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A value-based preventive maintenance policy for multi-component system with continuously degrading components

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ABSTRACT

A dynamic preventive maintenance policy for system with continuously degrading components is investigated in this paper. Different from traditional cost-centric preventive maintenance policy, our maintenance strategy is formulated from the value perspective. Component value is modelled as a function of component reliability distribution. Maintenance action is triggered whenever the system reliability drops below a certain threshold. Our policy mainly consists of two steps: (i) determine which component to maintain; (ii) determine to what degree the component should be maintained. In Step 1, we introduce the yield-cost importance to select the most important component. In Step 2, the optimal maintenance level is obtained by maximizing the net value of the maintenance action. Finally, numerical examples are given to illustrate the proposed policy.

1. Introduction

Maintenance plays an important role in industrial production, especially in areas where the loss of system failure is large. Various maintenance policies have been developed to improve system safety, reduce system failures and lower manufacturing cost. Preventive maintenance (PM) is a policy that occurs when the system is still operating, aiming to retain the system or specified components in a certain condition [1–4]. PM policy focusing on single-component degrading system has been extensively studied [5–7]. However, in recent years, due to the increasing complexity and variety of production systems, more attention is being paid to PM on multi-component systems [8].

The existing PM policies for multi-component degrading system can be categorized into two classes. The first class assumes that each component only has two states, *i.e.*, functioning or failed. Component degradation is described in terms of failure rate or hazard rate, and so on with the objective to find an optimum strategy that minimizes maintenance cost. Usually, PM is triggered when the system reliability or availability falls below a certain prescribed level. As a result, the problem becomes optimization of PM thresholds or other parameters that lead to cost minimization [9,10]. For instance, Zhou and Li [11] derived a dynamic PM policy by sequentially optimizing maintenance cost at every maintenance point. Samrout et al. [12] addressed the problem of PM optimization by referring component degradation to as proportional hazard rate. Lin and Wang [13] investigated the PM problem under reliability constraints and adopted importance measures to minimize non-periodic PM cost. For some more recent works, see *e.g.* [14–16].

The second class is based on discrete-state Markov chains, where component states are usually divided into several classes such as ‘as good as new’, ‘preventive maintenance due’ and ‘failed’ [17–19]. Gürler and Kaya [20] proposed an approximation to represent component lifetime as a number of finite stages. Nourelfath and Ait-Kadi [21] addressed the problem of prioritizing resources between components under the reliability constraint. Modelling by discrete Markov chains still owns some disadvantages, *e.g.*, the classification of component states is arbitrary. Moreover, it assumes that failures can only occur at discrete time points. Therefore, it is more appropriate to treat component degradation as a continuous stochastic process.

In the literature, most maintenance policies are cost-centred, *i.e.*, policies are developed by minimizing maintenance cost [22]. However, for companies, as maintenance action is meant to generate profit, it is more reasonable to view maintenance as a value-generating action. Wang [1] highlighted the critical idea that when making the maintenance decision, cost, along with the value resulting from improved reliability, should be considered. Hitherto, few studies have been undertaken to address the problem of value-based maintenance policy [23,24].

Motivated by the idea of maintenance value, our PM policy is developed from the value perspective. In the previous works, for

Acronym: Cdf, cumulative distribution function; Pdf, probability density function; PM, preventive maintenance

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Notation

c_i	one-time component maintenance cost of component i, function of component reliability distribution
$c(t)$	operating cost
$F(t)$	system lifetime distribution
$F_i(t)$	lifetime distribution of component i
$g_i(\bullet)$	value function of component i
$h_i(\bullet)$	degradation path of component i
I_B^i	Birmbaum importance of component i
I_Z^i	yield-cost importance of component i
L_i	failure threshold of component i
n	number of components
$R(t)$	system reliability distribution
$R_i(t)$	reliability distribution of component i
S	mission duration
T	system lifetime
T_k	time point of the kth PM action
$v(t)$	operating revenue
$X_i(t;\mu_i,\theta_i)$	degradation level of component i over time t, where μ_i is a fixed parameter, θ_i is a random variable
$Y(t)$	system yield function
Z_i	net value generated by maintenance of component i
Z_S	net value within usage duration
π	maintenance action
π^*	optimal maintenance action
$\Psi(\bullet)$	system structure function
σ	reliability threshold for PM

imperfect maintenance, the repair rate was assumed to be constant and the maintenance cost was invariant [25]. However, maintenance cost of complex system would vary, especially for imperfect maintenance, where maintenance cost would be different if the maintenance degree varies [26,27]. Resources should be allocated to components with less maintenance cost [28].

In this study, a PM policy for multi-component system concerning continuously degrading components is developed. The maintenance objective is to maximize the maintenance net value. Different from previous stationary maintenance policies, a dynamic PM policy is proposed, with the advantage of incorporating short-term information. The PM policy consists of two steps: (i) determine which component to maintain; (ii) determine to what degree the component should be maintained. The yield-cost importance is introduced to determine the most importance component.

The rest of this paper is organized as follows. Section 2 presents system description and reliability analysis for the system composed of continuously degrading components. Section 3 constructs the PM objective and introduces yield-cost importance to make the maintenance decision. Section 4 gives a numerical example to illustrate the proposed method. Finally, Section 5 concludes the study.

2. Assumptions and model specifications

2.1. Basic assumptions

In this study, the following assumptions are used:

(1) Components are mutually independent.
(2) Each component is continuously monitored.
(3) Compared to the time period between two consecutive PM actions, the duration of PM activity is negligible.
(4) Degradation is the only cause of system failure. The effects of aging, wear and other cumulative damages are integrated into a degradation process.
(5) Only one maintenance crew is available and only one component can be maintained at a time.
(6) Maintenance action does not change the degradation path of components. The impact of maintenance activity lies in restoring the system or component to a new state. The degradation path is regarded as a characteristic of the system in filed operation, which is not influenced by maintenance.

The aforementioned assumptions were used in the literatures, *e.g.*, [29,30].

2.2. System description

The system considered here is a series–parallel system with degrading components. Denote the degradation level of component i over time t as $X_i(t;\mu_i,\theta_i)$, where μ_i is the fixed-effect parameter, and θ_i is the random-effect parameter; in most cases, $X_i(t;\mu,\theta)$ is a monotonic function over time t [31]. Fig. 1 gives simple description of the component degradation process. In addition, $X_i(t;\mu_i,\theta_i)$ is non-negative due to the nature of degradation measurements.

2.3. Reliability and lifetime distribution analysis

In this paper, component failure is defined as "soft failure", *i.e.*, a component fails whenever the degradation level $X_i(t;\mu_i,\theta_i)$ exceeds threshold value L_i. The set of failure threshold values, $L=\{L_i;\ i=1,2,\ldots,n\}$, is assumed to be pre-set. Without loss of generality, degradation level is assumed to be monotonically increasing, and reliability of component i at time t is represented by the probability that $X_i(t;\mu_i,\theta_i)$ stays below threshold L_i:

$$R_i(t)=P\{X_i(t;\mu_i,\theta_i)<L_i\}. \tag{1}$$

Let $W_i(t)$ denote the functioning identifier of component i at time t:

$$W_i(t)=\begin{cases}1 & \text{if component } i \text{ functions at time } t.\\ 0 & \text{if component } i \text{ fails at time } t.\end{cases} \tag{2}$$

The system reliability is

$$R(t)=P\{\Psi(\mathbf{W}(t))=1\}, \tag{3}$$

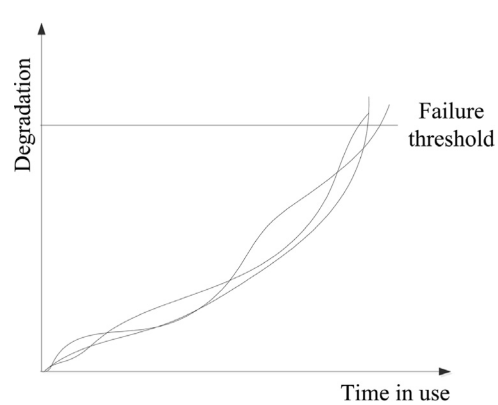

Fig. 1. Component degradation process.