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A delay time model for a mission-based system subject to periodic and random inspection and postponed replacement

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ABSTRACT

We propose an inspection and replacement policy for a single component system that successively executes missions with random durations. The failure process of the system can be divided into two states, namely, normal and defective, following the delay time concept. Inspections are carried out periodically and immediately after the completion of each mission (random inspections). The failed state is always identified immediately, whereas the defective state can only be revealed by an inspection. If the system fails or is defective at a periodic inspection, then replacement is immediate. If, however, the system is defective at a random inspection, then replacement will be postponed if the time to the subsequent periodic inspection is shorter than a pre-determined threshold, and immediate otherwise. We derive the long run expected cost per unit time and then investigate the optimal periodic inspection interval and postponement threshold. A numerical example is presented to demonstrate the applicability of the proposed maintenance policy.

1. Introduction

To meet stringent reliability requirements and reduce the occurrence frequency of failures, preventive maintenance including inspection, preventive replacement (repair) and routine service is often implemented for real-world systems. Inspections, which may have different depths or levels [28], are of great importance among preventive maintenance, as they provide information about the system state for the implementation of repair or replacement. This is the case considered in this paper, where the decision making about preventive replacement depends mainly on the outcome of inspections.

Due to its implementation simplicity, periodic inspection is one of the most commonly applied strategies, and has been widely discussed in the literature [9,12,20,23,24]. However, in many industrial applications, it is not suitable to inspect systems in a strict periodic fashion. A typical example is that a database system has to complete successive, non-overlapping missions [10]. For such a system, inspections are generally performed at the completion of each mission to prevent losses of production due to the sudden suspension of missions [18]. Particularly, when each mission has a random duration, these inspections are called random inspections [14]. For muti-component systems, opportunistic inspections (that are also random) could be implemented, where a hard failure creates an opportunity to inspect all the components suffering soft failures [6,11,25,26]. Note, however, that in many cases deploying only one type of inspection is not sufficient in terms of the maintenance cost, rather some combined inspection policies are recommended since more decision options could be offered [15,16]. In view of this, we schedule both random and periodic inspection policies for a mission-based system, where missions are executed with random durations. The downtime cost is considered in similar policies [12,13], but in this paper it is not needed since failure replacement is immediate.

It is noted that most random maintenance models developed for mission-based systems assume that the system state is binary, i.e., normal or failed. To establish the relationship between inspections and failures for such models, one has to make a fundamental assumption that replacement (repair) of failures is undertaken at the time of a random inspection. Nevertheless, the majority of failures observed in industry are actually self-announcing and immediately removed. Such failures are addressed in some random maintenance models [34–36], but replacement is the only maintenance action for these models. In contrast, our paper considers the failure time of the mission-based system as a two-stage process, where a defective (potential failure) stage is involved. Failures of the system are always self-announcing, while the defective state could only be identified at inspections. Compared with a binary state system, more preventive maintenance measures could be provided for such a system to rectify

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the remaining problems before the required function is completely lost.

The above mentioned two-stage failure process is normally modeled using the delay time concept, which was first proposed and studied by Christer [4]. According to the delay time concept, the delay time is defined as the period from the initial point that a defect can be first identified by an inspection to the occurrence of a failure if the defect is unattended [28]. Numerous research efforts have been devoted to this area for single-component systems as well as multi-component systems. For single-component systems, the delay time concept has been adopted under various modeling scenarios, such as safety critical systems [1], preparedness systems [3], imperfect inspections and repairs [2,7,8,17,27,35]. For multi-component systems, the delay time concept has been applied to the block-based inspection model [33] and the muti-failure mode inspection model [31]. A state-of-the-art review on the delay time-based maintenance modeling in recent years can be found in Wang [29]. For this paper, we focus on a single-component system.

Multiple inspection policies have drawn extensive attentions in delay time-based studies. The main purpose of such policies is to enhance the efficiency of inspections and improve the performance of systems [30]. A two-phase inspection policy is proposed for a system raised from a heterogeneous population, where two different inspection intervals are arranged [21,22]. A similar policy is considered for a production process, but the two types of inspections have different levels and can reveal different stages of the system [28]. It is noted, however, the above mentioned papers did not address the random inspection issue. This motivates our study, where a combined periodic and random inspection policy is proposed for a mission-based system adopting the delay time concept. On one hand, inspections are carried out at the completion of each mission so as to exploit the idle periods between missions and mitigate the system downtime due to inspections. On the other hand, to enhance the effectiveness of inspections in case that mission durations may be large, periodic inspections are also scheduled.

Most delay time-based maintenance models assume the instantaneous execution of replacement once the defective state is identified. In contrast, we relax this assumption and allow replacement to be postponed for a cost-saving purpose. This has also been applied to the traditional two-stage failure process [5,37] and the extended three-stage failure process [32]. However, in these papers the decisions about replacement are related to periodic inspections but not to random inspections. In this paper, whether to postpone replacement of the defective system depends on the outcome of random inspections. To be specific, if the system is defective at a random inspection, replacement is postponed when the time to the following periodic inspection is less than a given threshold, otherwise replacement is immediate. On the other hand, replacement is immediate when the system fails or is defective at a periodic inspection. Compared with an instant replacement, the postponed replacement enables maintenance resources, such as repairmen and spare parts, to be prepared properly in advance. Moreover, it can avoid excessive maintenance and prolong the average system lifetime, and thus reduce the lifecycle cost.

The remainder of this paper is organized as follows. Section 2 provides the detailed notations and assumptions. Section 3 studies the expected renewal cycle cost and length of the system under the proposed inspection and replacement policy. For comparison, some simpler maintenance policies are investigated in Section 4. Section 5 presents a numerical example to illustrate the proposed policy. Section 6 provides the final remarks.

2. Notations and assumptions

For a maintenance modeling purpose, the basic notations and assumptions are presented as follows.

2.1. Notations

z_j	random variable representing the duration of the jth mission, $j = 1, 2, \ldots$
$H_{z_j}(t)$	cumulative distribution function (cdf) of z_j
$W(t)$	expected number of missions completed in $(0, t)$
X	random variable representing the time to defect initiation
$U_X(x)$	cdf of X
$u_X(x)$	probability density function (pdf) of X
Y	random variable representing the delay time
$V_Y(y)$	cdf of Y
$v_Y(y)$	pdf of Y
T	periodic inspection interval
t_l	threshold for postponing replacement of a defective system identified at a random inspection
C_{ip}	average cost of a periodic inspection
C_{ir}	average cost of a random inspection
C_{dp}	average cost of an immediate replacement at the time of a periodic inspection
C_{dr}	average cost of an immediate replacement at the time of a random inspection
C_f	average cost of a failure replacement
C_{dl}	average cost of a postponed replacement

2.2. Assumptions

(1) We consider a single-component system. The system executes missions successively, and the mission durations are independent random variables that follow an identical distribution.
(2) The failure process of the system is divided into two independent stages, i.e., normal and defective stages.
(3) Failure of the system is self-announcing, whereas the defective state can only be revealed by inspection. Both random and periodic inspections always reveal the state of the system (perfect inspection).
(4) Both random and periodic inspections are instantaneous. However, a periodic inspection will cause the shutdown of the system and the suspension of a mission, and thus is more costly than a random inspection.
(5) If the system fails or is defective at a periodic inspection, it is replaced immediately. If, however, the system is defective at a random inspection, replacement will be postponed when the time to the following periodic inspection is less than a predetermined threshold, otherwise replacement is immediate.
(6) The immediate replacement cost at a random inspection is equal to that at a periodic inspection.
(7) Considering that maintenance resources can be prepared adequately in advance, it is assumed that a postponed replacement costs less than an immediate replacement.

Most of the above assumptions can be justified in practice [14,29]. Specially, Assumption (4) is motivated by industrial observations where maintainers tend to utilize the free time of systems to conduct preventive maintenance with the purpose of reducing downtime costs, such as the computer systems and naval ship systems studied in Nakagawa et al. [12,13] and Zhao et al. [34]. In addition, the assumptions about inspection downtime