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Optimal opportunistic indirect grouping of preventive replacements in multicomponent systems

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ABSTRACT

For complex systems operating in critical environments, original equipment manufacturers, operators and/or regulators often specify replacement intervals for major components before failure can occur. The fixed costs to teardown the overall system can be an important constituent of the total costs. Thus, when a preventive maintenance is scheduled to replace a given component, it may well be desirable to replace one or more other components that are within their replacement window (interval), so as to avoid repeating the teardown costs in a short while. This paper presents a novel network tree formulation of this opportunistic indirect grouping of periodic events problem. We show that, given a fixed time horizon and a moderately large number of major components, the replacement optimization problem can be represented as a tree of possible replacement combinations. Although these trees can become enormous, we have developed a Python implementation of a depth-first shortest path algorithm that can be very effective because many of the nodes of this tree do not need to be examined. Even when several million nodes need to be examined, only a few of them, typically a few hundreds, need to be maintained in memory at any one time. For larger number of components and longer time horizons, the trees can still become so large that it is impossible to examine it completely. In this case, the depth first search still rapidly finds a sequence of improving solutions and can be a very good heuristic for the problem.

1. Introduction

Many multicomponent systems used in industrial applications requiring high reliability such as air transportation, military equipment, high-pace production systems are usually required to undergo preventive replacements (PR) of key components or subsystems at repeating intervals often specified in terms of operating hours before any major failure can occur. Due to the contribution of these components or subsystems to the overall system reliability, each is required to be replaced within a very strict replacement window. Failure to do so can result in the grounding of the fleet or equipment by regulatory authorities. It is very common for these components to have replacement windows with different periodicities or component lives. Because, there is generally a very high fixed cost to bring such systems to the repair facilities and have them opened to carry out the replacements of components, it is often more economical to conduct opportunistic replacements of other components that are within their replacement window. For the owners of such equipments, the periodicities of preventive maintenance (PM) actions are already set and changes to these values are beyond their control. These periodicities have to be strictly followed. The sole margin of action resides in the possibility of carrying out a replacement ahead of it scheduled time when another replacement falls within its window of replacement.

Components are said to be economically dependent if the cost of replacing several components jointly in a system is less than the sum of the cost of several separate replacements of the same components (see Cho & Parlar (1991)). For these economically dependent components the opportunistic replacement policy is usually found to be optimal. Given the high fixed teardown cost, it is reasonable to assume that combining two or multiple replacements will yield substantial savings. However, moving forward the PR of a component (opportunistic replacement) to have it jointly performed with another replacement will change the replacements dates of subsequent replacements and possibly prevent a naturally occurring opportunistic replacement from taking place (see Fig. 1). Parts (a) and (b) of Fig. 1 show the replacements instants of two components with periodicities T_1 and T_2. Part (c) displays the superposition of the replacement instants of both components. There is a naturally occurring grouping of PM actions at instant $5T_1$ which is the same as instant $4T_2$. Part (d) of Fig. 1 depicts the effect of carrying out the first replacement of the second component at instant T_1. Advancing the replacement of component 2,

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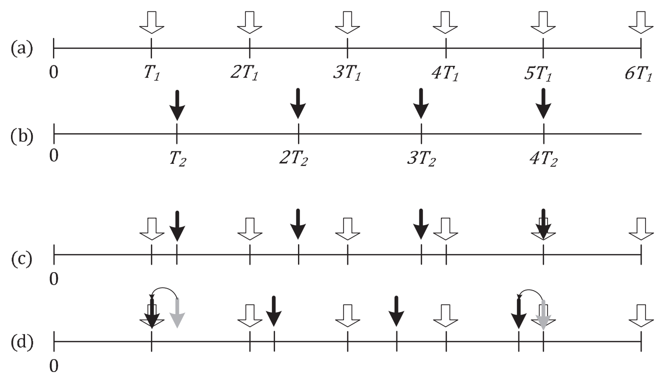

Fig. 1. Example of PM grouping for a two-component problem.

undoes the naturally occurring grouping that were to happen at time $4T_2$. Therefore, a myopic grouping of maintenance activities that considers short-term gains (shortsighted policy) is not guaranteed to work. All possible actions and their effects over the planning horizon have to be considered.

In the literature devoted to the modeling and optimization of maintenance activities for multicomponent systems, many papers have dealt with the determination of optimal opportunistic replacements: Sethi (1977), L'Ecuyer and Haurie (1983), Kececioglu and Sun (1995), Grigoriev, van de Klundert, and Spieksma (2006), Zhou, Xi, and Lee (2009), Laggoune, Chateauneuf, and Aissani (2010), Moghaddam and Usher (2011), Tambe, Mohite, and Kulkarni (2013), and Vu, Do, Barros, and Bérenguer (2015). The multicomponent models are classified by Cho and Parlar (1991) based on the dependence/interaction between the components and yield three types of dependence: economic, structural and stochastic. Recent reviews on multicomponent systems maintenance can be found in Nicolai and Dekker (2008), Nowakowski and Werbika (2009) and Ab-Samat and Kamaruddin (2014). Nowakowski and Werbika (2009) proposed several schemes to classify these multicomponent models into groups including the opportunistic models group. Since then, many variants of opportunistic models have appeared covering a variety of PM actions, corrective actions, perfect or imperfect maintenance, performance measures, maintenance costs, solutions methods and applications. For example, Laggoune, Chateauneuf, and Aissani (2009) proposed an approach to determine a PM plan for a multi-component series system subjected to random failures, where the cost rate is minimized under general lifetime distribution. In Laggoune et al. (2010), the authors extended their previous model to handle small size failure data samples by applying the Bootstrap technique. Moghaddam and Usher (2011) developed a multiobjective optimization model to determine the optimal preventive maintenance and replacement schedules in a repairable multi-component system under three possible actions: maintenance, replacement, or do nothing. A plan of actions for each component in the system is determined while minimizing the total cost and maximizing overall system reliability simultaneously over the planning horizon. A generational genetic algorithm and a simulated annealing metaheuristics are designed to solve the obtained mathematical model. Zhou, Lu, and Xi (2010) proposed an opportunistic preventive maintenance policy for multi-unit series systems based on dynamic programming which maximizes the short-term cumulative opportunistic maintenance cost savings. Tambe et al. (2013) presented an approach for opportunistic maintenance decision making for a multi-component system at planned as well as unplanned opportunities. The authors then applied their model to a real-life case study of a high pressure die casting machine. Gustavsson, Patriksson, Stromberg, Wojciechowski, and Onnheim (2014) introduced the preventive maintenance scheduling problem with interval costs, which is used to schedule PM of the components of a system over a finite and discretized time horizon. Their model and solutions methods are applied to three cases: maintenance of rail grinding, scheduling component replacements in aircraft engines, and components replacement in wind mills in a wind farm. Do Van, Barros, Bérenguer, Bouvard, and Brissaud (2013) presented a dynamic grouping maintenance strategy for multicomponent systems with positive economic dependence. Chang (2014) developed three optimal PM policies for systems subject to random working times and minimal repairs. Nguyen, Do, and Grall (2015) developed a novel predictive maintenance policy with multi-level decision-making for multicomponent systems with complex structure.

More recently, with advances in degradation modeling (see Ye & Xie (2015) for a review), models have appeared that use the degradation information to guide the selection of components to be opportunistically replaced. Bian and Gebraeel (2014) proposed a stochastic modeling framework to characterize the interactions between the degradation processes of interdependent components. Liu, Xu, Xie, and Kuo (2014) developed a two-phase approach to optimize the PM policy for a system with continuously degrading components. Zhang and Zeng (2015a, 2015b) dealt with the modeling of deterioration state space partitioning methods for the opportunistic maintenance modeling of identical multi-unit systems with economic dependence. Xia, Jin, Xi, and Ni (2015) developed a novel production-driven opportunistic maintenance strategy considering both machine degradation and the characteristics of batch production.

According to Dekker, Wildeman, and Van Der Duyn Schouten (1997), components subject to PM actions can be grouped to jointly undergo PM actions in order to save on teardown (set-up, preparation) costs. The models dealing with the grouping of PM are split in two classes: the fixed group models where all components are always jointly maintained and the optimization over groups models in which several groups are optimally generated. Dekker et al. (1997) presents an extensive coverage of the both groups of models. The optimization over groups models are further divided in two classes: direct grouping where the components are partitioned into a number of fixed groups which are always maintained together and the indirect grouping where the groups are not fixed over time, but are formed indirectly when the maintenance of different components coincide.

In this paper, we propose a new model for grouping PM actions for multiple major components/subsystems with windows of replacement not exceeding their mandatory replacement periodicities. This is a problem commonly encountered in the maintenance of fleets of high reliability systems used for air transportation, naval, mining, oil & gas, and military operations. The proposed model was used to solve a maintenance grouping problem for a company contracted to maintain engines used in the aerospace industry. The cost of removing a helicopter or aircraft from the flight schedule and sending it to the contractor for the duration of the maintenance activities is significantly higher than the cost of several of the major components to be replaced. These highly reliable systems have high level of redundancy where individual parts can fail without major components or subsystems failing. For these systems, failed parts are replaced at the earliest convenient time (overnight, next scheduled stop or landing, etc.) without affecting the overall age of subsystems/major components (minimal repair). Therefore, the grouping problem is only concerned with the PM actions and does not include corrective actions. The PM actions are carried out on groups of subsystems for which manufacturers or regulators have set mandatory replacement periodicities not to be exceeded.