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Comparing effectiveness and efficiency in technical specifications and maintenance optimization

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Abstract

Optimization of technical specification requirements and maintenance (TS&M) has been found interesting from the very beginning at Nuclear Power Plants (NPPs). However, the resolution of such a kind of optimization problem has been limited often to focus only on individual TS&M-related parameters (STI, AOT, PM frequency, etc.) and/or adopting an individual optimization criterion (availability, costs, plant risks, etc.). Nevertheless, a number of reasons exist (e.g. interaction, similar scope, etc.) that justify the interest to focus on the coordinated optimization of all of the relevant TS&M-related parameters based on multiple criteria.

The purpose of this paper is on signifying benefits and improvement areas in performing the coordinated optimization of TS&M through reviewing the effectiveness and efficiency of common strategies for optimizing TS&M at system level. A case of application is provided for a stand-by safety-related system to demonstrate the basic procedure and to extract a number of conclusions and recommendations from the results achieved. Thus, it is concluded that the optimized values depend on the particular TS&M-related parameters being involved and the solutions with the largest benefit (minimum risk or minimum cost) are achieved when considering the simultaneous optimization of all of them, although increased computational resources are also required. Consequently, it is necessary to analyze not only the value reached but also the performance of the optimization procedure through effectiveness and efficiency measures which lead to recommendations on potential improvement areas.

Keywords: Optimization; Effectiveness; Efficiency; Technical specifications; Preventive maintenance; Allowed outage times; Surveillance test intervals; Probabilistic risk analysis; Genetic algorithms

1. Introduction

Technical specification and maintenance (TS&M) activities are associated with controlling risk or with satisfying requirements at Nuclear Power Plants (NPPs), which are candidate to be evaluated for their resource effectiveness in risk-informed applications [1]. The resource versus risk-control effectiveness principles formally enters in optimization problems where the cost or the burden is to be minimized while the risk or performance is constrained to be at a given level. This relationship applies when TS&M activities are optimized to minimize the cost while controlling unavailability of safety-related systems and plant risk, and vice versa. In the past, normally, the resolution of such a kind of optimization problems have been limited to focus only on a single parameter (STI, AOT, PM frequency, etc.) and/or adopting a single optimization criterion (availability, costs, plant risks, etc.) [2–8]. However, the interaction that exists between TS&M requirements, and the similar purpose of the different TS&M tasks on increasing the system availability, which in some cases may be redundant, have brought a growing interest at present to focus on the coordinated optimization of relevant TS&M-related parameters based on multiple criteria [9–14].

The purpose of this paper is on highlighting benefits and improvement areas in performing the coordinated optimization of TS&M through reviewing the effectiveness and efficiency of common strategies used for optimizing TS&M at system level. A case of application is provided for a stand-by safety-related system to demonstrate the basic procedure and to extract a number of conclusions and recommendations from the results achieved. Particular attention is paid to show the interaction among these parameters by means of highlighting the impact that each

Abbreviations: AOT, allowed outage time; CM, corrective maintenance; LCO, limiting condition for operation; MCS, minimal cut set; NPP, nuclear power plant; OM, overhaul maintenance; PAR, proportional age reduction model; PAS, proportional age setback model; PM, preventive maintenance; PRA, probabilistic risk assessment; STI, surveillance test interval; SSGA, steady-state genetic algorithm; TS&M, technical specification and maintenance.

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one has on the various contributions to the unavailability and cost functions at system level. In addition, measures of effectiveness and efficiency used to compare the solutions found for the different optimization alternatives are introduced.

2. Problem formulation

The constrained optimization of TS&M will be formulated at system level by adopting either the model of risk or cost as the objective function to be minimized while the remaining function will be considered as an additional restriction imposed on the decision variables. TS&M are represented through appropriate parameters included within the models of risk and cost, which will be adopted as decision variables for the optimization process. The variable x_i will be used with a general meaning, representing a given parameter, i, in the model that may be adopted as a decision variable belonging to the vector of decision variables, $\mathbf{x}$, to be optimized.

2.1. Risk function

The system unavailability model is often formulated into the PRA adopting the rare-event approximation [15], which is an upper bound that can be represented as follows:

$$U(\mathbf{x}) \approx \sum_j \prod_k u_{jk}(\mathbf{x}) \tag{1}$$

where the sum in j extents to the number of minimal cut sets (MCS) after the reduction of the system structure function and the product in k extents to the number of basic events relevant to the corresponding MCS. In addition, $u_{jk}(\mathbf{x})$ is the unavailability associated with the basic event k belonging to MCS, j, which quantifies a given unavailability state of a safety component that depends on the vector of decision variables $\mathbf{x}$. Consequently, quantification of the different contributions to the component unavailability is needed to derive the final risk function using Eq. (1), which, in turn, will be used as the objective (or restriction) function in the constrained optimization problem. The unavailability contributions of a component normally in stand-by is divided into two categories: (1) unavailability due to random failures, named the reliability effect, and (2) unavailability due to testing and maintenance downtimes, named the downtime effect. These models are presented in detail in Ref. [13] and are summarized here in Table 1, where:

- T surveillance test interval (STI),
- t mean time of testing,
- ρ cyclic or per-demand failure probability,
- λ stand-by failure rate considering either a PAR or PAS model [16],
- λ_0 residual stand-by failure rate,
- α linear aging factor,
- $\Psi(z)$ represents the working conditions that can be set equal to one under normal or nominal operational and environmental conditions,
- ε maintenance effectiveness that range in the interval [0,1],
- m mean time for preventive maintenance,
- M the period to perform time-directed preventive maintenance,
- L overhaul period to replace the component by a new one,
- μ mean time to repair when there are no time limitations on conducting such a repair,
- D allowed outage time (AOT), maximum downtime of the component to perform, for example, corrective maintenance.

2.2. Cost function

The relevant costs in analyzing TS&M optimization of safety-related equipment at system level include the contributions of stand-by components, which undertake surveillance testing with period T, preventive maintenance with period M and corrective maintenance to restore their operability after a failure has been discovered during a test. Consequently, summing up the corresponding cost contributions of the relevant components to yield the cost model:

$$C(\mathbf{x}) = \sum_i c_i(\mathbf{x}) \tag{2}$$

which will be used as the objective (or restriction) function in the constrained optimization problem. These models are presented in detail in Ref. [13] and are summarized here in Table 2, where the new parameters are defined as follows:

- c_{ht} hourly costs associated with conducting surveillance testing,
- c_{hm} hourly costs associated with conducting preventive maintenance,
- c_{hc} hourly costs associated with conducting corrective maintenance,
- c_u total cost associated with the loss of production due to the plant shutdown,
- c_r total cost of replacing the component.

2.3. Constraints

The suggestion of a valid solution for the optimization problem must be founded on realistic criteria related to both regulatory and utilities acceptance, which will act as constraints in the optimization process. Therefore, the problem consists not only in planning TS&M strategies by means of a selection of several of them for a component or a group in a system, but also it is intended to optimize the selection to produce the minimum risk within certain