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Joint optimal lot sizing and preventive maintenance policy for a production facility subject to condition monitoring

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ABSTRACT

In this paper, we consider the joint optimization of economic manufacturing quantity (EMQ) and preventive maintenance (PM) policy for a production facility subject to deterioration and condition monitoring (CM). Unlike the previous joint models of EMQ and maintenance policy which used traditional maintenance approaches, we propose the proportional hazards model (PHM) to consider CM information as well as the age of the production facility. The deterioration process is determined by the age and covariate values and the covariate process is modeled as a continuous-time Markov process. The condition information is available at each inspection epoch, which is the end of each production run. The hazard rate is estimated after obtaining the new information through CM. The problem is formulated and solved in the semi-Markov decision process (SMDP) framework. The objective is to minimize the long-run expected average cost per unit time. Also, the mean residual life (MRL) of the production facility is calculated as an important statistic for practical applications. A numerical example is provided and a comparison with the age-based policy shows an outstanding performance of the new model and the control policy proposed in this paper.

1. Introduction

There has been a growing interest in determining the economic manufacturing quantity (EMQ) of products in the production and inventory control. The traditional EMQ models are rarely applied in practice, because their assumptions are not completely satisfied. To make these models more realistic, considerable research has been done to relax some of these assumptions, which can be summarized as follows:

- Multi-product systems (Ben-Daya and Hariga, 2000; Pasandideh et al., 2010; Taleizadeh et al., 2014),
- dynamic demand rate (Bouslah et al., 2013; Larson, 1997; Pal et al., 2013; Shah et al., 2014; Sicilia et al., 2014),
- imperfect quality of the manufactured product (Makis, 1998; Moon et al., 2002; Avinadav and Raz, 2003; Khan et al., 2011; Tai, 2013; Sarkar et al., 2014),
- deterioration of the production facility and the age-based PM policy (Groenevelt et al., 1992; Tse and Makis, 1994; Fung and Makis, 1998; Ben-Daya, 2002),
- CM of the deteriorating production facility and utilization of this information for production and maintenance decision making. This is a new practical extension, which is the main focus in this paper.

Recently, Glock (2012) and Glock et al. (2014) provided a literature review on lot sizing. They mentioned that deterioration will affect the productivity of an inventory system. However, most of the models have considered the joint optimization of production quantity and quality control of the product deterioration which can be classified as imperfect quality. Another kind of deterioration in the system can be the production facility deterioration with usage and age which may result in its failure causing substantial downtime and failure cost.

Abbreviation: PM, Preventive maintenance; CM, Condition monitoring; CBM, Condition-based maintenance; PHM, Proportional hazards model; EMQ, Economic manufacturing quantity; MRL, Mean residual life; SMDP, Semi-Markov decision process

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Nomenclature

Notation

Q	production lot size
p	production rate
d	demand rate
T	predetermined age to perform preventive maintenance of the production facility
ξ	failure time of the production facility
$f(t)$	density function of ξ
q_{ij}	instantaneous transition rate of the covariate process from state i to j
$P_{i,j}(t)$	transition probability from state i to j in t time units
ν_i	exponential distribution parameter of the covariate process in state i, $i=0,1$
Δ	length of the inspection interval
z	value of the covariate process
$h(t)$	hazard rate at time t
W	preventive maintenance level
C_I	inspection cost
C_L	lost production cost rate
C_H	inventory holding cost rate
C_P	preventive maintenance cost
C_F	corrective maintenance cost
K	set-up cost
τ	expected sojourn time

In one of the early works, Groenevelt et al. (1992) developed a model considering a random machine breakdown and analyzed the optimal lot size and the associated re-ordering policy. To incorporate PM in the context of lot-sizing problems, Tse and Makis (1994) presented a model where they considered both PM and failure replacement to minimize the long-run expected average cost per unit time. They introduced two types of failure: major and minor failures. When the major failure happens, the machine is replaced by a new one. However, minor failure is corrected by minimal repair and production can be resumed immediately at lower cost. They found the optimal lot size and preventive replacement time. Also, Ben-Daya (2002) considered imperfect PM on EMQ model. The author assumed that the age of the system is reduced proportional to the PM level. The system is restored to as good as new condition, when it is out of control or after m inspections. The decision variable is the number of inspections (m) to minimize the expected total cost per unit time. Then, Suliman and Jawad (2012) extended Ben-Daya (2002) by assuming that the failure may occur at any time after system shifts to the out-of-control state. They also incorporated shortage cost and non-negligible PM time. Similarly, Liao and Sheu (2011) proposed a model considering perfect and imperfect PM in a deteriorating production system with increasing hazard rate. They assumed that the probability of performing perfect PM depends on the number of imperfect PM since the last renewal cycle. When failure occurs, the delayed repair is triggered and the production resumes with lower production rate until perfect PM is performed. They minimized the total cost to find the optimum run time in EMQ model. Recently, Rivera-Gomez et al. (2013) developed a model to determine the optimal production plan in a system subject to reliability and quality deterioration. They considered different maintenance actions (minimal repair, major repair and preventive maintenance) in their model to minimize the related cost including the inventory holding, backlog, overhaul, preventive maintenance, and defective costs. Then, Sarkar and Sarkar (2013) proposed an interesting model in the joint optimization of EMQ, maintenance and quality framework. They assumed exponential demand, time-varying production rate under the effect of inflation and time value of money. Costs are dependent on the system reliability, because a more reliable system can produce more products. The reliability parameter is a decision variable to maximize the profit in a production system.

However, the above-mentioned joint optimization of EMQ and maintenance policies have been applied only to traditional maintenance policies and CBM has not been considered yet for the EMQ models. CBM analysis recommends maintenance actions based on the information collected through CM. Due to the low cost and wide availability of highly effective hardware and software for installing data collection and information systems, CM and CBM have become the main elements of modern maintenance management programs with an increased focus on predictive maintenance. The condition of the machine is monitored at regular intervals. Once the condition is critical, the machine is preventively maintained. This approach has been applied widely, since it can increase the production efficiency by maximizing the equipment availability or/and minimizing the related costs. For an extensive review on CBM models readers are referred to Jardine et al. (2006), Rehorn et al. (2005), and Si et al. (2011).

One of the powerful and popular statistical models that is suitable for modeling degrading systems in the CBM framework is PHM. The PHM considers both age and condition variables called covariates using a hazard rate. This model was introduced by Cox (1972). Later, Kumar and Klefsjo (1994) reviewed the literature on the PHM. Increasingly, PHM is gaining popularity as a useful model for different applications such as Ding and He (2011), Feng et al. (2010), and Tian and Liao (2011). Makis and Jardine (1992) developed the optimal maintenance policy for a PH model minimizing the long-run expected average cost per unit time. They considered a PHM with Markov covariate process and periodic monitoring. Then, Wu and Ryan (2010) extended their work by considering possible state transitions between inspection times.

However, the joint optimization of manufacturing quantity and maintenance for a deteriorating production facility using PHM has not yet been considered, which is a better representation of real systems subject to CM. In this paper, we propose a joint optimization of EMQ and a preventive maintenance policy for a production system subject to CM at the opportunistic epochs when a production run is completed using PHM to minimize the long-run expected average cost per unit time. The main contributions of this paper can be summarized as follows:

(i) Development of the EMQ model considering production system deterioration and CBM. The production facility is subject to deterioration and the joint optimization of EMQ and maintenance policy using PHM is addressed.
(ii) Consideration of both maintenance and production costs which include the set-up, inventory holding, and shortage costs as well as inspection, preventive, and corrective maintenance costs.
(iii) Development of the semi-Markov decision process (SMDP) framework and the algorithm to obtain the optimal lot size and maintenance policy for the proposed model.
(iv) Numerical studies and a comparison with the traditional age-based policy.