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Uncertain multiobjective redundancy allocation problem of repairable systems based on artificial bee colony algorithm

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Abstract Based on the uncertainty theory, this paper is devoted to the redundancy allocation problem in repairable parallel-series systems with uncertain factors, where the failure rate, repair rate and other relative coefficients involved are considered as uncertain variables. The availability of the system and the corresponding designing cost are considered as two optimization objectives. A crisp multiobjective optimization formulation is presented on the basis of uncertainty theory to solve this resultant problem. For solving this problem efficiently, a new multiobjective artificial bee colony algorithm is proposed to search the Pareto efficient set, which introduces rank value and crowding distance in the greedy selection strategy, applies fast non-dominated sort procedure in the exploitation search and inserts tournament selection in the onlooker bee phase. It shows that the proposed algorithm outperforms NSGA-II greatly and can solve multiobjective redundancy allocation problem efficiently. Finally, a numerical example is provided to illustrate this approach.

1. Introduction

Many real system design problems require the use of redundancy to meet high reliability specifications. A redundancy allocation problem (RAP) basically involves the determination of the number of redundancies to be allocated in each subsystem with the purpose of maximizing system reliability, which is a fundamental reliability optimization model and can be formulated as a difficult combinatorial optimization problem. The RAP with single objective has been extensively studied.[1,2] With the development of system design, it has been increasingly recognized that many practical design situations we encounter often involve multiple and conflicting objectives, which should be considered and optimized at the same time. For instance, it is often required to minimize the total system cost while maximizing the system reliability simultaneously. Considering that the decision-makers always require a full consideration of possible trade-offs and an availability-cost report in materiel solution

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analysis, researchers investigating RAP in such kind of complex situations often look for the determination of an entire Pareto optimal solution set.[3–5] These studies mentioned are all performed in deterministic environment, in which the reliability values of the components are assumed to be deterministic and known with certainty.

Unfortunately, in many practical situations, it is impossible to determine a fixed number that shows reliability of a component under all conditions. Furthermore, it is often difficult to accurately assess system failure rate and repair rate until the system is deployed or fielded. Thus, the RAP is always indeterministic with vague or imprecise statements, which can be boiled down to problems of observing the parameters themselves, deficiency in history and statistical data, insufficient theory, incomplete knowledge and the subjectivity and preference of human judgment, etc. With the wide application of fuzzy set theory[6] in engineering practice, many scholars consider this kind of indeterminacy as fuzziness and study RAP as a fuzzy programming problem.[7–9] In these literatures the parameters (coefficients) involved are treated as fuzzy variables, and the possibility measure[10] is applied to describing or formulate RAP as an imprecise model.

However, since the possibility measure has no self-duality, one event with possibility measure of 1 may be an impossible event, while one event with possibility measure of 0 may be a certain event.[11] That is to say, it is not reasonable to use the possibility measure to characterize the performance of redundancy system and optimize RAP in such kind of environment. Actually, these types of indeterminacy in RAP mentioned above should be called uncertainty, rather than fuzziness. A lot of surveys have shown that human beings usually overweight unlikely events, and the personal belief degree may have much larger variance than the real frequency.[12] Liu[13] declared that it is inappropriate to apply both probability theory and fuzzy set theory to uncertainty, because both theories may lead to counterintuitive results in this case. In order to deal with such kind of uncertainty problem, Liu[14] founded the uncertainty theory, which is a branch of mathematics based on normality, duality, subadditivity, and product axioms, as a means of handling uncertainty that is due to imprecision rather than randomness. So far, there has been little research on RAP using uncertainty theory, which is indeed one of the most important areas in decision analysis because many real world decision problems involve uncertainty. The RAP with multiple optimization objectives in uncertain environment is called uncertain multiobjective RAP (UMRAP), and the optimization problem under consideration becomes an uncertain multiobjective programming problem.

In this paper, a UMRAP in repairable series-parallel systems is studied, with the aim of maximizing the system availability A_s while minimizing the total cost C_s simultaneously, where the failure rate, repair rate and coefficients in objective functions are considered as uncertain variables. As a consequence, the objectives are also uncertain variables. Since the uncertain variables cannot be compared directly, the equivalent deterministic models should be proposed to remove the uncertain ambiguity first. Different real-life RAPs call for different meanings of deterministic models to satisfy their needs in practical application. Given the fact that the expected value of uncertain variable is widely used in real-life problem, in this paper expected value of availability and cost are considered. Moreover, when the designer is risk averse, the obtained design has to be done with high confidence levels, and the designs with large deviation are not desirable. Therefore, the associated variance of availability and cost are also considered. Thus, the uncertain biobjective RAP presented in this paper can be converted into a deterministic RAP with four objectives. However, for a programming problem with four objectives, the Pareto optimal set obtained always contains hundreds or even thousands of Pareto efficient solutions. It is difficult for designers to find satisfactory and meaningful trade-offs, and to select a preferred final design solution. To reduce the Pareto optimal set and to achieve a smaller practical set that can be easily analyzed by the designers, a new method, which involves breaking the original RAP with four objectives into two biobjective RAPs, is proposed in this paper. That is, optimize the expected value and associated variance of availability and cost respectively, then obtain two Pareto optimal sets in these two biobjective RAPs. It is proved that the intersection of these two Pareto optimal sets is Pareto efficient to the original RAP with four objectives. The solutions in the intersection will guarantee that both the expected value and associated variance are desirable. Considering the uncertain and NP-hard nature in UMRAP, where the size of the problem and thus the computational effort increases exponentially, meta-heuristics and evolutionary algorithms should be widely applied to UMRAP for successful generation of optimal solutions.

The artificial bee colony (ABC) algorithm, a meta-heuristic bionic algorithm based on the intelligent foraging behavior of honey bees proposed by Karaboga in 2005,[15] is a relatively new member of swarm intelligence. ABC algorithm is one of the adaptive meta-heuristic optimization methods inspired by nature, which is distinctly different from its siblings, such as genetic algorithms and ant colony optimization, in that it is a constructive, rather than an improvement, algorithm. It is inspired by the behavior of real honey bees foraging behavior, where the self-organization and division of labor features can be seen clearly. Especially, in ABC algorithm, the possible solutions are represented by the positions of food source, rather than the individuals. The ABC algorithm provides a new idea for the research of meta-heuristic algorithm and becomes one of the important research directions of solving complex optimization problem gradually. So far, due to its simplicity and ease of implementation, the ABC algorithm has been adopted by researchers in a variety of fields, including machines scheduling problem,[16] flexible job-shop scheduling problem,[17] hybrid intelligent problem,[18] etc. And it has been experimentally validated that its effectiveness and efficiency on algorithm performance are competitive to other optimization algorithms.[19–21]

To solve the uncertain, NP-hard and multiobjective characteristic of UMRAP, in this paper, a modified multiobjective ABC (MOABC) algorithm is designed for obtaining Pareto optimal set in UMRAP, which inserts the fast non-dominated sort procedure from the well-known fast non-dominated sorting genetic algorithm (NSGA-II)[22] into basic ABC algorithm. To the best of our knowledge, this paper is the first application of ABC algorithm in reliability design with multiple objectives. In order to test the performance of the proposed MOABC algorithm in multiobjective optimization problem, three well-known test problems are presented to compare its performance with NSGA-II, the result of which shows that the MOABC outperforms NSGA-II greatly. Moreover, a multiobjective RAP from Ref. 23 is presented and solved by MOABC, and it shows that the obtained result in Ref. 23 is not on the Pareto front