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A reliability-based approach to optimize preventive maintenance scheduling for coherent systems

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ABSTRACT

In this paper, the problem of reliability-based periodic preventive maintenance (PM) planning for systems with deteriorating components has been considered. The objective is to maintain a certain level of reliability with minimal total maintenance related cost. In the proposed approach, the planning horizon is divided into pre-specified inspection periods. For any given interval, a decision must be made to perform one of the three actions on each component (simple service, preventive repair and preventive replacement). Any of these activities has a distinct effect on the reliability of the components and the corresponding cost based on the required resources. The cost function includes repair cost, replacement cost, system downtime cost and random failure cost. It is assumed that the random failures follow a Non-Homogeneous Poisson Process. Minimum system reliability and PM resources are the main constraints considered. Since the problem under study is combinatorial in nature involving several non-linear decision variables, a simulated annealing algorithm is employed to provide good solutions within reasonable search time. Some illustrative examples have been solved to assess the performance of the proposed approach.

1. Introduction

Reliability is an important measure of performance with the profound impact on the economy and safety of the industrial systems. Its value depends on the system configuration as well as on the components reliabilities. In general, system reliability depends on its age and the maintenance policy applied. It usually decreases as components deteriorate. To keep the reliability of a system at a desired level, performing proper maintenance actions is necessary. According to the time performed, maintenance is classified into two main categories: corrective maintenance (CM) and preventive maintenance (PM). Corrective maintenance is usually performed after the system breakdown. Preventive maintenance corresponds to the scheduled actions which are performed while the system is still operational. It aims at keeping the system in available state by improving the conditions of its components. Generally, PM is more advantageous as it may prevent serious losses due to unpredicted failures [1–5,26–28]. The PM actions are usually performed at predetermined points in time to keep the reliability of the system at a desired level.

There are various maintenance actions which have different effects on the component reliability. The system reliability, in turn, is derived by the components reliabilities and the system configuration. In this regard, determining the types and frequencies of PM actions is a crucial planning decision. Many PM scheduling problems are combinatorial in nature, due to the large number of parameters involved and their strong and non-linear interdependencies. For such problems, the solution space grows exponentially when the number of variables increases. In fact, we have a "*combinatorial explosion*" when the system has many components and/or the planning horizon is long. For real sized problems with large number of variables, traditional enumeration base techniques such as Branch and Bound are inefficient as they suffer from the excessive computational times required.

In recent years, heuristic algorithms such as genetic algorithm (GA) and simulated annealing (SA) have been widely employed in combinatorial optimization, including solving complex PM scheduling problems [9–11]. Although these techniques do not necessarily guarantee global optimal solutions, they are usually not restricted to the problem size and structure and could provide good solutions within reasonable computational time. Munoz et al. [10] were among the firsts who applied GA to optimize maintenance scheduling. Chung et al. [11] proposed a double tier GA approach for multi-factory production networks to keep the system's reliability in a specified acceptable level, and to minimize

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the makespan of the jobs. To minimize periodic PM costs for a series-parallel system, Mohanta et al. [13] have presented a comparison of results for optimization of captive power plant maintenance scheduling based on loss of load probability. They have employed both GA and hybrid GA/SA techniques as optimization procedures. Other applications of heuristic algorithms for PM scheduling are presented in [12,14] and the references therein.

In this paper, a reliability-based problem is considered for complex systems with deteriorating components in which various PM actions may be performed on a given component in any of the equally spaced inspection intervals. The objective is to determine an optimized maintenance plan to minimize total maintenance related costs with respect to a desired level of system reliability. Therefore, the rest of this paper is organized as follows: in Section 2, types of PM actions and the corresponding effects on the reliability of the system are presented. In Section 3, a formal definition of the coherent systems is given. In Section 4, the Non-Homogenous Poisson Process (NHPP) is reviewed and applied for modeling the failures process of the system. In Section 5, the statement of the problem is presented and explicit formulations for the reliability function under PM actions are derived. For obtaining the optimum solution, the SA algorithm is used in Section 6. To assess the performance of the proposed approach, three illustrative examples are analyzed in Section 7. Finally, Section 8 provides some conclusion remarks and suggestions for future research works.

Hereafter and by convention, the cost and time units are considered to be US dollar and one working hour, respectively.

2. Types of PM actions and their effects

As mentioned above, the maintenance actions are performed to enhance system reliability by increasing the reliabilities of its components. For a given component, the maintenance actions performed may vary in successive inspection intervals. Generally, PM actions may be categorized into three types [13]:

- ***Inspection only:*** when different parts of a system are inspected, usually simple services such as lubricating, adjusting/calibrating, tightening the loose parts, cleaning dust, and adding supplements (oil, waters, etc.) are also done. This type-action emphasizes on maintaining a system on the normal operating condition. It usually requires less resources and tools and hence the improvement is limitary. These services do not improve the reliability and availability of the system. Instead, they help to maintain the current state of the component and hence reduce the rate of degradation.
- ***Low level repair:*** this action is mainly employed for replacing some simple parts such as springs, seals, belts and bearings. It may also include the activities of repairing those parts/subsystems that are expensive to acquire or uneasy to replace. Examples for this type of maintenance are engine overhauls, disassembly and reassembly of machineries, surface treatments of the moving parts and calibrations. A repair usually improves the state of the components in terms of the reliability, but does not make it “As Good As New” (AGAN).
- ***High level repair (Replacement):*** this type is the highest level and the most resource demanding type of maintenance activities that involves replacement of subsystems or major components with new ones. It is usually adopted for the key components to avoid serious damages to the whole system due to the random failures of such items. In addition, the components which have undergone repairs for several times and were not worthy to go on using, may also take this type-action. Replacement makes the state of the component AGAN.

In PM scheduling, all components are inspected in N intervals of equal durations. In each inspection, based on the component deterioration state and its role in the reliability of the system, one of the three PM actions may be performed. For a given component, the PM action has its own cost and resource requirement (manpower, spare parts, etc). Similarly, the different PM actions have distinct effects on the component's reliability. In turn, the reliability of the system is derived by its components reliabilities and the system configuration.

The main goal of this paper is therefore to determine an optimal PM action for each component in such a way that the required level of the system reliability is maintained with minimal total PM cost.

Here the approach proposed by Tsai et al. [3] for the Weibull distribution is used to calculate the reliability of a component undergoing a given maintenance policy. It is defined as:

$$R_{i,0,n} = R_{i,f,n-1} + m_2(1 - R_{i,f,n-1}), \quad \forall n, i \tag{1}$$

and

$$R_{i,n}(t) = R_{i,0,n} Exp\left(-\left[\frac{(t-(n-1)t_p)}{m_1\sigma}\right]^{\beta}\right), \; (n-1)t_p \le t \le nt_p \quad \forall n, i \tag{2}$$

In the above formulas:

β, σ	Shape and scale parameters for the Weibull distribution
t_p	Time interval between inspections
$R_{i,0,n}$	Reliability of the ith component at the beginning of nth inspection period
$R_{i,f,n-1}$	Reliability of the ith component at the end of $(n-1)$th inspection period
$R_{i,n}(t)$	Instant reliability of ith component during the nth period
m_1, m_2	Improvement factors due to various PM actions $(0 \le m_1, m_2 \le 1)$

The reliability of the ith component at the beginning of the nth period is shown in Eq. (1). It implies that the component reliability at the beginning of the period is equal to the reliability at the end of the previous period plus improved reliability as a result of the maintenance at current period. Then, the reliability of the ith component at the beginning of the nth period is substituted into Eq. (2) and hence the reliability function of the ith component during the nth period is derived. It is noted that in Eq. (2), the parameter $m_1$is determined by the hazard rate function of the component. Also, the coefficient m_2 in Eq. (1) reflects the effect of the PM action performed on the component's reliability.

3. Coherent systems

A system is said to be coherent if each of its components is relevant and its structure function is monotone. In other words, for coherent system the system structure function is nondecreasing in each of its arguments. Generally, there are two basic requirements that every engineering system must satisfy. First, the system should not contain any component whose functioning has absolutely no influence on whether or not the system works. Such a component, if exist, is called irrelevant. In optimal designs, engineers remove irrelevant components since there is a simpler system that has the same performance. Second, replacing a failed component with a functioning component would not make the system deteriorate. This implies that the structure function must be increasing in each argument [15].