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Optimizing bi-objective redundancy allocation problem with a mixed redundancy strategy

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ABSTRACT

Redundancy Allocation Problem (RAP) is a challenging subject which has attracted the attention of many authors. Generally, in the RAP there are two strategies for using the redundant components: active and standby. In this paper a new redundancy strategy, called mixed redundancy, is introduced and considered in a multi-objective optimization RAP. Results demonstrate that the new strategy increases the reliability value of the system considerably. This improvement can be very important for system designers, because the reliability of any systems with the structure of redundant components can be increased by changing the redundancy strategy, not by only adding redundant component. Moreover, this improvement dose not increases the cost and other known physical characteristics of the system.

1. Introduction

To improve the reliability of a system, there are four options: (a) increasing component reliability; (b) using redundant components in parallel; (c) a combination of component reliability enhancement and using redundant components in parallel; and (d) reassignment of interchangeable components [1]. The second option which is called the Redundancy Allocation Problem (RAP) is a more challenging topic for researchers because of its wide scope. Real-world applications of this problem can be found in most industrial systems such as telecommunication systems, transformation systems, electrical systems, space exploration and satellite systems [2,3]. In the RAP, there are two general classes. In the first class, there are discrete component choices with known characteristics such as reliability, cost, weight, etc. In this class the objective is to determine the necessary components and their corresponding preferred redundancy levels. For the second class, component reliability is not known in advance and is treated as a design variable and component cost, weight, volume, etc. are defined as increasing functions of component reliability [4]. This paper considers the first type of problem.

Traditionally, in RAP studies, two different strategies are considered to determine how the redundant components must be used. These strategies are called active and standby strategies. In the active strategy, all redundant components simultaneously start to operate from time zero, although only one of these components is necessary at any particular point in time. There are three variants of the standby redundancy called cold, warm, and hot standby. In cold-standby redundancy the redundant components are protected from the operational stresses associated with system operation and therefore the component does not fail before its start. In the warm-standby redundancy, the components are more affected by operational stresses than the cold- standby strategy. In the hot-standby redundancy, the occurrence of failure in component does not depend on whether the component is idle or in operation. The mathematical formulation for the hot-standby strategy is the same with the active redundancy case. In the standby redundancy strategy, the redundant components are sequentially used in the system at failure times of operating component by switching to one of the redundant components to continue the system operation [5,6]. In this paper a new redundancy strategy which is a combination of active and cold-standby strategies, is introduced. In this paper, the new redundancy strategy is called mixed redundancy strategy.

As mentioned, in standby strategies one has to use a switching system for activation of a standby redundant component in case of online component failure. There are two scenarios for the switching system in the standby strategy. In the firth scenario (Sce.1), the failure detection and switching hardware (or software) is continually monitoring system performance to detect a failure and to activate the redundant component. It is assumed that switch failure can occur at any time and switch reliability, is a non-increasing function of time ($\rho_i(t)$) and does not depend on the number of required switches. In the second scenario (Sce.2),

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failure of switching will happen, when the switch is required, with a constant probability (ρ_i) [3].

Single objective redundancy allocation problem (SORAP) is the main subject for most reliability optimization studies and they have always formulated the problem by considering active redundancy. For this purpose, exact optimization methods like dynamic programming [7,8], integer programming [9], Lagrangean multipliers [10], and various types of the meta-heuristic algorithms such as genetic algorithm [11], ant colony optimization [12], immune algorithm [13], the improved surrogate constraint method [14], variable neighborhood search (VNS) algorithms [15], Tabu search (TS) algorithm [16], and particle swarm optimization [17,18,19] are used to maximize the system reliability.

For the multi-objective redundancy allocation problem (MORAP), Kulturel-Konak et al. [20] solved the RAP with three objective functions for maximizing system reliability, minimizing the cost and the weight of the system using Tabu Search (TS) method. Coit and Konak [21] proposed a new mathematical model for the MORAP in order to maximize the reliability of each subsystem simultaneously. They used a multiple weighted objective heuristic to transform the multi-objective problem in to a single objective problem. Salazar et al. [22] solved three types of reliability optimization problems including, the redundancy allocation problem (to find the optimal number of redundant components), the reliability allocation problem (to find the reliability of components) and the reliability–redundancy allocation problem (to determine the redundancy and reliability of components simultaneously) in multi-objective mode by considering NSGA-II. Taboada and Coit [23] considered the RAP as a multi-objective problem with three objective of maximizing system reliability, minimizing the cost and weight of the system. They proposed an algorithm for solving this problem, called MOEA-DAP. This algorithm mainly differs from other multi-objective evolutionary algorithms (MOEA) in the structure of crossover operation.

Taboada et al. [24] proposed an algorithm, called MOMS-GA, to solve the multi-objective RAP in multi-state systems, where the availability, cost and weight of the systems are considered as the three objectives. Wang et al. [25] considered MORAP to maximize the reliability of the system and minimize the purchasing cost of the component. To solve the proposed multi-objective model, they used NSGA-II. Liang and Lo [26] proposed a modified variable neighborhood search (VNS) algorithm to solve the MORAP. They considered three types of MORAP to maximize system reliability and minimize system cost or system weight. Soylu and Ulusoy [27] developed a MORAP to maximize the minimum subsystem reliability, while minimizing the overall system cost. They found the Pareto solutions of this problem by the augmented ε-constraint approach for small and medium sized instances. After finding the Pareto solutions, they used a well-known sorting procedure called UTADIS, to categorize the solutions into preference-ordered classes. Khalili-Damghani and Amiri [28] proposed a procedure based on the efficient epsilon-constraint method and data envelopment analysis (DEA) to solve a binary-state MORAP.

Li et al. [29] proposed a new two-stage approach for the multi-objective redundancy allocation problem. They initially find the Pareto optimal set using the NSGA algorithm. Then a self-organizing map (SOM) is applied to classify those Pareto optimal solutions into several clusters and finally, within each cluster, data envelopment analysis (DEA) is performed to determine the final solutions of the problem. Recently, Garg and Sharma [30] developed a multi-objective particle swarm optimization algorithm (MOPSO) for the reliability optimization problem of a series system. They also solved a real case study in a pharmaceutical plant.

For the standby strategy, fewer studies have been conducted. Robinson and Neuts [31] studied a cold-standby redundancy system with non-repairable components. Also the imperfect switching problem was studied by Shankar and Gururajan [32] and Gurov and Utkin [33]. For the case of series–parallel system, Coit [3] presents an integer programming solution to the redundancy allocation problem when the system only uses the cold-standby redundancy. He considered imperfect switching and the k-Erlang distribution for TTF of components. In a new study, Ardakan and Hamadani [34] investigated the reliability-redundancy allocation problem by considering the cold-standby redundancy strategy. They demonstrated that the cold-standby strategy exhibits a better performance and yields higher reliability values compared to active strategy.

Recently few studies have been conducted which consider active and cold-standby redundancies in a specific system simultaneously in order to design more realistic models for the RAP. Coit and Liu [35] presented a new mathematical model for the RAP to determine the optimal system design configuration by considering a predetermined redundancy strategy (active or cold-standby) for each subsystem. In 2003, Coit [4] presented an integer programming method for solving the problem in which the selection of active or cold-standby redundancy strategy for each subsystem was a decision variable. Tavakkoli-Moghaddam et al. [6] and Chambari et al. [36] proposed a genetic algorithm and a simulated annealing algorithm respectively, to solve this problem. Also, the presented mathematical model by Coit [4] is extended in multi-objective mode by Safari [37] and Chambari et al. [38].

In all the previous studies, the redundancy strategy was considered as predetermined active, standby, or a combination of both and the researchers tried to improve system reliability by using new or improved solving methods to find a better solution for the problems. However, results of these studies demonstrated that changing the solution methods is not an effective approach to find a better solution for the system structure and it seems that in order to improve the reliability of systems, fundamental innovations are necessary. Hence, in this paper in order to improve system reliability, a new redundancy strategy is developed and a famous benchmark problem is used to demonstrate the advantage of using the new strategy. In the new strategy, each subsystem uses some active and some standby components simultaneously and the aim is to determine the number of components in each case. The new strategy is applicable in all real systems using redundant components. The new redundancy strategy is called mixed strategy. The related mathematical formulation for this strategy is derived and a bi-objective model, by considering the reliability and cost as the objectives, is developed.

It has been proved that the RAP belongs to the NP-hard class of optimization problems [39]. Therefore, it is too difficult to solve such problems with traditional optimization methods and as a result meta-heuristic algorithms have been widely used in the literature to tackle these sorts of problems. In this paper a powerful multi-objective evolutionary algorithm known as NSGA-II is developed for solving the problem.

The rest of the paper is organized as follows: In Section 2 the mixed redundancy strategy is described in details. Section 3 presents the modeling of the problem, and in Section 4, the developed NSGA-II is introduced for solving the proposed nonlinear model when both active and cold-standby redundancy can be selected for individual subsystems. Section 5 considers a well-known numerical example to demonstrate the advantages of the new redundancy strategy and the efficiency of the proposed methodology through computational experiment. The final conclusion is given in Section 6.

2. The proposed mixed redundancy strategy

The proposed mixed strategy is considered as a combination of traditional active and standby strategies. In this strategy, each