University of Groningen

Condition-based maintenance for complex systems

Olde Keizer, Minou Catharina Anselma

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Olde Keizer, M. C. A. (2016). *Condition-based maintenance for complex systems: coordinating maintenance and logistics planning for the process industries*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen, SOM research school.

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 25-03-2023

8

Conclusions and future research

8.1. Introduction

Condition-Based Maintenance (CBM) offers great potential in the process industries. Under this policy, maintenance is only performed when necessary, while failures are limited by monitoring the equipment. Developing an efficient CBM policy can be complex, since systems generally comprise multiple components subject to various inter-component dependencies. In this thesis, we provided insights into the optimal CBM policy structure for various ill-researched complex system settings. In Chapter 2, we proposed a classification of the different types of dependencies (structural, stochastic, resource, and economic dependence), along with a literature review on CBM policies. Based on the revealed gaps in the literature, Chapters 3-7 investigated the optimal CBM policy structure for specific system configurations.

Our key finding is that CBM planning extends beyond merely using monitoring information to schedule maintenance right before component failure. Component dependencies can severely complicate the maintenance decisions at the system level. Many complex systems require a custom-fit, dynamic CBM policy, as classical maintenance policies or threshold CBM policies can be significantly more expensive.

In this final chapter, we provide an overview of the insights that we obtained, and use these to construct general guidelines for performing maintenance on complex systems. We focus on decisions such as when to inspect, when to maintain, when to add a redundant component to the system, and when to order spares. In addition, we compare the performances of our CBM policies for specific system settings to both classical maintenance policies (such as failure-based maintenance, age-based maintenance, and block replacement) and threshold (or control-limit) CBM policies. We conclude this chapter by providing some recommendations for future research.

8.2. CBM guidelines for complex systems

8.2.1. Scheduling inspections

The process industries often deal with externally determined inspection moments, typically because physical inspections are legally enforced with a fixed periodicity. Also in case of internally decided inspection moments, inspections are commonly performed periodically, without clear justifications for the chosen periodicity. As inspections can involve safety risks or require a temporary system shutdown, optimizing the inspection moments constitutes an important element of CBM planning. Moreover, relatively new systems require less frequent inspections than equipment that is approaching the end of its life, which reveals the need for an aperiodic inspection schedule. In Chapters 3 and 4, we simultaneously optimized the aperiodic inspections moments and maintenance decisions for systems subject to both *economic dependence* and *structural dependence* (through a series configuration in Chapter 3 and a parallel setting in Chapter 4). For both system configurations, we observed significant cost savings compared with a periodic inspection scheme, thus stressing the importance of optimizing both the inspection and maintenance decisions.

8.2.2. Scheduling maintenance

Although a threshold CBM policy is typically optimal for single-component systems, multi-component systems require an efficient maintenance policy at the system level. Components are not necessarily replaced at their individual optimal replacement moments, as further discussed below.

Clustering maintenance actions For systems subject to (positive) *economic dependence*, combining (or clustering) maintenance on several components yields a lower cost than maintaining each component separately. We investigated the effects of economic dependence in Chapters 3-6 for different system structures (series, parallel, and k-out-of-N), i.e., for various cases of *structural dependence*. For all cases, we found that maintenance clustering becomes more rewarding under a stronger degree of economic dependence. Such maintenance clustering can either be achieved by performing preventive maintenance at an earlier stage (also known as opportunistic maintenance) or by postponing maintenance actions, as explained below.

Performing preventive maintenance at an earlier stage Threshold CBM policies can incorporate clustering possibilities by including an additional, opportunistic maintenance threshold as done in Chapters 3 and 4. This threshold is typically set lower than the preventive replacement threshold, and serves to decide which components should be replaced opportunistically if at least one component requires a preventive or corrective replacement. We found that *economic dependence* forms an incentive to lower the opportunistic replacement threshold, such that maintenance actions are clustered more often. In Chapters 5 and 6, we applied dynamic CBM policies, where we optimized the maintenance decisions for each possible system state. Also under such policies, maintenance should sometimes be performed at an earlier stage to allow maintenance clustering.

Postponing preventive maintenance Maintenance clustering can also be achieved by postponing preventive maintenance rather than performing it at an earlier stage. This property cannot be captured by threshold policies, but requires dynamic CBM policies as considered in Chapters 5-7. Postponing preventive maintenance increases the probability of a component failure, and is therefore mainly suitable for systems that incorporate redundancy (i.e., *structural dependence*). This setting is investigated in Chapters 5 and 6, and results indicated that preventive maintenance is postponed more frequently under a stronger degree of *economic dependence*. Preventive maintenance actions can thus either be postponed or scheduled at an earlier stage, depending on the complete system state and the system structure.

For systems subject to both redundancy (i.e., *structural dependence*) and load sharing (i.e., *stochastic dependence*), a component failure does not necessarily affect the system availability, but will increase the load on the remaining components. The latter forms an incentive to avoid failures, so postponing preventive maintenance is not always rewarding. Indeed, Chapter 6 revealed that the optimal policy is heavily influenced by both the degree of *economic dependence* and the degree of load sharing.

A different incentive for postponing preventive maintenance arises when multiple components share a set of spares (i.e., *resource dependence*). Chapter 7 showed that a lack of spares can form an incentive to postpone preventive maintenance until either a component fails or an order for additional spares arrives. Consider for example the case with one spare on hand, and two identical components that are equally close to failure. Rather than using the spare to replace any one of these components and risking a failure of the other component, the spare is kept on hand until more spares arrive. Naturally, the spare is used in the event of a component failure.

Postponing corrective maintenance For systems with redundancy (i.e., *structural dependence*), the system performance is not necessarily affected by component downtime. This means that corrective maintenance can sometimes be postponed until other components require preventive maintenance, provided that the cost savings from the *economic dependence* outweigh the increased probability of a system failure. In Chapter 5, we found that corrective maintenance is indeed sometimes postponed to reduce costs on a k-out-of-N system with economic dependence. In Chapter 6, however, we found that load sharing (i.e., *stochastic dependence*) forms an incentive to perform corrective maintenance as soon as possible. Similar to postponing preventive maintenance, we observed that the optimal CBM policy structure depends heavily on both the degree of economic dependence and load sharing.

8.2.3. Adding a redundant component

When system availability is crucial, redundancy can be incorporated by installing more components than strictly necessary (i.e., *structural dependence*). We investigated redundancy through a k-out-of-N setting in Chapter 5, and through a parallel setting in Chapter 6. Both systems are also subject to *economic dependence.* The main advantage of installing redundant components is the increased system availability, and thereby the decreased probability of an expensive system failure. For the k-out-of-N setting, we found that installing one redundant component (i.e., choosing $N = k + 1$) reduces costs substantially compared with selecting $N = k$. Adding a second redundant component, however, appeared to be less beneficial in this particular example.

An additional benefit of incorporating redundancy is that the load can be shared among the components (i.e., *stochastic dependence*), thereby lowering the deterioration rate of each functioning component. We investigated this scenario for a parallel system (i.e., *structural dependence*) in Chapter 6, and found that adding a redundant component is most beneficial for systems with both a strong degree of *economic dependence* and a strong degree of load sharing.

8.2.4. Ordering spares

In practice, components can only be replaced if the required spares are on hand. Typically, a time lag (i.e., lead time) exists between the moment of ordering a spare and receiving it, which reveals the need for an efficient inventory policy. In Chapter 7, we therefore considered multiple components with a shared set of spares (i.e., *resource dependence*), for which we jointly optimized the maintenance and inventory decisions. We based both the maintenance and the inventory decisions on the system condition, and found that an order for spares should be postponed if all components are relatively new. The (s, S) inventory policy, popular both in theory and practice, is not able to incorporate this property, and can therefore be significantly more expensive than our condition-based inventory policy.

In addition, we observed in Chapter 7 that a joint optimization for all components leads to significant lower costs than a decomposed approach at the component level. We can thus conclude that pooling spares is beneficial, as fewer spares are needed to ensure an efficient maintenance policy.

8.3. Comparison with other maintenance policies

8.3.1. Classical maintenance policies

Throughout this thesis, we compared the performances of our CBM policies with those of various classical maintenance policies, varying from Failure-Based Maintenance (FBM) to preventive maintenance strategies such as Age-Based Maintenance (ABM) and Block Replacement (BR). We found that the FBM and BR strategies can be obtained as special cases of the threshold CBM policies considered in Chapters 3 and 4.

Corrective maintenance In Chapters 3-5, we compared the performances of our CBM policy to those of a purely corrective, FBM policy for a series, parallel, and k-out-of-N system, respectively (i.e., different cases of structural dependence), all subject to economic dependence. In all cases, FBM was found to perform significantly worse than CBM. Indeed, failures should be prevented in the process industries, as they can lead to safety issues and losses of revenue, confirming that FBM is not suitable for critical components.

Preventive maintenance In Chapter 5, we optimized the CBM decisions for a k-out-of-N system (i.e., structural dependence) subject to economic dependence, and compared the performances to those of an ABM policy. Under ABM, each component is replaced upon reaching a certain age. Clustering opportunities cannot be incorporated in this type of preventive maintenance policy. Indeed, we found that ABM can be up to 50 percent more expensive than CBM, and that this difference increases for systems subject to stronger degrees of economic dependence.

Contrary to ABM, BR is a preventive maintenance strategy in which all maintenance actions are clustered; complete system replacements are performed with a certain periodicity. In this thesis, we distinguished between BR with and without corrective replacements upon component failure between two consecutive system replacements. The former is considered in Chapters 3 and 4, while both cases are investigated in Chapter 5. Although BR with intermediate corrective replacements does outperform the ABM strategy in Chapter 5, overall results indicate that BR is also significantly more expensive than CBM.

8.3.2. Threshold CBM policies

In Chapters 3 and 4, we applied a threshold CBM policy consisting of thresholds for preventive replacements and for opportunistic replacements, whereas we constructed more dynamic CBM policies in Chapters 5-7. Throughout these chapters, we compared our results with those of threshold policies with and without a threshold for opportunistic maintenance (i.e., with and without clustering possibilities).

In Chapters 3 and 5, we observed that including an opportunistic replacement threshold can be rewarding, as costs can be reduced by incorporating clustering possibilities. Nevertheless, we also observed that even larger cost decreases can be obtained by considering a more dynamic CBM policy that is not restricted to thresholds, as developed in Chapters 5 and 6. In these chapters, a threshold policy is too restrictive due to the redundancy that allows maintenance to be postponed. In Chapter 7, where no economic dependence is considered, we actually observed that the optimal CBM policy shows much resemblance with a threshold policy. Whether or not CBM can be successfully implemented through thresholds is thus dependent on the types of dependencies within the system.

8.4. Recommendations for future research

8.4.1. Heuristics for large systems

This thesis incorporates a variety of exact methods to obtain the optimal CBM policy for several system structures. We focused on obtaining insights into the optimal policy structure, for which we studied systems consisting of up to six components. The resulting policies proved complex, and difficult to extend to more components, while computing times increase dramatically with the number of components. For large systems consisting of many components, we therefore recommend the development of heuristics which incorporate the insights that we obtained.

8.4.2. Other types or combinations of dependencies

Chapter 2 revealed that several types of dependencies have not been researched yet in a CBM setting. This holds in particular for systems subject to resource dependence, e.g. through a shared set of tools, a fixed budget, or differently skilled maintenance workers. Negative economic dependence has also not been studied yet for CBM, as well as mandatory joint replacements of certain components (i.e., structural dependence on a technical level). Moreover, very limited research has been performed on the joint effects of several types of dependencies. Most existing research focuses on combinations with structural dependence from a performance point of view and economic dependence, while joint effects of other types of dependencies have received little attention to date. As systems in the process industries are often complex and generally comprise multiple dependencies, there is a clear need for insights into the optimal policy structures for various systems.

8.4.3. Non-negligible maintenance durations

Besides revealing ill-researched types of dependencies, Chapter 2 also showed that most contributions on CBM (including this thesis) assume negligible maintenance durations. A general justification for this assumption is that maintenance durations in practice are typically short compared with the overall period for which maintenance is scheduled. Nevertheless, non-negligible maintenance durations can for example form an additional incentive to cluster maintenance. This holds in particular for a series structure (i.e., structural dependence through performance), where maintenance on one component requires the complete system to be shut down for the duration of the maintenance action. Alternatively, a redundant setting could form an incentive to avoid simultaneous replacements. In a two-component parallel system, for example, a simultaneous replacement of both components will imply a system stop. Future research on non-negligible maintenance durations can thus be deemed at least as important as extending the existing research on negligible maintenance durations to other types of dependencies.

8.4.4. Varying component functionality

In Chapters 5 and 6, we considered active redundant systems. In these systems, all components are fully operational and subject to failure, although fewer components would suffice. Under the assumption that maintenance is only possible at fixed, predetermined moments in time, it could be interesting to switch off certain components or set them to a lower speed. If a component approaches the end of its lifetime, e.g., switching off this component will prevent failure and allow maintenance clustering with other components at a later point in time. Alternatively, a component can be kept running at a lower speed, reducing its deterioration rate. The latter can also prove effective for avoiding or achieving simultaneous replacements of multiple components.