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Selective maintenance optimization for series-parallel systems with continuously monitored stochastic degrading components subject to imperfect maintenance

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Abstract: This paper addresses a degradation-based selective maintenance decision problem in a continuously monitored multi-component system, carrying out several missions with scheduled inter-mission breaks. Each system's component is modeled as a time-dependent stochastic process. Each component is also assigned a list of maintenance actions ranging from imperfect maintenance actions up to complete overhauling. Both corrective and preventive imperfect maintenance are allowed. To improve the probability of the system successfully completing the next mission, maintenance is performed on the system's components during the break. The selective maintenance problem aims thus at finding a cost-optimal subset of maintenance actions, to be performed on the system during the limited duration of the break, which guarantees the successful completion of the next mission with a minimum reliability level. The fundamental constructs and the relevant parameters of this new nonlinear selective maintenance optimization problem are developed and thoroughly discussed. A numerical example is provided to illustrate the proposed approach.

Keywords: Selective maintenance; Imperfect maintenance; Reliability; Stochastic processes; Optimization.

1. INTRODUCTION

Industrial systems, such as those used in maritime or avionic enterprises, are required to operate according to an alternating sequence of missions and scheduled breaks. To prepare the system operating the next mission with a desired reliability level, maintenance activities are performed on the system's components during a break. However, due the limitation in the break's duration and the maintenance budget, it is often necessary to select a joint optimal subset of components to maintain and the level of maintenance actions to be performed on these components. This kind of maintenance policy is known in the literature as selective maintenance.

The selective maintenance strategy appeared first in the paper by Rice et al. (1998). Since, the selective maintenance problem attracted the researchers' interest and many papers appeared in the literature. Cassady et al. (2001b) and Cassady et al. (2001a) first extended the work of Rice et al. (1998) by relaxing some restrictive hypothesis and taking into account three maintenance options: a minimal repair, a corrective and preventive replacements of components. They solved the resulting selective maintenance problems using enumeration methods. Dealing with large sized systems, Rajagopalan and Cassady (2006) proposed improved enumeration procedures, Khatab et al. (2007) proposed two heuristic-based methods, and Lust et al. (2009)developed an exact method based on the branch-and-bound procedure combined with a Tabu search based algorithm. Maaroufi et al. (2013) consider failure propagation. Iyoub et al. (2006) addressed the selective maintenance problem taking into account resource allocation. (Maillart et al., 2009; Khatab et al., 2015) extend the original model to deal with multi-mission selective maintenance problem. Zhu et al. (2011) studied selective maintenance problem under imperfect maintenance and used the age reduction coefficient approach of (Malik, 1979). Pandey et al. (2013) also studied the selective maintenance problem under imperfect maintenance and used the hybrid hazard rate approach Lin et al. (2000). In a more recent work, Khatab and Aghezzaf (2016) investigated the selective maintenance problem under random quality of imperfect maintenance actions.

From the literature review conducted, we found that the selective maintenance decision problem have been addressed only on the basis of statistical information on the system's components lifetimes. The main drawback of the components' lifetimes distribution is that it only allows

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to evaluate whether a component is still functioning of failed. In this case, the failure rate is widely used to represent component's aging. However, system's components sustain damage and deteriorate with age and usage. It is therefore more practical to base components' failures on the physics of failure. In the literature, a component' deterioration process is generally modeled as a time-dependent stochastic process, for example, random deterioration rate, Markov, Wiener, Gamma and Inverse Gaussian processes, that are well known, among others, for their particular mathematical properties and clear physical interpretations (Ye and Xie, 2015; van Noortwijk, 2009; Zhang et al., 2015). The present paper addresses the selective maintenance decision problem for a system composed of several components each of which is stochastic degrading and subject to imperfect maintenance.

Dealing with preventive maintenance optimization problems of mutli-component systems in stochastic degradation-based setting, only few works appeared in the literature (Marseguerra et al., 2002; Castanier et al., 2005). The majority of the existing works adopted asymptotic cost rate model for optimizing maintenance policies without taking into account limitations is maintenance resources. Furthermore, since the asymptotic cost rate optimization model assume an infinite time horizon, it can no longer be valid for engineering systems with a relatively short and finite operating life. In (Cheng et al., 2012), the authors derived the probability distribution of maintenance cost in a finite time setting. However their approach merely relies on a system assumed to be reduced to a single components. Liu et al. (2014) developed a dynamic preventive maintenance policy from maintenance value perspective for a multi-component degrading system during a finite time span. In (Liu et al., 2014)the system is assumed to be continuously operating and times required to perform maintenance are not accounted for. The resulting optimization problem is a non-constrained optimization program, i.e. free from maintenance resources' constraints.

The present work investigates the selective maintenance decision problem for a continuously monitored multi-components system. A component is assumed to degrade according to a specific and appropriate time-dependent stochastic process and fails whenever its degradation level reaches a given threshold. Each component is assigned a list of maintenance actions composed of the overhaul action in addition to several imperfect maintenance actions. To model imperfect maintenance, we used the degradation reduction coefficient (Do et al., 2015) and extend it to a multi-level and multi-component systems executing an alternating sequence of consecutive missions and scheduled breaks. To meet the required reliability level for the system to execute the next mission, the maintenance activities are performed on the system's components during the break. Due to limited break duration, maintenance resources and the single available repairman, not all components are likely to be maintained. The selective maintenance decision problem consists first in selecting a subset of components and then choosing the level of maintenance to be performed on each of these selected components. We then formulated the nonlinear selective maintenance problem accordingly. In the present paper, the objective of the selective maintenance optimization problem is to minimize the total maintenance cost subject to required reliability level and time allotted to the break constraints.

The remainder of the paper is organized as follows. Section 2 describes the main characteristics of the investigated system. In this section, the degradation model of a system's component is described and its corresponding conditional reliability to successfully operate the ext mission is then derived. The imperfect maintenance model is given in Section 3. Time and cost of maintenance actions are also given. In Sections 4 a formulation of the selective maintenance optimization problem is presented, and some of its major properties are discussed. To illustrate the proposed approach a numerical example is provided and discussed in section 5. Conclusions and some future research directions are discussed in Section 6.

2. SYSTEM'S DESCRIPTION AND COMPONENT'S DEGRADATION MODEL

We consider a series-parallel system composed of n subsystems each of which is composed of N_i $(i = 1, \ldots, n)$ s-independent, and possibly, non-identical components C_{ij} $(j = 1, \ldots, N_i)$. We assume that the system has just finished executing mission m and is now starting a scheduled break of a fixed length $\mathcal{T}_0$ during which some components may be selected to be maintained. Thereafter, the system is planned to execute the next mission of known duration U_{m+1} with a desired minimum required reliability level. Component C_{ij} can be either in a functioning or failed state. Two binary state variables $Y_{ij}(m)$ and $X_{ij}(m+1)$ are then used:

$$Y_{ij}(m) = \begin{cases} 1, \text{ if } C_{ij} \text{ is functioning at the end of} \\ \text{mission } m, \\ 0, \text{ otherwise.} \end{cases} \quad (1)$$

$$X_{ij}(m+1) = \begin{cases} 1, \text{ if } C_{ij} \text{ is functioning at the beginning} \\ \text{ of mission } m+1, \\ 0, \text{ otherwise.} \end{cases} \quad (2)$$

The degradation of component C_{ij} is determined by physics-of-failure and summarized, at a given time t, by an measurable scalar random variable $D_{ij}(t)$ which can take either a linear or nonlinear forms. In the absence of maintenance, we assume that $D_{ij}(t)$ takes positive real values and is a monotone non-decreasing function over time. Without loss of generality, in the present work, components are assumed to degrade according to a Gamma process. Such degradation process model is suitable to characterize monotonically accumulating gradual damage over time (Abdel-Hameed, 1975; van Noortwijk, 2009). The Gamma degradation process of component C_{ij} is a time-dependent stochastic process $\{D_{ij}(t) : t \geq 0\}$ with the following characteristics:

(1) $D_{ij}(0) = 0$ with probability one,

(2) $D_{ij}(t)$ has independent increments,

(3) For all $0 \leq s < t$, the random variable $\Delta D_{ij}(s,t) = D_{ij}(t) - D_{ij}(s)$ follows a Gamma distribution whose