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Establishment of the optimal time interval between periodic inspections for redundant systems

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ABSTRACT

For redundant systems with periodic inspections, the establishment of the optimal time interval between inspections that maximize availability and minimize costs is a challenging issue. This paper develops a model to analyze the reliability and determine the optimal interval between inspections of redundant systems subjected to periodic inspections. It uses discrete time Markov Chains to define the transition probabilities between the state of the systems and the costs related with each state. To optimize the time between inspections, the total cost per cycle was minimized using the Markov Chain properties followed by a numerical search technique. Four models of systems are analyzed and numerical examples for systems comprised of two and three components are presented: Model I – Active redundancy without component repair; Model II – Active redundancy with component repair; Model III – Standby redundancy without component repair and Model IV – Standby redundancy with component repair. The main advantage of the model used in this paper is the inclusion of costs for unavailability and production losses through the definition of the downtime costs that penalize the model when the system fails. This model can also be extended and generalized to determine the optimal interval between inspections in systems with active or inactive redundancies and with n components.

1. Introduction

There is an increasing emphasis and expectation for companies to uphold high standards of corporate social responsibility that protects not only the environment, but the health and safety of people as a whole. Emerging trends, such as the widespread use of lean manufacturing and six-sigma, have forced industries to operate in a more cost efficient manner. The optimal combination between redundancy application and maintenance efforts has become essential to ensuring safety, reducing operational costs by eliminating unnecessary activities, and enabling a steady flow process.

Redundant systems are widely used in industries where risk processes need high levels of reliability. For example, pump systems in oil refinery industries, cooling systems in steel plants, turbines in airplanes and reactors in nuclear companies. There are basically two primary types of redundancies: active or hot redundancy and inactive or cold standby redundancy. The use of hot or cold redundancy depends on the components utilized and characteristics required by the system.

In these systems, if continuous monitoring is not possible, periodic inspections are necessary to ensure that the system is working and that adequate redundancy is in place when it is required. During periodic inspections, hidden component failures are detected and repaired at predetermined time intervals. The time interval between inspections should be optimized in order to maximize availability and safety while also minimizing costs [1]. Frequent inspections increase the availability of the system, but involve higher costs of preventive maintenance. On the other hand, longer periods between inspections decrease inspection total costs, but can increase the costs of corrective maintenance (system repair, safety accidents) and downtime since there are longer periods where the system can be unavailable [2,3]. The establishment of the optimum interval between inspections is important to ensure satisfactory system availability along with the lowest possible cost.

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Reliability analysis of redundant systems has been studied for many years considering different approaches and methods. The most common methods used are Markov and semi-Markov models associated with Laplace transforms and numerical solutions. These methods were used by Laprie et al. [4] to study a system where the operating unit's failure rate increased when the other unit was under repair. Ref. [5] also used these methods to analyze a system with sequential preventive maintenance. The disappointment and interference time were modeled by Kapur and Kapoor [6]. Studying a system subject to preventive and corrective maintenance, Ref. [7] presented an algorithm to calculate the time until the first system down. Ref. [8] used Markov process to analyze a system with operation and repair priorities, while a system with a unit that switches from a cold-standby to a warm-standby position is modeled in [9].

By combining Markov and semi-Markov process with genetic algorithms, authors in [10,11] optimized the maintenance of multi-state systems. Ref. [12] analyzed a system with flexible intervals between maintenance interventions and Ref. [13] optimized the availability of a manufacturing system. The authors in [14] combined Markov process, genetic algorithms, and universal moment generation function to study multi-state degraded systems, while Ref. [15] used non-linear programming instead of UMGF to optimize a replacement policy. Finally, Ref. [16] analyzes imperfect maintenance utilizing Markov process and Bayesian networks.

Most of the papers that use Markov processes do not analyze the costs related with the operation and maintenance of the redundant system. The main objective of these papers is to define the reliability and availability of the system. A few papers analyze the costs involved in the maintenance, but they do not include the costs of unavailability and safety accidents (downtime), as seen in [14] that just considered the costs of procurement, preventive and corrective maintenance and [15] that just considered the costs of ordering and purchase of components.

Since the issue of redundant systems with periodic inspections has been partially covered, this paper aims to develop a model to analyze the reliability and determine the optimal time interval between inspections of redundant systems subjected to periodic inspections using discrete time Markov Chains.

The maintenance process of a redundant system is a stochastic process, since it has n components and each one can be up or down (operating or failed state) at any time. Each combination of component states represents a state-space in the Markov Chain process. When periodic inspections are employed, the system state (up or down) is observed at discrete time points (only in the inspections). This scenario justifies the application of a discrete time Markov Chain.

The main advantage of the model proposed in this paper is the inclusion of the costs of unavailability and safety accidents through the definition of downtime costs that penalize the cost model when the system fails; thus increasing the total costs the longer the system is down. Besides that advantage, this model can be generalized and used for determining the optimal time interval between inspections in systems with active or inactive redundancies and with n components. Models for two and three components are presented in this paper.

This article is organized as follows. Section 2 describes the research approach, presenting a brief review of the main studies related with preventive maintenance of redundant systems. Section 3 lists the assumptions and notation used and explains the methodology applied to modeling the problem. In Section 4, numerical examples are presented and analyzed. Section 5 summarizes the article and includes concluding remarks.

2. Research approach

Over the course of the last 60 years, there have been many papers which have been published about preventive maintenance applied in redundant systems. Early studies were concerned with determining system reliability and defining the best time between inspections while considering the maximization of availability. Since the first part of the problem was well explored and due to the increasing importance of incurred related costs to companies, recent papers aim to determine the optimal time interval between inspection considering not only availability, but also the minimization of costs incurred by maintenance activities. The most important papers related with this study are referenced next.

The author in [7] proposed a model for two similar units in cold-standby to determine the time to first system-down state using the Markov renewal process along with Laplace–Stieltjes transform. Using a similar approach, Ref. [6] included the concept of disappointment and interference time. Ref. [8], working with dissimilar units, added the repair time and component priorities to work and repair in his model.

A model to determine the reliability of two similar units in active redundancy is presented in [4]. The authors use the Markov model and Laplace transforms to approximate expressions for system reliability and mean time to failure in a model that has an increasing failure rate when one unit is under repair or inspection. Also, working with two units in active redundancy and using the same methods, the author in [5] shows a model to analyze the reliability in a system which component status alternates between working and under repair.

Applying Bayesian networks to formulate a failure model and continuous Markov chains to model maintenance behavior, Ref. [16] proposed the combination of both models according to a compositional multi-formalism approach to analyze the impact of imperfect maintenance on system safety.

The authors in [15] presented a model for a cold standby redundant system with preventive time-based replacement. Based on the Markov renewal process the system availability is derived and the costs of ordering and purchase are determined. Using a non-linear programming model to minimize costs subjected to the constraint of availability, genetic algorithms were proposed to search optimal alternatives.

Ref. [17] proposed a model to find the optimal periodic interval for complex repairable systems subject to soft or hard failures, with minimal repairs. The authors use a recursive procedure and numerical examples to solve the problem. The author in [18] developed cost functions for periodic testing and scheduled maintenance and optimized them based on the average cost. Ref. [19] presented an equation to evaluate failure frequency and the failure rate of a redundant system with two identical components based on the minimization of the total failure frequency of the system. These equations provide methods to determine the optimum maintenance interval for the system.

In a recent study, the authors in [14] applied the Markov process and universal moment generating function to evaluate system availability and the cost function of a series–parallel system subjected to imperfect preventive maintenance. After dividing the space into a set of subsets using space partitioning, this approach applied genetic algorithms and tabu search to select subspaces and find the best solutions.

To facilitate modeling, researchers Hokstad and Frovig [20] and Nourelfath et al. [14] ignored the time to repair of components, assuming they are instantaneous, and analyzed availability and costs of the system using the Markov process. The solution for this type of system can be also obtained by Petri Nets and Quantile-based inspection, as shown in [21,22], respectively.