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Optimization of the dependability and performance measures of a generic model for multi-state deteriorating systems under maintenance

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ABSTRACT

In this paper, a general model for multi-state deteriorating systems with condition based preventive maintenance is introduced and analyzed extensively. The system experiences various levels of deterioration and at each stage, an inspection is carried out at constant time intervals in order to identify what kind of preventive maintenance, the system should undergo. When the system fails, despite preventive maintenance, a repair procedure is carried out and the system is restored to its initial fully operational state. The proposed model incorporates also imperfect maintenance, either minimal or major, failed maintenance and sudden failures that may occur mostly due to external factors at any deterioration state as well. Moreover, the sojourn times are assumed to be generally distributed. The main dependability and performance measures of the proposed model are computed while the corresponding transient measures are estimated using Monte Carlo simulation. Our endmost aim is to distinguish inspection and consequently maintenance policies that optimize multi-state deteriorating system's dependability and/or performance. Additionally, multi-objective optimization problems are formulated and solve in order to distinguish preventive maintenance policies that optimize simultaneously both the dependability and performance measures.

1. Introduction

During the last decades the design of larger scale, higher complexity and precision engineering systems has proliferated basically due to the rapid development of technology. In consequence, extensive research of complex engineering systems has been carried out, which has shown that complex systems reveal multiple states from perfectly operational to totally failed, during their operational time [19]. Additionally, it has been observed that the failure process of these systems is affected not only by the operational time, but also by the condition of the system itself [17]. As a result, a complex engineering system can operate on various deterioration states under degraded efficiency conditions before it experiences a total failure. Such systems, are called Multi-state systems (MSS) and were introduced by Murchland in [24] (see also [13]) and have been studied extensively the last decades [5,21,29,19,17]. The reliability and the performance of multi-state systems have gained a lot of research effort as well, since the effects of deterioration on a system's dependability are of critical importance (see for example [18,38,17]). In order to improve the output performance of the operating engineering system which decreases with the deterioration level, leading finally to an unacceptable functioning level, the system should be inspected regularly and maintenance should be incorporated whenever it is considered necessary.

Maintenance actions can be carried out in order to keep or restore a system in a normal functioning condition or even to extend its lifetime. These actions can be generally divided into two types: corrective maintenance and preventive maintenance actions. The corrective maintenance (repair or/and replacement) restores a failed system at an operational condition. On the other hand, preventive maintenance can be defined as a set of actions taking place regularly at pre-defined intervals during the operational time of a system or a device, in order to reduce or even eliminate the accumulated deterioration [5]. Usually, preventive maintenance is more effective than corrective, since it aims in preserving a system available for as long as possible, avoiding hence unexpected failures that incur cost and losses [1]. Nevertheless, preventive maintenance itself causes system downtime which is also costly. Thus, preventive maintenance is worthwhile to be performed when the cost and/or the downtime incurred by a system failure, which can be recovered by a repair, is higher than the corresponding cost of preventive maintenance. Consequently, an appropriate preventive maintenance policy that manages to reduce the total downtime cost should be scheduled. Such preventive maintenance policy is capable of

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improving system availability in the steady state as well, or even minimizing the mean time to failure of the system [25,31,34].

Generally, there exist two types of preventive maintenance actions, i.e. condition based and time based preventive maintenance [16]. In condition based maintenance the system or device is continuously monitored and inspections are carried out on a regular basis. After inspection, depending on the system state, the system can be left without any action taken, or minimal maintenance is performed to recover the system to its previous deterioration stage, or finally major maintenance is carried out to bring the system to an as good as new state. Contrarily, time-based preventive maintenance is carried out at pre-defined time intervals independently of the system's state.

Condition-based preventive maintenance has been extensively studied in the literature. In [6], a continuously operating service device whose condition deteriorates with time in service is studied and a Markov process which takes into account deterioration and Poisson failures, minimal repair, periodic minimal maintenance, and major maintenance is used to model the evolution of the system in time. A similar device, which is randomly inspected within exponential inter-inspection times, is considered in [25] and a condition-based maintenance model is proposed according to maximum availability or minimum costs. In [33], the optimal preventive maintenance policies for multi-state systems are studied and the improved effective age is utilized to model the effect of an imperfect PM, while the deterioration of the system is assumed to follow a non-homogeneous continuous time Markov process with finite state space. The authors find the optimal PM schedule that minimizes the average cost rate for each repair type and highlight that in determining the optimal scheduled PM, choosing the right repair type will significantly improve the efficiency of the system maintenance. The interested reader can find a review on past and current research on condition-based maintenance optimization models for stochastically deteriorating system and on optimal maintenance policy selection issues associated with methods used as well as applications in [35] and [9] correspondingly.

In this paper, condition-based preventive maintenance is considered for a multi-state system which experiences several stages of deterioration until it fails. The aim of the current work consists in determining the inspection policy and consequently the preventive maintenance policies that optimize the multi-state system dependability and/or performance measures. Maintenance optimization of multi-state systems has gained a lot of research effort recently [20,13,39]. Based on the relevant literature, the present work extends previous research on this area and more specifically, a generalized multi-state deteriorating system under condition-based maintenance is provided. The initial deterioration model is introduced in [6] where the system is inspected regularly according to an exponentially distributed inspection time. The inspection rate is the same regardless the deterioration level and the failure rate at each deterioration state is assumed to be the same. This model is extended in [29], where two different inspection rates are considered depending on the level of deterioration and additionally the failure rate increases with respect to the system degradation level. Moreover in [22], this model is further extended by assuming that the two different inspection intervals are constant and hence the inspection procedure is governed by the unit step function. Additionally in [21], the duration of either minimal or major maintenance follow general distributions and hence the evolution in time of the system is described by a semi-Markov process. Finally in [21], imperfect maintenance, either minimal or major, failed maintenance and sudden failures that may occur mostly due to external factors at any deterioration state, are incorporated into the model. General sojourn time distributions are proposed for the states of the system and a semi-Markov process is used to model system's evolution in time. In the current work a general multi-state deteriorating system under minimal and major maintenance actions is proposed by extending the model presented in [21], assuming that the deterioration can lead the system from a certain deterioration level to any other worsen state and not only to the next one. By this assumption, the fact that the system may experience a deterioration of multiple levels is modeled. Taking into account these generalizations, a semi-Markov process is used to model the system's evolution in time. Based on the semi-Markov theory, the system asymptotic availability and the corresponding operational cost can be computed. By formulating and solving some optimization problems, that can be also formulated as multi-objective optimization problems, the optimal inspection, and thus, maintenance policies that maximize the asymptotic availability and/or minimize the operational cost can be provided. Furthermore, the effects of the inspection polices on the transient behavior of the multi-state deteriorating system are examined. For the transient behavior, dependability and performance measures are estimated using Monte Carlo simulation methods.

The proposed model can be used to model a wide variety of systems under certain specifications. Such multi-state systems can be applied in health-care, in electrical power generation systems [1], wireless communication systems with transmission stations, in coal transportation systems, information or data processing systems [19], in production systems, in machinery systems, in continuous materials or energy transmission systems, in gas pipeline networks [27]. The interested reader can refer to [15,26] for a comprehensive presentation of multi-state reliability theory and its applications.

The rest of this paper is organized as follows: In Section 2 the general multi-state deterioration system with preventive maintenance is described in details. In Section 3 the main dependability measures are defined for the multi-state deteriorating system. Moreover, the optimization aspect is considered in Section 4. Some numerical results are presented in Section 5. Finally, the paper concludes by providing a short discussion and given directions for future work.

2. Multi-state deterioration system with minimal, major, imperfect and failed maintenance

2.1. Model description

A multi-state deteriorating system which experiences gradual degradation until it fails is modeled. Condition-based maintenance actions are proposed to be performed in order to prevent the system from a total failure and extend its lifetime. Inspections are performed in order to observe system's condition and identify when maintenance is needed. Two different types of maintenance can be implemented. Either minor maintenance is performed and the system is restored to its previous deterioration stage or major maintenance is carried out to bring the system to an as good as new state. The type of maintenance actions depends on the level of system degradation. Finally, when the system experiences a total failure, a repair mechanism is initiated to recover the system to its fully operational state.

More precisely, we consider a system that starts to operate in its perfect functioning condition, denoted by state (0,0) in Fig. 1. The level of deterioration increases with system's operational time. It is assumed that the system experience k different deterioration levels which are identified by the inspection procedure. State $(i,0)$, $0 \le i \le k$ in Fig. 1, represents the i-th deterioration level. At each deterioration state, an inspection is carried out in order to identify the condition of the system. Thus, from each state $(i,0)$, $0 \le i \le k$ the system may enter the inspection state $(i,1)$, $0 \le i \le k$. On the other hand, when the deterioration progresses to the next level, the system may enter from state $(i,0)$ to the deterioration state $(i+1,0)$, $0 \le i < k$. However, the deterioration may cause a transition to a worsen deterioration state than state $(i+1,0)$. To model this phenomenon we allow transition from every deterioration state $(i,0)$, $0 \le i < k$ to all the worsen deterioration states $(j,0)$, $i+1 \le j \le k$. This assumption seems to be more realistic compared to the scenario of considering only one deterioration level transitions. Nevertheless, as the deterioration level to be reached from state $(i,0)$ increases, the probability of deterioration that causes a