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Simultaneous control of production, repair/replacement and preventive maintenance of deteriorating manufacturing systems

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ABSTRACT

This paper presents a method to find the optimal production, repair/replacement and preventive maintenance policies for a degraded manufacturing system. The system is subject to random machine failures and repairs. The status of the system is deemed to degrade with repair activities. When a failure occurs, the machine is either repaired or replaced, and a replacement action renews the machine, while a repair action brings it to a degraded operational state, with the next repair time increasing as the number of repairs increases as well. A preventive maintenance action is considered in order to improve the reliability of the machine, thereby reducing the amount of disruptions caused by machine failures. The decision variables are the production rate, the preventive maintenance rate and the repair/replacement switching policy upon machine failure. The objective of the study is to find the decision variables that minimize the overall cost, including repair, replacement, preventive maintenance, inventory holding and backlog costs over an infinite planning horizon. The proposed model is based on a semi-Markov decision process, and the stochastic dynamic programming method is used to obtain the optimality conditions. A numerical example is given to illustrate the proposed model, and a sensitivity analysis is considered in order to confirm the structure of the control policy and to illustrate the usefulness of the proposed approach.

1. Introduction

Recent years have seen considerable growth in interest in production planning and preventive maintenance control in manufacturing systems (see Dong-Ping (2009) and references therein). Such systems are subject to multiple uncertainties, including machine failures and repairs, explaining why repairable systems have attracted the attention of several researchers working in the field of deteriorating production systems (Soro et al., 2010). After a machine experiences a large number of failures, repair costs may become very high, and in such a situation, it becomes more reasonable to replace the machine with a new one. A preventive maintenance action could also be considered in order to increase the operating time of the machine and reduce the amount of production disruptions due to failures.

In a manufacturing environment, production activities, repairs, replacement and preventive maintenance actions are mutually interdependent. Gabriella et al. (2008) present a general overview of models and discuss some sectors of interaction between maintenance and production. Until now, no work has been conducted, which provides, in the same model, the production planning, the repair/replacement and the preventive maintenance policies for systems that deteriorate with age and the number of failures. In this paper, we combine the production, repair/replacement and preventive maintenance control activities of a stochastic manufacturing system subject to random breakdowns. Many articles have been written on the interactions between production, corrective maintenance, preventive maintenance, replacement and machine deteriorations without integrating them in a unified model as in this paper.

Preventive maintenance is usually planned and aimed at increasing the reliability of a deteriorating system or decreasing the operating costs of repairable systems (see Boukas and Haurie, 1990; Dellagi et al., 2007; Yuan et al., 2001; Kyriakidis and Dimitrakos, 2006; Karamatsoukis and Kyriakidis (2010)). Boukas and Haurie (1990) included an age-dependent machine failure rate and allowed the control to influence the jump rate from the machine operation mode to a preventive maintenance mode. They determined the production rate and maintenance rule, which minimize the total expected cost of a two-machine system.

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However, with the numerical scheme adopted in their work, it remains computationally difficult to obtain the optimal control of a large scale flexible manufacturing systems. To deal with this difficulty, Kenné and Boukas (2003) proposed a hierarchical control approach to determine the production and preventive maintenance policies for large scale manufacturing systems. A review of hierarchical approaches under uncertainties can be found in Sethi and Zhang (1994). Dehayem et al. (2009) used a hierarchical approach to develop a semi-Markov decision model in order to come up with a lower level determination of the optimal repair and replacement policy for a system that deteriorates with age, and is subject to damage failures. At higher levels, with that policy adopted, they derived a production plan for the system over an infinite horizon. However, there is no evidence that the structure of the control policy obtained at a lower level remains valid at a higher level of the hierarchy.

Yao et al. (2005) studied the joint preventive maintenance and production policies for an unreliable production system in which maintenance/repair times are non-negligible and random. Gharbi et al. (2007) assumed that failure frequencies can be reduced through preventive maintenance, and developed joint production and preventive maintenance policies depending on produced part inventory levels. In both authors' models, they assumed that maintenance actions always restore the machine to a perfect condition or does not change the failure rate of the system, and that the machine therefore performs similarly from one failure to the next. A more realistic assumption would be that the machine does not always return to a perfect condition following a corrective maintenance. Such a repair is called an imperfect repair (Liao, 2007).

While it is true that the imperfect repair model has been well documented for repair and replacement policies in manufacturing systems (Kijima et al., 1988; Love et al., 2000; Pérès and Noyes, 2003; Dimitrakos and Kyriakidis, 2008a, most available results unfortunately concern only cases where production and demand satisfaction are not taken into account. The authors considered that repair, replacement and preventive maintenance require a short time, and that they do not therefore significantly affect production activities (see Beichelt, 1992; Makis and Jardine, 1993).

If a machine is not initially new or is not new after each maintenance activity, it will clearly have different dynamics after each breakdown and repair. As stated by Pérès-Ocon and Torres-Castro (2002), under particular conditions involving exponential times, such a system can be modeled as continuous-time Markov chains or with Markov decision process (see Pavitsos and Kyriakidis, 2009). However, that is not the case when the probability distributions of operating and repair times follow general distributions, and where a semi-Markov process can then be used for modeling the system (see Dimitrakos and Kyriakidis, 2008b. Sloan (2008) developed a semi-Markov decision process model of a single-stage production system with multiple products and multiple maintenance actions. Such a model simultaneously determines maintenance and production schedules, while taking into account the fact that equipment conditions affect the yield of each product differently.

From previous and available studies, the research gap is that some of works on production planning took into account the fact that system deteriorates with age, but did not consider the cases in which parameters, such as repair time, change with the number of failures by increasing. One reason for this is that considering the variations in such parameters renders the problem more complex. Moreover, available studies did not simultaneously take into account the effect of a preventive maintenance control, repair/replacement and the effect of increasing repair times with the number of failures while controlling production. The mutual interdependency of those actions is therefore under-represented in the literature.

Our aim in this paper is to develop optimal strategies for manufacturing systems which take into account the deterioration of a machine in accordance with the number of failures (i.e., the repair time increases with the number of failures). Thus, repair activities depend on the machine's repair history and Markovian decision processes are no longer appropriate for the model of the control problem. The model proposed in this paper will provide the following three policies simultaneously:

- Repair/replacement switching policy based on the age of the machine and the number of failures above which the machine must be replaced if a failure occurs.
- Preventive maintenance policy based on the age of the machine at which preventive maintenance must be performed.
- Production policy based on the age of the machine and the stock level of finished goods.

The resulting simultaneous control approach consists in developing a semi-Markov decision process (SMDP) in order to determine optimal production, repair/replacement and preventive maintenance policies for the system. Such policies are determined in order to minimize inventory, backlog, repair, replacement and preventive maintenance costs over an infinite planning horizon.

The paper is organized as follows. In Section 2, we present the industrial context of the problem under study. In Section 3, we define the notations and assumptions used in the model. The problem statement is presented in Section 4. Numerical examples are presented in Section 5, and a sensitivity analysis is given in Section 6 to illustrate the usefulness of the proposed approach. Discussions are given in Section 7, and the paper is finally concluded in Section 8 with extensions.

2. Industrial context

The study presented in this paper has many applications, especially in the production industry. As stated by Badia and Berrade (to appear), many engineering systems are subject to the so-called unrevealed failures, which include failures that can only be detected through special tests, inspections or monitoring. Examples of such systems include seal machines, filling machines, machining centers, grinders, milling and many other machining tools. They generally have a large number of components (treadmill, ball screws, spindle heads, precision gear boxes, axis drive components, rotary tables, saddles, pallets and short, etc.), which stochastically deteriorate over time; thus causing the machines to also deteriorate over time. Very often, the parts of such machines are broken or damaged, even though the machine may be operational.

For example, worn nozzle, abrasives in pumped liquid, relief valve stuck, partially plugged or improperly adjusted, cavitations, worn bearing will not necessarily stop a liquid filling machine. A worn bearing, for example, will create a knocking noise, but still leave the machine operational. A machine failure may thus be attributable to one or more removable and repairable component. Over time, the number of components to be checked and repaired at failure increases, thus increasing the mean repair time as well.

Preventive interventions, which are intended to reduce breakdown risk and maintain the smooth operation of machines, provide the opportunity to clean and adjust valves, control stroke and flow injection, replace worn nozzles with properly sized ones, etc.

The model presented in this paper is suitable for repairable manufacturing systems characterized by deterioration due to production and failures. The overall production system is renewed through a replacement after a sequence of successive failures and repairs, in order to allow it to maintain a competitive advantage.