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Two tuned multi-objective meta-heuristic algorithms for solving a fuzzy multi-state redundancy allocation problem under discount strategies

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ABSTRACT

In this study, a bi-objective multi-state redundancy allocation problem of series–parallel systems consisting of some serial subsystems, each with non-repairable components in parallel, is investigated. Furthermore, due to uncertainty involved, both the performance rates and the availabilities of components are considered fuzzy. In addition, two strategies of all-unit and incremental-quantity discounts are used to purchase the components and that the fuzzy universal generating function (FUGF) is employed to evaluate the system availability. The aim is to find the optimal redundancy so as within limited budget and system weight the maximum system availability is obtained while the total cost is minimized. Since the bi-objective mathematical formulation of the problem is shown to be strongly NP-hard, a controlled elitism non-dominated ranked genetic algorithm (CE-NRGA) is developed to find the Pareto solutions of the problem at hand. Besides, since there is no benchmark available in the literature, a non-dominated sorting genetic algorithm (NSGA-II) is utilized to validate the results obtained. To improve the performance of the adopted algorithms, a multi-objective version of the Taguchi method is used to tune the parameters of the algorithms. Finally, several numerical examples are generated to evaluate the efficiency of the algorithms for which a variety of multi-objective metrics is employed to compare the results.

1. Introduction

Redundancy allocation plays an important role in optimizing real world systems in telecommunication, electrical, electronic, manufacturing, or even transportation industries that comprise a collection of components and subsystems. A redundancy is a component added to a subsystem in order to increase the number of alternative paths and, as a consequence, to enlarge system reliability [1]. Substantial efforts have been made during the past two decades to develop reliability criteria to measure quality of generators, transmissions, and distributions in composite systems [2]. In general, there are two major approaches to increase the system reliability; (i) enhancing the reliability of the components, and (ii) using redundant components in different subsystems.

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The redundancy allocation problem (RAP) is a complex combinatorial optimization problem that is possible to be formulated for systems with series–parallel structure; systems with some subsystems in series, each having several components in parallel [3]. The early works in RAP are based on the binary-state assumption, i.e. components and subsystems are allowed to take only two possible states: working perfectly or completely failed. From the literature, Garg et al. [4] proposed a two-phase approach to solve RAP, where in the first phase a bee colony algorithm was developed and in the second phase a procedure to improve the solutions was introduced. Khalili-Damghani et al. [5] used a decision support system for solving multi-objective RAPs, where they applied the technique for order performance by similarity to ideal solution (TOPSIS) method to decrease the dimension. Other works on RAP of binary-state systems are due to [6–9] for repairable and [10–14] for non-repairable components.

Although the multi-state version of RAP has not been sufficiently analysed in comparison with the binary state, it has being paid more attention in recent years. Liu et al. [15] proposed a model for a series–parallel multi-state RAP with repairable components. In their model, in addition to determining the optimal redundancy, a component replacement strategy under imperfect repair was also developed. Wang and Li [16] utilized a hybrid algorithm of particle swarm optimization (PSO) and local search (LS) to solve the RAP of series–parallel multi-state systems (MSS). Ouzineb et al. [17] solved a multi-state non-homogenous series–parallel RAP using an effective heuristic algorithm comprised of genetic algorithm (GA) and Tabu search (TS). Furthermore, Sharma and Agarwal [18] proposed an ant colony algorithm (ACA) to solve a single-objective multi-state series–parallel RAP, in which non-identical components were used. A TS was also utilized by Ouzineb et al. [3] for solving a single-objective version of a homogeneous multi-state series–parallel RAP. In addition, a universal generating function (UGF) was proposed by Pandey et al. [19] to evaluate system reliability of a repairable multi-state series–parallel RAP. Other researchers who also used UGF to evaluate reliability of MSS are [19–21].

The fuzzy set approach has been adopted in the literature to model problems in uncertain environments. However, few works utilized this approach in the RAP literature. Ebrahimipour et al. [12] proposed an emotional learning-based fuzzy inference system to improve the system reliability of a series–parallel binary-state RAP. A fuzzy multi-objective software reliability allocation model was also developed by Hou et al. [22]. Garg and Sharma [23] modelled a fuzzy multi-objective RAP of a series system where a PSO was utilized to solve the problem. Ebrahimipour and Sheikhalishahi [24] introduced a multi-objective model for a binary-state heterogeneous RAP problem with triangular fuzzy component reliability and discount rates, where a multi-objective PSO was employed to solve the problem. A linear programming RAP model for a series–parallel system was provided by Mahapatra and Roy [25], in which cost, weight, and reliabilities of the components were assumed fuzzy numbers.

It is difficult to accurately estimate component performance rates and probabilities of many real-world MSSs because of two main reasons. The first reason is inaccuracy and insufficiency of available data. The second is based on the fact that MSSs are often used as an approximation for continuous-state systems in order to simplify computational burden [26]. As a result, Ding and Lisnianski [26] proposed a multi-state RAP model in which performance rates and/or their corresponding state probabilities were assumed fuzzy numbers. A fuzzy continuous-time Markov model with finite discrete states was also presented by Liu and Huang [27] to assess the fuzzy state probability of multi-state elements at any time instant.

In this paper, a multi-objective multi-state homogeneous RAP problem is addressed, where performance rates and availability of the components are assumed as fuzzy. In addition, since the problem is formulated in a fuzzy environment, the FUGF method is improved to evaluate system availability. In addition, since there are often some discounts available in the market to purchase components, two discount policies of all-unit (AUD) and incremental quantity (IQD) are used [28,29]. Moreover, since the developed model of the problem is shown to be strongly NP-hard, a multi-objective meta-heuristic algorithm of controlled elitism non-dominated ranked genetic algorithm (CE-NRGA) is developed to find Pareto solutions of the problem. The multi-objective meta-heuristics have received growing attention in recent years; the most utilized being NSGA II [30–33], MOPSO [34–36], MOGA [37,38]. The non-dominated ranked genetic algorithm (NRGA) proposed by Al Jadaan et al. [39] has also been shown to be an efficient multi-objective algorithm, where it was employed to solve different optimization problems in project scheduling [40], facility layout [41], and flexible job shop [42]. Furthermore, since there is no benchmark available in the literature, a NSGA-II is also utilized for validation. Table 1 shows a brief review of relevant RAP literature, based on which the novelty of this research becomes clearer.

The rest of the paper is organized as follows. In Section 2, the problem is described, the assumptions are made, the notations are introduced, and the mathematical formulation of the problem is developed. Section 3 contains the solution algorithms employed to solve the problem. Computational illustrations and comparisons are given in Section 4, where some problem instances are generated, the parameters of the algorithms are tuned using a multi-objective version of the Taguchi method, and the results are analyzed. Finally, conclusion and future study come in Section 5.

2. Problem description

Consider a series–parallel system depicted in Fig. 1 that consists of m subsystems in series, each subsystem i having n_i components in parallel. The multi-state components used in a subsystem are identical, each with a fuzzy performance rate and availability. All-unit and incremental quantity discount policies are available in the market to purchase the components. The aim is to find optimal numbers along with an appropriate type of components in each subsystem so that the total system cost is minimized while the system availability is maximized. The assumptions involved in this problem are described as follows.