Reliability Engineering and System Safety 145 (2016) 93–103

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Reducing costs by clustering maintenance activities for multiple critical units

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ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form
4 September 2015
Accepted 12 September 2015
Available online 21 September 2015

Keywords:
Condition-based maintenance
Clustering
Multi-unit systems
Critical units

ABSTRACT

Advances in sensor technology have enabled companies to make significant progress towards achieving condition-based maintenance (CBM). CBM provides the opportunity to perform maintenance actions more effectively. However, scheduling maintenance at the unit level may imply a high maintenance frequency at the asset level, which can be costly and undesirable for safety reasons. In this paper, we consider systems consisting of multiple critical units for which a strict and conservative maintenance strategy is enforced. Although this implies that benefits cannot be obtained by delaying maintenance activities, the clustering of them can be beneficial. We consider two simple, practical systems for condition monitoring that involve either one signal (alarm) or two signals (alert, alarm). Our analysis and results provide general insights into when and how to cluster maintenance operations, with the objective of minimizing the total maintenance costs. Moreover, they show that clustering is essential for a broad range of circumstances, including those at a considered real-life case of equipment maintenance at Europe's largest gas field.

1. Introduction

Recent advances in sensor technology have delivered important opportunities for condition monitoring of industrial systems and condition-based maintenance. Condition monitoring is defined as “the collection of real-time sensor information from a functioning device in order to monitor and learn about the condition of that device” [18]. Condition-based maintenance is preventive maintenance based on condition monitoring [14]. The main advantage of condition-based maintenance compared to time-based maintenance is that it takes conditions of equipment into account, and thereby leads to more effectively planned maintenance actions and improved utilization of the lifespan of a unit. For single-unit systems, the benefits are obvious and one should strictly adhere to a policy of condition-based maintenance without hesitation. However, not all business cases are as straightforward as this.

Many real-life systems contain multiple units subject to deterioration. Applying CBM for each unit separately minimizes the maintenance frequency at the unit level, but also implies many (small) maintenance operations at the asset level, which may not be cost effective. Units are often economically dependent [10] since the costs of a maintenance action on one or more units consists of a fixed part (e.g. fixed costs associated with work preparation, transport, scaffolding, safety precautions and possible plant shutdowns) and a variable part (e.g. man-hours, materials and safety precautions at unit-level). If the fixed part is considerable, then clustering maintenance operations of various units may be preferable to minimize the total maintenance costs at the asset level.

As we explain in more detail in Section 2, existing studies on multi-component systems with condition monitoring focus on rather complex models and policies. The focus is mainly on methods and algorithms to solve these models, their computational performance, and proposed approximations. In general, only a few examples are considered, and insights on how the optimal maintenance strategy depends on the various characteristics of a situation are lacking. Instead, we focus on simple settings and policies that are easy to implement, and derive general insights on the effects of the number of units, the cost structure, and the mean times until signals.

Our approach is to consider a system that consists of a number of identical critical units. Such systems are widespread in practice in for example the process industry, the maritime industry, and the transport industry [6,8,31], and it applies to the real-life case discussed in Section 7. Each unit contains a sensor that provides

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http://dx.doi.org/10.1016/j.ress.2015.09.003
0951-8320/

either one signal (alarm) or two signals (alert, alarm). These one and two-level signal systems are based on the P-F interval introduced by Moubray [21] and are very common in industry. Some failures/systems only have a single symptom that can be detected (alarm), but for others two symptoms with different P-F intervals might occur. An example of the latter is a bearing that shows increased vibration levels about 6 months before failure, while a month prior to failure an increased heat generation could be detected [5].

For both systems, which we will refer to as alarm-maintain and alert-alarm-maintain, an operational guideline in place enforces a maintenance action within a fixed time period after an alarm in order to prevent an impending failure. Because of the criticality of the units benefits cannot be obtained by delaying maintenance activities. However, it can be beneficial to cluster maintenance activities. In this paper, the cost performance of two clustering policies will be evaluated and compared with the policy that does not cluster maintenance activities.

The remainder of this paper is organized as follows. In Section 2, we discuss the existing literature on multi-unit systems with condition monitoring. In Section 3, we formally describe the problem we consider. In Sections 4 and 5, we analyze the alarm-maintain and the alert-alarm-maintain system, respectively, under the assumption that the time until an alarm (and also until an alert in the latter system) is exponentially distributed. In Section 6, we relax this assumption to check the robustness of our results under different time-to-signal distributions. We discuss our results and implications for a real-life case of equipment maintenance at the Groningen gas field in Section 7. We end in Section 8 with conclusions and directions for future research.

2. Literature review

In this section we review studies that consider multi-unit systems with condition monitoring. For broader reviews on multi-component systems we refer to Cho and Parlar [10], Dekker et al. [11], Nicolai and Dekker [22], and Wang [28].

Anisimov and Gürler [1] and Gürler and Kaya [13] consider a system with identical components with operating times consisting of a number of sequential phases with exponential durations. Anisimov and Gürler [1] propose a grouping policy that replaces all components if the fraction of components that is in the last state before failure exceeds a certain threshold. The focus is on various methods (exact and approximate) to optimize this fraction. The maintenance policy adopted by Gürler and Kaya [13] either performs preventive or corrective maintenance on single units, or replaces the entire system if at least N components are beyond a certain deterioration state K. Approximations are proposed to evaluate the policy. Only limited insights on the performance of the grouping policy for varying characteristics of the model are provided by these studies.

Other studies limit themselves to systems with a fixed and small number of units. Castanier et al. [9] consider systems with two units in series that deteriorate gradually and that are monitored by non-periodic inspections. Set-up costs are saved when inspections or replacements are combined. Koochaki et al. [17] analyze a serial production system consisting of three components, each following either a condition-based or an age-based maintenance policy. The effect of maintenance clustering on maintenance costs and line productivity is considered for a few specific system configurations. Tian and Liao [25] consider multi-component systems with failure rates that are described as proportional hazards models. The components are economically dependent and an advanced policy is proposed that dictates the grouping of preventive replacements. Two examples, respectively with two and three components, are considered.

Stochastic dependence between the components is considered in two studies. Hong et al. [15] investigate the influence of dependent stochastic degradation of multiple components on the optimal maintenance decisions. Emphasis is on the copula that are used to model the dependent stochastic deterioration of the components. Song et al. [24] consider systems where each individual component may fail due to two competing statistically dependent failure modes, and the failure processes among the components are also statistically dependent. Reliability analysis is performed for two specific series systems and one specific parallel system.

Some studies mainly focus on the computational performance of their algorithms. Barata et al. [2] consider a rather comprehensive model to optimize maintenance decisions for multi-component systems. Emphasis is on the optimization procedure and the required computing times. System downtime for a two-component series system is considered for two settings of the parameters. Zhou et al. [32] develop an algorithm for maintenance optimization of series–parallel systems with multi-state economically dependent components. Stochastic ordering theory is used to reduce the search space and improve the computational efficiency. A single system configuration is considered, with the main focus on the computational performance of the algorithm.

More advanced algorithms are proposed by the following authors. Van Horenbeek and Pintelon [27] consider a system with components that are economically and structurally interdependent. The entire system has to be stopped and a set-up cost has to be paid if preventive or corrective maintenance is performed on one or more components. A rather complex policy is proposed and applied to a single numerical example. Bouvard et al. [6] aim to group maintenance actions for components of a system to reduce set-up costs. An advanced algorithm is proposed that consists of various steps. A few numerical experiments are performed, but these do not provide general insights. Marseguerra et al. [19] consider a continuously monitored multi-component system and use a Genetic Algorithm for determining the optimal degradation level beyond which preventive maintenance has to be performed. Clustering of maintenance activities is not taken into account.

Wijnmalen and Hontelez [29] consider a rather complicated system with various component types. The repair cost depends on the condition of the component. The system set-up cost is reduced when components of various types are repaired simultaneously; the type set-up cost is reduced when components of the same type are repaired simultaneously. A heuristic approach based on a decomposition of the multi-component problem into several single-component Markov decision problems is presented. The focus is mainly on the performance of the heuristics, general insights are not provided.

There are also studies that take a broader perspective than just maintenance. Hsu [16] consider a serial production system consisting of a number of stations, where parts must proceed through the stations. Each station is maintained when it breaks down or when a certain number of parts has been processed. The joint performance of the stations is studied, but clustering of maintenance actions is not considered. Xu et al. [30] jointly consider multi-component safety related systems and the production systems that are being protected. An extensive model is proposed and a specific illustrative example of a high integrity pressure protection system is analyzed.

Finally, Van Der Duyn Schouten and Vanneste [26] consider the grouping of maintenance actions for a set of identical components based on their age. Instead of the exact ages of the components, three age groups are considered. In an approximated model that