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Decision Support

On the upgrading policy after the redesign of a component for reliability improvement

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ABSTRACT

We consider an OEM who is responsible for the availability of her systems in the field through performance-based contracts. She detects that a critical reparable component in her systems has a poor reliability performance. She decides to improve its reliability by a redesign of that component and an upgrade of the systems by replacing the old components with the improved ones. We introduce a model for studying the following two upgrading policies that she may implement after the redesign: (1) Upgrade all systems preventively just after the redesign (at time 0), (2) Upgrade systems one-by-one correctively; i.e., only when an old component fails. Under Policy 2, the OEM decides on an initial supply quantity of the improved components. Once this initial supply is depleted, she can procure improved components in fixed-sized batches with a higher unit price. Per policy, we derive total cost functions, which include procurement/replenishment costs of the new components, upgrading costs, repair costs of the new components, inventory holding costs and downtime costs. We perform exact analysis and provide an efficient optimization algorithm for Policy 2. Through a numerical study, we derive insights on which of the two policies is the best one and we show how this depends on the lifetime of the systems, the reliability of the old components, the improvement level in the reliability, the increase in the unit price, downtime costs, the size of installed base, and the batch size.

1. Introduction

Advanced technical systems (e.g. power generators, manufacturing systems, computer networks, medical systems, material handling systems, defense systems) serve for primary operations in our society. They must be kept up and running for operational continuity in power plants, factories, banks, hospital, airports, warehouses, etc. Interruptions of these systems lead to significant losses; for example, downtime costs of computer systems of large e-commerce companies and brokerage companies can reach up to $1,000,000 per hour (cnet news, 2001; Patterson, 2002). In general, the opportunity costs due to downtime of bottleneck machines in factories are also very high, the downtime of step-and-scan systems in semiconductor companies may result in losses of millions of Euros (Kranenburg & van Houtum, 2009). Extensive maintenance activities are carried out for these systems to avoid these high costs; taken together, downtime costs and maintenance costs of such systems may account for 70–80 percent of their Total Cost of Ownership; see e.g. Öner, Franssen, uller, and van Houtum (2007), and Saranga and Dinesh Kumar (2006).

Consequently, after-sales service has evolved into an important business. According to a report by the Aberdeen Group, spare parts and after-sales services accounted for 8 percent of the annual gross domestic product in the United States in 2003, and the total annual global spending on after-sales services was over $1.5 trillion (AberdeenGroup, 2003). A large portion of after-sales service business is carried on by Original Equipment Manufacturers (OEMs) as it provides competitive advantages in sales and enables long-lasting revenue generation with high profit margins which may contribute significantly to business sustainability and growth; see Kim, Cohen, and Netessine (2007), and Cohen, Agrawal, and Agrawal (2006).

Traditionally, OEMs provide after-sales services to their customers through so-called *time and material contracts*. Under a time and material contract, a customer pays the OEM for spare parts, labor, and other resources that are used during service activities. However, *performance-based contracts* are becoming more common recently. Under a performance-based contract, the customer pays for a certain service level with respect to the availability of the system(s) and OEMs become responsible for the costs of resources (spare parts, labor, etc.) used for services and downtime costs; see Cohen et al. (2006), and Guajardo, Cohen, Kim, and Netessine (2012).

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OEMs monitor the systems that they support through performance-based contracts to determine systemic problems that lead to dissatisfaction of availability requirements and/or significant maintenance costs and downtime costs. One of the frequently identified problems is a poor reliability level of one or multiple *critical components* due to its/their design. A critical component of a system is a component whose failures lead to system failures; whenever we refer to a component in the remainder of this paper, we mean a critical component. OEMs may choose to redesign such components to improve their reliability and upgrade the systems in the field by replacing the components in the field (old components) with the improved ones (new components).

In this paper, we address the problem about the timing of upgrades once an OEM improves a component through redesign: she might choose either to upgrade the systems in the field immediately when the component has been redesigned or to replace the old components only when they fail. We develop a quantitative model to support the economical comparison of these options and derive insights about the effect of various relevant parameters on their superiority against each other.

We consider a situation in which the OEM supports a general number of systems in the field through a performance-based contract which specifies a downtime penalty: the OEM pays a certain amount of money to its customers per unit of downtime. Repair-on-site is applied for the improved component; that is, when a component fails, it is repaired at the customer site rather than being replaced by a ready-for-use one. So, no spare parts are kept on stock.

In general, an OEM and a supplier of the new components might agree on different terms for the supply of the new parts, such as one-for-one replenishment, replenishment in batches, unit price, etc. The setting that we investigate is as follows: The OEM can buy any number of new parts just after the redesign (at time 0) and she can replenish new parts only in batches after time 0. The replenishment lead time is zero (we also discuss the cases with positive replenishment lead time in a separate section). The OEM and the supplier agree on a fixed batch size and unit price(s) of the new parts through negotiations. The unit price after time 0 is larger than or equal to the unit price at time 0. This is a very likely situation as the production facility of the supplier might undergo some changes after time 0 (e.g., the production line or the technology might change) and an extra effort might be necessary to produce the new parts. Although the replenishment lead time is zero, the OEM keeps inventory of the new parts due to the increase in the unit price of the new parts after time 0 and the fixed batch size after time 0.

The OEM considers the following two upgrading policies for the N systems in the field:

- Policy 1 – Upgrade all systems preventively at time 0: N new components are bought at time 0 and all the old components in the field are preventively replaced with the new ones at time 0.
- Policy 2 – Upgrade systems one-by-one correctively: A number of new components is bought at time 0 (initial supply) and is kept on stock. When an old component in the field fails, it is correctively replaced with a new one from the inventory. The OEM replenishes new components in batches whenever a new components is needed and there is a stock out after time 0.

Under Policy 1, the OEM faces less failures and less downtime as all old components are replaced with the new ones immediately after the redesign. However, she forfeits the remaining lifetimes of the old components. Under Policy 2, the OEM benefits from the remaining lifetimes; however, she faces more failures and downtime. An increase in the unit price after time 0 (which is probable as we stated above) favors Policy 1. All factors that play a role in Policy 1 are predetermined. The initial supply quantity is a decision that the OEM has to make and it affects the costs incurred under Policy 2. All other factors in Policy 2 are predetermined.

The contributions of this paper are: First, we introduce a model for the upgrading problem with Policy 1 and Policy 2 for a general number of systems. We formulate total costs incurred under Policy 1 and Policy 2. These costs include procurement costs of the new components, costs incurred for upgrading the systems, costs incurred during repairs of the new components and downtime costs under Policy 1; and costs of the initial supply, costs incurred for upgrading the systems, repair costs incurred during repairs of the new components, replenishment costs after time 0, inventory storage costs and downtime costs under Policy 2. We develop a problem formulation in which the relationship between the initial supply quantity and the costs affected by the initial supply quantity under Policy 2 is explicitly established. Second, we perform an exact analysis on the total costs under Policy 2 and we derive several analytical properties. Third, we develop an efficient solution procedure for the optimal initial supply quantity in Policy 2. Fourth, we perform a numerical study and provide insights about conditions which favor each policy. We use the percentage difference in the MTBF of the old components and the MTBF of the new components as a measure of the reliability improvement. Policy 1 is advantageous for low values of the number of systems, long lifetime of the systems, low values of the MTBF of the old components (for fixed percentage improvement in MTBF), high values of the percentage improvement in MTBF, high values of the increase in the unit price of the new components after time 0, large batch sizes, and high values of the downtime penalty. The reverse of each of these conditions favors Policy 2. Our numerical study shows that varying any of the mentioned factors may lead to a change in the best policy.

The outline of this paper is as follows. We summarize the literature related to our model in Section 2. We present our model assumptions and problem formulation in Section 3. In Section 4, we derive the total cost function per policy and provide a number of analytical properties and an optimization procedure for the total cost function of Policy 2. We give the setting and the results of our numerical study in Section 5. In Section 6, we discuss the extension and use of our model for cases with positive replenishment lead times. We finalize the paper by drawing conclusions and give directions for future research in Section 7.

2. Literature

Our model is closely related to the area of research which investigates replacement decisions due to technological obsolescence. In practice, new units (components or systems) which have the same functionality as the old ones in use but with a higher performance often become available in the market. The higher performance could be in terms of reliability, efficiency, energy consumption, purchase cost, etc. The timings of replacements of old units with the new ones are studied in this area. The major difference between our model and the existing ones is that the perspective of an OEM, who is responsible for the availability of an installed base of systems through a performance-based contract, is taken in our model while the perspective of users/owners of one or multiple units is taken in the others. Related to this, we only consider the improvement in terms of reliability as the other performance measures are not relevant for availability, and so is not a concern of the OEM within the scope of our problem.

The replacement decision literature can be considered in two streams. The first stream addresses replacement problems for a single unit while multiple units are considered in the second stream. In the first stream, the problems are formulated periodically in general. At each period, one has to decide whether to replace the old unit with one of the available improved ones. Sethi and Chand (1979), Chand and Sethi (1982), and Dogramaci and Fraiman (2004) introduce models with deterministic technological changes; that is, the timing and the nature of changes are known with certainty. Nair and Hopp (1992), Nair (1995), Rajagopalan, Singh, and Morton (1998), and