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Improved joint preventive maintenance and hedging point policy

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ABSTRACT

We investigate the preventive maintenance and inventory control problem of a one-machine, one-product manufacturing system subject to random breakdowns. Both preventive and corrective interventions have random and non-negligible durations during which an excess of final products inventory is necessary to fulfill demand. The objective of this study is to find the production rate and the preventive maintenance schedule that minimize the total cost of maintenance and inventory/backlog in the case of periodic preventive maintenance. A near-optimal policy characterization with a simple structure is carried out using a numerical approach. Such a policy is a combination of a hedging point policy and a modified periodic preventive maintenance strategy, under which preventive maintenance actions are performed only if the inventory level exceeds a sufficient level. A simulation-based experimental approach is adopted to achieve a close approximation of the optimal control parameters. It is concluded from a sensitivity analysis and a comparative analysis that the near-optimal control policy leads to a significant cost reduction as compared to the combination of a hedging point policy and a classical periodic preventive maintenance policy.

1. Introduction

Operation planning is critical for the proper functioning of a firm (Karen et al., 2003). Planning requires making decisions based on a large amount of information concerning customer demand, the production process, raw material supply, failures and preventive maintenance, which may be sources of uncertainties that the system must deal with in order to enhance profitability. This paper aims to present a better insight of the interaction between failures and preventive maintenance with inventory in a manufacturing system in which repair and maintenance durations are random and non-negligible.

Barlow and Hunter (1960) and Barlow and Proschan (1965) introduced the basis of the two main preventive maintenance (PM) strategies: the age replacement policy (ARP), which consists in performing PM whenever the age of the unit reaches a predefined age threshold, and the block-replacement policy (BRP), which calls for PM to be performed at regular intervals. Under both the ARP and the BRP, units are replaced as failures occur (corrective maintenance, CM). The above authors showed that the ARP is better than the BRP from an economic point of view, in the sense that the BRP can result in the replacement of relatively new units. However, the ARP is more difficult to implement and manage than the BRP because the ARP requires tracking the ages of units and involves modifying PM planning after each maintenance action. An interesting improvement of these policies proposed by Berg and Epstein (1976) and Archibald and Dekker (1996) is based on the BRP, but involves the skipping PM of components whose age falls below a certain threshold. This policy retains the advantages of both the BRP and the ARP and results in maintenance costs that are slightly higher than with the ARP. These maintenance models assume that CM and PM are performed instantaneously. In most cases, maintenance durations are non-negligible and production interruptions due to maintenance require times to repair that may lead to inventory shortages and penalty costs. With respect to these close interactions, it would be interesting to address such control problems through combined preventive maintenance and inventory policies.

Several authors have broached the problem of preventive maintenance and buffer inventory control. The evolution of the inventory level during a maintenance cycle with non-zero maintenance times has been analyzed in order to determine and minimize the exact overall cost. The mathematical models used in the literature to control maintenance activities are based either on a BRP (Cheung and Hausman, 1997; Chelbi and Ait-Kadi, 2004) or on an ARP (Gharbi et al., 2007; Rezg et al., 2008). These preventive maintenance strategies are combined with an inventory control policy that consists in building up and maintaining a buffer stock

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to respond to demand during maintenance operations. However, the optimality of the structure of such joint control policies has not been established, and the authors' works are limited by restrictive assumptions, such as the absence of breakdowns during stock build-up periods, the loss of unmet demands during repair periods, or inventory levels being set to zero after maintenance activities, as mentioned in Rezg et al. (2008) and stipulated in references herein. As well, this approach is limited by the calculation of convolution products representing the sum of random variables (i.e., time between failures plus CM duration), which are hard to express for most probability distributions (Chelbi and Ait-Kadi, 2000).

Markov decision models have also proved successful in solving the maintenance control problem of a deteriorating machine, inspected at discrete time epochs, that provides a downstream buffer. For a predefined inventory policy, similar to that previously mentioned, Van der Duyn Schouten and Vanneste (1995), Kyriakidis and Dimitrakos (2006) and Dimitrakos and Kyriakidis (2008) showed the optimality of control-limit type policy, such that PM is performed if the degree of deterioration exceeds a critical level that depends on the buffer content.

Joint consideration of production planning and corrective maintenance problems in flexible manufacturing systems has been tackled using the optimal control theory (Rishel, 1975; Kimemia and Gershwin, 1983), which has culminated in the hedging point policy (HPP) concept (Akella and Kumar, 1986). Within such a policy, a finished goods inventory surplus is maintained during times of excess capacity in order to deal with future interruptions and possible shortages due to machine breakdowns. The optimality of the HPP has been demonstrated for failure and repair times described by homogeneous Markov processes (i.e., constant transition rates), and therefore, for a failure replacement maintenance strategy. For general machine up and down times, several extensions have been proposed in order to increase the system capacity with either CM or PM—or both (Kenné and Nkeungoue, 2008). On the one hand, CM has been considered by controlling the repair rate, with failure models which are not age dependent (Kenné et al., 2003; Pellerin et al., 2007). On the other, PM has been introduced, in the case of an increasing failure rate, with age-dependent control policies derived from the HPP and the ARP (Boukas and Haurie, 1990; Kenné and Gharbi, 1999; Gharbi and Kenné, 2000). More specifically, PM is skipped if the inventory level is below the hedging point in Kenné and Gharbi (1999) and Gharbi and Kenné (2000). An interesting way to proceed would be to control PM interventions with BRP instead of ARP, since BRP does not require a tracking of the deterioration of the machine, and is easier to control.

Primarily, this paper addresses joint maintenance and inventory control problems in the case of periodically scheduled PM (BRP) during which maintenance can be skipped. This is motivated by the ease with which a BRP is planned and managed. Furthermore, the idea of skipping PM is based on the modified BRP proposed by Berg and Epstein (1976) and Archibald and Dekker (1996) in order to avoid consecutive failures and PM, which lead to a waste of components and a risk of shortage. We also relax the restrictive assumptions commonly used in preventive maintenance and buffer inventory control with regards to the occurrence of breakdowns during stock build-up periods, the loss of unmet demand, and the periodicity of the inventory trajectory. The problem is addressed as an optimal control problem, and our main contribution lies in providing a near-optimal joint control policy. First, the characterization of the near-optimal joint control policy is obtained through a numerical approach. A close approximation of the associated control parameters is then achieved using a flexible simulation-based experimental approach. A near-optimal joint control policy is thus completely determined, and a comparison is made with the combination of the HPP and classical BRP.

The paper is organized as follows: Section 2 states the preventive maintenance and inventory control problem. Numerical methods are then used in Section 3 to carry out a characterization of the near-optimal policy with a simple structure described by several control parameters. The optimal control parameters and the incurred cost are obtained through a simulation-based experimental approach described in Section 4 and illustrated in Section 5 using an example. Subsequently, a sensitivity analysis of the control policies obtained with regards to the cost parameters is presented in Section 6. The control policies are compared in Section 7 for a wide range of time and cost configurations, and finally, concluding remarks are given in Section 8.

2. Control problem statement

We consider the simultaneous control of the production and maintenance activities of a failure-prone facility producing one part type. There is a transition from operational mode (OP) to PM each T units of time, while the transition from OP to a failure mode (CM) randomly depends on the increasing failure rate distribution of the considered production system. In the corresponding transition diagram, a PM can be performed right after a CM, given that PM activities are scheduled at fixed time periods (i.e., at each kT, $k=1, 2, 3 \ldots$). From a practical point of view, a machine may have multiple operational states, as illustrated in Fig. 1, where the operational mode, OP, is considered as a set of N

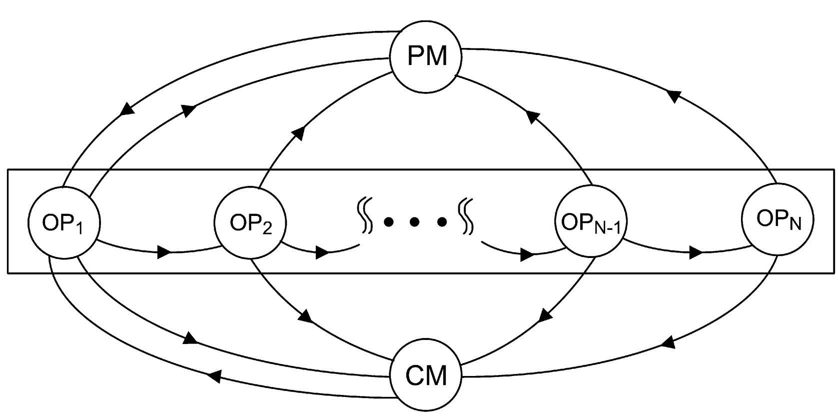

Fig. 1. States transition diagram with multiple operational sub-states.