Journal of Manufacturing Systems 37 (2015) 33–43

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Robust series–parallel systems design under combined interval–ellipsoidal uncertainty sets

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ARTICLE INFO

Article history:
Received 19 June 2013
Received in revised form
17 September 2015
Accepted 18 September 2015
Available online 21 October 2015

Keywords:
System design
Reliability optimization
Redundancy allocation
Robust optimization
Interval–ellipsoidal uncertainty set

ABSTRACT

System reliability is an important requirement in design stage of systems, which depends on some parameters such as components' reliabilities which are estimated in advance. Due to some factors, the estimated reliabilities for components may vary during and prior to implementation. Therefore, it is important to consider various controllable and uncontrollable factors, which influence the system reliability, in the design phase of systems. Consequently, the need for presenting robust designs, which are insensitive or less sensitive to these variations, is necessary in the area of system engineering. In most cases especially for new and evolving systems, or for strategic design of systems, less or no historical data are available. Therefore, stochastic, fuzzy or interval programming approaches are no longer applicable to consider the uncertainty. In this paper, for the first time an uncertainty set in the form of combined interval–ellipsoidal is considered to study the behavior of variations. A robust optimization approach is employed to deal with this kind of uncertainty in reliability optimization problems. The findings indicate that applying the proposed robust reliability models, results in robust and reliable designs in practice which is crucial for many systems such as medical systems, nuclear systems and the like.

1. Introduction

Reliability engineering is a sub-discipline within systems engineering which involves some methods to ensure the reliability of systems for a specified time period under predetermined conditions. There are different methods for reliability optimization of systems. Soltani [1] presented a comprehensive review on reliability optimization problems considering both deterministic and non-deterministic problems. For more study on redundancy allocation problems readers are also referred to references [2–10,42]. In reality, the reliability of systems may not be constant and may vary due to some factors such as improper storage conditions, using manner, temperature, pressure, humidity, etc. To tackle such uncertainty, there are some approaches such as stochastic programming, fuzzy programming, interval programming and robust optimization. Studies of system reliability by considering the components' reliabilities as imprecise values were initiated by some researchers such as Coolen and Newby [11] who considered Bayesian reliability analysis.

In the stochastic programming framework, the estimation of reliability is considered as a random variable with a given distribution. A common approach to cope with difficult stochastic programming problems is to maximize the expected value. Rubinstein et al. [12] maximized the expected values of the random system reliability and used a Genetic Algorithm (GA) to solve the Redundancy Allocation Problem (RAP) with uncertain properties of components. However, the maximization of the expected value is not appropriate for decision makers who are risk-averse. Therefore, it is useful to consider the problem as multiple objectives of maximizing the system reliability estimate and minimizing the variance of that estimate. Marseguerra et al. [13] considered reliability optimization of a network system with stochastic components' reliabilities which were generated by Monte Carlo simulation. They found the optimal redundancy level through maximizing network reliability estimate and minimizing its associated variance. Coit and Smith [14] considered specified mean and standard deviation for components' reliabilities. Reddy et al. [15] considered a series–parallel system with stochastic components' reliabilities. They used a simulation method to generate feasible configurations and select the best configuration from reliability standpoint. Tekiner and Coit [16] considered the problem of minimizing the coefficient of variation of the system reliability

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http://dx.doi.org/10.1016/j.jmsy.2015.09.008
0278-6125/

estimate and presented two algorithms to deal with it. Zhao and Liu [17] developed a stochastic programming technique for RAP.

In the field of fuzzy programming, some researchers applied the fuzzy set theory to reliability analysis. Park [18] used fuzzy in the reliability apportionment problem for a two-component series system subject to a single constraint and solved it by fuzzy nonlinear programming technique. Mahapatra and Mahapatra [19] considered the problem of minimizing system cost of a series system with the target of system reliability in fuzzy environment and formulated the reliability model as a fuzzy parametric geometric programming problem. Recently, Soltani and Sadjadi [20] presented a robust possibilitic programming approach and developed robust models for RAP with active strategy.

In the area of interval programming as a non-probabilistic way to treat uncertainty, Sahoo et al. [21] considered a multi-objective reliability optimization problem by maximizing the system reliability and minimizing the system cost in a system with interval valued reliability of components, and formulated four different problems using interval mathematics. They solved these problems by applying GA and the concept of Pareto optimality. Taguchi et al. [22] considered the reliability optimization problem as a nonlinear programming with interval coefficients in the objective and solved the resulted problem by GA. Taguchi et al. [23] transformed an optimal design of system reliability problem with interval coefficients into a single objective nonlinear integer programming problem without interval coefficients and solved it by an improved GA. Bhunia et al. [24] considered a reliability optimization problem in an n-stage series system with interval values of reliabilities and stochastic resource constraints with known probability distributions such as uniform, normal and log normal distributions. After converting the problem into its equivalent deterministic form, they employed a GA method to solve the problem. Gupta et al. [25] considered RAP for series system with interval valued reliabilities of components and solved it by a GA based penalty function technique. Tang et al. [26] used partial order relations and interval operations. In their approach, an interval optimization problem of system reliability is transformed into a single objective linear programming problem without interval coefficients. Sahoo et al. [27] developed a GA to solve reliability-redundancy optimization problem of series–parallel/parallel–series/complex systems with interval valued reliabilities of components. Cheng [28] considered the uncertain parameters of mechanical components as non-probabilistic interval variables. They formulated the optimal design as a two-level optimization problem. More recently, Soltani et al. [29] presented an interval programming approach for RAP with the choice of a redundancy strategy.

Regarding regret based approaches, Feizollahi and Modarres [30], Soltani et al. [31] and Sadjadi and Soltani [41] considered series–parallel systems with, respectively, active, cold standby and with the choice of redundancy strategies considering interval uncertainty for reliabilities of components and used a Min–Max regret criterion as a robustness measure to deal with interval uncertainty.

In the interval approach, uncertainties are characterized by crisp sets and the system's reliability is usually evaluated based on the lower and upper bounds of the low-level's reliability. In the stochastic programming approach, the uncertain parameters are viewed as random variables with known probability distributions. In the fuzzy programming approach, the uncertain parameters are viewed as fuzzy numbers or fuzzy sets with known membership functions. However, in real-world, it is not easy for decision makers to specify either probability distributions or membership functions or both. In many practical situations, the probability distribution function of components' lifetimes may be unknown or partially known. In fact, there are not sufficient statistical data in most of the cases where the system is newly designed or manufactured. Therefore, only some partial information about the components is known. In addition, in most cases the upper and lower bounds of intervals are not known exactly.

An approach to tackle these difficulties is to consider an uncertainty set for the uncertain parameters. The robust counterpart optimization is an approach for modeling uncertainty in data in which the uncertain parameters are assumed to take arbitrary values in a prescribed closed uncertainty set such as ellipsoid, polyhedral, box, or their intersections. This technique generally refers to modeling of optimization problems with data uncertainty to obtain a solution which is guaranteed to be good for all or most possible realizations of the uncertain parameters. Soyster [32] is the first who introduced the idea of robust optimization within the concept of uncertainty set. His proposed robust formulation, results in a high protection while being more conservative in practice. Bertsimas and Sim [33] defined a family of polyhedral uncertainty sets that encode a budget of uncertainty in terms of cardinality constraints and proposed a less conservative robust optimization approach by not allowing all uncertain parameters to have their worst case. They developed a robust optimization technique in which the number of uncertain parameters is bounded above by a protection level also called the budget of uncertainty. In their approach, the protection level controls the tradeoff between the probability of violation and the effect to the objective function of the nominal problem. Ben-Tal and Nemirovski [34] considered another uncertainty set in the form of interval–ellipsoid. They introduced the safety parameter Ω as the radius of the ellipsoid to control the probability of deviation from the nominal values. They also discussed about probability guarantees of the robust solutions. The proposed approach of Ben-Tal and Nemirovski [34] consider the worst case of uncertain parameters and it is more conservative than Bertsimas and Sim's approach. Because of the importance of high reliability in many systems, it is reasonable to consider uncertainty in a combined interval–ellipsoidal uncertainty set. Consequently, this paper follows the same approach as Ben-Tal and Nemirovski's [34].

In the more recent literature of robust optimization for RAP, Feizollahi et al. [35,40] considered budgeted uncertainty set for components' reliabilities and presented robust counterparts for RAP in series–parallel systems with, respectively, active and cold standby strategies. Soltani et al. [44] also presented a robust counterpart model with budgeted uncertainty set for RAP in series-parallel systems with component mixing. In the present paper, for the first time, a perturbation set in the form of combined interval–ellipsoidal uncertainty is considered for uncertain components' reliabilities and the robust counterpart optimization approach is applied to RAP. The purpose of the robust optimization approach is to accept a suboptimal solution for the nominal values of the data, in order to ensure that the solution remains feasible and near optimal when the data changes [36].

The remainder of the paper is structured as follows. Section 2 describes the problem statement and formulation along with a brief overview on uncertainty set. The computational results are presented in Section 3. Finally, the paper is concluded in Section 4 along with some future research directions.

2. Problem statement and formulation

In this paper, the RAP is considered in series–parallel systems and the aim is to design a reliable system by choosing suitable components and the corresponding redundancy levels. In calculating the reliability of a system, reliabilities of components play important roles. In the real world, especially for new and evolving designs or strategic design of systems, the estimations of components' reliabilities are often uncertain and consequently the estimation of system reliability accompanies with uncertainty. To deal with