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Alternatives and challenges in optimizing industrial safety using genetic algorithms

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Abstract

Safety (S) improvement of industrial installations leans on the optimal allocation of designs that use more reliable equipment and testing and maintenance activities to assure a high level of reliability, availability and maintainability (RAM) for their safety-related systems. However, this also requires assigning a certain amount of resources (C) that are usually limited. Therefore, the decision-maker in this context faces in general a multiple-objective optimization problem (MOP) based on RAMS + C criteria where the parameters of design, testing and maintenance act as decision variables. Solutions to the MOP can be obtained by solving the problem directly, or by transforming it into several single-objective problems. A general framework for such MOP based on RAMS + C criteria is proposed in this paper. Then, problem formulation and fundamentals of two major groups of resolution alternatives are presented. Next, both alternatives are implemented in this paper using genetic algorithms (GAs), named single-objective GA and multi-objective GA, respectively, which are then used in the case of application to solve the problem of testing and maintenance optimization based on unavailability and cost criteria. The results show the capabilities and limitations of both approaches. Based on them, future challenges are identified in this field and guidelines provided for further research.

Keywords: Reliability, Availability, Maintainability and Safety (RAMS); Safety optimization; Genetic algorithms; Testing and maintenance; Multi-criteria decision-making

1. Introduction

Safety of industrial installations has been a matter of concern to many experts for more than five decades [1,2]. The relevance of this topic in the normal operation of industrial installations can be realized, for example, analyzing the cost associated with their safety-related systems devoted to prevent or mitigate accidents, which ranges from 2–5 to 30–40%, the latter for example at nuclear and chemical plants [3].

Many studies have been developed in this period aimed at improving safety systems, with the main focus on developing designs that use more reliable and redundant equipment (e.g. intrinsic reliability allocation) and implementing an appropriate surveillance and maintenance policy to assure that an acceptable standard of reliability, availability and maintainability (RAM) of the safety systems is kept during all the plant operational life (e.g. testing and preventive maintenance optimization) [4–9].

This way, reliability allocation and optimization of testing and maintenance activities aim to increase RAM of safety-related systems, which, in turn, should yield to an improved level of plant safety (S). However, increased amounts of resources (e.g. costs, task force, etc.) have to be assigned in the above areas to achieve better scores in Reliability, Availability, Maintainability and Safety (RAMS). Therefore, analysts in this field normally face a multiple-criteria decision-making problem (MCDM) typically searching for the appropriate amount of reliability, and testing and maintenance that balances RAMS and Costs (RAMS + C) [4].

On the other hand, previous years have seen an important advancement and proliferation in the use of genetic algorithms (GAs) to solve both single-criterion and multiple-criteria optimization with application to several

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industrial and societal problems [10]. In particular, one can find in the literature many examples of optimizing safety or production of industrial installations which consider as a whole or partially RAMS and cost attributes for the decision-making process [11–20].

This paper aims to provide the fundamentals and a practical view of some of the current alternatives, their capabilities and limitations, and future challenges in the use of the state-of-the-art GAs in the field of safety optimization based on RAMS + C criteria, and with particular application to testing and maintenance optimization of safety-related systems.

Firstly, Section 2 gives an overview of the MCDM with application to the optimal allocation of reliability, and testing and maintenance planning of safety-related equipment (SRE) based on RAMS + C criteria. Next, Section 3 provides typical formulations of such MCDM problem and current resolution strategies. This section introduces two main alternatives in searching for solutions. One of them is based on formulating the problem as a multi-objective optimization problem (MOP) based on the above RAMS + C criteria, which is to be solved directly. The second option consists of transforming the original MOP into several single-objective optimization problems (SOP) that are to be solved sequentially. The introduction to Section 4 reviews briefly the state-of-the-art use of GAs to solve both SOP and MOP. Sections 4.1 and 4.2 describe in detail two GA-based optimization strategies, named single-objective genetic algorithm (SOGA) and multi-objective genetic algorithm (MOGA), belonging to both categories of resolution alternatives, respectively, which are particularized herein to solve an optimization problem based on unavailability and cost ($A[U]+C$) criteria. Then, Section 5 provides a case of application where it is intended to provide a practical view of the capabilities and limitations using SOGA and MOGA algorithms to solve, in particular, a T and M optimization problem based on availability (unavailability) and cost criteria named herein by $A[U]+C$, but with the aim to envisage future challenges in facing the resolution of this particular problem and other more general ones (e.g. reliability allocation and testing and maintenance optimization simultaneously) formulated on RAMS + C criteria as a whole by using GA. Section 6 presents our concluding remarks.

2. Overview of the MCDM on safety optimization based on RAMS + C

Resolution of an engineering problem of resource allocation that maximizes safety at minimum cost falls into the MCDM field [4], in which at least two criteria are usually involved corresponding to safety (or risk) and cost [5,6], which are obviously opposed. Safety of industrial installations relies on the attributes of RAM of its SRE, and therefore, the whole RAMS + C criteria may enter the decision-making process with a broader scope.

In general, the relevant criteria need to be formulated in terms of the decision variables using appropriate models. These models have to be able to show the relationships among the criteria (decision criteria) and the variables of interest involved for the decision-making (decision variables). In particular, herein, the models used to consider the RAMS + C criteria correspond to

$$R(\mathbf{x}) = \text{Reliability of the SRE} \tag{1}$$

$$A(\mathbf{x}) = \text{Availability of the SRE, which is often evaluated as } 1-U(\mathbf{x}),\text{ with } U(\mathbf{x}) \text{ the unavailability associated with the SRE, therefore represented herein by A[U]} \tag{2}$$

$$M(\mathbf{x}) = \text{Maintainability of the SRE, which is often represented by the unavailability contribution of the SRE as a consequence of performing tests and maintenance} \tag{3}$$

$$S(\mathbf{x}) = \text{Level of plant safety, which is normally evaluated in terms of plant risk (e.g. Probabilistic Risk Analysis of a Nuclear Power Plant), with Risk}(\mathbf{x}) \text{ representing in general the frequency of damage to public health, environmental damage or damage to property} \tag{4}$$

$$C(\mathbf{x}) = \text{The associated cost required to guarantee a given level of RAMS} \tag{5}$$

Most of the past applications reported in the scientific literature simplify the above problem to face the decision-making process based on a subset of the whole RAMS + C criteria. Ref. [11] shows an example of decision-making in the field of safety optimization based on $A[U]+C$ criteria, where the models adopted for $U(\mathbf{x})$ and $C(\mathbf{x})$ are also described in detail.

On the other hand, vector $\mathbf{x}$ in Eqs. (1)–(5) represents the vector of decision variables given by

$$\mathbf{x} = \{x_1, x_2, \ldots, x_n\} \tag{6}$$

This vector encodes some of the parameters used to develop the quantification models for the RAMS + C criteria. The selection of the parameters that will act as decision variables being involved in the MCDM problem depends on which problem is going to be solved, that is, on what direction the improvement of the plant safety is pursued. For example, the case of application will focus on parameters related with testing and maintenance activities for the equipment belonging to the safety system (T, M, L, ε, μ, D, etc.) [5–9,11–17], with the aim at optimizing the availability of safety systems and