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Condition-based maintenance for complex systems

Olde Keizer, Minou Catharina Anselma

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Introduction

1.1. Maintenance in the process industries

Technical systems often deal with increasing wear and tear caused by usage, age, or random shocks. If ignored, this deterioration may eventually cause a system to fail, which can lead to high costs, system unavailability, and safety hazards. Performing preventive maintenance can help to prevent failures and their corresponding detriments by repairing or replacing a component before a system breakdown occurs [1].

For many complex systems, maintenance costs can constitute a large part, between 15 and 70 percent, of the total production costs [2]. For power plants, up to 30 percent of the production costs is spent on maintenance [3], while this can be up to 60 percent for manufacturing firms, with up to one third of these costs due to unnecessary or poorly executed maintenance [4]. Therefore, it is essential to develop efficient maintenance strategies that minimize costs, while maximizing safety and availability.

Maintenance planning in the process industries is particularly complex for a number of reasons. Plants often work nonstop, which implies that limited time is available for performing maintenance, and that failures should be prevented to avoid downtime of the equipment and loss of revenue. Furthermore, both system breakdowns and maintenance activities can involve certain safety threats. This stresses the importance of preventing failures, and often forces the number of visits to be kept to a minimum.

1.2. Maintenance strategies

Common maintenance actions include replacements and repairs. While a replacement changes the state of a component to as-good-as-new, a repair only improves the current state of a component to a (stochastic) better one. Both repairs and replacements can be performed either preventively or correctively. In case of a preventive maintenance action, the exact timing depends on the maintenance strategy chosen, while a corrective maintenance operation is performed after a failure has occurred. Several maintenance strategies are available [5, 6], which are schematically represented in Figure 1.1.

Failure-based maintenance is a purely reactive maintenance strategy, where no preventive maintenance actions are scheduled. Instead, corrective maintenance is initiated upon failure of a component. To avoid such unexpected failures, several proactive, preventive maintenance strategies are commonly applied in practice. Under age-based maintenance, a maintenance action is initiated preventively upon reaching a certain age, or correctively upon failure, whichever occurs

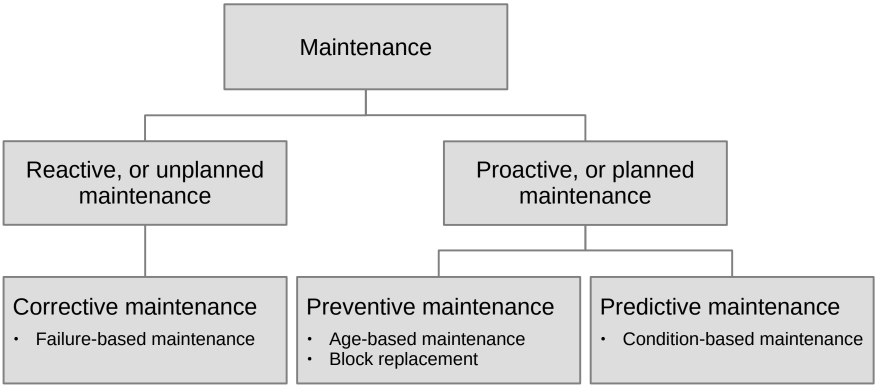


Figure 1.1. Overview of maintenance strategies (explained in [5, 6], constructed using [7]).

first. The replacement age is optimized to minimize costs or maximize availability. Under a block replacement strategy, the complete system is preventively replaced with a certain periodicity. A failure can initiate a corrective replacement, but does not reschedule the next preventive replacement. For this strategy, the replacement periodicity requires optimization. Condition-Based Maintenance (CBM) is a more flexible, predictive strategy that intends to perform maintenance right on time. The concept of CBM is to monitor the condition of the equipment and to base the maintenance decisions on it. Common indicators of the system condition include vibration, temperature, and the size and shape of metal particles that can be detected through oil analysis.

For the process industries, it is clear from the complexity issues described in Section 1.1 that corrective maintenance is not a suitable strategy. Failures must be prevented rather than solved. Typically, this is achieved by applying preventive maintenance strategies, such as age-based maintenance and block replacement. However, to ensure that failures indeed rarely occur, such strategies should err on the side of caution, implying that maintenance is often performed earlier than necessary from an equipment condition point of view. CBM therefore offers a lot of potential, especially in the process industries. It can postpone maintenance activities, compared to preventive maintenance, while limiting failures by constantly monitoring the condition of the equipment. Compared to classical preventive maintenance policies, CBM is thus a more efficient policy [1, 8]. Indeed, CBM has been proved to minimize maintenance costs, improve operational safety, and reduce the number and severity of failures [9]. Nowadays, many process industry companies experiment intensively with CBM, but preventive maintenance is still the norm.

1.3. Condition monitoring and CBM

Recent developments in condition monitoring of technical systems allow maintenance managers to obtain a good view on the current state of their equipment. The information on the condition of the machinery can be obtained by either performing physical inspections, or continuously monitoring the equipment. Although complex systems are more and more equipped with condition monitoring instruments, such as sensors, meters and computational devices [10], we observe in practice that a mixture of physical inspections and continuous monitoring is applied. In the process industries, the use of (Wi-Fi) sensors can be prohibited due to safety reasons, while placing sensors may not yet be cost efficient for other systems (e.g., large systems such as a railway network). Furthermore, effective CBM requires a measurable parameter that correlates strongly with the onset of failure [11], which often appears to be problematic. Gas distribution companies, for instance, lack proper models that can link internal fouling of heat exchangers to available process data (e.g., temperatures, flows) [12], making visual inspection the only suitable way to appropriately determine the asset's condition. Physical inspections and continuous monitoring will thus continue to co-exist, certainly for the near future.

In case physical inspections are required to reveal the system condition, a distinction can be made between periodic and aperiodic inspections. Whereas the periodic inspection moments are fixed in advance, and thus better facilitate the planning and scheduling of the required personnel, tools, and spares, aperiodic inspection moments can be set according to the condition of the equipment. A system that is close to failure will require more frequent inspections than a relatively new system. Aperiodic inspections are especially suitable for systems where the number of visits should be limited due to safety issues or where an inspection requires the system to be shut down.

The condition data obtained can be used to determine a deterioration model, on which the maintenance strategy will be based. Several deterioration models relevant for condition monitoring are reviewed by [13]. In general, it is assumed that deterioration follows an increasing trend over time with random fluctuations around that trend. Examples of degradation processes are Brownian motion processes with drift, (compound) Poisson processes, Gamma processes, and Markov chains with limited numbers of states.

It is commonly assumed that a failure will occur as soon as the condition of a component exceeds the so-called failure level, which can be either fixed or uncertain. Upon such failure, a corrective replacement is initiated, while preventive maintenance is scheduled according to the CBM policy, for example upon reaching a certain deterioration threshold. Failures can either be noticed immediately or require an inspection to be observed. The latter case applies for example in a standby system or in a system where a failure does not imply a system stop, but where the quality of the produced output is reduced.

1.4. CBM for complex systems

Systems that require maintenance typically consist of multiple components, where different settings or levels can be considered. For example, the system can refer to a wind farm, consisting of multiple windmills (referred to as components), but the system can also refer to a single windmill, where the components are given by the gearbox, generator, or blades.

For a single-component system, CBM is often successfully implemented through a deterioration threshold; upon reaching this threshold, a maintenance action is initiated. Such a strategy may however not result in a close-to-optimal solution for multi-component systems, because several dependencies can exist between these components. Indeed, it does not necessarily hold true that the optimal decision for one component is optimal for the complete, multi-component system [14]. This brings us to the main objective of this thesis, which is to study the effectiveness of CBM at the system level, taking dependencies between components of a system into account. Therefore, we review dependence types in what remains of this section, before discussing our contributions in Section 1.5.

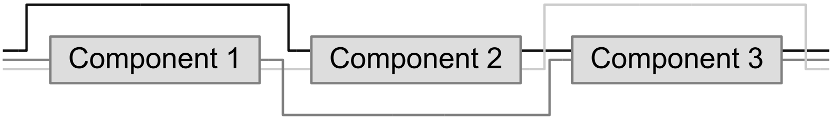
Generally, it is assumed that three types of dependencies exist for systems consisting of multiple components: structural dependence, stochastic dependence, and economic dependence [15]. However, recent developments in the maintenance literature have led to more advanced and integrated maintenance models that better capture realistic system properties. A new distinction between four types of dependencies is thus presented in this thesis: structural, stochastic, resource, and economic dependence. Below, we shortly propose our new classification. In Chapter 2, more details are provided, along with examples from practice.

1.4.1. Structural dependence

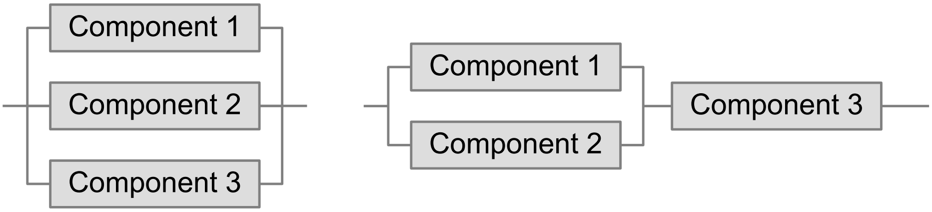
We define structural dependence as the dependence that arises from the structure of the system. This can be either from a technical point of view, or from a performance point of view.

Originally, structural dependence was introduced as the case where maintenance on one component requires maintenance on other components as well.

(a) Series (3-out-of-3) system



(b) 2-out-of-3 system



(c) Parallel (1-out-of-3) system **(d)** Example of a series-parallel system

Figure 1.2. Different system configurations for a system consisting of three components.

A common example is given by a bicycle chain and a cassette, which are always replaced simultaneously [16]. According to our classification, this is an example of structural dependence on a technical level. Other examples arise when maintenance on a component prohibits, rather than requires, maintenance on other components, e.g., due to limited space. Similarly, some maintenance activities can prohibit the usage of other components, e.g., due to safety issues.

Alternatively, the structure of the components can also affect the system performance. In a series configuration, each component is critical to the system, whereas one component suffices in a parallel setting. The intermediate case is known as a k-out-of-N system, which consists of N components of which only k need to function. Both the series and parallel configurations can be viewed as special cases of the k-out-of-N setting [17]. Alternatively, as a series system is extremely prone to failures, redundant components can be installed for some of the component types, resulting in a series-parallel system. For a system consisting of three components, Figure 1.2 shows these possible configurations. We remark that three different paths are possible for the 2-out-of-3 system, as any one of these components is allowed to be in the failed state.

In practice, companies often employ redundancy by installing more components than strictly necessary. In this way, the system availability is increased, while the risk of a system failure is reduced. We distinguish between active redundancy (where all components are fully operational and subject to deterioration) and standby redundancy (where the redundant components do not contribute to the system performance, but are placed in standby) [18]. There are tree types of standby redundancy: hot standby, warm standby, and cold standby [19]. Whereas all components are functioning and subject to normal deterioration under hot standby, cold standby means that the components are shut down and do not deteriorate at all. The intermediate case is known as warm standby, where the redundant components are functioning, but at a lower rate than when fully employed. Under standby redundancy, additional complexity arises as the switching moments from standby to operation (and vice versa) require optimization as well. Both the parallel and k-out-of-N systems are examples of configurations through which (active or standby) redundancy can be employed.

1.4.2. Stochastic dependence

Stochastic dependence applies if the deterioration processes of components are dependent on each other [20]. This type of dependence can occur in three different ways. First, a failure of a component can have an immediate impact on other components as well, leading to a sudden, one-time increase in deterioration or even failure. This case is referred to as failure-induced damage. Second, a failure of a component can increase the load to be borne by the remaining components, thereby structurally accelerating their deterioration rate. We refer to this case as load sharing. Third, the deterioration processes of several components can be correlated if they operate under similar conditions. This correlation is typically positive, indicating that a large increase in deterioration for one component is often associated with large increases in deterioration for other components as well (and vice versa). We refer to this case as common-mode deterioration.

1.4.3. Resource dependence

In this thesis, we introduce resource dependence as a new type of dependence. Resource dependence can arise when several components share a set of resources, such as maintenance workers, tools, spares, or budget. The components can also be connected through transport options (e.g., limited space in a van to transport resources to the plant). This requires additional decisions on how to allocate the available resources. A limitation on the available maintenance workers, tools, or transport options mainly imposes a restriction on the maintenance actions that can be performed simultaneously, while a fixed budget restricts the total number of maintenance actions that can be performed. Spares are lost upon usage, which leads to additional complexity. Typically, spares arrive after a certain lead time, and therefore need to be ordered in advance, for which several inventory policies can be applied. As a separate or sequential optimization of the maintenance and inventory decisions does not necessarily lead to a globally optimal policy [21], decisions on the maintenance and inventory strategy should be taken from an integrated service logistics perspective.

1.4.4. Economic dependence

Economic dependence applies when combining maintenance actions on several components yields a higher cost (negative economic dependence) or a lower cost (positive economic dependence) than maintaining each component separately. Negative economic dependence for example arises when additional, temporary personnel needs to be hired to maintain multiple components at once, and thus forms an incentive to perform maintenance actions sequentially rather than simultaneously. Positive economic dependence can occur if shared set-up costs are involved for repairing or replacing one or more components. In practice, shared set-up costs can arise from traveling to the plant, scheduling personnel, ordering spare parts, or doing paperwork. These fixed costs are typically independent of the number of components that are maintained, thereby posing an incentive to combine, or cluster, maintenance actions. This process of maintaining additional components to save on set-up costs is referred to as opportunistic maintenance.

1.5. Contribution

Over the past decades, a lot of research has been performed in the field of maintenance strategies, on which a number of surveys have been written, e.g., [15, 20, 22–26]. However, the major part of this research considers preventive maintenance strategies rather than predictive maintenance strategies, such as CBM. Furthermore, most existing literature on CBM focuses on a system consisting of just one component, while not much research has been performed for systems containing two or more components, as is often the case in the process industries. To overcome this issue, this thesis focuses on several ill-researched topics related to CBM for various complex systems.

1.5.1. Scope

First, a detailed classification of dependencies is provided in Chapter 2, along with a literature review on CBM. We hereby focus on the consequences of different types of dependencies on the optimal CBM policy structure. This chapter reveals numerous gaps in the CBM literature, which form the basis for the remainder of this thesis. The remaining chapters thus serve to provide insights in the optimal policy structure for various ill-researched, complex systems and settings.

To this extent, we start off with investigating the added benefits of aperiodic inspection moments for systems with both structural and economic dependence in Chapters 3 and 4. This case applies to companies with internally decided inspection moments, where inspections can involve certain costs or risks, and should therefore only be performed if necessary. We investigate this setting for two main system structures: a series system in Chapter 3, and a parallel system in Chapter 4.

In the process industries, however, companies often deal with externally determined rather than internally decided inspection moments, for example because inspections are legally forced with a certain periodicity. In the remaining chapters, we thus focus on periodically inspected systems. Chapter 5 thereby focuses on the joint effects of structural dependence and economic dependence, while we add stochastic dependence (through load sharing) in Chapter 6. Both chapters consider active redundancy, through a k-out-of-N setting in Chapter 5 and a parallel setting in Chapter 6. The remaining type of dependence, resource dependence, is investigated in Chapter 7, where we jointly optimize the (condition-based) maintenance and inventory decisions for multiple components with a shared set of spares.

Throughout this thesis, we apply a broad variety of methods to find the cost-minimizing, or availability-maximizing, CBM policies. In Chapters 3 and 4, we construct a stochastic model based on (semi-)regenerative properties of the maintained system state. In Chapter 5, we apply dynamic programming, and in Chapters 6 and 7, we construct Markov Decision Processes. In addition, we regularly apply simulation to compare our results with other maintenance policies. Below, a more detailed overview of the different chapters is provided.

1.5.2. Thesis outline

As recent contributions on CBM focus more and more on complex system structures, with multiple components subject to various inter-component dependencies, we found that existing classifications of these dependencies are no longer sufficient. For that reason, we propose an extended classification scheme in **Chapter 2**. In the past, a distinction was made between structural, stochastic, and economic dependence. While we extend the notion of structural dependence to include the case where the system performance depends on the structure of the components (e.g., a series or parallel system), we add resource dependence as the case where multiple components share for instance a set of maintenance workers, tools, or spares. Based on this classification, various real-life examples are provided, and the advances made with respect to CBM are reviewed. The implications of dependencies on the optimal CBM structure are investigated, and current gaps in the literature are highlighted.

In **Chapter 3**, we consider a two-component series system subject to economic dependence. Both the aperiodic inspection moments and the (corrective, preventive, and opportunistic) replacements are scheduled according to deterioration thresholds, which are optimized simultaneously to either minimize the maintenance cost or maximize the system availability. Based on the analysis in [14], a stochastic model is constructed using semi-regenerative properties of the maintained system state. Whereas an upper bound is used by [14] for approximating the system unavailability time, we provide a more accurate approximation, and show that this greatly influences the resulting optimal maintenance strategy. In addition, results indicate that the CBM policy outperforms several classical maintenance strategies (such as failure-based maintenance and block replacement), which can be viewed as special cases of our CBM policy, and that including opportunistic replacements and aperiodic inspection moments can reduce costs substantially. In fact, a stronger degree of economic dependence will lead to more frequent maintenance clustering.

Chapter 4 also focuses on a two-component system subject to economic dependence, but with a parallel structure rather than a series structure. In this setting, a component failure does not imply a system stop, but will result in some lost revenue. This case applies for example to a factory with two production lines, where the output is reduced if only one line is available. The stochastic model from Chapter 3 is applied to this case, and results indicate that the parallel setting facilitates easier generalization to systems containing three or more components. Furthermore, we find that the insights obtained in Chapter 3 also apply to the parallel setting considered in this chapter. Both the failure-based maintenance and block replacement strategies are special cases of the CBM policy, and including aperiodic inspections and clustering maintenance activities can reduce costs significantly.

To investigate the joint effects of structural and economic dependence, a multi-component system subject to both (active) redundancy, through a k-out-of-N structure, and economic dependence is studied in **Chapter 5**. The system is inspected periodically, and a dynamic programming model is constructed to find the cost-minimizing replacement decisions. Results indicate that the optimal

CBM policy shows non-monotonic behavior. On the one hand, preventive replacements are performed to avoid (more expensive) corrective replacements, but on the other hand corrective replacements are postponed to allow for maintenance clustering at a later moment. Indeed, redundancy allows some components to be left in the failed state without affecting the system performance. Classical maintenance policies (such as failure-based maintenance, age-based maintenance, and block replacement) are not able to capture this behavior, and are thus shown to result in significantly more expensive strategies. The same holds for CBM policies which base the replacement decisions on deterioration thresholds.

Besides achieving a high system availability, redundancy often allows the total system load to be shared among components, thereby reducing the deterioration rates of the functioning components. This load sharing forms an incentive to replace failed components as soon as possible, but the redundancy allows corrective replacements to be postponed to allow for clustering opportunities. To investigate this trade-off, **Chapter 6** considers a multi-component system subject to active redundancy (through a parallel structure), stochastic dependence (through load sharing), and economic dependence. The system is inspected periodically, and we construct a Markov Decision Process to find the cost-minimizing CBM policy. A numerical study reveals that maintenance clustering is most beneficial for systems subject to a strong degree of economic dependence and a low degree of load sharing, and that ignoring or misinterpreting the load sharing effects can result in a sub-optimal maintenance policy. Such complex systems require a custom-fit maintenance policy, and a CBM policy with deterioration thresholds does not necessarily result in a close-to-optimal strategy.

Most studies on CBM suppose that unlimited spare parts are always available, while in reality there may exist some time lag, also known as the lead time, between the ordering and receiving of spare parts [27]. In **Chapter 7**, we consider a multi-component system subject to resource dependence through a shared set of spares. Both the maintenance and inventory decisions are condition-based and simultaneously optimized. To this end, we construct a Markov Decision Process. Through a numerical analysis, we provide insights into the optimal (non-monotonic) policy structure. We show that the (s, S) inventory policy, popular in theory as well as practice, can be far from optimal, as well as a separate optimization of the maintenance and inventory decisions for each component. Significant cost savings can thus be obtained by performing a system-wide optimization, and basing both the maintenance and inventory decisions on the system's condition.

In **Chapter 8**, we provide an overview of the insights that we obtained, and use these to construct general guidelines for performing maintenance on complex systems. In addition, we provide recommendations for future research.

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