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Analysis and optimization of periodic inspection intervals in cold standby systems using Monte Carlo simulation

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ABSTRACT

Cold standby redundant systems are widely applied in processes requiring high reliability. When continuous monitoring is not possible, periodic inspections are employed to verify the components' condition and prevent system failures. This paper aims to develop a Monte Carlo simulation model to analyze and optimize the time interval between periodic inspections in cold standby systems considering the required availability and the lowest cost possible. Times-to-system-failure and their respective total cost per cycle were modeled and simulated. After determining the simulation error, a sensitivity analysis was conducted in order to verify the parameters effects in the optimal time interval between inspections. As a result, a simulation model was developed and can be used to optimize time intervals between periodic inspections of different cold standby systems. The main advantage of this method is the ability of considering any probability distribution to represent the times-to-failure and times-to-repair, not being limited to the exponential distribution.

1. Introduction

Maintenance has a key role in both the product quality warranty and in the reduction of downtime or equipment malfunction costs. The improvement of maintenance techniques enables a better control of system reliability as well as the reduction of operational costs [1].

Among the maintenance techniques, we have four possible strategies: *i*) planned corrective maintenance – when the equipment should run until failure; *ii*) emergency corrective maintenance – when the equipment failure is not expected; *iii*) preventive maintenance – when preventive activities are based on time; *iv*) predictive maintenance – when the equipment condition is monitored utilizing different techniques to determine the appropriate moment to perform the preventive maintenance [2,3].

Redundancy is used to improve the system reliability and availability and also reduce the costs of maintenance and equipment failure. When both the components are active and in the same operational environment, it is called hot standby or active redundancy [4]. An application of active redundancy is on electrical energy distribution systems. On the other hand, cold standby systems have one or more inactive components that start to operate when an active component fails. Feizollahi et al [5] mention the application of these systems in textile manufacturing, satellites, and space exploration.

Periodic inspections are used to verify the system condition and determine the necessity of preventive and corrective maintenance. Periodic inspections on redundant systems are essential when the system is operating in places of difficult access or when continuous monitoring is not possible [1], such as in offshore oil platforms and nuclear power plants.

The maintenance analysis and the redundancy utilization should have as an objective the reduction of the total maintenance costs. Besides the cost of manpower, replacement parts, consumables, and tools, the costs related to downtime, such as late delivery penalties and quality problems as well as the costs relating to the environment and human accidents should also be considered.

Many methods are used to analyze and simulate the reliability, maintenance interval, and total cost of preventive maintenance of redundant systems. Feizollahi et al. [5] present a strategy of cold standby using linear mixed integer programming (MIP) and equivalent binary models. The minimization of the system average cost rate is analyzed by Zhang and Wang [6] and Zhang and Wang [7]. Marseguerra and Zio [8] apply the Monte Carlo method to add and calculate the economic aspects, such as repair costs and components depreciation. Jackson [9] utilizes Markov Analysis combined with Monte Carlo simulation to model the system reliability where the times-to-failure fit a Weibull distribution. Markov Analysis uses probability density functions of times-to-failure to determine the system reliability. The author assumes these probabilities follow a Weibull distribution and solve them by

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numeric integration and simulation. This approach is accurate and practical for determining system reliability. However, the consideration of repair, inspections, and costs would be cumbersome, given that we would still have the problem of how to add these variables to a Markov system and how to solve the equations with many variables.

Monte Carlo simulation requires the performance of a high number of simulation runs to converge to a steady state with a good confidence interval. The advantage of its utilization is that some characteristics that are too complicated to be modeled analytically are easier solved using Monte Carlo simulation, such as situations where the times-to-failure probability distributions are not exponential [8].

The main objective of this paper is the development of a simulation model to analyze and optimize the times interval between periodic inspections of redundant systems in cold standby, minimizing the maintenance costs. Using Monte Carlo simulation, the operation and maintenance of a cold standby system is simulated ten thousand times in order to obtain the mean-time-to-system-failure (MTBF) and the average cost of maintenance per cycle. Different scenarios are simulated varying the parameters of failure, maintenance, and costs and the times interval between inspections are optimized by numerical search technique.

The components conditional probability of failure can follow at least six different patterns according to component characteristics. Components that experience wear out or are subject to deteriorating conditions, such as most of mechanical components (rotating shafts, valves and cams) have an increasing conditional probability of failure. On the other hand, many electronic components (such as transistors, resistors, integrated circuits) exhibit a constant conditional probability of failure during their lifetime, which means they do not degrade with time [10]. Components having constant conditional probability of failure during their lifetime suffer random failures, have constant failure-rate, and their times-to-failure are well modeled by the exponential distribution. However, those components that have an increasing conditional probability of failure have their times-to-failure better represented by a Weibull distribution with shape parameter closer to two [11]. The Weibull distribution is widely used in reliability modeling since distributions as exponential, normal, and Rayleigh are particular cases of it.

The main contribution of this study is the ability of using Weibull distribution for the components times-to-failure. Most of the studies on redundant systems are based on mathematical models that use analytical equations and Markov chains to represent the system operation. Given the complexity of dealing with analytical equations using the probability density functions of some distributions (such as Weibull distribution) and the Markov chain properties itself (constant transition probability), these methods use exponential distribution for times-to-failure and times-to-repair. Exponential distribution is appropriate to model times-to-failure and times-to-repair of many components. However, as explained before, for many other components, such as for mechanic systems that degrade over time due to fatigue and wear, this approach is not appropriate. The distributions of times-to-failure of these systems are better represented by the Weibull distribution with an increasing failure rate. The simulation model developed in this study allows for the application of any probability distribution for times-to-failure and times-to-repair, being more embracing than analytical models.

Another contribution is the addition into the model of costs relating to inspections, corrective maintenance of components, and reactivation of the entire system after failure. The cost variable is extremely important in the management decision making regarding the maintenance of redundant systems. Frequent inspections improve system reliability and availability, but require higher costs for preventive maintenance. Alternatively, having lengthy periods between inspections decrease the costs of inspections, but increase the risk of system failure and the probability of corrective maintenance. The application of the model developed in this study can help solving this trade-off establishing an optimal time interval between periodic inspections, considering the required reliability along with the lowest cost possible.

Most of the papers that use analytical models do not analyze costs related with operation and maintenance of the redundant system. The main objective of these papers is to define the system reliability and availability. The addition of costs in these analytical models is possible [12,13], but it is not very explored because it adds variables to a problem that is already complex. The model presented in this study adds costs without adding too much complexity to the model"

The main difference between references [12,13] and this study is that none of the two references consider periodic inspections and both of them use Markov chains (exponential distribution) and genetic algorithms to optimize preventive replacement time12 and preventive maintenance and redundancy allocation13, respectively. This study optimizes time interval between periodic inspections using Monte Carlo simulation and considering Weibull distribution for times-to-failure.

This paper is organized as follows. Section 2 presents a review of the most important studies regarding the preventive maintenance of redundant systems and Monte Carlo simulation. In Section 3, assumptions and notations are listed and the methodology explained. Section 4 presents and discusses numerical examples. Section 5 summarizes the study and includes final observations.

2. Research approach

Many different methods are used in the literature to analyze the reliability and maintenance of redundant systems in cold standby. In the beginning, systems reliability was studied using probability theory and Markov chains [14,15]. As the systems became more complex, the methods of optimization, such as genetic algorithms, non-linear programming, and universal moment generation function, have been incorporated in the studies [12,13].

The problem with using Markov chains to analyze systems reliability and maintenance is that it requires components times-between-failure following an exponential or phase-type probability distribution, as can be seen in Liu et al [16]. as well as Hellmich and Berg [17]. The exponential distribution is appropriate and convenient to model the times-between-failure and times-to-repair for many components. However, in cases where there is degradation over time due to fatigue and wear, constant failure rate is not appropriate and other approaches, such as Monte Carlo simulation, need to be utilized [18].

Simulations utilize a mathematical, logical, and statistical model to represent the operation of a real system. In order to obtain data that is statistically reliable, the simulation has to be run many times. Industry usually uses a standard of 10,000 simulation runs. However, the number of simulation runs depends on the acceptable error. The simulation error can be determined dividing the standard deviation by the number of simulated data. The larger the standard deviation is or the smaller the percentage of the acceptable error is, the larger the number of simulation runs needed [19].

Huang et al [20]. simulate a system in warm standby comprising two groups of equipment using block diagrams. Jackson [6] analyzes the number of iterations in Monte Carlo simulations for complex systems where high accuracy is required. The author determines that more than 10,000 iterations are necessary to model the system reliability with more than four decimal places of accuracy.

Only a few studies approaching the reliability analysis of redundant systems using Monte Carlo simulation were found in the literature. Some of them analyzing systems reliability, such as Miau et al. [21] for a complex ring-standby structure and Xubin and Yufeng [22] for a multi-unit cold standby system with unreliable switch. Other studies also consider maintenance in their analysis. Xiao et al. [23] estimate the dependability for a consecutive-k-out-of-n:F repairable system. Srinivasa Rao and Naikan [24] assess the reliability of a repairable system using a hybrid approach that combines the continuous Markov approach with system dynamics simulation. Kishan and Jain [25] use