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Technical Paper

Selective maintenance optimization for systems operating missions and scheduled breaks with stochastic durations

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ABSTRACT

This paper deals with selective maintenance of a multi-component system, performing several missions seceded by scheduled breaks. To improve the probability of successfully completing its next mission, the system's components are maintained during these breaks. A list of possible maintenance actions on each component of the system, ranging from minimal repair to overhaul through intermediate imperfect maintenance actions, is available. Durations of the missions as well as those of the breaks are assumed stochastic variables with known distributions. The resulting selective maintenance optimization problem is thus modeled as a mixed-integer non-linear stochastic program. Its objective is to determine a cost-optimal subset of maintenance actions to be performed on the system's components, during the limited stochastic duration of the break, to meet a predetermined minimum system's reliability to operate the next mission. The fundamental constructs and the relevant parameters of this decision-making problem are developed and discussed. An illustrative example is provided to demonstrate the added value of solving this selective maintenance problem as a stochastic optimization program.

1. Introduction

Systems such as maritime vessels, aircraft and nuclear power plant operate according to an alternating sequence of missions and scheduled breaks. To prepare the system to successfully execute its next mission, the necessary maintenance of its components is to be performed during the scheduled intermissions break. The limited duration of the scheduled break together with the possible budget and maintenance resources constraints, allow only a limited set of components may be selected to receive some specific maintenance actions. It is therefore necessary to identify an optimal subset of components to maintain and the type of maintenance actions to be performed on these components to meet the predetermined reliability level required for the next mission. In the literature, this kind of maintenance strategy is known as the selective maintenance.

Selective maintenance was first initiated in [21]. In this work, the authors considered a series-parallel system in which the subsystems are assumed to be composed of independent and identically distributed (*i.i.d*) components each having a lifetime that is also assumed to be exponentially distributed. The only available maintenance option is the replacement of components at failure. To overcome the restrictive hypothesis of identical subsystem components in [21,3] developed a more general modeling framework for selective maintenance of a system whose reliability block diagram may be a combination of series, parallel and bridge structures.

In [2], the authors studied the selective maintenance problem in a series-parallel system, made of components having a Weibull distributed lifetimes. For each component of the system three maintenance actions are available, namely a minimal repair, a corrective replacement of a failed component, in addition to a preventive replacement of a working component. To solve this selective maintenance problem, the authors proposed an enumeration method. However, since the selective maintenance optimization problem is combinatorial in essence, enumeration solution methods become rapidly impractical when the number of the components of the system increases. To deal with large sized systems [20], proposed four improved enumeration procedures to reduce the computational time. Two heuristic-based methods are proposed by [7]. These heuristics are adapted from those used to solve the redundancy allocation problem [1,5,22]. In [12] the authors proposed two methods to efficiently solve the selective maintenance problem for systems with a large

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number of components. They proposed an exact method based on the branch-and-bound procedure and a Tabu search based algorithm. The authors in [13] studied the selective maintenance problem for a system where some components are subject to both global failure propagation and isolation. To solve this problem, a set of rules were then proposed aiming to reducing the search space. More recent papers considered the imperfect maintenance in the selective maintenance setting. Imperfect repair was indeed addressed by Liu and Huang in [11] where the age reduction coefficient approach [14] is used to model imperfect preventive maintenance. The same imperfect maintenance model has been studied in [26] and applied to the selective maintenance on a machining line system of the automobile engine connecting rod. Pandey et al. [17] also studied the selective maintenance problem for binary systems under imperfect PM. The hybrid hazard rate approach introduced in [10] is used to model the imperfect PM actions. In [11,17] a set of maintenance levels are allowed to improve the reliability of a system component. A maintenance level may be select from a minimal repair to a replacement, through intermediate imperfect maintenance actions. In [11,26], the only parameter that determines the improvement in the component health is the age reduction coefficient, while in [17], the age reduction coefficient, in addition to the adjustment coefficient impact the component health. In more recent work [6], the authors studied the selective maintenance problem when the quality of imperfect maintenance are stochastic. A nonlinear and stochastic optimization optimization was then proposed and solved for a series-parallel system.

Wong and Chung [25] studied a maintenance policy for a system under a random time horizon. The system is minimally repaired at failure and replaced by a new one whenever its age reaches a specified value. Conditions under which the optimal age replacement exists are derived for the particular case where the system's lifetime is Weibull distributed. The approach proposed in [25] is generalized in [9,8] where the authors proposed a maintenance optimization model for a system operating under a random time horizon with general lifetime distributions. These papers merely rely to systems considered as a single units operating continuously over time. In addition, the only available imperfect maintenance action is the minimal repair. Times to perform either replacement or a minimal repair actions are not accounted for. Consequently, maintenance resources constraints are not addressed in these papers.

The selective maintenance problems addressed up until now assume that the durations of the breaks as well as that of the next mission are deterministic and known constants. However, this assumption may no longer be valid in many real-world situations where it is usually difficult to evaluate the exact duration of a mission to be operated by the system. Indeed, a mission's duration may be impacted by the occurrence of unexpected events which may cause the system to either abort the mission or continue operating the mission but at lower (higher) cadence increasing (decreasing) henceforth the mission's duration. For example, weather conditions can randomly change at any time, and thus the duration of a vessel's mission can take more or less time than expected before the vessel returns back to the dock. In addition to the density of water on which the displacement is performed, vessels' and ships' motion also varies in function of the type and quantity of the products being transported. This may increase or shorten the duration of the mission that is executed. Also, in case of air traffic jams, aircraft might be rerouted to other airports, resulting in a possible increase or decrease of the flight duration. The duration of a break is also difficult to evaluate precisely. Adverse a sudden change in the weather conditions may lead to delaying the take-off of an aircraft or the departure of vessels from the port. In freight transport, the departure of a vessel may be impacted by the traffic density and infrastructure (river locks and hydroelectric dams) management. It is therefore more realistic to consider that mission as well as break durations are not usually precisely known but are rather random and are governed by some appropriate probability distributions.

This paper addresses the selective maintenance problem when the durations of both the break and the next mission to be performed by the system are stochastic. This selective maintenance problem is formulated as a stochastic optimization problem. Thus, right after each mission, the system becomes available for maintenance during a limited duration of the break, and maintenance is carried out on it to meet the required reliability level for the execution of the next mission. Due to limited maintenance resources, not all components can be maintained. The selective maintenance problem to be solved consists first in selecting a subset of components to be maintained and then choosing the level of maintenance to be performed on each selected component. The objective function may either consist of maximizing the successful completion of the next mission while taking into account the maintenance budget and time allotted to the break, or minimizing the total maintenance cost subject to required reliability level and time allotted to the break, or minimizing the total maintenance time subject to required reliability level and maintenance budget. The present paper focuses on the second objective function.

A preliminary work of the present paper appeared in a conference paper [4] where the authors studied the selective maintenance when only missions' durations are considered to be stochastic. In the present work, missions as well as scheduled breaks are considered to be of stochastic durations. Furthermore, the present paper provided more details and the selective maintenance optimization problem developed here is written in a more elegant and comprehensive way.

The remainder of this paper is organized as follows. Section 2 describes the investigated system and defines maintenance time and cost structure of each component of the system. In Section 3, the probability model of mission completion is developed. Sections 4 and 5 present a formulation of the stochastic selective maintenance optimization model, and also discuss some of its major properties. In Section 6, A numerical example is provided and discusses how the stochasticity of the mission and break durations impact the maintenance level selection decisions. Conclusions and some future works are drawn in Section 7.

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

2.1. System's description

The selective maintenance problem addressed in the present work concerns a system $\mathcal{S}$ composed of n subsystems S_i (i = 1, ..., n) each of which is composed of N_i independent, and possibly, non-identical components C_{ij} (j = 1, ..., N_i). Components, subsystems and the system are of binary states since they are assumed to be either in a functioning or in a failed states. The system is assumed to have just finished a mission and then, turned off during the scheduled break of finite length and becomes available for possible maintenance activities. The system is thereafter used to execute the next mission of a given duration. In the present work, the duration of the next mission is denoted by U and considered stochastic rather than deterministic. Therefore, we consider U as random variable governed by the probability density function (pdf) $f_U(u)$ and the cumulative distribution function (cdf)$F_U(u)$.

When the system is set for maintenance at the end of the current mission, a component can be either in an functioning state or in a failed state. Hence, two state variables X_{ij} and Y_{ij} are used to