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Periodic inspection optimization model for a two-component repairable system with failure interaction

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ABSTRACT

This paper proposes a model to find the optimal periodic inspection interval on a finite time horizon for a two-component repairable system with failure interaction. Failure of the first component is soft, namely, it does not cause the system stop. The second component's failure is hard, i.e. as soon as it occurs, the system stops operating. Failure of the first component has no effect on the second component's behavior; however, any failure of the second component increases the first component's failure rate. Failure of the first component increases the system operating costs and is detected only if inspection is performed. Thus, the first component is periodically inspected and if a failure is observed during the inspection, it is repaired. When the second component fails it is also repaired. Repairs of components restore them to as good as new. The objective is to find the optimal inspection interval for the first component such that, on a finite time horizon, the expected total cost is minimized. The proposed modeling approach can be used in electrical distribution systems, where capacitor bank (first component) and high power transformer (second component) are coupled in a distribution substation. A simplified numerical example is given.

1. Introduction

Over the last few decades the maintenance of multi-component systems has become more and more complex. One reason is that the systems are becoming more complicated having several interacting components. On the one hand, interactions between components complicate the modeling and optimization of maintenance actions. On the other hand, interactions also offer the opportunity to group maintenance which may save costs (Nicola & Dekker, 2008). Multi-component maintenance models are concerned with optimal maintenance policies for a system consisting of several units of machines or several pieces of equipment, which may or may not depend on each other (Cho & Parlar, 1991). The goal is to take into account the interactions among the units and to develop a policy yielding lower maintenance cost for the system.

The interactions between units can be classified into economic, structural and stochastic dependence. Economic dependence implies that grouping maintenance actions either save costs (economies of scale) or result in higher costs (because of, e.g. high down-time costs), as compared to individual maintenance. Stochastic dependence occurs if the condition of components influences the lifetime distribution of other components. Structural dependence applies if components structurally form a part, so that maintenance of a failed component implies maintenance of working components (Cho & Parlar, 1991; Nicola & Dekker, 2008; Thomas, 1986).

Stochastic dependence or failure interaction between components can be defined in many different ways. In their seminal work on stochastic dependence (Murthy & Nguyen, 1985a, 1985b), authors introduce three different types of failure interaction for a two-component system. Type I failure interaction implies that the failure of component 1 can induce a failure of the other component with probability p and has no effect on the other component with probability $1 - p$. Type II failure interaction implies that the failure of component 1 can induce a failure of component 2 with probability p, whereas every failure of component 2 acts as a shock to component 1, without inducing an instantaneous failure, but affecting its failure rate. Type III failure interaction implies that the failure of each component affects the failure rate of the other component. That is, every failure of one of the components acts as a shock to the other component.

Ozekici (1988) proposes an optimal periodic preventive replacement policy for a multi-component system with stochastic/economic dependencies between components. Nakagawa and Murthy (1993) derive the optimal number of failures to minimize the expected cost per unit of a two component system with shock damage interaction for an infinite time case. Sheu and Liou (1992) consider an optimal replacement policy for a k-out-of-n system subject to shocks.

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Nomenclature

$\lambda_1(x)$	the average failure rate of the first component at time x
$\lambda_1^j(x)$	the failure rate of the first component at time x, provided that the number of failures of the second component from the beginning of planning horizon until time x is equal to j; $j = 0, 1, 2, \ldots$
λ_2	the failure rate of the second component
$N_2(x)$	a random variable representing the number of failures of the second component from the beginning of planning horizon until time x
p	the percent of the first component's failure rate increase due to the occurrence of one failure of the second component
T	the planning horizon length (e.g. one year) which is known and fixed
n	the number of inspections to be performed on the first component during the cycle T
τ	the time between two consecutive inspections, $\tau = T/n$
τ_L	the minimum feasible inspection interval
C_1^s	the cost of each inspection of the first component
C_1^d	the cost of each perfect repair of the first component
C_1^p	the downtime penalty cost associated to the first component per each unit of elapsed time from the soft failure of the first component to its detection at the inspection time
t	the initial age of the first component at the beginning of the cycle T
$((k-1)\tau, k\tau]$	kth inspection interval in the cycle T, $k = 1, 2, \ldots, n$
$P_k(t)$	the probability that the first component dose not fail in kth inspection interval of the cycle T, provided that we know that its age at the beginning of the cycle T is equal to t and that it is as good as new at that time
$e_k(t)$	the expected survival time of the first component in kth inspection interval of the cycle T, provided that we know the initial age of this component at the beginning of the cycle T is equal to t and it was healthy until t
$E[C_1^{((k-1)\tau,k\tau]}]$	the expected total cost of the first component in kth inspection interval of the cycle T, i.e. from a scheduled inspection at $k\tau$ over time period $((k-1)\tau, k\tau]$
$E\left[C_1^T\right]$	the expected total cost of the first component in the cycle T

Jhang and Sheu (2000) propose a generalized age and block replacement model for a multi-component system with failure interaction. The ith component ($1 \leqslant i \leqslant N$) has two types of failures. Type 1 (minor failures) occur with probability $q_i(t)$ and is corrected by minimal repair, whereas type 2 (catastrophic failures) occur with probability $(1 - q_i(t))$ and induce the total failure of all other components in the system. An unscheduled replacement of the system is, then, performed. In Scarf and Deara (1998, 2003), block replacement and modified block replacement policies for two-component systems with failure dependence and economic dependence are considered. Where tractable, long-run costs per unit time are calculated using renewal theory based arguments; otherwise simulation studies are carried out.

Satow and Osaki (2003) propose a two parameter (T, k) replacement model for a two-component system with shock damage interaction. The system is replaced preventively whenever the total damage of component 2 exceeds k or the age of the system reaches time T. Zequeira and Berenguer (2005) study inspection policies for a two-component parallel standby system with failure interaction and compared staggered and non-staggered inspections through numerical examples considering constant hazard rates. Barros, Berenguer, and Grall (2006) introduce imperfect monitoring in a two-component system with a parallel structure and stochastic dependences. Lai and Chen (2006) propose an economic periodic replacement model for a two-component system with failure rate interaction. The system is completely replaced upon failure, or preventively replaced at age T, whichever occurs first.

The failures of the components of a system can be classified into hard and soft failures (Meeker & Escobar, 1998; Taghipour, Banjevic, & Jardine, 2010; Wang, 2008). Hard failures are self-announcing and are fixed as soon as they occur. Soft failures are failures that do not make the system stop, but can reduce the system's performance and increase the system operating costs. Soft failures are usually not self-announcing and are detected and fixed only at the scheduled inspection. Thus, there is a time delay between real occurrence of a soft failure and its detection.

The delay-time concept has been widely used for modeling the problems of inspection maintenance and planned maintenance interventions. The delay time defines, Wang (2008), the failure process of an asset as a two-stage process. The first stage is the normal operating stage from new to the point that a hidden defect has been identified. The second stage is defined as the failure delay time from the point of defect identification to failure. It is the existence of such a failure delay time which provides the opportunity for preventive maintenance to be carried out to remove or rectify the identified defects before failures. With appropriate modeling of the durations of these two stages, optimal inspection intervals can be identified to optimize a criterion function of interest.

In Wang (2008), an outline of the delay time concept has been given and two delay time inspection models of a single component and a complex system has been introduced. Using this concept, in Wang (2009), an inspection model for a process with two types of inspections and repairs is addressed. However, as opposed to assuming that failure can be observed only by an inspection, it is assumed that failures can reveal by themselves. For the two types of inspection, i.e. minor and major inspection, the problem is, then, to determine the optimal constant inspection intervals. In Wang, Banjevic, and Pecht (2010), a multi-component and multi-failure mode inspection model based on the delay time concept is proposed.

There have been not many papers that treated maintenances for a finite time span, because it is more difficult theoretically to discuss optimal policies for a finite time span. However, the working times of most units are finite in the actual field, Nakagawa and Mizutani (2009). The importance of maintenance for aged units is much higher than that for new ones because probabilities of occurrences of severe events would increase. Therefore, maintenance plans have to be reestablished at appropriated times for a specified finite interval. In Nakagawa and Mizutani (2009), modified replacement policies which convert three usual models of periodic replacement with minimal repair, block replacement and simple replacement to replacement ones for a finite time span have been proposed.

Taghipour et al. (2010) propose a model to find the optimal periodic inspection interval which minimizes the expected total cost on a finite time horizon for a complex repairable system. The system considered in their study consists of several components at risk of occurrence of hard and soft failures and it is assumed that there is no failure interaction between components. However, in practice, for example in energy sector, there are several multi-component systems where failure of, at least, one component increases other components' failure rate. Thus, this