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A bi-objective model to optimize reliability and cost of system with a choice of redundancy strategies ☆

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ABSTRACT

Reliability problems are an important type of optimization problems that are motivated by different needs of real-world applications such as telecommunication systems, transformation systems, and electrical systems, so on. This paper studies a special type of these problems which is called redundancy allocation problem (RAP) and develops a bi-objective RAP (BORAP). The model includes non-repairable series–parallel systems in which the redundancy strategy is considered as a decision variable for individual subsystems. The objective functions of the model are (1) maximizing system reliability and (2) minimizing the system cost. Meanwhile, subject to system-level constraint, the best redundancy strategy among active or cold-standby, component type, and the redundancy level for each subsystem should be determined. To have a more practical model, we have also considered non-constant component hazard functions and imperfect switching of cold-standby redundant component. To solve the model, since RAP belong to the NP-hard class of the optimization problems, two effective multi-objective metaheuristic algorithms named non-dominated sorting genetic algorithms (NSGA-II) and multi-objective particle swarm optimization (MOPSO) are proposed. Finally, the performance of the algorithms is analyzed on a typical case and conclusions are demonstrated.

1. Introduction

An important subject that many researchers are engaged with is the optimization of system reliability. This optimization causes efficient utilization of available resources and also optimal development of system design architecture. Optimization of the reliability has been studied by many researchers. Therefore, different types of optimization models have been developed for this problem. A famous model of the reliability optimization problems is named redundancy allocation problem (RAP).

In these types of the models, different kinds of redundancy strategies can be used to improve the reliability of a system by incorporating redundant components. RAPs have been proved to belong to the NP-hard class of optimization problems (Chern, 1992). Therefore, for solving these types of models, metaheuristic algorithms have been used in the literature. Most of them were developed for a single objective. However, to model real-world problems, it is more realistic to consider RAP or any other related optimization with different practical objectives such as cost, weight, etc. In this paper, we present a bi-objective RAP (BORAP) in which (1) maximization of the system reliability and (2) minimization of the system cost are two objective functions of the model.

Redundancy strategies are generally classified into two main categories, namely active and standby strategies. In an active redundancy strategy, it is assumed that all of the redundant components are implemented together from time zero. Of course, at any given time, only one of these components is used. On the other hand, in a standby redundancy strategy, a sequential order is used for implementing the redundant components and these components can be added to incorporate into the operation of the system at component failure times. Standby redundancy is classified into three variant redundancy strategies, namely, cold, warm, and hot (Ebling, 1997). In this paper, in addition to the active redundancy, cold-standby redundancy is considered. In the formulation of the problem, following crucial decisions should be made:

- The selection of the best redundancy strategy between the active and cold-standby strategies.
- The selection of type of components among discrete choices.
- The determination of a system-level configuration for each subsystem.

In the literature, most of the studies considered only active redundancy, and all of the (few) studies that consider both of the

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Nomenclature

i	index of subsystem $i = 1, 2, \ldots, s$
s	number of subsystems
n_i	number of components used in subsystem $i, n_i \in \{1, 2, \ldots, n_{\max,i}\}$
n	$(n_1, n_2, \ldots, n_s)$
$n_{\max,i}$	upper bound for n_i ($n_i \leqslant n_{\max,i}$)
m_i	number of available component choices for a subsystem i
z_i	index of component choice used for a subsystem $i, z_i \in \{1, 2, \ldots, m_i\}$
z	$(z_1, z_2, \ldots, z_s)$
A	set of all subsystems using active redundancy
S	set of all subsystems using cold-standby redundancy
t	mission time (fixed)
$r_{i,z_i}(t)$	reliability at time t for the z_ith available component for subsystem i
$\lambda_{i,z_i}, k_{i,z_i}$	scale and shape parameters the Gamma distribution for z_ith available component for subsystem i
$f_{i,z_i}^{(j)}(t)$	is the pdf for the z_ith failure arrival for subsystem i, i.e., sum of j iid component failure times
W	system-level constraint limit for weight
c_{i,z_i}, w_{i,z_i}	cost and weight for the z_ith available component for the subsystem i
$\rho_i(t)$	failure-detection/switching reliability at time t (Scenario 1)
ρ_i	failure-detection/switching reliability success probability (Scenario 2)
$\delta_i(t, n_i)$	$\begin{cases} \rho_i(t), & \text{Scenario 1} \\ \rho_i^{n_i-1}, & \text{Scenario2} \end{cases}$
$R(t; z, n)$	system reliability at time t for designing vectors z and n
$\widetilde{R}(t; z, n)$	approximation of $R(t; z, n)$

two redundancy strategies simultaneously have only single objective to optimize.

For the active redundancy strategy different kinds of solution methods have been proposed to maximize the system reliability, including dynamic programming, integer programming (Bulfin & Liu, 1985; Fyffe, Hines, & Lee, 1968; Gen, Ida, & Lee, 1990; Ng & Sancho, 2001), and various types of the metaheuristic algorithms (Beji, Jarboui, Eddaly, & Chanbchoub, 2010; Liang & Chen, 2007; Nahas, Nourelfath, & Ait-Kadi, 2007; Ouzineb, Nourelfath, & Gendreau, 2008).

Fewer studies have been for the cold-standby redundancy strategy. Robinson and Neuts (1989) studied system design of non-repairable systems by considering cold-standby redundancy. Shankar and Gururajan (1993) and Gurov and Utkin (1993) studied the imperfect switching problem. Coit (2001), by considering a strictly cold-standby redundancy, presented an integer programming approach to the single-objective RAP. He considered imperfect switching and the k-Erlang distribution for time-to-failure.

Finally, although considering active and cold-standby redundancies simultaneously makes a model more realistic, few such studies have been done. Coit and Liu (2000), by considering predetermined redundancy strategy for each subsystem, presented system designs which consist of multiple subsystems. In another study, Coit (2003) proposed a zero-one integer programming method in which selection of active or, cold-standby redundancy strategy for each subsystem is an additional decision variable. In addition, since Coit's (2003) problem is NP-hard, Tavakkoli-Moghaddam, Safari, and Sassani (2008) proposed a genetic algorithm to solve it.

The above mentioned models have a single objective function; however some authors considered more than one objective in their models and proposed a multi-objective RAP (MORAP). Sakawa (1981), for an active redundancy RAP, considered a large series system with four objectives; maximization of system reliability and, minimization of cost, weight and volume. Dhingra (1992) by combining goal programming and the goal attainment method generated Pareto optimal solutions in a four-stage series system for maximizing system reliability and minimizing cost, weight and volume. Busacca, Marseguerra, and Zio (2001) suggested a multi-objective genetic algorithm (GA) (for maximizing reliability and minimizing cost) that is applied to a design problem for identifying the optimal system configuration and components. A multi-criteria formulation was proposed by Coit, Jin, and Wattanapongsakorn (2004) for maximizing the estimated system reliability and minimizing the associated variance of the estimation. Taboada, Baheranwala, and Coit (2007) and Taboada and Coit (2007) formulated MORAPs with three objectives, including maximization of the system reliability and minimization of cost and weight of the system. Furthermore, Li, Liao, and Coit (2009) considered the MORAP with various objectives including reliability, total cost and total weight.

In all of the above mentioned MORAPs, only active redundancy was considered and none of them considered standby strategy. In this paper, for the first time, a bi-objective model is developed for the series–parallel system in which both of the active and cold-standby strategies are considered simultaneously. Our model aims to maximize system reliability and minimize system cost when the redundancy strategy can be chosen for each subsystem. To solve the model, two effective multi-objective metaheuristic algorithms named NSGA-II and MOPSO are proposed.

The rest of the paper is organized as follows. Section 2 defines the problem more precisely and describes the mathematical model and basic assumptions. Section 3 develops the proposed NSGA-II and MOPSO for the BORAP. Section 4 describes computational experiment and provides analysis of the results for a set of test problems. Finally, concluding remarks come in Section 5.

2. Problem definition

This paper studies a series–parallel BORAP with s subsystems when both of the active and cold-standby redundancy strategies can be chosen for each subsystem. Generally, in the cold-standby redundancy two principal scenarios are considered for failure detection and switching (Coit, 2001). In the first scenario, to detect a failure and activate redundant components, the hardware of failure detecting and switching monitors system works continuously. In such a scenario, switch failure can occur at any time. Thus, whenever a failure is detected, a redundant component is activated. In this scenario, switch reliability function $\rho_i(t)$ is a non-increasing function of time. In the second scenario, failure depends on the requirement of the switch. It means that when a switch is required, a failure is possible. Therefore, whenever switching is required, successful switching has a constant probability (ρ_i). Some typical assumptions are considered for this model as follows: