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A robust loss function approach for a multi-objective redundancy allocation problem

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ABSTRACT

A redundancy allocation problem consists of the selection of a number of redundancies to be allocated in each subsystem of a series–parallel configuration to maximize system reliability, while minimizing overall system cost. Most existing studies either ignore system cost or assume deterministic component reliabilities. However, the selection of a network system design requires the estimation of its reliability and cost. Therefore, the uncertainty associated with such estimates must be considered in the decision process. In this study, an efficient method based on the loss function approach is proposed to solve the redundancy allocation problem. This approach not only optimizes the overall system reliability and cost estimates simultaneously, but also considers their associated variance–covariance structure. Experimental results obtained using a standard example show the effectiveness of the proposed method and its superior performance when compared to existing approaches.

1. Introduction

The redundancy allocation problem (RAP), a common reliability optimization problem [1,2], is crucial to design any modern complex systems such as safety systems, electrical power systems, transportation systems, satellite systems, telecommunication systems, etc. with very strict reliability requirements[3]. Chern [1] proved that the RAP is an NP-hard problem. The traditional objective for this problem is to identify optimal system configuration (the number and type of redundant components in each subsystem) to maximize system reliability (see for example [4–16]). Wang and Li [16] proposed a particle swarm optimization based approach to maximize the system availability with a limited budget of multi-state systems with bridge topology. Agarwal and Sharma [15] advanced an ant colony optimization algorithm for complex binary systems. Fyffe et al. [4] used a dynamic programming approach for improving system reliability. However, their approach suffered from inefficiencies and non-convergence. As a result, some other researchers involving Ghare and Taylor [5], Bulfin and Liu [6], Misra and Sharma [7] and Abouei and Hamadani [14] amended it using integer programming techniques. Besides, an improved dynamic programming technique was suggested by Nakagawa and Miyazaki [8]. A similar problem was formulated as a non-linear optimization problem (see for example, Tillman et al. [9,10]). Interested readers are referred to the review papers and the text-book by Kuo [17–19], in which the authors reviewed the most recent works in the RAP literature.

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Although, most of the existing approaches in the RAP literature concentrate only on maximizing reliability to obtain optimal design configuration, it is usually impossible for a single-objective approach to represent a practical problem truly. Fundamentally, RAP involves allocating redundant components into the system to get an optimal system design layout with the purpose of maximizing system reliability. The reliability improvement is obtained by adding redundant components using additional cost. Consequently, multi-objective techniques have been attracted researchers' attention in which objectives are maximizing the reliability and minimizing the cost of the system (e.g. acquisition, operation, maintenance costs). Busacca et al. [20] applied a multi-objective genetic algorithm (MOGA) to obtain the optimal system configuration in terms of both the reliability and the cost objectives. Tian and Zuo [40] employed physical programming with GA to solve the RAP. The objectives were combined into a single objective function to minimize system cost and weight while maximizing the system performance utility. Lately, Taboada and Coit [21], Garg and Sharma [22] and Khalili-Damghani et al. [23] suggested multi-objective algorithms to attain non-dominated solutions of multi-objective RAP (MORAP), based on which the decision maker(DM) manually selects the best design.

Most of the system reliability optimization studies assume the reliability values of the components are deterministic. However, in practical environments, the reliability of components is often estimated from field or by test data. Therefore, there is a natural uncertainty related to the estimates. Furthermore, decision makers (DMs) are generally risk-averse. They prefer a network design with a high reliability estimate assured by a low variability (for example the protection system in nuclear reactors [20,24]). When it is taken no notice, poor solutions that have unacceptable levels of uncertainty and risk can be attained. In other words, if there is an uncertainty in the constituent component reliability estimates, a system configuration, which maximizes system reliability estimate and minimizes cost estimate, is not a valid solution particular for new systems with few failure data. As a result, high system reliability, low system cost, and low variability in system reliability and cost become significant together. Nevertheless, simultaneous optimization of these objectives has not been mentioned by existing researches. Therefore, new design optimization methods are required to clearly consider variability. In this regard, the variances of the system reliability and cost estimate are a good sign to exhibit the variability at the system-levels.

Reliability optimization researchers have rarely considered variability involved in the reliability. To be more specific, only four researchers investigated this issue [25–27]. Marseguerra et al. [25] considered MORAP with two objectives of maximizing the reliability estimate and minimizing its associated variance. They applied a combination of genetic algorithm and Monte-Carlo simulation to identify a set of non-dominated solutions. Similarly, Coit et al. [26] proposed a novel approach to optimize reliability and its variance employing the weighted objective method with iteratively changing weights to obtain a Pareto optimal set. Also, as a metric to indicate estimation uncertainty in a posterior approach, Tekiner-Mogulkoc and Coit [27] used the variance of the component and system reliability estimates. They suggested a new formulation based on the coefficient of variation (CV) as a posterior method to obtain non-dominated solutions. It seems that none of existing approaches that consider variability in process optimization are efficient to solve practical applicability because they have the huge computing time due to the large amount of evaluation needed to obtain all efficient solutions. In these methods, after all (or most) of the Pareto optimal solutions are created, the DM choose the best one manually. Since a large number of solution is generated, it becomes complicated to choose the optimal solution. Whereas various components available in market may have diverse reliability and cost (e.g. from different brands) that affect system performance, these approaches neglected to consider system cost as an objective function.

In this paper, the system design problem is thus formulated with multiple objectives of:

1 – Maximizing the system reliability estimate.
2 – Minimizing the overall system cost.
3 – Minimizing system reliability variance estimate, and
4 – Minimizing the overall system cost variance.

To the best of the authors' knowledge there is no research considering the mentioned characteristics simultaneously. The proposed method has special benefits compared to others. The main point of the presented solution approach is that it provides a convenient method to obtain a solution with high reliability estimate, low system cost, and low variability in system reliability and cost, directly. In short, the research work proposed in this paper is novel, where the final solution presents a distinctive perspective on system design.

To structure the literature review of the RAP and to demonstrate differences between the current work and other approaches, a systematic state-of-the-art survey is shown in Table 1 to briefly review the existing studies on the RAP in terms of the modeling and the solution approach. As shown in Table 1, while many approaches correspond to deterministic modeling and ignore system cost as an objective function, a smaller part is associated with optimization of multi-objective RAP, where a few papers solve the problem with respect to uncertain conditions.

The rest of the paper is categorized as follows. Robust multi-objective redundancy allocation problem is formulated in Section 2. In Section 3, the suggested approach is stated and Section 4 demonstrates the practicality of the proposed method employing a numerical example. Furthermore, a comparative analysis between the proposed methodology and other relevant approaches is performed in this Section. Finally, some concluding remarks and suggestions for future research are provided in Section 5.