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Joint optimization of condition-based maintenance and production lot-sizing

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ABSTRACT

Due to the development of sensor technologies nowadays, condition-based maintenance (CBM) programs can be established and optimized based on the data collected through condition monitoring. The CBM activities can significantly increase the uptime of a machine. However, they should be conducted in a coordinated way with the production plan to reduce the interruptions. On the other hand, the production lot size should also be optimized by taking the CBM activities into account. Relatively fewer works have been done to investigate the impact of the CBM policy on production lot-sizing and to propose joint optimization models of both the economic manufacturing quantity (EMQ) and CBM policy. In this paper, we evaluate the average long-run cost rate of a degrading manufacturing system using renewal theory. The optimal EMQ and CBM policy can be obtained by minimizing the average long-run cost rate that includes setup cost, inventory holding cost, lost sales cost, predictive maintenance cost and corrective maintenance cost. Unlike previous works on this topic, we allow the use of continuous time and continuous state degradation processes, which broadens the application area of this model. Numerical examples are provided to illustrate the utilization of our model.

1. Introduction

Many manufacturing systems are subject to deterioration with usage, e.g., lithography machines in semiconductor industry, wind farms, and boring machines in automotive industry (Francone et al., 2010; Guo, Watson, Tavner, & Xiang, 2009; Rausch & Liao, 2010). Due to the development of sensor technologies nowadays, we can continuously monitor the degradation behavior of systems to facilitate the prediction of system failures. A maintenance program can be established and optimized based on the information collected through condition monitoring, which is called condition-based maintenance (CBM). Research in the CBM area grows rapidly (Jardine, Lin, & Banjevic, 2006; Peng, Dong, & Zuo, 2010). For maintenance optimization in the CBM area, many mathematical models have been proposed to determine the control limits and/or inspection intervals in order to minimize the total cost (including downtime, unexpected failures, replacements, inspections, etc.) or to maximize the reliability or availability of systems (Van Noortwijk, 2009). Relatively fewer works have been done to investigate the impact of the CBM policies on production scheduling and to propose joint optimization models for the economic manufacturing quantity (EMQ) and CBM policy. However, scheduling maintenance activities by only considering costs related to downtime and inspection/maintenance may interrupt the production plan and incur additional costs (e.g., inventory holding costs or lost sales). In this paper, we establish a new model to evaluate the total cost of production lot-sizing and CBM simultaneously, and try to obtain the optimal solution by minimizing the average long-run cost rate of production and maintenance for a degrading manufacturing system.

For real world applications, e.g., a boring process for mechanical parts, the plant manager not only needs to specify the schedule of maintenance in order to guarantee the proper running of boring machines, but also has to determine the lot size of production. Traditionally, these two decisions are made separately for the reasons of minimizing different cost elements. The maintenance schedule is normally optimized to minimize the cost of maintenance, downtime and failure, whereas the production lot size is usually determined to minimize the cost of inventory, setup and lost sales. But the wear-out or sudden failures of boring tools may happen in the middle of the production of a lot. If the failed boring tools cannot be fixed immediately, lost sales may occur due to this period of downtime. The determination of production lot size should therefore consider the failure processes of boring tools. Moreover, the

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Acronyms

CBM	Condition-based Maintenance
EMQ	Economic Manufacturing Quantity

Notation

t	production time of the manufacturing system
$X(t)$	degradation state of the manufacturing system at t
H	failure threshold of the degradation process $X(.)$
T_H	first passage time of $X(.)$ over H
C	control limit of $X(.)$
T_C	first passage time of $X(.)$ over C
$f_{T_C}(.)$	pdf of T_C
$f_{T_H}(.\|T_C = t_c)$	pdf of T_H under the condition that $T_C{=}t_c$
t'	operational time including production time and idle time
$I(t')$	on-hand inventory level at time t'
d	demand rate
u	production rate
Q	production quantity/lot size
t_0	production time for a lot
n	number of lots produced
S	random duration of corrective maintenance
$F_S(.)$	cdf of corrective maintenance time S
$f_S(.)$	pdf of corrective maintenance time S
l	constant duration of predictive maintenance
$C(t')$	cumulative production and maintenance cost until time t'
$E[TC]$	expected total production and maintenance cost per cycle
$E[K]$	expected length of a cycle
C_S	setup cost per lot
$E[SC]$	expected setup cost per cycle
$E[HC]$	expected inventory holding cost per cycle
C_I	holding cost per unit held in inventory per time unit
C_L	cost of lost sales per unit
$E[LS]$	expected lost sales cost per cycle
$E[PM]$	expected predictive maintenance cost per cycle
C_P	cost related to the predictive maintenance activities triggered by the control limit C after the production of a lot
$E[CM]$	expected corrective maintenance cost per cycle
C_C	cost due to the unexpected machine failure, including corrective maintenance cost, scrap costs due to the machine failure, costs of changing staff working schedule or transportation schedule, etc
$CR(Q,C)$	average long-run total cost rate

scheduled preventive maintenance are better conducted during the idle periods of boring machines to not interrupt the production of a lot, which requires an integrated approach to decide on maintenance schedule and production lot size.

For deteriorating systems, the optimization models of CBM policies were created to determine the optimal control limits and/or inspection intervals, based on the stochastic degradation processes that are estimated from the condition monitoring data. For instance, by assuming the random coefficient model for degradation processes (Lu & Meeker, 1993), Wang (2000) proposed a model for single-component system to determine the optimal CBM policy in terms of a criterion of interest, which can be cost, downtime or reliability. Gebraeel, Lawley, Li, and Ryan, (2005, 2006) extended the random coefficient model to estimate residual life distributions from sensor signals by Bayesian updating. Using this technique, a single-unit replacement problem is formulated as a Markov decision process to develop a structured replacement policy by Elwany, Gebraeel, and Maillart (2011).

Markovian-based models were also applied to describe cumulative damages (Bogdanoff & Kozin, 1985; Neves, Santiago, & Maia, 2011). Application studies on marine engine cylinder liners were provided for discrete time and state Markov wear processes with both stationary (Giorgio, Guida, & Pulcini, 2010) and non-stationary (Giorgio, Guida, & Pulcini, 2011) transition matrices. A continuous time and state Markov process with non-stationary transition probabilities was also proposed by Giorgio, Guida, & Pulcini, 2015. Cumulative damages were also explicitly considered in estimating the probability distribution of the tensile strength of materials (Durham & Padgett, 1997). Optimal replacement policies were developed for partially observable Markov processes (Makis & Jiang, 2003). Sequential condition-based maintenance policies were also proposed with a dynamic inspection interval and/or a dynamic control limit using Markovian-based models (Castanier, Bérenguer, & Grall, 2003; Chen & Trivedi, 2005; Chen & Wu, 2007).

For monotonic stochastic deteriorations with independent increments, Gamma processes were used for the purpose of optimizing condition-based maintenance (Van Noortwijk, 2009). The CBM models using Gamma processes were developed to have a single-level control limit or a multi-level control limit (Grall, Berenguer, & Dieulle, 2002) under the scenarios of periodic inspection, aperiodic inspection (Dieulle, Berenguer, Grall, & Roussignol, 2003) or continuous monitoring (Liao, Elsayed, & Chan, 2006). Partial repair was also investigated in previous research using Gamma processes (Newby & Barker, 2006). CBM policies for multi-deteriorating mode systems were also studied (Ponchet, Fouladirad, & Grall, 2010). Inverse Gaussian processes can also be used to model such stochastic deteriorations (Wang & Xu, 2010).

Dynamic environment factors were also considered in the Markov-based degradation processes (Kharoufeh, 2003; Singpurwalla, 1995). Proportional hazards models have been used to relate the system's condition variables and external factors to the failure of a system in replacement optimization (Ghasemi, Yacout, & Ouali, 2007; Golmakani & Fattahipour, 2011; Lin, Banjevic, & Jardine, 2006; Vlok, Coetzee, Banjevic, Jardine, & Makis, 2002; Wu & Ryan, 2011). A CBM policy for multi-component systems was proposed using proportional hazards model (Tian & Liao, 2011).

Reliability and maintenance of manufacturing systems have a direct impact on production capacity, thus many researches on production planning have been done to obtain the economic manufacturing quantity (EMQ) considering the effect of maintenance activities on manufacturing systems. Lee and Rosenblatt (1987) optimized the production cycle and the inspection intervals of maintenance simultaneously for systems with non-self announcing failures. Extensions of this work have been done to relax the assumption of a constant restoration cost and to further specify the costs resulting from producing defective items when the process is out of control (Lee & Park, 1991; Lee & Rosenblatt, 1989). Tseng (1996) reformulated Lee and Rosenblatt's (1987) model by assuming that the process lifetime is arbitrarily distributed with an increasing failure rate, and a preventive maintenance policy with equal intervals during the production run is introduced to improve the reliability of the deteriorating system. Some useful structural results of Tseng's (1996) model have been developed to improve the efficiency of the solution procedure (Wang, 2006; Wang & Sheu, 2000). Boukas and Haurie (1990) combined production and preventive maintenance planning in cases where the machine's failure probability increases with its age, using the hedging point

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