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Reliability evaluation and optimal design in heterogeneous multi-state series-parallel systems

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ABSTRACT

This paper addresses the heterogeneous redundancy allocation problem in multi-state series-parallel reliability structures with the objective to minimize the total cost of system design satisfying the given reliability constraint and the consumer load demand. The demand distribution is presented as a piecewise cumulative load curve and each subsystem is allowed to consist of parallel redundant components of not more than three types. The system uses binary capacitated components chosen from a list of available products to provide redundancy so as to increase system performance and reliability. The components are characterized by their feeding capacity, reliability and cost. A system that consists of elements with different reliability and productivity parameters has the capacity strongly dependent upon the selection of constituent components. A binomial probability based method to compute exact system reliability index is suggested. To analyze the problem and suggest an optimal/near-optimal system structure, an ant colony optimization algorithm has been presented. The solution approach consists of a series of simple steps as used in early ant colony optimization algorithms dealing with other optimization problems and offers straightforward analysis. Four multi-state system design problems have been solved for illustration. Two problems are taken from the literature and solved to compare the algorithm with the other existing methods. The other two problems are based upon randomly generated data. The results show that the method can be appealing to many researchers with regard to the time efficiency and yet without compromising over the solution quality.

1. Introduction

In a critical real world environment an important aspect of engineering design process includes evaluation and maximization of reliability of many physical complex systems. The problem of achieving optimal design of such systems is well known and has been investigated in many different formulations and through different optimization techniques. For a good literature survey on reliability optimization one can refer to Kuo and Prasad [26] and Kuo et al. [27]. Exact optimization approaches to determine optimal redundancy include Dynamic Programming, Integer Programming, and Mixed-Integer & Non-Linear Programming. Approximate techniques viz. iterative heuristics [27] and meta-heuristics [16] such as Genetic Algorithms (GA) [10,28,33], Tabu Search (TS) [38,39] and Ant Colony Optimization (ACO) [2,3,6,9,11–15,19,21,22,25,29–31,35,44,45,49,50] aim at seeking practically good solutions in reasonable time.

The binary state reliability modeling assumes that the system as well as the components exist in only two states viz. (i) up with full operational capacity, and (ii) down with complete failure. Although many practical applications have been

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successfully analyzed using binary reliability theory, it is recognized that there are systems whose behavior can be better studied by a function with different levels, depending on the operating conditions of the constitutive binary-state or multi-state elements. Systems characterized by more than two (but finite) levels of performance or system states are referred to as multi-state systems (MSS). Consider a communication network that provides message passing where the information security is achieved via information encoding. If the encoding unit (subsystem) fails, the network will still perform message passing, though with the lower level of security. Thus the communication network has minimum three levels of performance. Another example of MSS is a computer system, where the elements' performance is characterized by data processing speed. In a pipeline system, the amount of oil running through a crucial point determines the productivity or the performance of the system in a particular state [36], while the system state in a power generation plant is considered to be the amount of power generated. Flow networks such as oil and gas production networks, logistics and transportation systems, and distribution networks are required to supply the demand from source to sink through multi-state links. In such cases the binary reliability assessment will lead to incorrect decision-making regarding network performance and, therefore, the multi-state behavior of the network and its components must be incorporated to correctly evaluate the network reliability index.

In MSS the number of system states increases drastically with the increase in the number of system elements. This "high dimensionality" makes the reliability analysis more difficult and a time consuming affair. The first attempt to introduce the concept of MSS and multi-state components was made in the 1970s [7,17,34,41]. The basic concepts were laid down during this period and the properties of MSS were studied. Griffith [23], Natvig [37], and Block and Savits [8] then followed giving proper definitions of multi-state monotone system, multi-state coherent system, and minimal path and cut vectors. Furthermore, Funnemark and Natvig [20] obtained upper and lower bounds for the availability and unavailability values, to any level, in a fixed time interval for multi-state monotone systems based on corresponding information on the multi-state components. Aven [4,5] proposed two efficient algorithms for reliability evaluation and performance measures for monotone MSS with s-independent multi-state components using minimal paths and minimal cuts. Ushakov [46–48] introduced the concept of Universal Generating Function (UGF), which was later extended to Universal Moment Generating Function (UMGF) and proved to be an efficient approach to deal with high-dimension combinatorial problems.

In order to achieve more reliable complex technical designs redundancy is widely applied. However, inclusion of redundant elements in a system structure also increases its cost and weight, and affects other parameters. Therefore, a trade-off is required to achieve the desired reliability at the minimum resources consumption. Many authors have formulated the structure optimization problem of multi-state series-parallel systems, both as homogeneous and heterogeneous redundancy allocation problems (RAP), and suggested different approaches to achieve optimal system design. El-Neveihi et al. [18] were the first to formulate the reliability optimization problem allocating the multi-state elements into *k*-series systems and thereby maximizing the expected number of systems functioning at a minimum level. Zeblah [49] described an ACO method to solve reliability maximization problem for multi-state series-parallel power systems subject to a cost constraint and used UMGF technique to evaluate system reliability.

Heuristics are often more advantageous than exact algorithms because of the less computation time required to solve large-scale problems. Recently, significant research effort has been devoted to the development of meta-heuristic methods for handling the redundancy optimization problem. Meta-heuristics are generally based on probabilistic search and artificial reasoning and can deal with NP hard problems such as RAP using simpler mathematical modeling and derivation. If a sufficiently large number of iterations are used, they produce very high quality solutions compared to other optimization algorithms used to see global optima. TS, GA and Simulated Annealing (SA) are some of the meta-heuristics that have been applied to numerous problems so far. Lisnianski et al. [33], Levitin et al. [28] and Lisnianski and Levitin [32] used GA in combination with UGF to solve the redundancy optimization problems in multi-state series, parallel, series-parallel and bridge structures. Ouzineb et al. [38] and Taboda et al. [42] combined UGF with TS and GA techniques respectively to handle redundancy optimization in homogeneous series parallel MSS. While Ouzineb et al. [38] minimized the design cost of a system composed of capacitated binary components, Taboda et al. [42] handled multi-objective optimization for a system made up of multi-state components. Recently, Ouzineb et al. [39] proposed a heuristic (referred as SP/TG) based on a combination of space partitioning, GA and TS to solve non-homogeneous redundancy optimization problems. They used a fast procedure based on UGF to evaluate multi-state system availability. Tian et al. [43] presented an optimization model for a multi-state series-parallel system to jointly determine the optimal component state distribution and optimal redundancy for each stage. The physical programming approach was used to model and solve this reliability-redundancy optimization problem with two design objectives: system utility, and system cost. The formulated single-objective nonlinear optimization model is then solved using GA.

In this paper an ACO [12] algorithm is proposed to determine the minimum cost structure design for a heterogeneous multi-state series-parallel system achieving the desired system reliability index to meet the given consumer load demand. The system under consideration exhibits multi-state behavior due to the availability of multiple-choice components for each subsystem. The problem was initially formulated by Ushakov [47] and analyzed as both of homogeneous and heterogeneous redundancy optimization by Lisnianski et al. [33] and Levitin et al. [28] (Le-GA) respectively using GA combined with UGF. Later Ramirez-Marquez and Coit [40] and, Agarwal and Gupta [1] developed heuristic algorithms to obtain optimal homogeneous structures for these systems. Gupta and Agarwal [24] presented a heuristic algorithm to solve the two power system problems by allowing subsystem structures to be composed of maximum two types of components from the list of available products and suggested a binomial probability based formula to evaluate system reliability. Further, for these systems Agarwal and Sharma [3] adapted ACO and demonstrated its efficiency over prevalent methods. In this paper, we derive a formula to compute the reliability index in which maximum three types of components can be used within each subsystem.