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Reliability–redundancy allocation problem with cold-standby redundancy strategy

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ABSTRACT

This paper considers the mixed-integer non-linear optimization of reliability–redundancy allocation problem (RRAP) to determine simultaneous reliability and redundancy level of components. In the RRAP, it is necessary to create a trade-off between component reliabilities and the number of redundant components with the aim of maximizing system reliability through component reliability choices and component redundancy levels. RRAPs have been generally formulated by considering an active redundancy strategy. A large number of solution methods have been developed to deal with these problems. In this paper, a cold-standby strategy for redundant components is used, for the first time, to model the RRAP; a modified genetic algorithm is developed to solve the proposed non-linear mixed-integer problem; and three famous benchmark problems are used for comparison. The results indicate that the cold-standby strategy exhibits a better performance and yields higher reliability values compared to the previous studies.

1. Introduction

High-reliability systems play crucial roles in modern industry. System reliability may be enhanced by: (a) raising component reliability, (b) providing redundant components in parallel, (c) using a combination of enhanced component reliability and redundant components provisioned in parallel, and (d) reassigning interchangeable components [1]. The second and third options are called redundancy allocation problem (RAP) and reliability–redundancy allocation problem (RRAP), respectively. In RAPs, there are discrete component choices with known characteristics such as reliability, cost, and weight, where the aim is to find the optimal/near optimal number of redundancies in each subsystem in order to maximize the overall system reliability subject to some constraints. The reliability–redundancy allocation problem (RRAP) is the problem of maximizing system reliability through component reliability choices and component redundancy, which forms a difficult but realistic optimization problem in which component reliability is not given but treated as a design variable while component cost, weight, volume, etc. are defined in advance as increasing non-linear functions of component reliability [2].

In reliability studies, either of two different strategies, called active and standby, may be considered for determining how the redundant components must be used. In the active strategy, all redundant components simultaneously start to operate from time zero although only one is required at any particular time. The standby redundancy may take one of the three cold, warm, or hot variant forms. In the cold variant, the redundant components are protected from operational stresses associated with system operation so that no component fails before its start. The components in the warm-standby redundancy are affected by operational stresses more than those in the cold variant. Finally, in the hot-standby redundancy, component failure does not depend on whether the component is idle or in operation. The mathematical formulation for the hot-standby

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strategy is the same as that with the active redundancy case. In the standby redundancy strategy, the redundant components are sequentially used in the system at failure times of operating components by switching to one of the redundant components in order to continue system operation [3,4].

Activation of a standby redundant component in case of online component failure in standby strategies requires a switching system that is based on one of two scenarios. In the first scenario ($S1$), the failure detection and switching hardware/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 that switch reliability is a non-increasing function of time ($\rho_i(t)$) which does not depend on the number of switching required. In the second scenario ($S2$), failure of switching will happen with a constant probability, (ρ_i), when the switch is required [5].

Reliability–redundancy allocation problems (RRAP) have been generally formulated by considering the active redundancy strategy and using different solution methods. For this purpose, exact optimization methods such as dynamic programming [6], branch-and-bound approach [6,7], and implicit enumeration [8] have been used to maximize system reliability. Hikita et al. [9] developed a surrogate constraint method to solve the RRAP. They developed a dynamic programming to solve single-constrained surrogate problems. However, this method requires that either the objective function be separable or the surrogate problem be formulated as a multi-stage decision making problem. Their approach is only useful for special structures which include parallel-series and series–parallel designs [10].

Since RAP and RRAP have been proved to be NP-hard optimization problems [11,12], they are too difficult and time-consuming to solve using traditional optimization methods, especially when the problem size is large. For this reason, numerous meta-heuristic algorithms such as genetic algorithm [4,13–17], Tabu search [18,19], ant colony optimization [20–23], artificial immune system [10,24,25], artificial neural networks [26], artificial bee colony algorithm [27,28], particle swarm optimization [29], Memetic algorithm [30] and a combination of these algorithms [31] have been widely employed over the past decade for solving reliability optimization problems.

Recently, Yeh and Hsieh [28] developed a penalty guided artificial bee colony algorithm (ABC) for solving the reliability–redundancy allocation problems. In order to improve the solutions, they also proposed a local search for their ABC algorithm. Hsieh and You [10] developed a two-phase approach based on immune algorithm to solve the same problem. According to this approach, an immune algorithm (IA) is developed in the first phase to solve the problem, followed by a new procedure in the second phase to improve the solutions. Wu et al. [32] presented an improved particle swarm optimization (IPSO) algorithm for the RRAP. Zou et al. [33] developed an effective global harmony search algorithm (EGHS) to solve the RRAP. The EGHS algorithm combined the harmony search algorithm (HS) with the concepts of swarm intelligence in particle swarm optimization (PSO) algorithm to solve the problem. Wang and Li [34] proposed a differential evolution (DE) algorithm combined with a harmony search (HS) algorithm.

Valian and Valian [35] proposed a cuckoo search (CS) algorithm and used some well-known benchmark problems to test the performance of the algorithms in solving the reliability redundancy-allocation problem. In a different study, Valian et al. [36] presented an improved cuckoo search algorithm by enhancing the accuracy and convergence rate of the cuckoo search algorithm. Afonso et al. [37] proposed a modified version of the imperialist competitive algorithm (ICA) and compared the results obtained from their proposed ICA with the best-known results of different benchmarks reported in the literature to demonstrate the capability of their proposed algorithm.

As it is clear from the literature, all the previous studies of the reliability–redundancy allocation problem have considered the active strategy for redundant components and their efforts have been directed at improving system reliability by developing novel, modified, or combined meta-heuristic algorithms. In the present study, however, the cold-standby strategy is used for the first time and a new mathematical formulation is presented for the problem under the non-linear constraints of weight, cost, and volume.

The rest of the paper is organized as follows. In Section 2, the formulation of the RRAP, the mathematical formulation of the cold-standby strategy, and three benchmark problems are presented. Section 3 presents the GA developed for solving the proposed non-linear models. Section 4 considers the experimental results to demonstrate the advantages of the cold-standby strategy and the efficiency of the proposed methodology. Finally, conclusions are presented in Section 5.

2. Formulation of the reliability–redundancy allocation problem

The objective of reliability optimization is to improve system reliability. The reliability–redundancy allocation problems are useful for system designs that are largely assembled and manufactured using off-the-shelf components, and that have high reliability requirements [29]. A reliability–redundancy allocation problem is generally formulated with the objective of maximizing system reliability under some non-linear constraints. Therefore, in this paper, the RRAP is considered with the objective of maximizing system reliability subject to the multiple non-linear constraints of weight, cost, and volume. The mixed-integer non-linear programming model of RRAP is generally formulated as follows:

$$\text{Maximize } R_s = f(r, n) \tag{1}$$

$$\text{subject to } g_j(r, n) \leqslant l_j \quad j = 1, 2, \ldots, k \tag{2}$$

$$0 \leqslant r_i \leqslant 1, \quad r_i \in \Re, \quad n_i \in Z^+, \quad 1 \leqslant i \leqslant m$$