Reliability Engineering and System Safety 181 (2019) 17–27

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Multi-objective optimization in redundant system considering load sharing

Cassio Pereira de Paula, Lais Bittencourt Visnadi, Helio Fiori de Castro*

School of Mechanical Engineering, University of Campinas, Brazil

ARTICLE INFO

Keywords:
Availability
Markov Chain
failure dependency
NSGA-II
Multi-objective optimization

ABSTRACT

Reliability allocation problem (RAP) deals with the dilemma between reliability (or availability) increase and some undesirable consequences, as an increase in cost. Therefore, new installations or maintenance investments should be optimally allocated to maximize the reliability (or availability), considering all restrictions. This paper proposes a solution for the RAP problem, taking into account failure dependency among redundant components. Because of that, a stochastic approach, based on Markov Chain, is applied. The multi-objective problem is solved with NSGA-II (Non-Dominated Sorting Genetic Algorithm II), assuming availability and overall costs as objective functions. Two examples are tested with the proposed approach. The first case is a hypothetical system with 5 subsystems in series. The second example is a real industrial application. In both cases, a Pareto front is obtained, allowing an analysis of viable solutions to be adopted. Additionally, the failure dependency effect is also present in the optimization results. Therefore, it is possible to investigate the influence on the system availability and final cost.

1. Introduction

The increasing competitiveness in the industrial environment creates the necessity of growing productivity at a lower cost. Thus, it is necessary to ensure that the equipment can perform its design functions appropriately. In this manner, the purpose of using redundant systems is to guarantee the system's ability to overcome some components failure to avoid productivity losses. At the same time, a component failure may cause an overload on its redundancies, increasing the remaining components failure rate consequently. In addition, redundant systems tend to increase operational costs, as more equipment represent more design and maintenance costs.

In this context, the present paper proposes to optimize both availability and costs for a series system with active redundant components subjected to a failure dependency, i.e. the failure of a component affects the failure rate of the others. It is important to consider load-sharing in such optimization problem for more accurate results. This approach was never applied on previous works. The main objective is to solve a multi-objective optimization problem to increase system availability and decrease the overall cost. As availability is considered, it is necessary to consider the maintenance process. Besides, a failure dependence model is also presented in order to characterize the effect in the remaining components failure rate.

Hence, it is necessary to begin defining active redundant system. Fig. 1 represents the active redundant system first considered in this work, which is represented by the parallel series configuration with five subsystems. In each subsystem, all components operate simultaneously, sharing the total load. Subsystem 1 is composed of y_1 redundant identical components, while subsystem 2 likewise has y_2 identical components. Likewise, in subsystem i, there are y_i identical redundant components.

The concern about allocation of redundant components for increasing availability is called Redundancy Allocation Problem (RAP). Some studies have dealt with this matter including the consideration of cost, but as a constraint of the problem [1–3,4], although it is more interesting to consider the cost as an objective of the optimization problem, so both availability and cost are optimized, as it was recently done on [5–9].

The cost model applied in this research was proposed by Castro and Cavalca [10]. Their work proposed an availability optimization procedure, considering failure and repair rates and design and maintenance cost. The availability model was based on probability and combination theory, but it does not consider the relation of the current system state with previous states. To take that into account, the Markov processes are generally applied for modelling repairable systems, as it was done on [11–13].

There are many methods for solving RAPs, as shown by the state-of-art survey provided on [14]. One of the methods used for solving this kind of problem is the Genetic Algorithm (GA), a precursor of the optimization algorithm used in this article. It was first proposed by

* Corresponding author.
E-mail address: heliofc@fem.unicamp.br (H.F. de Castro).

https://doi.org/10.1016/j.ress.2018.08.012
Received 23 October 2017; Received in revised form 23 July 2018; Accepted 26 August 2018
Available online 31 August 2018

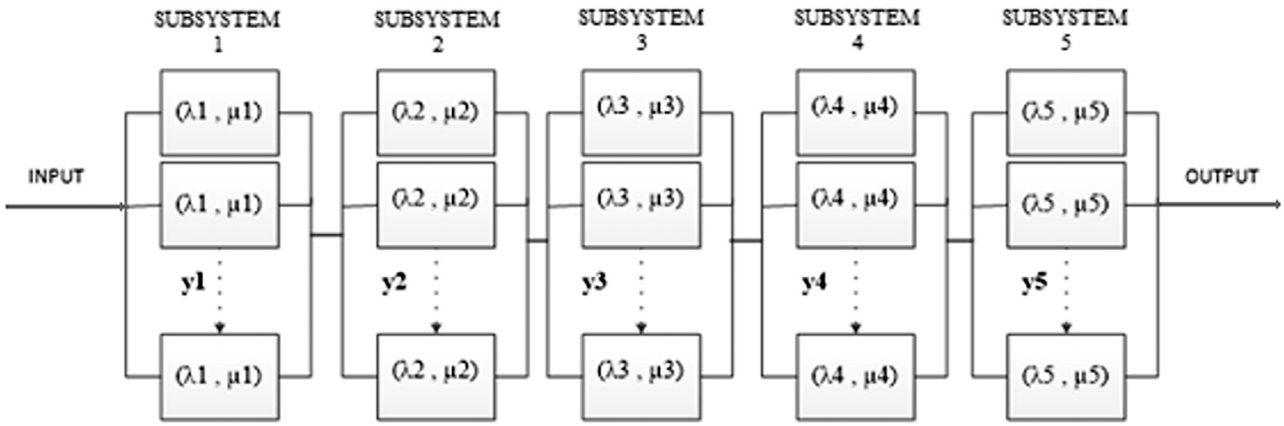

Fig. 1. Redundant System.

Holland [15] and it is the most popular technique in evolutionary programming. One important advantage of this method is that it is not sensitive to noise and local optima during the search.

The method applied on this paper is the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), suitable for multi-objective problems. It was proposed by Deb et al. [16]. Detailed explanations, applications of the method and comparison with other multi-objective optimization methods are found on [17]. RAPs considering both cost and availability as objective functions solved by NSGA-II were already performed [18–20]. This last one showed that this optimization algorithm provided a better solution than the standard solution present on literature. A RAP considering optimization of both availability and cost, using Markov process and NSGA-II was developed by [21].

The main contribution of this paper is the inclusion of the load sharing condition on the RAP. A failure dependency model was proposed by Yu et al. [22]. It allows the consideration of no load sharing and weak, proportional and strong load sharing between components on the same subsystem. Models with parameters estimated by statistical methodology were developed on [23–26].

Keizer et al. [27] analyses the influence of considering load sharing on maintenance costs, recognizing that to identify the failure dependency among components may be difficult. The present paper proposes a failure dependency model that allows the model of more load sharing conditions than the existing ones.

Linmin et al. [28] proposed a design optimization in RAPs with failure dependency. The failure dependency model applied was the one proposed by Yu et al. [22]. Their methodology included the Markov model and the optimization was performed by the Genetic Algorithm (GA). However, the objective function was the cost, while availability was a constraint of the problem. Different conditions of dependency were tested on a numerical example, and the conclusion was that these conditions affect the results of the optimization problem on both optimal number of components and repair teams.

Similarly, Xiao et al. [29] also performed an optimization on a RAP using GA, minimizing the cost and considering availability as a restriction. It considers a performance model based on the load that the element is carrying as well as a failure rate based on this load, so that a balance between increasing performance and reducing failure rate is pursued.

Consider load sharing in a RAP problem with the application of Markov Chain and assuming a multi-objective evolutionary algorithm to obtain the Pareto front is the main contribution of this paper. Although research about optimizing systems considering load sharing has already been done, the optimization of both cost and availability is inedited, and it is important because provides more results for decision making. Numerical examples are presented in order to better illustrate the importance of the proposed method. Firstly, a hypothetical system is studied with different conditions of failure dependency, in order to analyse the possible influence of this modelling compared to the model without failure dependency. Next, a case with real data of an industrial water collection system is considered, so that investments decisions may be taken according to the provided solutions. In this case, the system is modelled with moderate and high failure.

The problem formulation is pointed out in Section 2, considering the cost model previously proposed in [10]. The numerical examples and proper analysis are found in Section 3 and conclusions are in Section 4.

2. Problem formulation

In the reliability theory, there are systems which failure and repair rates cannot be considered independent of the current state of operation. This type of project cannot be analysed through classical formulation of system reliability. Thus, if one component fails, an additional load is transferred to other components, what results in an increase of the remaining components failure rates. The failure dependency model proposed by Yu et al. [22] depends on only one parameter that indicates the linearity of the dependency. The present work considers a model that includes a proportionality parameter. Table 1 summarizes the notations used on this section.

In this problem, the decision variables are: the ideal number of redundant components y_i in each subsystem and a proper distribution of

Table 1
Notations.

A	Availability
A^*	Availability complement
c_i	Design cost of each component of the subsystem (i)
C	Design cost of the system
$Crec_i$	Overall costs with maintenance resources except spare parts
cm_i	Maintenance costs related to spare parts
CM	Maintenance cost of the system
CO_i	Components in operation in subsystem i
f_1	First objective function
f_2	Second objective function
FC_i	Number of failed components in subsystem i
Ns	Number of states
n	Number of subsystems
Q	Transition rate matrix
Rec_i	Maintenance resource percentage
S	State
T	Time interval
y_i	Number of redundant components
α	Proportionality coefficient of failed components on failure rate
B	Impact of the maintenance resource amount in the repair rate increase
γ	Linearity coefficient of failed components on failure rate
λ_i	Failure rate
λ_0	Initial failure rate
μ_i	Repair rate
μ_0	Initial repair rate