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A new model for reliability optimization of series-parallel systems with non-homogeneous components

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ABSTRACT

In discussions related to reliability optimization using redundancy allocation, one of the structures that has attracted the attention of many researchers, is series-parallel structure. In models previously presented for reliability optimization of series-parallel systems, there is a restricting assumption based on which all components of a subsystem must be homogeneous. This constraint limits system designers in selecting components and prevents achieving higher levels of reliability. In this paper, a new model is proposed for reliability optimization of series-parallel systems, which makes possible the use of non-homogeneous components in each subsystem. As a result of this flexibility, the process of supplying system components will be easier. To solve the proposed model, since the redundancy allocation problem (RAP) belongs to the NP-hard class of optimization problems, a genetic algorithm (GA) is developed. The computational results of the designed GA are indicative of high performance of the proposed model in increasing system reliability and decreasing costs.

1. Introduction

Reliability is defined as the probability of a system or component performing a required function under stated operating conditions without failure, for a given period of time. Nowadays, reliability is an indispensable factor in the designing and manufacturing of products, since in sensitive industries such as auto, aviation, and defense industries, any failure in the performance of systems may lead to irreparable damages. To increase the reliability of a system, there are generally four categories of solutions, including increasing the reliability of components, using the redundant components in parallel, a combination of the previous options, and replacing the repairable components [1]. Among these, the second is one of the most economical options that has been taken into consideration by many researchers. The problems of this class are called Redundancy Allocation Problems (RAPs) [2]. This paper also pertains to RAP.

Various system structures can be considered in RAP, such as k-out-of-n [3], network, series, parallel, series-parallel [4], complex systems, etc [5]. Among these, the series-parallel is one of the most widely used structures that is also considered in this paper. This structure is formed by a number of subsystems that are connected in series, and there are also some components in each subsystem which are connected in parallel.

The components of a series-parallel system can be placed in a subsystem in either active or standby mode. When one or more components are placed in active mode, they all operate simultaneously as soon as the system starts to operate. Standby mode can be considered in three variants of cold, warm, and hot standby. In cold standby, components remain protected against failure as long as they are not in operational conditions. In warm standby, there is a possibility of the components failure even before operation. In fact, the components are more likely to be damaged in warm standby compared with cold standby. In hot standby, the failure of components is not related to whether the components are idle or in operation. The mathematical models of this mode are considered to be similar to the active mode [5,6]. Fig. 1 shows a series-parallel system including s subsystems. In this figure, the active and standby components are indicated with dark and light colors, respectively.

The number of active and standby components indicates the redundancy strategy of a subsystem. Three redundancy strategies have already been presented called active, standby, and mixed strategies. In active redundancy presented by Fyffe et al. [7], all components of the subsystem are in active mode. In standby redundancy presented by Coit [8], the subsystem contains only one active and at least one standby component. In mixed redundancy presented by Ardakan and Hamadani [9], at least two active components and one standby component are placed in the subsystem. It should be noted that in the standby and mixed strategies, standby components are activated in turns by a switch after the failure of all active ones. Furthermore, in all the strategies, the

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Nomenclature

s	number of subsystems
n_i	number of components used in subsystem $i\left(i \in \{1, 2, \ldots, s\}\right)$
$n_{A,i}$	number of active components used in subsystem i
$n_{S,i}$	number of standby components used in subsystem i
m_i	number of available component choices for subsystem i
j	index of active component choice used for subsystem i $\left(j \in \{1, 2, \ldots, m_i\}\right)$
z	index of standby component choice used for subsystem i $\left(z \in \{1, 2, \ldots, m_i\}\right)$
$n_{Max,i}$	upper bound for n_i
N	set of all subsystems with no redundancy
A	set of all subsystems using active redundancy
S	set of all subsystems using standby redundancy
M_1	set of all subsystems using first type of mixed redundancy
M_2	set of all subsystems using second type of mixed redundancy
$R(t)$	system reliability at time t
$f_{t_{ij}}$	*pdf* of the failure time for the component of type j in subsystem i
$r_{ij}(t)$	reliability at time t for the component of type j in subsystem i
(λ_{ij}, k_{ij})	scale and shape parameters of the gamma distribution for the component of type j in subsystem i
(c_{ij}, w_{ij})	cost and weight for the component of type j in subsystem i
$f_{T_{ij}^{(Max)}}$	*pdf* of maximum failure times for the active components of type j in subsystem i
$f_{T_{ij}^{(k)}}$	*pdf* of failure time for the active component of type j with number k in subsystem i
$f_{T_{iz}^{(k)}}$	*pdf* of failure time for the standby component of type z with number k in subsystem i
$f_{S_{iz}^{v}}$	*pdf* of summation of the failure times for the standby components of type z with numbers 1 to v in subsystem i
(C, W)	system-level constraint limits for cost and weight
t	mission time
$\rho_i(t)$	failure detection/switching reliability at time t (Scenario 1)
ρ_i	failure detection/switching reliability success probability (Scenario 2)
$(c_{switch,i}, w_{switch,i})$	cost and weight of switch used in subsystem i

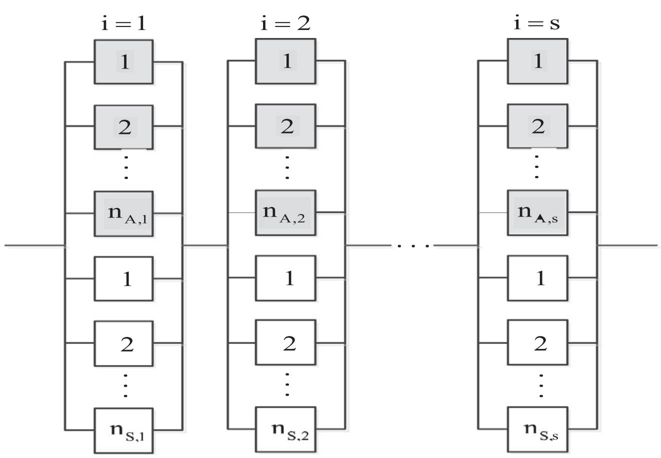

Fig. 1. Series–parallel structure.

components of a subsystem must be homogeneous.

Generally, RAP has been formulated by considering active redundancy. In this regard, various exact techniques, including dynamic programming [7,10,11], integer programming [12,13], Lagrangian multipliers [14], branch and bound [15,16] and numerous meta-heuristics such as, ant colony optimization (ACO) [17,18], genetic algorithm (GA) [19], immune algorithm [20], particle swarm optimization (PSO) [21,22], tabu search (TS) [23], and variable neighborhood search (VNS) [24] have been proposed to solve the RAP. Research on the other strategies began since 2000. Coit et al. [3] proposed a new model for k-out-of-n systems in which the redundancy strategy of each subsystem is predetermined (active or standby). Coit [8] presented an integer programming method for RAP when subsystems use only the standby redundancy. In 2003, Coit [25] presented a new model using integer programing in which the selection of redundancy strategy for each subsystem is a decision variable. In 2008, Tavakkoli-Moghaddam et al. [5] designed a GA to solve the model proposed by Coit [25]. Also, by taking cost and reliability as the objective functions, Safari [26] and Chambari et al. [27] extended this model in multi-objective form. Ardakan et al. [9] introduced a new strategy called mixed redundancy, and proposed a GA to solve the proposed model.

In 2015, Ardakan et al. [28] considered cost and reliability as the objective functions and extended the model proposed by Ardakan et al. [9] in multi-objective form. Zaretalab et al. [29] developed an algorithm based on SA to solve a multi-objective RAP (MORAP). Based on the strengths of both PSO and simplified swarm optimization (SSO), Huang [30] developed a particle-based simplified swarm optimization (PSSO) to optimize a reliability–redundancy allocation problem (RRAP). Ghorabaee et al. [31] considered a MORAP for k-out-of-n systems and introduced new modified methods of diversity preservation and constraint handling. Dolatshahi-Zand and Khalili-Damghani [32] proposed a MORAP to design Tehran's SCADA (Supervisory Control and Data Acquisition) water resource management control center. Kong et al. [33] proposed a simplified version of PSO (SPSO) to solve RAP. They presented a new position updating scheme without velocity, with stochastic disturbance and a low probability.

Recently, Teimouri et al. [34] presented a memory-based electromagnetism-like mechanism (MBEM) for RAP. Their algorithm employs a memory matrix in each iteration to improve the obtained solutions. Guilani et al. [35] developed a model for RAP in which the failure rates of the system components increase with the passage of time. Mellal and Zio [36] developed a penalty guided stochastic fractal search and applied it to ten numerical case studies. Zhang and Chen [37] formulated the RRAP with interval-valued reliability of components and developed a multi-objective PSO (MOPSO) to solve it.

In all the previous redundancy strategies, there is a limiting assumption on the basis that all components of a subsystem must be homogeneous. This limitation leads to an increase in the design costs of the system and prevents the attainment of higher levels of reliability; obviously, it is possible to design a system that provides the desired reliability with a lower cost, using non-homogeneous components instead of homogeneous ones. Furthermore, this issue can bring about constraints for system designers, since it restricts them from selecting components and reduces flexibility. In addition to these points, the homogeneity of the subsystems' components can cause problems in the process of supplying the