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Selective maintenance optimization when quality of imperfect maintenance actions are stochastic

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ABSTRACT

This paper addresses the selective maintenance optimization problem in a multi-component system, carrying out several missions with scheduled inter-mission breaks. To improve the probability of the system successfully completing the next mission, maintenance is performed on the system's components during the break. Each component is assigned a list of eligible maintenance actions ranging from minimal repair, through intermediate imperfect maintenance actions, to replacement. The quality of a maintenance action is assumed to be stochastic, reflecting the degree of expertise of the repairman and the tools used to perform the maintenance action. This quality is thus treated as a random variable with an identified probability distribution. 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 that the pre-set minimum probability of successfully completing the next mission is attained. The fundamental constructs and the relevant parameters of this nonlinear and stochastic optimization problem are developed and thoroughly discussed. It is then put into practice for a series–parallel system and the added value of solving it as a stochastic problem is demonstrated on some test cases.

1. Introduction

In the course of their activity, many industrial enterprises, such as those active in maritime, nuclear and military industry, operate their systems according to an alternating sequence of missions and scheduled breaks. At the end of each mission, the system is made available for possible maintenance during the break. To prepare the system for the next mission, i.e. to bring its reliability to the required level, scheduled breaks are usually used to perform the necessary maintenance activities on its components. However, due the limited duration of these scheduled breaks and the budget devoted to maintenance, it is often impossible to maintain all components of the system. It is therefore necessary to identify an 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.

Selective maintenance can be traced back to the work of Rice et al. [1]. The authors considered a series–parallel system where the subsystems are composed of independent and identically distributed (*i.i.d*) components with exponentially distributed lifetimes. Cassady et al. [2] extended the work of Rice et al. [1] and developed a modeling framework for selective maintenance optimization problem while relaxing the restrictive hypothesis of identical subsystems. Three selective maintenance optimization problems were then proposed and solved. In [3], three maintenance actions are considered: a minimal repair, a corrective replacement of failed components and also a preventive replacement of functioning components. An enumeration method is proposed and applied for a series–parallel system, made of components with Weibull distributed lifetimes. To deal with large sized systems, Rajagopalan and Cassady [4] proposed four improved enumeration procedures to reduce the computational time. In [5], the authors proposed two heuristic-based methods. Lust et al. [6] also proposed an exact method based on the branch-and-bound procedure combined with a Tabu search based algorithm. In [7], the authors studied selective maintenance under failure propagation and proposed a set of rules to reduce the search space. In [8], the selective maintenance problem taking into account resource allocation is investigated. In [9,10], the authors extend the original problem of [1] to deal with multi-mission selective maintenance problem.

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In [11], the authors used the age reduction coefficient approach [12] to model imperfect preventive maintenance. The selective maintenance studied in [11] is applied on a machining line system of the automobile engine connecting rod. Pandey et al. [13] also studied the selective maintenance problem for binary systems under imperfect PM. The hybrid hazard rate approach introduced in [14] is used to model the imperfect PM actions. Accordingly, both age reduction coefficient and adjustment coefficient impact the component's health. In [13] different levels of maintenance are allowed to improve the reliability of a system component. The authors also proposed relationships between the level of imperfect repair and the amount of resources consumed for maintenance. In a recent paper [15], selective maintenance is studied for a fleet composed of a number of independent and identical systems. The fleet is required to execute a set of sequential missions and return to a common base where maintenance actions may be performed on some selected components. A nonlinear cost-based optimization model and its linearized version are proposed and solved. It is shown that the resulting linear optimization model offers a good approximation of the original one.

Selective maintenance have been also studied for multi-state systems (MSS). The first work is reported in [16] where system's components and the system itself may be in $(K+1)$ possible states. Replacement of failed components is the only available maintenance option. In [17], the authors considered a MSS where components are characterized by two operating states while the system performs at several output performance levels. A genetic algorithm is used to solve the resulting selective maintenance optimization problem. To overcome the restrictive hypothesis of binary components in [17], Pandey et al. [18] considered a MSS where components are characterized by more than one performance level (i.e. multi-state components). The transition rates between the component's states are assumed constant, i.e. components are modeled as continuous-time Markov chains. The more recent work in [19] studied selective maintenance for a MSS taking into account economic dependencies among systems' components. Such dependency is also considered to deal with maintenance optimization of MSS. In [20], several levels of imperfect maintenance are considered and the system is composed of multi-state components modeled in a similar way as in [18]. A linear programming-based procedure is proposed to reduce the search space.

Dealing with imperfect maintenance in a selective maintenance setting, both age reduction and adjustment parameters are assumed to be constant. However, this assumption may no longer be valid in many real-world situations where it is difficult to evaluate precisely the quality of a maintenance action. Indeed, such a quality is closely related to the qualification and the degree of expertise of the repairmen, in addition to the maintenance methods and tools used to perform the maintenance action. It is therefore more realistic to assume that the quality effect of a maintenance action is stochastic and therefore could be modeled as a random variable governed by an appropriate probability distribution.

The present paper addresses the selective maintenance problem taking into consideration the random quality of imperfect maintenance. We build upon the age reduction model proposed by Wu and Clements-Croone [21] and extend it to a multi-level and multi-component systems executing an alternating sequence of consecutive missions and scheduled breaks. We then formulated the nonlinear and stochastic selective maintenance problem accordingly. 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 and maintenance resources, 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. 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 investigated system and the maintenance time and cost structures of each component. Section 3 discusses the stochastic quality model of imperfect maintenance. In Section 4, the probability model of the mission completion is derived based on the results of Section 3. In Sections 5 and 6, a formulation of the selective maintenance optimization problem is presented, and then some of its major properties are discussed. To illustrate the proposed approach some numerical examples and their solutions are provided and discussed in Section 7. Conclusions and some future research directions are discussed in Section 8.

2. System's description, maintenance time and cost models

Consider a binary system composed of n independent components C_i $(i=1,\ldots,n)$. We assume that the system has just finished executing mission m and is now starting a scheduled break of a fixed length during which possible maintenance activities can be performed. Thereafter, the system is planned to execute the next mission of known duration with a predetermined required level of reliability. At the end of mission m, each component can be either in an functioning or failed state. Two state variables $Y_i(m)$ and $X_i(m+1)$ are then used to identify the status of component C_i, respectively, at the end of mission m and the beginning of mission $m+1$:

$$Y_i(m)=\begin{cases}1, & \text{if } C_i \text{ is functioning at the end of mission } m,\\ 0, & \text{otherwise.}\end{cases} \tag{1}$$

$$X_i(m+1)=\begin{cases}1, & \text{if } C_i \text{ is functioning at the beginning of mission } m+1,\\ 0, & \text{otherwise.}\end{cases} \tag{2}$$

To each component C_i corresponds a list of L_i available maintenance options (levels) $\{1,\ldots,l_i,\ldots,L_i\}$ where the particular values $l_i=1$ and $l_i=L_i$ denotes, respectively, the case where C_i is minimally repaired and C_i is *as good as new* after maintenance. Values of l_i where $1<l_i<L_i$ represent intermediate maintenance levels such that when performed they bring the system's health condition between the *as good as new* and *as bad as old* conditions.

Depending on the required system's reliability level to execute the next mission, a component C_i may be selected for a maintenance action with some level $l_i>0$. Maintenance cost and time consumed by a component C_i depend on the level l_i of the maintenance performed, and on the component's age together with its state, which can be either functioning of failed. Indeed, a low expected value of the improvement level induces a low maintenance cost. In this case, the component health condition will approach the as bad as old condition. On the other hand, the cost induced by an improvement level on a young component is lower than that induced by the same improvement level performed on a more aging component. In addition, it is realistic and practical to assume that maintenance of a failed component is costly than its maintenance when it is still functioning. This assumption is commonly and widely used in the literature. In the present work, it is also assumed that maintenance costs and times of a replacement are dependent only on the component status (functioning or failed). Furthermore, minimal repair maintenance level as a maintenance level is eligible only for a failed component and its