Reliability Engineering and System Safety 121 (2014) 207–220

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A preventive maintenance model with a two-level inspection policy based on a three-stage failure process

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ARTICLE INFO

Article history:
Received 3 February 2013
Received in revised form
21 August 2013
Accepted 26 August 2013
Available online 3 September 2013

Keywords:
Preventive maintenance
Inspection
Delay time
Three-stage failure process
Delayed maintenance

ABSTRACT

Inspection is always an important preventive maintenance (PM) activity and can have different depths and cover all or part of plant systems. This paper introduces a two-level inspection policy model for a single component plant system based on a three-stage failure process. Such a failure process divides the system's life into three stages: good, minor defective and severe defective stages. The first level of inspection, the minor inspection, can only identify the minor defective stage with a certain probability, but can always reveal the severe defective stage. The major inspection can however identify both defective stages perfectly. Once the system is found to be in the minor defective stage, a shortened inspection interval is adopted. If however the system is found to be in the severe defective stage, we may delay the maintenance action if the time to the next planned PM window is less than a threshold level, but otherwise, replace immediately. This corresponds to the well adopted maintenance policy in practice such as periodic inspections with planned PMs. A numerical example is presented to demonstrate the proposed model by comparing with other models.

1. Introduction

Preventive maintenance (PM) including inspection, preventive repair or replacement of defective items is generally adopted in practice to prevent system's failures [1–3]. Inspections are common activities in most PM programs where the deteriorating system can be inspected at certain intervals to reveal its state [4–6]. Inspections can have different depths or levels depending on the time, skills and the system to be inspected.

Most PM models consider one level inspection to check the whole system at a fixed interval; see Chiang and Yuan [7], Badía et al. [8], Wang et al. [9]. In practice, however, a multi-inspection scheme at different levels is also very common. For example, a weekly visual inspection is performed to check for the appearance of a defective component by an operator and a longer monthly inspection is carried out to perform a thorough check for the same component by a professional technician. Some recent papers have studied multiple level inspections, where each level is associated with a different interval, cost and depth. Nakagawa et al. [10] considered two inspection policies, where a system is inspected at periodic or successive times and also at every completion of working cycles. Chun [11] introduced a multiple inspection policy under which a product is checked repeatedly by a single inspector or sequentially by multi-inspectors. Berrade et al. [12,13] considered two inspection frequencies to detect early failures where the inspection identifies the system state with same effect and Scarf et al. [14,15] presented hybrid policies with two different intervals for inspections and replacements. Wang [16] proposed a model addressing multiple nested inspections of production plant at different intervals, where the inspections are assumed to be perfect. Wang [17] considered a production process subjected to two types of deteriorations caused by minor process defects and major defects, and proposed an inspection model in which minor inspections can perfectly identify whether the process is in control or out of control whereas major inspections can identify the major defect with a finite probability. The models in [14–17] were based on the delay time concept which defined a two-stage failure process [18].

The delay time concept was proposed by Christer in 1976 and then applied to maintenance problems in Christer and Waller [19]. The period from new to the initial point of a defect (potential failure) is defined as the normal stage and the time between this initial point and the occurrence of a failure is the delay time stage [20]. Different from the conventional time to failure definition, such delay time

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http://dx.doi.org/10.1016/j.ress.2013.08.007

provides an opportunity to remove or rectify the defects before they transform into failures if an inspection is undertaken at the delay time stage. Such definition assumes that the system can be in one of the two states before failure, namely normal or defective. Numerous inspection and PM models have been proposed based on the delay time concept, see Wang [21] for a recent survey on delay time models. Such delay time models have the obvious advantages than other inspection models proposed in literature in that they directly modeled the relationship between system failures and PM actions. There are two types of delay time-based inspection models, namely a single component system and a complex system with many components [18,21]. In this paper we consider just a single component system subject to a dominant failure mode. Subsequently we use a component or system interchangeably all referring to a single unit system subject to a single failure mode and the only maintenance action is replacement if needed.

It is noted however that in many industrial applications, the state of the system is described by a state space of more than two. In view of this situation, the two-stage delay time concept was extended to a three-stage failure process [22], which generates three possible states of the system in operation, i.e., normal, minor defective and severe defective before failure, respectively. This further dividing of the delay time into two deteriorating stages provides more modeling options since different maintenance actions may be needed at different stages of the failure process. However, Wang [22] did not consider multiple level inspections in the work.

Most works assume that the defective and failed state can be always revealed if they were there [3,7]. However, some defects may be missed during inspections, as a perfect inspection requires more time and cost [23,24]. This leads to the concept of imperfect inspection and such an imperfect inspection may be destructive or non-destructive. The destructive inspection process is subject to false positives and false negatives, see Berrade et al. [12,13], Okumura et al. [25]. But we focus on imperfect, but non-destructive inspection by which the actual state of system is either detected correctly with a certain probability or undetected. Though this limitation was dealt with in the previous delay time models [18], it was not addressed in a three-stage failure process setting. Moreover, under such a three-stage failure process, the initial defective stage may be more difficult to be identified than a later severe defective stage. Another assumption shared by most papers is that maintenance actions are always undertaken immediately once a defective state is identified, see Cui et al. [2], Badía et al. [8], Scarf and Cavalcante [24]. In some practical situations, it may be cost-effective to delay the repair or replacement to a later time in order to avoid over-maintenance. A delayed repair is considered by Zhang [26] where the model was based on a geometrical process.

In this paper, we introduce a two-level inspection policy consisting of minor and major inspections for a single component system based on the three-stage failure process. This single component system can be a system on its own or part of a larger system. It is assumed that the minor inspection can only identify the minor defective stage with a limited probability, but can always identify the severe defective stage. Differently, the major inspection can always identify the defective stage no matter it is minor or severe. This is very close to what observed in practice. In case when the component is found to be in the minor defective stage by an inspection, a shortened inspection interval is introduced in order to have more opportunities to identify the severe defective stage before failure. Of course once the failure occurs, repair or replacement has to be carried out immediately to restore the production.

In additional to periodic inspections, there may be planned PMs either on the component or the larger system where the component is in, such PM usually has more time allocated and the system is down anyway. In steel industry, such PM is called “downday” and is usually performed at an interval of few weeks [27]. During such PM, repair and replacement of defective components are carried out comprehensively. The timing of such PM is usually determined for the larger system or by some technical or production constraints imposed on the system so it is beyond the scope here in this paper. However, it is the ideal repair or replacement window for dealing with the defective components identified at previous inspections. This leads to the case that if the component is found to be in the severe defective stage by an inspection, a repair or replacement action can be delayed to the next planned PM if the time till the next planned PM is less than a predetermined threshold. Otherwise the repair or replacement action has to be undertaken immediately. This is a common practice observed in the process industry such as steel making. It may be beneficial since a replacement at the time of an inspection may cost more due to the extra downtime required. The decision variables in this paper are the inspection intervals for minor and major inspections and the threshold level. The objective is to minimize the long run expected cost per unit time.

The new contributions of this paper are as follows

(1) We consider a three-stage failure process subject to two-level of inspections, minor and major inspections.
(2) The inspection is imperfect for the identification of the minor defective stage by the minor inspection with a certain probability.
(3) If the system is found to be in the minor defective stage, instead of taking a maintenance action, a shortened inspection interval is recommended.
(4) We also consider to delay the maintenance action if the time to the next planned PM is shorter than a predetermined threshold at the time of a major defect identification.

The remaining part of the paper is organized as follows. Section 2 provides the modeling assumptions and notations. Section 3 models the two-level inspection policy with PM based on the three-stage failure process. For the purpose of comparison, Section 4 models one level inspection policy with PM and a two-level inspection policy without PM. Section 5 presents a numerical example. Section 6 concludes the paper and suggests some future works.

2. Modeling assumptions and notation

We first present some modeling assumptions and notations for a model building purpose. However, most of assumptions have been adopted in practice/studies and explained in the introduction section of this paper.

(1) The failure process is divided into three stages, namely normal, minor and severe defective stages. These three stages are independent.
(2) The component is subjected to minor inspections at interval t and major inspections at interval T, and also a planned PM at interval t_{pm}. It is assumed that the major inspection interval is a multiple of the minor inspection interval as $T = Nt$. The downtime due to inspections is either negligible compared with the inspection intervals or the inspections can be performed online so there is no downtime. However, the costs of both inspections are considered.