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A dynamic predictive maintenance policy for complex multi-component systems

Adriaan Van Horenbeek *, Liliane Pintelon

Department of Mechanical Engineering, Centre for Industrial Management/Traffic and Infrastructure, KU Leuven, Celestijnenlaan 300A, BE-3001 Heverlee, Belgium

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ABSTRACT

The use of prognostic methods in maintenance in order to predict remaining useful life is receiving more attention over the past years. The use of these techniques in maintenance decision making and optimization in multi-component systems is however a still underexplored area. The objective of this paper is to optimally plan maintenance for a multi-component system based on prognostic/predictive information while considering different component dependencies (i.e. economic, structural and stochastic dependence). Consequently, this paper presents a dynamic predictive maintenance policy for multi-component systems that minimizes the long-term mean maintenance cost per unit time. The proposed maintenance policy is a dynamic method as the maintenance schedule is updated when new information on the degradation and remaining useful life of components becomes available. The performance, regarding the objective of minimal long-term mean cost per unit time, of the developed dynamic predictive maintenance policy is compared to five other conventional maintenance policies, these are: block-based maintenance, age-based maintenance, age-based maintenance with grouping, inspection condition-based maintenance and continuous condition-based maintenance. The ability of the predictive maintenance policy to react to changing component deterioration and dependencies within a multi-component system is quantified and the results show significant cost savings.

1. Introduction

1.1. Problem statement

The complexity of industrial equipment is ever increasing, which introduces many interdependencies between the components. Neglecting these interdependencies when scheduling maintenance actions leads to inefficient maintenance (e.g. higher costs and downtime). Maintenance policies should be adapted to take into account these interactions between components and equipment in order to find a system-wide and even plant-wide optimal maintenance policy. A multi-component and system approach needs to be taken in maintenance optimization models. Nicolai and Dekker [1] give an overview of optimal maintenance policies for multi-component systems based on the dependence between components (i.e. stochastic, structural or economic dependence). However, no models that use prognostic/predictive information or a prediction of remaining useful life (RUL) are mentioned. This is striking as the use of prognostics in maintenance is increasing over the past years [2–4]. Therefore, the link between prognostic algorithms and decision making based on the resulting remaining useful life distributions should be established in a predictive maintenance policy.

Currently a lot of attention is paid to condition-based maintenance in literature, and more recently to predictive maintenance policies. A thorough literature overview of both condition-based and predictive maintenance policies is given by Jardine et al. [2]. A multi-component systems approach for condition-based maintenance optimization is applied by Tian and Liao [5] where economic dependence between components exists. Yang et al. [6] schedule maintenance based on the predicted machine degradation by taking into account the complex interaction between components, production process and maintenance operations. The advantage of using predictive information over threshold setting maintenance policies is illustrated by Camci [7]. Bouvard et al. [8] introduce a dynamic condition-based maintenance planning model which uses updated failure probability functions based on component degradation, where the groups of maintenance operations are rescheduled at each decision moment. Although condition-based maintenance takes advantage of the known state of components, setting a degradation threshold beyond which preventive maintenance is carried out is not always an optimal

* Corresponding author. Tel.: +32 16 32 24 97; fax: +32 16 32 29 86.
E-mail address: Adriaan.vanhorenbeek@cib.kuleuven.be (A. Van Horenbeek).

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solution compared to predictive maintenance, certainly not when considering interdependent multi-component systems [7]. Predictive maintenance makes use, in addition to current degradation information, of predictive information in the form of the remaining useful life of components to optimally schedule maintenance actions, while condition-based maintenance only uses current component state information. Proactive maintenance decisions can be made based on the predictive information which results in a dynamic maintenance schedule. Moreover, the predictive information makes it possible to take into account component interdependencies into the maintenance schedule.

1.2. Objective of the paper

Although some initial research has been done on condition-based and predictive maintenance policies it is clear that the use of predictive information in advanced maintenance policies for multi-component systems is still an underexplored area of research [1,2]. Moreover, modeling the combination of dependencies between components is an open area identified in literature, since combining more than one makes the models too complicated to analyze or solve [1,9]. The aim of this paper is to develop a dynamic predictive maintenance policy, which builds further on the research performed by Wildeman et al. [10] and Bouvard et al. [8], for a complex multi-component system considering different levels and combinations of dependencies between the components. The dependence between components is modeled as specified by Nicolai and Dekker [1], where stochastic, structural and economic dependence are defined. *Stochastic dependence* considers the effect of the deterioration of a component on the lifetime distribution of other components. If components structurally form a part or subassembly in a way that maintenance of a failed component implies maintenance on working components, *structural dependence* between those components exists. While *economic dependence* implies that grouping maintenance on components either saves costs or results in higher costs compared to individual maintenance. By taking into account different levels of dependence (i.e. from no dependence over partial dependence to maximal dependence) between components, not only the capability to adapt to different deterioration patterns for several components, but also the capability to adapt to different interactions between components of the dynamic predictive maintenance policy is illustrated. The considered objective is to minimize the long-term mean maintenance cost. To validate the performance of the dynamic predictive maintenance policy it is compared, for the same system but with different dependencies between the components, to five conventional maintenance policies. This allows to quantify the added value of predictive information in maintenance optimization and decision making for complex multi-component systems. The considered maintenance policies are the following; block-based maintenance, age-based maintenance, age-based maintenance with grouping, inspection condition-based maintenance and continuous condition-based maintenance.

The developed predictive maintenance policy is a dynamic maintenance policy, as information that becomes available on the short term (i.e. component degradation information and RUL) is taken into account to adapt the maintenance planning. Non-stationary situations, such as changing deterioration of components, varying use of components and opportunistic maintenance, can be incorporated. In this way, dynamic decisions are generated that may change over the planning horizon. This is in contrast with stationary models, where a long-term stable situation is assumed [9]. Within dynamic models, a further distinction between finite-horizon and rolling-horizon approaches can be made [9]. The considered predictive maintenance policy uses a rolling-horizon approach to schedule maintenance actions. These rolling-horizon models use a finite horizon, based on a long-term (i.e. infinite-horizon) plan, which is updated repeatedly as a maintenance action is performed or new short-term information becomes available. Rolling-horizon models aim to bridge the gap between finite- and infinite-horizon models and to combine the advantages of both, which yields more stable solutions compared to finite-horizon models [9].

1.3. State-of-the-art advancements

Compared to the papers found in literature and briefly discussed in Section 1.1, the research in this paper advances the state-of-the-art by developing a dynamic predictive maintenance policy, building on the research of Wildeman et al. [10] and Bouvard et al. [8], for a complex multi-component system. The main contributions of the paper can be summarized as follows:

- A combination of different dependencies (e.g. economic, stochastic and structural dependence) between the components in the system is considered in order to determine the added value of the developed predictive maintenance policy within different environments and configurations of multi-component systems.
- Partial dependence has never been considered in maintenance optimization. In previous studies found in literature the dependency in multi-component systems is assumed to exist or not. A major contribution of this paper is in this regard the incorporation of partial dependence in the decision making process.
- Imperfect maintenance is included in the developed model. Moreover, the effect of imperfect maintenance on the objective of minimal long-term mean cost per unit time is quantified.
- Dynamic models have been introduced in order to change maintenance planning according to short-term information, by using a rolling-horizon approach [10]. This approach is however only applicable when maintenance durations are assumed to be negligible. In order to resolve this issue, the developed dynamic predictive maintenance policy considers non-zero maintenance downtimes which introduce dependencies between the occurrence dates of the maintenance activities.
- A random failure condition or threshold is considered in order to include its dependence on uncertain operation conditions and deterioration changes.
- The performance of the predictive maintenance policy is compared to five other conventional maintenance policies for different levels of dependence (i.e. ranging from no to maximal dependence) between the components in the system.

Section 2 of this paper describes the degradation and maintenance model. The need for grouping maintenance is discussed in Section 3, while the developed dynamic predictive maintenance policy is discussed in Section 4. Section 5 elaborates on the component dependencies in the considered multi-component system and Section 6 handles the maintenance policies used for performance comparison of the developed predictive maintenance model. A numerical example is given in Section 7. Finally, the conclusions and future work are stated in Section 8.

2. Degradation and maintenance model

Consider a system with n non-identical components. A failure of component i causes the entire system to stop (i.e. n-component series system) and a system and/or component failure is noticed immediately without any inspection. Time is discretized with a sample time τ. Component degradation information is retrieved at