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Dynamic preventive maintenance strategy for an aging and deteriorating production system

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ABSTRACT

This paper proposes a dynamic preventive maintenance strategy for a multi-state deteriorating production system. A real-time operating state can be derived via the healthy index. A time-dependent state transition probability matrix is used to describe the aging and deteriorating system. The current probability transition matrix and the aging factor are estimated based on historical data. Then one can update the transition probability matrix the next time in terms of the aging factor. Multiple actions at risk are provided to maintain the system with time spent considered. The optimal maintenance action at each operating state and at each specific time is obtained at the minimum expected total cost per unit time during a given finite time interval.

1. Introduction

Extensive reviews of various maintenance policies on a deteriorating system can be found in Pierskalla and Voelker (1976), Sherif and Smith (1981), Valderz-Flores and Feldman (1989). However, such maintenance policies can be classified into two groups. The first group deals with the maintenance action which is taken under failure without inspection. Such a group includes:

(1) the age replacement policy (i.e. replacement upon failure or at age) (Barlow & Hunter, 1960) and their extensions by including minimal repair such as Bagai and Jaint (1994), Chen and Feldman (1997), Cleroux, Dubuc, and Tilquin (1979), Jhan and Sheu (1999), Mazzuchi and Soyer (1996), Sheu, Yeh, Lin, and Juang (1999);
(2) the block replacement policy (i.e. replacement at kT for $k = 1,2\ldots$ or upon failure) and the failure replacement policy (i.e. replacement upon failure) (Berg & Epstein, 1978; Block, Langberg, & Savits, 1993; Lam & Yeh, 1994); and
(3) the scheduled maintenance policies through predicting failure time statistically (Canfield, 1986; Chaudrhuri & Sahu, 1977).

The second group deals with the maintenance action which is taken under failure with inspection equipment. Such a system can be regarded as a multi-state deteriorating system with states in deteriorating order $1 < 2 < \cdots < i < \cdots < j < \cdots < L$, (1: perfect,..., L: complete failure). Lam and Yeh (1994) proposed a control-limit replacement policy under continuous inspection so that replacement is taken optimally upon the threshold state j^* which is identified by inspection or when the complete failure L is observed. Lam and Yeh (1994) proposed another control-limit replacement policy under inspection at each nd to determine the optimal (d^*,j^*) so that the replacement takes places at nd whenever the system state x at nd satisfies $j^* \leqslant x \leqslant L$. Chiang and Yuan (2001, 2000) proposed still another two control-limit preventive maintenance policies under continuous and periodic inspection respectively to determine optimal (i^*,j^*) (two threshold states $1 < i^* < j^* < L$) so that the repair (resp. replacement, do-nothing) is taken whenever the system state x satisfies $i^* \leqslant x < j^*$ (resp. $j^* \leqslant x \leqslant L$: otherwise).

Wood (1998) proposed a control limit rule that requires the system to be restored whenever its damage exceeds a certain level under continuous inspection. All of the methods stated above have to assume that the system satisfies a continuous-time Markov chain. Also, the threshold states were obtained and the optimal maintenance action taken is state-dependent only (i.e. not time-dependent).

Jardine, Banjevic, and Makis (1997) and Makis and Jardine (1992) proposed an optimal dynamic (i.e. both state- and time-dependent) replacement policy for condition-based maintenance. Wildeman, Dekker, and Smith (1997) proposed another dynamic preventive maintenance policy that a long-time tentative plan was taken based on a subsequent adaptation and according to available information on the short term with a rolling-horizon approach.

Chen, Chen, and Yuan (2003) proposed a dynamic preventive maintenance policy for a multi-state deteriorating system. The system is equipped with sufficient inspection equipment connected to a computer center. The measurement or inspection is taken in a

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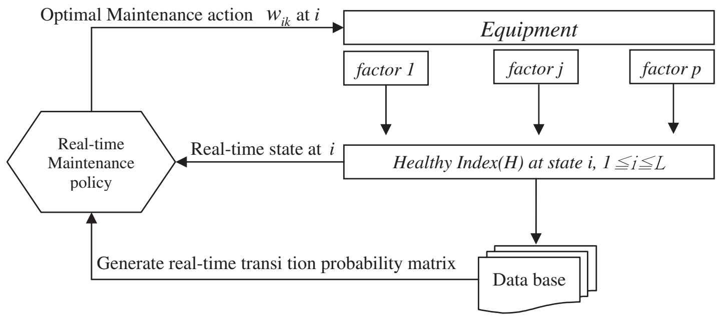

Fig. 1. The diagram of the dynamic preventive maintenance policy.

fixed time period nd for a fixed d. The system healthy index is calculated to identify the system state x and to choose the maintenance action at the minimum expected total cost from the set A_x of alternatives. However, a multi-state Markov chain with time independent transition probabilities is used to model the system without aging. The maintenance policy is state-dependent only. Liao, Elsayed, and Chan (2006) considered a condition-based maintenance model for continuously degrading system under continuous monitoring. The states of the system are randomly distributed with residual damage after maintenance. The optimum maintenance threshold is determined using condition-based availability limit policy. Lu, Tu, and Lu (2007) studied a predictive condition-based maintenance approach based on monitoring and predicting a system's deterioration. The system's deterioration is considered to be a stochastic dynamic process with continuous degrading. Yeh, Kao, and Chang (2009) proposed a maintenance scheme for leased equipment using failure rate reduction method and derives an optimal preventive maintenance policy that minimize expected total cost. A contemporary thorough review on these topics has been surveyed by Sheu, Lin, and Liao (2005) and Wang (2002).

By considering time-dependent transition probabilities, which are updated in terms of the aging factor in Chen and Wu (2007), Guo et al. (1998), this paper is to propose a dynamic multi-action preventive maintenance strategy for a system under aging and deteriorating environment.

2. System assumptions

2.1. System states in terms of a healthy index

1. The H value of a system quality level or healthy index ($H \in [0,1]$) can be characterized by system parameters (cf. Fig. 1) completely in a formula cited in Chen and Wu (2007), Sheu et al. (2005).
2. The values of such system parameters and the H value can be measured and calculated respectively at each inspection time t_n by inspection equipment and a computer in negligible time, where such inspection equipment is connected to the computer center.
3. At each inspection point t_n, the system state (or quality level) then is identified by the computer center in negligible time as follows: a sequence $0 = h_0 < h_1 < h_2 < \cdots < h_{L-1} < h_L = 1$ is predetermined properly so that the system state at each inspection point t_n is identified as $i \in \{1,2,\ldots,L\}$ if its index value $H \in (h_{i-1}, h_i)$.

2.2. System states

The system in this study can be regarded as deteriorating according to the order $1 < 2 < \cdots < L$, where 1 is the best state and L is the worst state, which is either the complete failure or the state in which the user thinks it no more worth while to maintain the system.

Besides, the system's temporary interruption state due to an unexpected cause denoted as D might also occur. However, its occurrence is self-indicative (i.e. without needing to be identified by inspection). Suppose that system interruption state D can be ignored at each inspection point as the probability of its occurrence at each inspection point. Hence, the system state space $S_{total} = S_H \cup \{D\}$, where $S_H = \{1,2,3,\ldots,L\}$.

2.3. Assumptions on maintenance policy for the system

1. The minimal repair will be taken under system interruption state D (i.e. restore the system back to the state before the system interruption state occurs) in negligible time.
2. The set of possibly chosen maintenance actions at state i and each inspection time is denoted as,

$$W_i = \{a_{i0}, a_L\} \cup \{a_{ik} | 1 \leqslant k \leqslant i-1, k \in S_H\}, \quad i = 2,3,\ldots,L-1,$$

   where a_{i0} denotes *do-nothing* and $a_{ik}(0 < k < i)$ denotes the action to restore the system state from i to a better k, and a_L is disposal/replacement.
3. Only *do-nothing* is taken at system state 1. Only Disposal/replacement a_L is taken at system state.
4. Each $a_{ik}(0 < k < i)$ has the risk $r_{kh}^{(a_{ik})}\left(r_{kh}^{(a_{ik})} \geqslant 0, h \in S_H\right)$, so that $\sum_{h=k}^{L} r_{kh}^{(a_{ik})} = 1$. i.e., whenever the action a_{ik} is taken at t_n, the actual state will be $h(k \leqslant h \leqslant L\text{-}1)$ with probability r_{kh}. The risk of $r_{kh}^{(a_{ik})}$ is independent of i, i.e., $r_{kh}^{(a_{ik})} = r_{kh}$ for all h and each i for simplicity.
5. One and only one maintenance action (including *do-nothing*) is taken at each inspection point t_n.
6. The action at the minimal expected total cost per unit time over $[t_n, t_{n+K}]$ is chosen immediately as the optimal action at each inspection point t_n.

2.4. Symbol description

β	discount rate
$c(a_{ik})$	expected cost of the action a_{ik} and $c(a_{i0}) = 0\ \forall i \in S_H$
$o(i)$	expected total cost during (t_n, t_{n+1}) due to minimal repairs or scrap at system state i and t_n
$O_n(a_{ik})$	expected total cost during (t_n, t_{n+1}) due to minimal repairs or scrap given the action a_{ik} at state i and t_n
R_L	replacement/disposal cost of the system