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Joint modeling of preventive maintenance and quality improvement for deteriorating single-machine manufacturing systems ☆

Biao Lu *, Xiaojun Zhou, Yanting Li

Department of Industrial Engineering and Management, School of Mechanical Engineering, Shanghai Jiao Tong University, PR China

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ABSTRACT

For a deteriorating single-machine manufacturing system, preventive maintenance (PM) is an effective way to improve the machine reliability and product quality. In conventional PM models, however, quality improvement has been seldom considered, which may lead to loss of economic benefits. In this paper, a joint model is proposed, in which quality improvement is integrated into PM decision-making. In the proposed model, process variables affecting product quality are identified, among which adjustable process variables are measures of the degradation states of quality-related components of the machine. Based on the response model, a process model is developed to quantitatively describe the impact of process variables on product quality. An integrated reliability model is built for the machine based on the proportional hazard model considering the effects of the degradation states of quality-related components on machine reliability. Quality loss is incorporated into the total cost, which is minimized to obtain the optimal PM schedule. A case study is conducted to illustrate the effectiveness of the joint model. It shows that the joint model can achieve a superior economic performance to the conventional PM model in general case. Economic benefits can be created by integrating quality improvement into PM decision-making.

1. Introduction

In a single-machine manufacturing system, the machine is usually subject to deteriorations with usage and age. The machine deteriorations can increase the risk of machine failure and deteriorate the product quality. Preventive maintenance (PM) is an effective way to prevent or slow down the machine deteriorations, and consequently improve simultaneously the machine reliability and the product quality. The PM strategies include time-based maintenance and condition-based maintenance. In the past several decades, time-based maintenance has received numerous research efforts, in which various PM policies, models and optimization approaches have been proposed. Some reviews and recent literatures on time-based maintenance are listed as follows: (Ahmad & Kamaruddin, 2012; Chen, 2012; Xia, Xi, Zhou, & Du, 2012; Doostparast, Kolahan, & Doostparast, 2014; Zhong & Jin, 2014; Ding & Kamaruddin, 2015; Sheu, Chang, Chen, & Zhang, 2015). Condition-based maintenance is a more recent PM strategy, dealing with the diagnostics and prognostics of the system and maintenance decision-making (Ahmad & Kamaruddin, 2012; Kim & Makis, 2013; Liu et al., 2013; Zhang, Ye, & Xie, 2014). In these existing research works, the motivation of PM is mainly to increase system reliability and/or availability.

In order to be competitive in a changing marketplace, manufacturing companies have to improve product quality. It has been recognized that maintenance of manufacturing equipment can contribute to the improvement of product quality (Muchiri, Pintelon, Gelders, & Martin, 2011; Dhouib, Gharbi, & Ben Aziza, 2012). In conventional (or existing) PM models, however, quality improvement has been seldom considered. When these models are applied to the manufacturing systems, PM actions may be insufficient to achieve satisfied product quality, which implies that the role of PM in quality improvement may not be effectively played. As a result, loss of benefits may be caused. In order to achieve economic benefits, it is highly desirable for the single-machine manufacturing systems to integrate quality improvement into PM decision- making.

In the past decades, many research works have been done on the integration of PM and quality improvement. Tagaras (1988) firstly formulated an integrated cost model for the joint analysis and optimization of maintenance operations and statistical process control (SPC) for a Markovian deterioration process. In the study,

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* Corresponding author at: Department of Industrial Engineering and Management, School of Mechanical Engineering, Shanghai Jiao Tong University, No. 800 Dong Chuan Road, Shanghai 200240, PR China. Tel.: +86 15121196826.

E-mail address: lubiao123@sjtu.edu.cn (B. Lu).

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when a process shift is detected, adjustment is conducted on the process to restore it to the normal state. PM is performed periodically to prevent the process from further deteriorations. Cassady, Bowden, Liew, and Pohl (2000) defined a combined control chart-PM strategy for a process which shifts to an out-of-control condition due to an equipment failure. Based on the joint PM and SPC strategy, many research efforts have been made recently from different aspects, which include process characteristics (Mehrafrooz & Noorossana, 2011; Xiang, 2013), control charting strategies (Charongrattanasakul & Pongpullponsak, 2011; Wang, 2012), and maintenance strategies or policies (Panagiotidou & Tagaras, 2010; Ho & Quinino, 2012; Yin, Zhang, Zhu, Deng, & He, 2015). The joint PM and SPC strategy mainly deals with the joint implementation and optimization of PM and SPC operations. In the models under this strategy, quality changes can be detected through SPC, but the root causes (or sources) of the quality changes are unknown. In addition, product quality deteriorations caused by machine deteriorations cannot be quantified due to the lack of a quantitative description of the relationship between machine condition and product quality.

Chen and Jin (2006) propose a quality-oriented-maintenance model for multiple interactive tooling components in discrete manufacturing processes. The degradations of tooling components may significantly deteriorate product quality. The impact of the states of tooling components on product quality is quantitatively described with the response model. Product quality can be improved though replacement of tooling components. The aim of this study is to determine the optimal replacement times for tooling components by minimizing the total cost which includes quality loss and replacement cost. Later, Ji-wen, Li-feng, Shi-chang, and Er-shun (2010) extends the model of Chen and Jin (2006) by incorporating the obsolescence cost into the total cost. These two studies deal with the maintenance problems for tooling components, but not for a machine consisting of multiple kinds of components.

In this paper, a joint model of PM and quality improvement is proposed for a deteriorating single-machine manufacturing system. In the proposed model, process variables affecting product quality are identified, among which adjustable process variables are measures of the degradation states of quality-related components (refer to the components of a machine having significant impact on product quality). Based on the response model, a process model is developed to quantitatively describe the impact of process variables on product quality. An integrated reliability model is built for the machine based on the proportional hazard model (PHM) considering the effects of the degradation states of quality-related components on machine reliability. The quality loss is measured by Taguchi's loss function and incorporated into the total cost, which is minimized to obtain the optimal PM schedule.

The differences between the proposed joint model and the existing models in the works cited previously are summarized as follows. (1) In conventional PM models (i.e. (Doostparast et al., 2014)), quality improvement has been seldom considered. In the proposed joint model, quality improvement is integrated into PM decision-making. (2) In the models under the joint PM and SPC strategy (i.e. (Yin et al., 2015)), process variables affecting product quality are unknown, and the impact of process variables on product quality is not addressed. In the proposed joint model, process variables are identified, and the impact of process variables on product quality is quantitatively described by a process model. With the process model, the deterioration (or improvement) of product quality due to the degradation (or PM) of quality-related components is quantified. (3) The quality-oriented-maintenance model in (Ji-wen et al., 2010) deals with the replacement problems for tooling components with constant failure rates. The proposed joint model deals with the maintenance problems for a deteriorating single-machine system of which quality-related components (similar to tooling components) are a part. In this model, an integrated reliability model is developed for the machine, and a PM policy is designed, in which imperfect PM for the machine and perfect PM for the quality-integrated components are jointly considered.

The rest of this paper is organized as follows. Section 2 presents the problem statement. The joint model is developed in Section 3. In Section 4, a case study is illustrated to demonstrate the effectiveness of the joint model. Some conclusions are presented in Section 5.

2. Problem statement

Consider a manufacturing system containing a single deteriorating machine which processes a kind of products during a time horizon. The time horizon for the production of a kind of products on a machine is always preplanned and finite. It is taken as the finite planning horizon for PM decision-making. Generally, the time horizon planned for the production of one kind of products is short compared to the lifetime of the machine. Therefore, replacement of the machine is not considered in the planning horizon. During production, the machine deteriorations can result in increasing failure rate and deteriorating product quality. Whenever the machine fails, minimal repair is conducted restore it back to the state prior to failure. PM is carried out on the machine whenever the failure rate of the machine reaches a predetermined threshold. And it is performed to improve the machine reliability and product quality simultaneously. Specifically, the product quality can be improved by replacing, readjusting and/or calibrating the quality-related components. A joint model of PM and quality improvement is proposed for the system to enable effective PM decision-making. A framework for developing the joint model is presented in Fig. 1.

First, the process variables affecting product quality are identified, and the drift processes of the adjustable process variables are modeled. Next, based on the response model, a process model is developed to quantitatively describe the impact of process variables on product quality, and then the quality deterioration process is determined. Then, an integrated reliability model is built up for the machine based on the PHM with the adjustable process variables integrated in as covariates. Finally, PM is modeled under the failure limit policy, and the total cost is formulated and minimized to obtain the optimal PM schedule.

Some assumptions are given as follows.

(1) PM restores the machine condition to somewhere between as good as new and as bad as old, and resets the adjustable process variables to their designed nominal

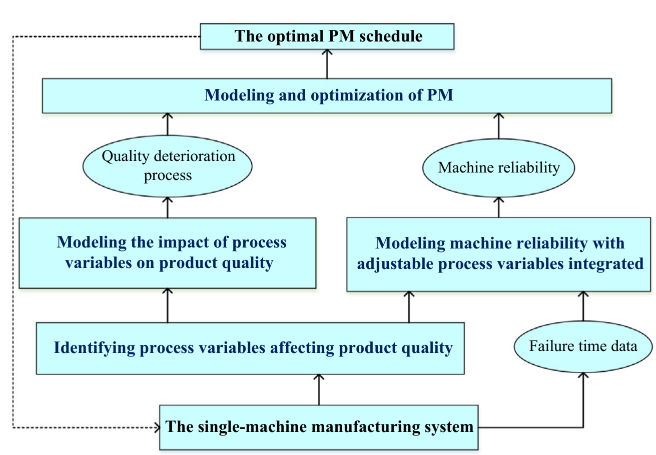

Fig. 1. A framework for developing the joint model.