized the average cost instead of the expected cost. Paul et al. (2015) considered a single stage production-inventory system with random disruption. Their model maximizes the total profit during the recovery time window by generating a revised maintenance plan after the breakdown occurs.

2.2. Safety stock

The accumulation of safety stock is one of the measures taken by businesses to avoid shortages in the event of a mismatch between supply and demand. The literature on unreliable manufacturing processes indicates that researchers analyze the performance of a system by assuming that both safety stock and a preventive maintenance plan are in place (see, e.g., Groenevelt et al., 1992a; Cheung and Hausman, 1997; Dohi et al., 2001; Giri et al., 2005 in Section 2.1). Sana and Chaudhuri (2010) designed a production-inventory model that conducted preventive maintenance and kept safety stock. The authors checked the status of the process based on the quality of the last item of the batch, and if it was of acceptable quality, then the whole batch was accepted. In this system, the preventive maintenance operations were performed only if there was no breakdown and a certain level of inventory had accumulated. They then