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Control-limit preventive maintenance policies for components subject to imperfect preventive maintenance and variable operational conditions

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ABSTRACT

This paper develops two component-level control-limit preventive maintenance (PM) policies for systems subject to the joint effect of partial recovery PM acts (imperfect PM acts) and variable operational conditions, and investigates the properties of the proposed policies. The extended proportional hazards model (EPHM) is used to model the system failure likelihood influenced by both factors. Several numerical experiments are conducted for policy property analysis, using real lifetime and operational condition data and typical characterization of imperfect PM acts and maintenance durations. The experimental results demonstrate the necessity of considering both factors when they do exist, characterize the joint effect of the two factors on the performance of an optimized PM policy, and explore the influence of the loading sequence of time-varying operational conditions on the performance of an optimized PM policy. The proposed policies extend the applicability of PM optimization techniques.

1. Introduction

Since 1960s, maintenance optimization has continuously been an interesting and important topic for the researchers for its growing impact on a company's competitiveness [1]. In the recent decades, the maintenance policies have gradually shifted from run-to-failure corrective maintenance (CM), time-based preventive maintenance (PM), to condition-based maintenance (CBM) and predictive maintenance (PdM) [2,3].

Essential elements of a maintenance policy include: (1) the objective, such as maximization of average system availability in an infinite time horizon [4–6], minimization of the overall production and maintenance losses in a finite time horizon [7], minimization of the average maintenance cost rate per operational time in an infinite time horizon [8,9], etc.; (2) the maintenance policy, such as periodic policy, control-limit policy [4,5], sequential policy [7–9], etc.; (3) the maintenance quality/effect, such as perfect PM act which restores a system to a state "as good as new", imperfect PM act which restores a system to a better but not "as good as new" state [10,11], etc.; (4) the degradation characteristics, such as a batch of systems' lifetime distribution [8], the stochastic, Markov, hidden Markov degradation models [12,13]; and (5) the maintenance constraints, such as limited maintenance resources, maintenance conflicts among adjacent components [7], etc.

As imperfect PM acts are very common in industrial practice (e.g. spraying lubricant to a drill bit or replacing a component for a walking robot), many recent studies tend to include the effect of imperfect PM acts in maintenance policies [10,11,14–16]. On the other hand, efforts in maintenance optimization are targeted towards establishing maintenance policies for systems subject to variable operational conditions based on proportional hazards model (PHM) and similar models [17,18], proportional intensity model (PIM) [19–21], etc. As systems under various operational conditions (e.g. temperature, humidity and vibration level) may exhibit significantly different degradation rate [22], it is necessary to treat the systems under various operational conditions separately.

Although there are many maintenance policies that consider the effect of imperfect PM acts and variable operational conditions [10,11,14–18], a maintenance policy which accounts for both of these two factors has not been reported yet. However, it is common to see a batch of systems subject to imperfect PM acts as well as different operational conditions (e.g. a batch of drill bits working with different thrust forces and receiving lubricant oil). As a result, it is necessary to develop practical maintenance policies for such systems, and study the properties of the policies for further insights.

Abbreviations: ARF, age reduction factor; BGA, ball grid array; CBM, condition-based maintenance; CM, corrective maintenance; EPHM, extended proportional hazards model; HRIF, hazard rate increase factor; HRLPM, hazard rate limit preventive maintenance; PM, preventive maintenance; PdM, predictive maintenance; PHM, proportional hazards model; PIM, proportional intensity model; PCB, printed circuit board; PSD, power spectral density; RLPM, reliability limit preventive maintenance

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Nomenclature

A_H	the expected average system availability in one replacement cycle in the HRLPM policy
A_R	the expected average system availability in one replacement cycle in the RLPM policy
K	the random positive number of PM acts (imperfect PM acts and entire replacement) a system receives in one replacement cycle in the HRLPM policy
L	the random positive number of PM acts (imperfect PM acts and entire replacement) a system receives in one replacement cycle in the RLPM policy
M	the maximum number of PM acts a historical training sample receives before it fails or gets suspended
N	the number of all the training samples for the EPHM
Q_j	cumulative system hazard (i.e. the expected number of system failures) in the jth PM interval
$R_n(\cdot)$	the EPHM's reliability function after the nth PM act and before the $(n+1)$th PM act
T_j	the jth PM interval, i.e. the overall system operation time between its $(j-1)$th PM act and its jth PM act
T_{MH}	the expected overall maintenance duration in one replacement cycle in the HRLPM policy
T_{MR}	the expected overall maintenance duration in one replacement cycle in the RLPM policy
T_{OH}	the expected overall operation time in one replacement cycle in the HRLPM policy
T_{OR}	the expected overall operation time in one replacement cycle in the RLPM policy
$\mathbf{Z}(t)$	vector of covariates
a_j	the HRIF due to the jth PM act
b_j	the ARF due to the jth PM act
h	the random hazard rate threshold
$h(\cdot)$	the PHM's hazard function
$h_0(\cdot)$	baseline hazard function
$h_n(\cdot)$	the hybrid imperfect PM model's hazard function after the nth PM act and before the $(n+1)$th PM act
l_j	the likelihood function for each training sample's jth event
n_j	the number of samples that fail or get suspended after they receive j PM acts
r	the random reliability threshold
t	global random time
t'	local random time between two PM acts
t_c	maintenance duration per CM act
t_p	maintenance duration per PM act
t_r	maintenance duration per replacement
y_j	system's effective age just before the jth PM act
$\lambda_n(\cdot)$	the EPHM's hazard function after the nth PM act and before the $(n+1)$th PM act
Γ_j	failure of suspension time of sample j
γ	the shape parameter of Weibull distribution
η	the scale parameter of Weibull distribution
δ_j	the event indicator of sample j
$\boldsymbol{\beta}$	vector of regression coefficients

By the above motivation, this paper develops two component-level control-limit PM policies for systems subject to the joint effect of imperfect PM acts and variable operational conditions, and investigates the properties of the proposed policies. Within the PM policies, the extended proportional hazards model (EPHM) is used to model the system failure likelihood influenced by both factors, which is capable of handling the case of time-varying operational conditions. Several numerical experiments are conducted for policy property analysis. The most related work might be [23], which presents an age-dependent reliability model considering effects of maintenance and working conditions. However, the work in [23] does not further establish a PM policy and the model in [23] is generally applicable to the case of constant working condition between two consecutive PM cats.

The rest of the paper is organized as follows: Section 2 provides a concise summary of the EPHM and the recursive algorithm for parameter estimation. Section 3 establishes two component-level control-limit PM policies based on the EPHM. Section 4 conducts several numerical experiments to investigate the properties of the proposed PM policies. Finally, Section 5 concludes the paper.

2. EPHM

In this paper, the EPHM is used to model the system failure likelihood influenced by imperfect PM acts and variable operational conditions. In essence, the EPHM is a hybrid model of the PHM and the hybrid imperfect PM model. Next, we outline all the essential elements of the EPHM.

2.1. Modeling

The EPHM is inspired by two models: the PHM [24–34] and the hybrid imperfect PM model [35–37]. Generally, the PHM has the functional form

$$h(t;\mathbf{Z}(t)) = h_0(t)\exp(\mathbf{Z}(t)'\boldsymbol{\beta}), \tag{1}$$

where $h(t;\,\mathbf{Z}(t))$ is the system's hazard/failure rate function, $h_0(t)$ is the baseline hazard rate function which is a function of system age, $\mathbf{Z}(t)'=(z_1(t),\,\ldots,z_m(t))$ is the vector of the covariates at random time t, and $\boldsymbol{\beta}'=(\beta_1,\,\ldots,\,\beta_m)$ is the vector of regression coefficient. Typically, $\mathbf{Z}(t)'$ could be the vector of variables that influence the system hazard rate. Using the systems' operational condition as a covariate enables the PHM to evaluate the effect of variable operational conditions on the systems' failure likelihood.

On the other hand, the hybrid imperfect PM model has the functional form

$$h_n\left(t'+\sum_{j=1}^{n} T_j\right) = A_n h(t'+b_n y_n), \tag{2}$$

where $h_n(t+\sum_{j=1}^{n} T_j)$ is the system's hazard function after the nth PM act and before the $(n+1)$th PM act, T_j is the jth PM interval (i.e. the overall system operation time between the $(j-1)$th and the jth PM acts), t' is the random local time after the jth PM act and before the $(j+1)$th PM act, $A_n = a_0\cdot a_1\cdots a_n$, where $a_j > 0$ is the hazard rate increase factor (HRIF) due to the jth PM act and $a_0=1$, $b_n > 0$ is the age reduction factor (ARF) due to the nth PM act, y_n is the system's effective age just before the nth PM act, where

$$\begin{aligned} y_n &= T_n + b_{n-1} y_{n-1} \\ &= T_n + b_{n-1}(T_{n-1} + b_{n-2} y_{n-2}) \\ &= T_n + b_{n-1} T_{n-1} + \cdots + \left(\prod_{j=1}^{n-1} b_j\right) T_1, \end{aligned} \tag{3}$$

and $y_1 = T_1$. In Eq. (2), the ARF measures the immediate effect of imperfect PM acts that restores a system to a younger but not zero