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Solving reliability redundancy allocation problems using an artificial bee colony algorithm

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ABSTRACT

This paper proposed a penalty guided artificial bee colony algorithm (ABC) to solve the reliability redundancy allocation problem (RAP). The redundancy allocation problem involves setting reliability objectives for components or subsystems in order to meet the resource consumption constraint, e.g. the total cost. RAP has been an active area of research for the past four decades. The difficulty that one is confronted with the RAP is the maintenance of feasibility with respect to three nonlinear constraints, namely, cost, weight and volume related constraints. In this paper nonlinearly mixed-integer reliability design problems are investigated where both the number of redundancy components and the corresponding component reliability in each subsystem are to be decided simultaneously so as to maximize the reliability of the system. The reliability design problems have been studied in the literature for decades, usually using mathematical programming or heuristic optimization approaches. To the best of our knowledge the ABC algorithm can search over promising feasible and infeasible regions to find the feasible optimal/near-optimal solution effectively and efficiently; numerical examples indicate that the proposed approach performs well with the reliability redundant allocation design problems considered in this paper and computational results compare favorably with previously-developed algorithms in the literature.

1. Introduction

System reliability optimization is very important in the real world and substantial effort has been made during the last two decades to develop reliability criteria to measure the quality of generation, transmission, and distribution in composite systems [1,2].

Generally two major approaches have been used to achieve higher system reliability. The first way is increasing the reliability of system components, and the second way is using redundant components in various subsystems. In the first way, the system reliability can be improved to some degree, but the required reliability enhancement may be never attainable even though the most currently reliable elements are used. Using the second way requires one to choose the optimal element combination and redundancy-levels; the system reliability can be also enhanced, but the cost, weight, volume, etc. will be increased as well. Besides the above two routes, the conjunction of the two approaches and reassignment of interchangeable elements are alternative feasible ways to enhance the system reliability [2,3]. Such problems of maximizing system reliability through redundancy and component reliability choices are called the "reliability-redundancy allocation problem" [2].

The redundancy allocation problem (RAP) may be the most common problem in the design-for-reliability approach [2]. It involves setting reliability objectives for components or subsystems in order to meet the resource consumption constraint, e.g. the total cost. Hence, RAP is becoming an increasingly important tool in the initial stages of or prior to the planning, designing and control of systems.

Based on the ways to enhance system reliability, the reliability design problems include the integer and mixed-integer reliability problems. In the integer reliability problems (redundancy allocation problems), the component redundancy allocation is to be decided while the component reliabilities are given. In optimizing the system reliability of mixed-integer reliability problems (reliability-redundancy allocation problems), the number of redundant components and the corresponding component reliabilities are to be decided simultaneously.

The major focus of recent work in the redundancy allocation problems has been on the development of heuristic/meta-heuristic algorithms for redundancy allocation [4–6,10,17]. A few works are directed toward exact solutions for such problems [2]. But a few approaches were proposed for the mixed-integer reliability problems of optimizing both the redundancy and component

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reliability [3,10,13,20,5] in literature. These system reliability problems are either subjected to the linear constraints [7,15,16] or to the nonlinear constraints [3,8,9,11,18,20,5]. Kuo and Prasad [2], Tillman et al. [19] and Yokota et al. [21] presented a good comprehensive survey of previous works.

In this paper, four mixed-integer reliability problems with multiple nonlinear constraints are considered and solved by using a novel meta-heuristic approach. The first three example problems include the series system, the series-parallel system [12,14] and the complex (bridge) system [3,11,13,20]. The last example problem is a gas turbine overspeed protection system [21,22]. The four reliability-redundancy allocation problems of maximizing the system reliability subject to multiple nonlinear constraints can be stated as following nonlinearly mixed-integer programming model:

$$\text{Maximize} \quad R = f(\mathbf{r},\mathbf{n}) \tag{1}$$

$$\text{such that} \quad g_i(\mathbf{r},\mathbf{n}) \le l_i$$
$$0 \le r_j \le 1, n_j \in \text{positive integer},$$
$$1 \le j \le m, \; 1 \le i \le \text{the number of constraint} \tag{2}$$

where r_j and n_j are the reliability and the number of components in the jth subsystem, respectively; $f(\cdot)$ is the objective function for the overall system reliability; $g(\cdot)$ is the constraint function and l is the resource limitation; and m is the number of subsystems. The goal is to determine the number of components and the components' reliability in each subsystem, so as to maximize the overall system reliability. This problem belongs to the category of constrained nonlinear mixed-integer optimization problems. For solving such kinds of mixed-integer reliability problems, most efforts have been devoted to nonlinearly-constrained reliability-redundancy allocation problems. It is known that the nonlinear mixed-integer programming problems are more difficult than pure redundancy allocation problems. Tillman et al. [19] and Gopal and Aggarwal [23] applied heuristic approaches to solve the reliability-redundancy allocation problem. Kuo et al. [24] demonstrated the Lagrange multipliers with the branch-and-bound method in a series system with four subsystems.

The iterative heuristic method and surrogate dual approach were used by Xu et al. [20] and Hikita et al. [3], respectively, to solve these mixed-integer reliability design problems. However, most of those require derivatives for all nonlinear constraint functions. That makes the exact optimal solutions to the reliability-redundancy allocation problem hard to derive because of the highly computational complexity. To overcome this difficulty, Yokota et al. [21] and Hsieh et al. [11] applied genetic algorithms to solve these mixed-integer reliability optimization problems.

Devised recently, the artificial bee colony algorithm is a new meta-heuristic approach, proposed by Basturk and Karaboga [25]. Because ABCs have the advantages of memory, multi-character, local search and the solution improvement mechanism, they are able to discover an excellent optimal solution. Although some applications using ABC are proposed in the literature, e.g., [29], to our knowledge it may be the first trial of application of ABCs to the reliability field in the literature. The meta-heuristic optimization approach employing penalty guided based ABCs to the mixed-integer reliability optimization problems is proposed in our work.

This paper is arranged as follows: Section 2 describes the acronyms and notations; Section 3 provides application of ABC to the mixed-integer reliability-redundancy optimization problems; Section 4 provides a description of the four test problems and the related data used for this study and the results of the experiments are also discussed. Finally, the conclusion of the paper is summarized and the directions for future research are described in Section 5.

2. Acronyms and notations

2.1. Acronyms

ABC	artificial bee colony
RAP	redundancy allocation problem

2.2. Notations

m	the number of subsystems in the system
n_i	the number of components in subsystem i, $1 \le i \le m$
$\mathbf{n}$	$\equiv(n_1, n_2, \ldots, n_m)$, the vector of the redundancy allocation for the system
r_i	the reliability of each component in subsystem i, $1 \le i \le m$
$\mathbf{r}$	$\equiv(r_1, r_2, \ldots, r_m)$, the vector of the component reliabilities for the system
q_i	$=1-r_i$, the failure probability of each component in subsystem i, $1 \le i \le m$
$R_i(n_i)$	$=1-q_i^{n_i}$, the reliability of subsystem i, $1 \le i \le m$
R	the system reliability
g_i	the ith constraint function
w_i	the weight of each component in subsystem i, $1 \le i \le m$
v_i	the volume of each component in subsystem i, $1 \le i \le m$.
c_i	the cost of each component in subsystem i, $1 \le i \le m$
V	the upper limit on the volume of the system
C	the upper limit on the cost of the system
W	the upper limit on the weight of the system
$f(\mathbf{r}, \mathbf{n})$	system reliability
$C_{UB}, W_{UB}\, V_{UB}$	the number of the required cost, weight and volume, respectively
$C(\cdot), W(\cdot), V(\cdot)$	the cost, weight and volume of "$\cdot$", respectively.
R_p	penalized system reliability.

3. Penalty guided ABC approach

The artificial bee colony algorithm is a new population-based meta-heuristic approach proposed by Basturk and Karaboga [25] and further developed by Karaboga and the coauthors [26–28]. This approach is inspired by the intelligent foraging behavior of the honeybee swarm.

The foraging bees are classified into three categories—employed, onlookers and scouts. All bees that are busy in currently exploiting a food source are classified as "employed". The employed bees bring loads of nectar from the food source to the hive and may share the information on the food source with onlooker bees. "Onlookers" are those bees that are waiting in the hive for information to be shared by employed bees, which pertain to their food sources, and "scouts" are those bees that are currently searching for new food sources in the vicinity of the hive. Employed bees share information on food sources by dancing in a common area in the hive, which is called dance area. The duration of a dance is proportional to the nectar content of the food source currently being exploited by the dancing bee. Onlooker bees that watch numerous dances before choosing a food source tend to choose a food source according to the probability proportional to the quality of that food source. Therefore, the good food sources attract more bees than the bad ones. Whenever a bee, whether it is scout or onlooker, finds a food source it becomes employed. Whenever a food source is exploited fully, all the employed bees associated with it abandon it and may again become scouts or onlookers. Scout bees can be visualized as performing the job of exploration, whereas employed and onlooker bees can be visualized as performing the job of exploitation. Motivated by this foraging behavior of honeybees, Basturk and Karaboga [25] proposed the artificial bee colony algorithm.