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Maintenance grouping strategy for multi-component systems with dynamic contexts

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A B S T R A C T

This paper presents a dynamic maintenance grouping strategy for multi-component systems with both "positive" and "negative" economic dependencies. Positive dependencies are commonly due to setup cost whereas negative dependencies are related to shutdown cost. Actually, grouping maintenance activities can save part of the setup cost, but can also in the same time increase the shutdown cost. Until now, both types of dependencies have been jointly taken into account only for simple system structures as pure series. The first aim of this paper is to investigate the case of systems with any combination of basic structures (series, parallel or k-out-of n structures). A cost model and a heuristic optimization scheme are proposed since the optimization of maintenance grouping strategy for such multi-component systems leads to a NP-complete problem. Then the second objective is to propose a finite horizon (dynamic) model in order to optimize online the maintenance strategy in the presence of dynamic contexts (change of the environment, the working condition, the production process, etc). A numerical example of a 16-component system is finally introduced to illustrate the use and the advantages of the proposed approach in the maintenance optimization framework.

1. Introduction

During the last few decades, maintenance for multi-component systems have been extensively discussed in the literature. A number of papers have been categorized and reported in [1–4]. These reviews show that most of works usually take advantages of positive economic dependencies to minimize maintenance costs by developing opportunistic maintenance policies [5–7] and grouping maintenance policies. Positive dependencies refer to situations in which the policies lead to maintenance setup costs or/and downtime costs saving by performing simultaneously several preventive maintenance activities. These reviews show also that the maintenance grouping policies can be classified on the basis of the planning horizon type: infinite horizons (stationary grouping models) and finite horizons (dynamic grouping models). The stationary models provide static rules for maintenance which cannot be changed neither updated. They are mainly based on intervention frequencies [8–10] or on control-limits policies [11–15]. In the dynamic context, some dynamic grouping models have been proposed to update and change the decision rule according to available short-term information (varying deterioration rate of components, unexpected opportunities, changes of utilization factors of components, etc). A first rolling horizon approach has been introduced in [16] with a dynamic programming algorithm to find the optimal maintenance planning in polynomial time. This model has drawn much attention and has been developed in many papers [17–22].

However, these previous works only deal with series structure systems (either explicitly or implicitly), which lead to obvious positive economic dependencies: when one component is stopped for maintenance, the whole system is stopped, the availability is zero and the economic benefits due to grouping some other maintenance preventive actions in the same stopping time can be obviously positive. It mainly depends on the value of the set-up cost. In case of any multi-unit systems with any combinations of series and parallel structures, the economic benefit is more questionable: it can be not relevant to group maintenance actions because of possible related shutdowns of the system. This leads to negative economic dependencies. Hence the grouping strategy has to be optimized with a more subtle compromise between set-up cost savings, system failure cost, and the system structure.

The first aim of this paper is to investigate the case of multi-unit systems with any combination of series and parallel structures. From a practical point of view, complex interconnections between components which could be the mixture of basic connections (e.g. series connections, parallel connections, and bridge

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Nomenclature

n	number of components of the system
N	number of preventive maintenance activities in the planning horizon
i^j	jth maintenance occurrence of component i over planning horizon, with $j = 1, \ldots$
λ_i, β_i	scale and shape parameters of component i
$r_i(\cdot)$	failure rate of component i
C_i^p	preventive maintenance cost of component i
C_i^c	corrective maintenance cost of component i
S	setup cost
C_{sys}^p	planned shutdown cost
C_{sys}^u	unplanned shutdown cost
π_i	indicator function of component i. $\pi_i = 1$ if i is a critical component, and $\pi_i = 0$ otherwise
π_{G^k}	indicator function of group G^k. $\pi_{G^k} = 1$ if G^k is a critical group, and $\pi_{G^k} = 0$ otherwise
$E_i(x)$	expected maintenance cost of component i within interval $[0, x]$
x_i^*	optimal preventive maintenance interval of component i when it is individually maintained
ϕ_i^*	minimal long-term average maintenance cost of component i
ϕ_{sys}^*	minimal long-term average maintenance cost of the system
T_{begin}, T_{end}	beginning and ending dates of the planning horizon
t_{i^1}, t_{i^j}	tentative execution time of maintenance activity i^1 and i^j respectively
G^k	kth group of maintenance activities in the planning horizon
t_{G^k}	execution time of group G^k
SGM	grouping structure
$EP(G^k)$	economic profit of group G^k
$EPS(SGM)$	total economic profit of grouping structure SGM

connections), see for example [23–27], are very relevant and the existing models may no longer be usable. A mean cost model and a heuristic optimization scheme are proposed since the optimization of maintenance grouping strategy for such multi-unit systems leads to a NP-complete problem.

Then the second aim is to propose a finite horizon (dynamic) model in order to optimize in real time the maintenance strategy. The goal is to take into account available information related to a change of the environment, the working condition, the production process, etc. Combining a rolling horizon approach with a genetic algorithm, the proposed dynamic maintenance strategy allows the update of the maintenance planning as soon as a short-term information related to such a dynamic context is available. Moreover, different dynamic contexts which may occur/change over time are reviewed and discussed in this paper. They are categorized into three groups related to (i) system structure (e.g. changes of the system structure); (ii) component level (e.g. changes of deterioration behavior); and (iii) system environment (e.g. changes of replenishment policy and production planning). In the presence of such dynamic contexts, an initial grouped maintenance planning may be no longer the optimal one and need to be updated.

This paper is organized as follows: Section 2 is devoted to the description of general assumptions and of the grouping maintenance problem. The impacts of the system structure on maintenance grouping are also analyzed. Section 3 focuses on the major challenge of grouping optimization and the development of the rolling horizon approach in the context of complex structure systems and dynamic contexts. In order to illustrate the proposed maintenance grouping strategy, a numerical example is introduced in Section 4. Finally, the last section presents the conclusions drawn from this work.

2. System modeling and problem statement

Consider a multi-component system structure consisting of n binary components, i.e. a component state is either "operational" or "failed". The failure behavior of components is described by a continuous distribution with the increasing failure rate. Due to the complexity of the system structure, two kinds of components are here considered: (i) a component is said critical one if its shutdown for whatever reasons leads to a shutdown of the system and (ii) a component is non-critical if the system can be still functioning when the component stops.

From practical point of view, the performance correlation may exist between components. In fact, the performance correlation (stochastic dependence) implies that the state of a component may influence the lifetime distribution of other components or several causes outside the system which bring about simultaneous failures and hence correlate the lifetimes (so-called common-causes failures). This correlation has been recently investigated for condition-based maintenance optimization, see for instance [28–31]. However, in such papers, the maintenance models can be applied for several particular structures (series or parallel structures with a small number of components). For complex structure system, taking into account the stochastic dependence in maintenance modeling may lead to very difficult problems to be solved, e.g., assessment of components reliability (failure behavior of components are jointly dependent); formulation and optimization of grouping maintenance (large number of dependent variables to be solved/optimized). That is why in this work, the performance correlation is not considered. It should be noted that the impacts of complex structure and dynamic contexts on grouping maintenance are the main concerns of the present paper.

2.1. Main definitions and assumptions before grouping

In the context of grouping maintenance activities, the maintenance policies are commonly first optimized independently at the component level [2,16]. We consider here periodic age-based maintenance policies: each component is preventively maintained after a fixed interval of time which is optimally determined according to the average maintenance cost of the component and to its lifetime distribution. The later will be discussed in Section 3.2. After a preventive action, the maintained component becomes "as good as new". Between two preventive maintenance actions, if a component fails, a minimal repair is then immediately performed to restore the component to "as bad as old" state. It is assumed in this work that both corrective and preventive maintenance durations can be neglected when compared to the duration of planning horizons and all necessary maintenance resources to execute maintenance actions are always available.

As mentioned above, performing a maintenance action may lead the system to be shut down. The shutdown cost can be due to the loss of the main function of the system, the restart cost, the