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Condition-based maintenance for complex systems

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CBM policies for complex systems: a review

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Abstract

Condition-based maintenance (CBM) has received increasing attention in the literature over the past years. The application of CBM in practice, however, is lagging behind. This is, at least in part, explained by the complexity of real-life systems as opposed to the stylized ones studied most often. To overcome this issue, research is focusing more and more on complex systems, with multiple components subject to various dependencies. Existing classifications of these dependencies in the literature are no longer sufficient. Therefore, we provide an extended classification scheme. Besides the types of dependencies identified in the past (economic, structural, and stochastic), we add resource dependence, where multiple components are connected through, e.g., shared spares, tools, or maintenance workers. Furthermore, we extend the existing 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 structure). We review the advances made with respect to CBM. Our main focus is on the implications of dependencies on the structure of the optimal CBM policy. We link our review to practice by providing real-life examples, thereby stressing current gaps in the literature.

2.1. Introduction

Complex systems are more and more equipped with condition monitoring instruments such as sensors, meters, and computational devices [1]. In addition, optimization techniques have greatly improved, and research on Condition-Based Maintenance (CBM) policies has received increasing attention over the past years. Nevertheless, implementation of CBM policies in practice is lagging behind. Systems often consist of many components, where different inter-component dependencies can exist that affect the availability of the complete system. To this extent, current research on CBM is focusing more and more on complex system structures and dependencies.

Maintenance policies for multi-component systems have been reviewed in the past by many authors, including [2–6], while CBM strategies have been considered in [6]. More recently, a review on joint maintenance and inventory optimization was written by [7], focusing on articles that optimize both types of decisions. Despite the increasing interest for CBM policies for complex systems in both theory and practice, no recent literature review exists on CBM policies for multi-component systems subject to different types of dependencies.

Existing literature overviews usually distinguish three types of dependencies (structural, stochastic, and economic) [4, 6, 8]. Structural dependence applies for instance when the repair or replacement of a component requires some other components to be dismantled or replaced as well. Stochastic dependence means for example that the deterioration process of one component is (partly) dependent on the state of one or more other components. Economic dependence applies when the combined maintenance of several components leads to a different cost than maintaining each component separately.

Due to recent developments in the maintenance literature, however, the above classification is no longer sufficient. We noticed an increased interest in other types of dependencies. For that reason, we distinguish four types of dependencies in this overview: structural, stochastic, resource, and economic dependence. Whereas stochastic and economic dependence have been considered before, we extend the notion of structural dependence by distinguishing between structural dependence from a technical point of view and from a performance point of view. In addition, we define a new type of dependence: resource dependence. Resource dependence applies when multiple components rely on (for example) a shared set of spares or tools, or a limited number of maintenance workers.

In this chapter, we provide an extensive literature overview on CBM policies for multi-component systems which incorporate at least one of the above dependencies. In addition, we make a strong link to practice by providing examples in which these dependencies occur, thereby stressing current gaps in the literature. Throughout this chapter, we focus on a system that consists of multiple components, where the system can for example refer to a wind farm, consisting of multiple windmills (referred to as components), but can also refer to a single windmill, where the components are, e.g., the gearbox, generator, or blades. Where needed, we indicate to which types of systems our findings apply. Despite recent developments that allow components to be monitored continuously, we observe in practice that certain components still require a physical inspection. Even if a system is monitored continuously, sometimes intervening for maintenance is only possible at discrete points in time. For that reason, we distinguish between articles that consider (a)periodic decision moments, and articles that allow maintenance decisions to be made at any moment in time. We focus in this review on the structure of the CBM policy that is applied to systems with different types of dependencies, which performance depends heavily on these dependencies. Our main contributions are that we propose a new, practice-based classification of dependencies, that we provide the first complete review on CBM policies for systems with these different types of dependencies, and that we locate gaps in the literature that require further research to enable a successful implementation of CBM in practice.

The remainder of this chapter is organized as follows. We discuss the existing contributions on CBM policies for systems with different types of dependencies. We start with the structural, static configuration of a system and its influence on the technical aspects and the system performance (i.e., structural dependence) in Section 2.2. Next, we consider the deterioration processes of the different components and their possible dependencies (i.e., stochastic dependence) in Section 2.3. Before maintenance can be performed, certain resources (such as spares or personnel) are required, which can impose restrictions on the execution of maintenance actions (i.e., resource dependence). The consequences of this type of dependence are investigated in Section 2.4. Finally, when performing maintenance, cost structures can influence the optimal maintenance policy (i.e., economic dependence). This type of dependence is investigated in Section 2.5. In these sections, we define the type of dependence, provide some examples from practice, and show the different policy structures that are described in the literature. Next, to investigate the interactions between different dependencies, we consider the articles that combine at least two types of dependencies in Section 2.6, along with the implications on the optimal maintenance policy structure. Section 2.7 concludes the chapter and summarizes the current gaps in the literature, thereby stressing the relevance of those gaps using examples from practice.

2.2. Structural dependence

Structural dependence concerns the structural, static relationships between different components. Originally, structural dependence was focusing on the situation where the replacement of a certain component requires the dismantling or replacement of other components [4, 6, 8]. Related to this notion, the case in which a component is stopped due to failure or maintenance of another component is considered in [9]. However, more situations exist in which components are dependent through the physical structure of the system. For that reason, we distinguish between structural dependence from a technical point of view (referred to as *technical dependence*) and from a performance point of view (referred to as *performance dependence*), as further explained below. Table 2.1 lists all contributions on CBM for multi-component systems which are subject to structural dependence.

2.2.1. Technical dependence

A certain technical system configuration can result in maintenance or usage restrictions. Two types of maintenance restrictions can be distinguished: maintenance on a certain component can either require or prohibit maintenance on other components. An example of the former can occur when replacing the cassette on a bike, which may also require the chain to be replaced. Another example concerns the tires of an airplane, which are required to have the same thickness and are thus replaced jointly. Furthermore, reaching a component that needs maintenance can require the disassembly of other components that are blocking the access. As a result, these components can be damaged, thus requiring their replacement as well. To date, no research has been performed on CBM for multi-component systems where maintenance on a certain component requires maintenance on other components. Sometimes, simultaneous replacement of certain components is not possible, or only to a limited extent, because of limited space to operate (e.g., in submarines). The situation where certain components cannot be maintained together is studied by [9], via a penalty cost structure. A sufficiently high penalty will prevent simultaneous maintenance of the involved components, and limit the possible maintenance scenarios.

Alternatively, a failure of or maintenance on a component can have consequences for the execution of activities by other components, which need to be halted. We refer to this as usage restrictions. One example concerns maintenance on a certain component that requires welding. The sparks generated can set off an explosion if other components are active. These components then need to be temporarily shut down. Another example concerns the processing of milk, where

Table 2.1. Summary of contributions on CBM that consider structural dependence.

Contribution	Structural dependence	CBM policy structure	Decision moments
[12]	Performance: series	No predetermined structure	Periodic: fixed
[13]	Performance: series	Thresholds for preventive imperfect repair (optimize) and preventive replacement (fixed)	Periodic: fixed
[14]	Performance: series-parallel-series	Threshold for preventive imperfect repair	Continuously
[15]	Performance: series	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[16]	Performance: arbitrary structure	Thresholds for maintenance initiation (fixed)	Periodic: fixed
[9]	Technical: maintenance	No predetermined structure (compared with threshold for preventive replacement)	Periodic: fixed
[17]	Performance: series	Thresholds for preventive imperfect repair and preventive replacement	Periodic: optimize interval
[18]	Performance: series-parallel (cold standby)	Thresholds for opportunistic replacement and preventive replacement	Continuously
[19]	Performance: arbitrary structure	Threshold for preventive replacement	Continuously
[20]	Performance: cold standby	Threshold for preventive imperfect repair (fixed, combined with BR)	Continuously
[21]	Performance: subsystems in series	Thresholds for maintenance initiation and ceasing on subsystem	Periodic: fixed
[22]	Performance: series	No predetermined structure	Periodic: fixed
[23]	Performance: series	Thresholds for opportunistic replacement and preventive replacement	Continuously
[24]	Performance: series or parallel	Threshold for preventive replacement	Continuously
[25]	Performance: series	No predetermined structure (compared with threshold for preventive replacement)	Aperiodic: optimize next inspection moment
[26]	Performance: k-out-of-N	Thresholds for opportunistic replacement and preventive replacement	Periodic: optimize interval
[27]	Performance: series or parallel	Thresholds for opportunistic replacement (fixed) and preventive replacement	Continuously

Continued on next page

Table 2.1 – continued from previous page

Contribution	Structural dependence	CBM policy structure	Decision moments
[28]	Performance: series	Threshold for preventive replacement	Periodic: optimize interval, or inspect each time unit
[29]	Performance: series	No predetermined structure (clustering through time windows)	Continuously
[30]	Performance: series-parallel	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[31]	Performance: series or parallel	Threshold for preventive replacement (fixed)	Periodic: optimize interval
[32]	Performance: cold/warm standby	Thresholds for switch from cold to warm standby and system replacement	Continuously
[33]	Performance: series-parallel	Threshold for maintenance initiation, use yield-cost importance measure to decide on which components to replace	Continuously
[34]	Performance: series or parallel	Threshold for preventive replacement	Periodic: optimize interval
[10]	Technical: usage, and performance: arbitrary structure	Threshold for preventive replacement (also initiate corrective replacements upon critical component failure)	Periodic: optimize interval
[35]	Performance: series	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[36]	Performance: series	Thresholds for opportunistic replacement and preventive replacement (time-dependent)	Periodic: fixed
[37]	Performance: series	Thresholds for opportunistic replacement and preventive replacement	Periodic: optimize interval
[38]	Performance: series	Threshold for preventive replacement (fixed)	Periodic: optimize interval
[39]	Performance: series	Threshold for preventive replacement	Periodic: optimize interval
[40]	Performance: k-out-of-N	Thresholds for maintenance initiation, opportunistic replacement, and preventive replacement	Periodic: optimize interval
[41]	Performance: series	Threshold for preventive replacement (fixed)	Aperiodic: find near-optimal inspection moments

Continued on next page

Table 2.1 – continued from previous page

Contribution	Structural dependence	CBM policy structure	Decision moments
[11]	Technical: usage, and performance: arbitrary structure	Threshold for maintenance initiation, then determine group to replace	Periodic: optimize interval
[42]	Performance: parallel	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[43]	Performance: series	Threshold for preventive replacement (combined with ABM)	Continuously
[44]	Performance: series	Threshold for preventive replacement (combined with ABM)	Continuously
[45]	Performance: series-parallel	Thresholds for opportunistic imperfect repairs (restoring to different states) and preventive replacement	Periodic: fixed
[46]	Performance: parallel	Threshold for preventive replacement and probability thresholds for grouping replacements	Periodic: optimize interval for each component separately
[47]	Performance: k-out-of-N	No predetermined structure (compared with threshold(s): for (opportunistic replacement and) preventive replacement)	Periodic: fixed
[48]	Performance: parallel	No predetermined structure (compared with threshold for preventive replacement)	Periodic: fixed

different processes have to take place shortly after each other, and all related components (such as dryers and mixers) are coupled via pipelines. One possibility to deal with this dependence is by including stock keeping possibilities between consecutive processes. Otherwise, in such a system, a component failure can cause other components to be idle as well, as studied by [10, 11].

2.2.2. Performance dependence

The system performance is determined by both the performance of the components and their configuration within the system. The system configuration can have huge consequences for the structure of the CBM policy to be used. Hereafter, we briefly describe some of the main structures found in practice using a well-known classification from system reliability/availability literature [49], where a central role is played by the concept of redundancy.

Series system In a series system, each component is critical for the performance of the system. The implications for the optimal maintenance policy can be two-fold. On the one hand, the failure of a single component can lead to high unavailability costs, so maintenance actions are performed at a relatively early stage to prevent downtime. From Table 2.1, we observe that the majority of the literature on series systems implements CBM through one or more thresholds, where a maintenance action is initiated as soon as the component condition exceeds the corresponding threshold. These thresholds can be set lower to intervene at an earlier stage, and are generally optimized to find a cost-efficient policy. On the other hand, the series structure can imply that the complete system may have to be stopped to perform maintenance on a certain component as discussed in Section 2.2.1. This offers a maintenance opportunity for the other components, which can be implemented through a high set-up cost for maintenance, and can be seen as a special case of economic dependence, discussed in Section 2.5. Most contributions listed in Table 2.1 ignore this aspect, assuming instantaneous replacements. In [29], maintenance opportunities are incorporated through a maintenance time window. As soon as a component requires maintenance, a combined maintenance action is performed on all components that are expected to require maintenance within a certain time window. By extending this time window, more maintenance actions will be clustered, and downtime will be prevented. The authors aim at finding the optimal time window length.

Parallel system When system unavailability should be prevented due to, e.g., a high unavailability cost or safety issues, redundancy can be incorporated by placing components in parallel. In case of a parallel setting, only one component needs to function, where any other component failure is typically assumed to have no impact on the system performance. Maintenance actions can thus be performed at a relatively late stage. Similar to the series configuration, the CBM policy is typically implemented using thresholds, which can be set higher to decrease the maintenance frequency.

In practice, however, a system with a parallel configuration can suffer from a component failure, even if the system is still functioning. Consider for example a ship with four engines. If one of the engines breaks down, the ship can continue, but at reduced speed. Rather than only incurring a downtime cost at the system level, as is common in literature, one can also include a downtime cost at the component level. This is for example done by [42], where each component incurs its own downtime cost (see also Chapter 4).

Combinations of series and parallel systems A series-parallel system is studied by [18, 30, 33, 45], where multiple subsystems are placed in series, each consisting of multiple components in parallel. In [14], a series-parallel-series system is considered, where each parallel component is replaced by multiple components in series. Whereas repair or replacement thresholds are used by [14, 18, 30, 45], maintenance is initiated when the system reliability drops below a certain threshold in [33]. The latter uses a yield-cost measure to decide which components to replace.

k-out-of-N system A k-out-of-N system consists of N components, and functions as long as at least k components function. Both series and parallel systems are special cases of the k-out-of-N system, and can be obtained by setting k equal to N or 1, respectively [50]. Such a k-out-of-N system is considered by [26, 40, 47] (see also Chapter 5). As these contributions also incorporate economic dependence, we discuss the corresponding policies in Section 2.6.

Arbitrary structure In practice, systems can consist of components in various structures, varying from a simple series system to a complex combination of components in parallel and series. Whereas most contributions in Table 2.1 focus on a specific structure, such as series, parallel, or k-out-of-N, no fixed structure is assumed by [10, 11, 16, 19]. Instead, the components are allowed to be placed in any setting. A complex system structure is considered in [10, 11], which can contain several subsystems with components in series. Similar to a pure series structure, this setting can result in a technical dependence. If one of these components is shut down, due to maintenance or failure, the dependent components become idle and are no longer subject to deterioration. Although the influence of this assumption on the resulting maintenance policy is not investigated by [10, 11], ignoring it can lead to an overestimation of the deterioration rates. Maintenance is then required less often than expected.

Redundancy Redundancy means that more components are installed than necessary, and is often employed in practice to increase system availability. Two types of redundancy exist: active redundancy and standby redundancy [51]. Under active redundancy, all components are used and contribute to the performance of the system, whereas under standby redundancy, the standby components do not contribute to the system performance until they are activated. Different types of standby redundancy can be distinguished: hot standby, warm standby, and cold standby [32]. Hot standby means that the redundant components can be switched on at any moment, so they are active and subject to failure when standby. Alternatively, components can be placed in cold standby, where standby components are shut down and do not deteriorate at all. The intermediate case is known as warm standby, where a standby component is deteriorating at a lower rate than when it is fully active. Most contributions listed in Table 2.1 consider active redundancy. (Cold) standby redundancy is investigated by [18, 20, 32]. This type of redundancy involves additional complexity, as the decision on when to switch components from standby to operation requires optimization as well. In [18, 20], it is assumed that a standby component can be switched to operation instantaneously, without additional cost. In [32], however, a standby component needs to be switched from cold standby to warm standby (which takes some fixed amount of time), before it becomes active. A two-component system is considered, where a threshold is used on the operational component to decide when the standby component needs to be switched from cold to warm standby. Results indicate that a larger warmup period leads to a lower switching threshold.

As an alternative to adding redundant components, companies sometimes own a complete redundant system in practice. This standby system is for example an older version of the current system, that is kept in case the new system is shut down for maintenance. Typically, this redundant system is kept in cold standby and therefore requires a start-up time, after which it performs at a lower rate than the new system, resulting in some lost revenue. The downtime cost, however, would be significantly higher without the redundant system. The structure of the CBM policy for such a setting has not yet been studied.

2.3. Stochastic dependence

Stochastic dependence means that the deterioration or failure processes of components are (partially) dependent. Table 2.2 provides an overview of the contributions considering stochastic dependence. This type of dependence can occur in different ways, which are discussed below.

2.3.1. Failure-induced damage

The failure of one component can cause a major, one-time damage on other components, leading to an immediate increase of the deterioration level or even an immediate failure of these components. For example, a propeller can come loose of an airplane and pierce the fuselage, causing tremendous additional damage and safety risks. Both [52] and [55] (where the latter is a more generalized version of the former) consider a two-component system where component 1 is subject

Table 2.2. Summary of contributions on CBM that consider stochastic dependence.

Contribution	Stochastic dependence	CBM policy structure	Decision moments
[14]	Load sharing (failure-based)	Threshold for preventive imperfect repair	Continuously
[52]	Failure-induced damage	Threshold for preventive replacement (combined with ABM)	Continuously
[24]	Common-mode deterioration	Threshold for preventive replacement	Continuously
[28]	Failure-induced damage	Threshold for preventive replacement	Periodic: optimize interval, or inspect each time unit
[31]	Common-mode deterioration	Threshold for preventive replacement (fixed)	Periodic: optimize interval
[34]	Common-mode deterioration	Threshold for preventive replacement	Periodic: optimize interval
[53]	Load sharing (failure-based)	No predetermined structure	Periodic: fixed
[37]	Load sharing (degradation-based)	Thresholds for opportunistic replacement and preventive replacement	Periodic: optimize interval
[39]	Common-mode deterioration	Threshold for preventive replacement	Periodic: optimize interval
[38]	Common-mode deterioration	Threshold for preventive replacement (fixed)	Periodic: optimize interval
[54]	Load sharing (failure-based and degradation-based)	Thresholds for preventive imperfect repair and preventive replacement	Periodic: optimize interval
[55]	Failure-induced damage	Threshold for preventive replacement (combined with ABM)	Continuously
[56]	Load sharing (failure-based)	Thresholds for opportunistic replacement and preventive replacement	Continuously
[46]	Common-mode deterioration	Threshold for preventive replacement and probability thresholds for grouping replacements	Periodic: optimize interval for each component separately
[48]	Load sharing (failure-based)	No predetermined structure (compared with threshold for preventive replacement)	Periodic: fixed
[57]	Load sharing (degradation-based)	Threshold for preventive replacement	Aperiodic: reliability threshold for next inspection moment

to random failures, each causing damage on component 2. A combined CBM and Age-Based Maintenance (ABM) policy is applied to these components: the complete system is replaced as soon as the accumulated damage on component 2 exceeds a preventive replacement threshold, or when the system reaches a certain age. In fact, these contributions study a single component that is subject to CBM, as component 1 is minimally repaired upon each failure. The results indicate that a pure CBM or a pure ABM strategy both result in a close-to-optimal solution.

Furthermore, a multi-component system is studied in [28], where a component failure can lead to failures of other components according to three different scenarios: no damage is caused and only the failed component requires a replacement, the component failure causes one other component to be replaced as well, or the component failure leads to a complete system replacement. Each scenario occurs with a given probability. CBM is implemented through a deterioration threshold for a preventive replacement, but no insights are provided on the influence of the stochastic dependence on the optimal policy.

2.3.2. Load sharing

Multiple components can share the total system load. If a component fails, the system keeps operating but the remaining components structurally need to work harder to realize the same output level. The failure of a component thus increases the load on the working components, which will hence deteriorate faster. In practice, this applies for example to a set of pumps that are used to distribute a certain amount of gas. We refer to this type of load sharing as *failure-based* load sharing. The simplest form of such load sharing is considered by [53, 56], where each component can be subject to two deterioration processes (normal and accelerated). Upon failure of a component, the remaining components will deteriorate according to the accelerated deterioration process, until maintenance is performed. Results indicate that the costs from ignoring this stochastic dependence increase significantly with both the number of components and the degree of dependence. In [14, 48], more than two deterioration rates are distinguished. The deterioration rates are assumed to depend on the number of functioning components. Whereas thresholds are used in [14] to decide on when to perform preventive imperfect repairs, a dynamic policy structure is considered by [48], which is shown to outperform a single preventive replacement threshold policy. Furthermore, results indicate that preventive replacements should be performed at an earlier stage for a system with a strong degree of load sharing (see also Chapter 6).

Apart from failure-based load sharing, component deterioration can also increase the load on the other components. We refer to this as *degradation-based* load sharing. For example, a system consisting of N components is considered in [57], where the deterioration rate of component N depends on the states of components 1 to $N-1$ (which deteriorate independently). Furthermore, a two-component system of which the deterioration rates depend on the states of both components is studied by [37]. In both articles, thresholds are used for scheduling maintenance actions. Results indicate that the stochastic dependence should be included in the model, as ignoring this aspect will result in a significantly more expensive maintenance policy.

In [54], both failure-based and degradation-based load sharing are considered, for a system consisting of a number of critical and non-critical components. The failure of a non-critical component will accelerate the deterioration of a critical component (failure-based load sharing), while the deterioration rate of a critical component also depends on the state of all critical components (degradation-based load sharing). The model is limited, however, in that imperfect repairs and replacements are only performed on the complete system. Such a system replacement is performed as soon as the sum of the deterioration levels of the components exceeds the corresponding thresholds.

For failure-based load sharing, we can conclude that the load sharing effect imposes an incentive to prevent failures. Preventive replacements should thus be performed relatively early. For degradation-based load sharing, this effect is even stronger. Preventive replacements become more rewarding, due to the incentive to keep components relatively new.

2.3.3. Common-mode deterioration

Several components can fail or deteriorate simultaneously, due to, e.g., similar working conditions. Such correlation is usually positive, indicating that an increase in deterioration for one component is often associated with an increase in deterioration for the other components (and vice versa). If the weather is nice, for example, all windmills of a farm are subject to relatively little deterioration, while a heavy storm could cause damage on the blades of multiple windmills at the same time. In line with [4, 8, 49], we refer to this type of dependence as common-mode deterioration. Alternatively, an example of common-mode failures concerns multiple components that share a common power supply, like electrical equipment at home. In [39], a system consisting of one independent component and multiple dependent components is considered. The deterioration rates of the dependent components are affected by environmental factors, like temperature, which are in turn affected by the state of the independent component. In [38], a system is considered where shocks occur that can affect all components. Both contributions schedule complete system replacements based on a preventive replacement threshold, but neither investigate the effect of the stochastic dependence on the resulting policy.

A bivariate degradation process is used by [24, 34] for a two-component system. The degree of stochastic dependence in these models is described by the correlation coefficient of this process. Both contributions implement CBM through a preventive replacement threshold. For a given threshold policy, ignoring the stochastic dependence can lead to an under- or over-estimation of the corresponding costs [24], thus stressing the importance of incorporating the stochastic dependence.

Correlation between deterioration processes can also be incorporated by using copulas (see e.g. Chapter 5 of [58]), as done in [31, 46]. Whereas the effects of the stochastic dependence in [31] are intertwined with the structure of the system (series or parallel), economic dependence is incorporated in [46]. We therefore discuss these contributions in Section 2.6.

2.4. Resource dependence

In this review chapter, we introduce resource dependence as a new type of dependence. Maintenance actions can only be scheduled if the required resources, such as spares or tools, are available. Resource dependence arises for example when several components are connected through a shared, limited set of spares. As a consequence, maintenance optimization is required on the system level rather than on the component level. Table 2.3 provides an overview of the existing contributions addressing this type of dependence. Below, we address the different forms of resource dependence in detail, along with the implications for the structure of the corresponding CBM policy. A very general type of resource dependence is considered in [9], where it is assumed that maintenance activities require certain resources that are consumed during the activity (similar to spares). New resources will arrive at given time instances, and the CBM model is optimized given the restrictions following from the currently available set of resources.

2.4.1. Maintenance worker restrictions

In practice, companies often assign a team (consisting of one or more maintenance workers) that is responsible for performing all maintenance tasks. Each maintenance activity typically requires at least one maintenance worker, and thus

Table 2.3. Summary of contributions on CBM that consider resource dependence.

Contribution	Resource dependence	CBM policy structure	Decision moments
[14]	Limited number of maintenance workers	Threshold for preventive imperfect repair	Continuously
[59]	Limited set of spares	Threshold for preventive replacement	Periodic: fixed
[9]	Limited pool of resources (such as tools, parts, personnel)	No predetermined structure (compared with threshold for preventive replacement)	Periodic: fixed
[60]	Limited set of spares	Threshold for preventive replacement	Periodic: optimize interval
[61]	Limited set of spares	Threshold for preventive replacement (fixed)	Periodic: fixed
[20]	Limited number of maintenance workers	Threshold for preventive imperfect repair (fixed, combined with BR)	Continuously
[62]	Limited set of spares	Threshold for preventive replacement (fixed)	Periodic: optimize interval
[27]	Limited number of maintenance workers	Thresholds for opportunistic replacement (fixed) and preventive replacement	Continuously
[33]	Limited number of maintenance workers	Threshold for maintenance initiation, use yield-cost importance measure to decide on which components to replace	Continuously
[63]	Limited set of spares	No predetermined structure	Periodic: fixed

the number of maintenance activities that can be performed simultaneously is restricted by the number of maintenance workers that are available. In the simplest case, a fixed number of maintenance workers is available, and one maintenance worker is required for a single maintenance activity. Under a CBM policy, this case is investigated for a single maintenance worker by [20, 33]. A two-component system is studied by [20], where a preventive replacement threshold is used to decide when a component is replaced. If a component reaches this threshold and the maintenance worker is not available (i.e., is working on the other component), then the system is shut down until maintenance on the other component is completed. In practice, however, downtime should be prevented whenever possible, for instance by letting the component continue to work in the deteriorated state until the maintenance worker is available. In [33], a single maintenance worker is considered in a multi-component system, under the assumption that maintenance actions are performed sequentially rather than simultaneously. A situation with multiple maintenance workers is considered by [14]. A restriction is imposed on the set of possible actions: maintenance can only be performed if sufficient maintenance workers are available. In this way, unnecessary downtime of the system is prevented. Different cases are considered in [27]: without maintenance worker constraints, with a single maintenance worker, and with multiple external maintenance workers with a certain response time. Also here, unnecessary downtime is prevented as components are not shut down immediately upon requiring maintenance. As the effects of the different limitations on maintenance workers are heavily intertwined with the economic and structural dependence in the system, we discuss these articles in more detail in Section 2.6, where the joint effects of multiple dependencies are discussed.

The number of available maintenance workers can vary over time rather than being fixed. Certain preventive replacements or repairs can then be postponed until more maintenance workers are available. Additionally, one maintenance worker could be able to perform certain preventive repairs (think of lubrication or replacing a filter), while a corrective replacement of a component could require more than one maintenance worker. This has not been investigated yet in a CBM setting.

So far, we focused on the number of workers, implicitly assuming that all workers can execute all maintenance activities. However, in practice there are many examples where workers can only deal with a subset of all activities. Especially in case of CBM with dependencies between the different components, usually resulting in more uncertainty with respect to which activities have to be executed, this may result in further restrictions. As far as we know, so far no attention has been paid to this aspect in the context of CBM policies.

2.4.2. Tool restrictions

A different example of resource dependence arises when a limited set of tools is present. This case shows much resemblance with that of maintenance worker restrictions, but additional complexity arises when certain jobs require a specific combination of tools. The maintenance activity can then only be performed if all these tools are available. In case a single tool is required for multiple jobs, a decision has to be made with respect to the order in which the components receive maintenance. This will complicate the maintenance model significantly. So far, these restrictions have not yet been investigated under a CBM strategy.

2.4.3. Spares restrictions

A complicated type of resource dependence arises when multiple components share spares. Whereas the set of tools or team of maintenance workers is not affected by the activities performed, a spare is used and therefore lost upon usage. Although the majority of the maintenance literature assumes that spares are always available, in practice spares typically arrive after a certain lead time, and thus need to be ordered in advance. Additional decisions, such as when to order spares, require optimization as well. Several types of inventory policies can be used. An (s,S) type inventory policy is applied by [59, 60], where an order for up to S spares is placed as soon as the inventory position (number of spares on hand plus on order) drops below s. In these contributions, s and S are regarded as decision variables. Results indicate that, for a larger lead time, costs can be reduced by stocking more spares, thus increasing s and S. A continuous review (s,Q) policy is applied by [62], where an order for Q spares is placed as soon as the inventory position drops below s. In this case, s and Q are the decision variables for the inventory policy, but the influence of the lead time on these variables is not investigated. In [61, 63], the inventory decisions are optimized at the start of each time unit, without using a predetermined inventory policy structure. An (s,S) type inventory policy is not necessarily optimal [63]. Instead, the ordering decisions can be condition-based, similar to the maintenance decisions, where spares are only ordered once components are sufficiently deteriorated (see also Chapter 7).

In [61, 62], the inventory decisions are optimized for a given CBM policy with a predetermined threshold for a preventive replacement. However, a separate or sequential optimization of the maintenance and inventory decisions will not necessarily lead to a globally optimal policy [7]. For that reason, these decisions are jointly optimized in [59, 60, 63]. A separate optimization at the component level can be much more expensive, as pooling opportunities for spares are not taken into account [63].

A related type of resource dependence arises when components are not lost upon failure, but can be restored to a functioning state. Rather than ordering new spare components, a decision needs to be made on when to overhaul the failed component. Such an overhaul does not necessarily restore the component to the as-good-as-new state, but is typically more cost efficient than ordering a new component. No research has been performed yet on overhauling components in a CBM setting.

2.4.4. Transport restrictions

Maintenance workers, tools, and spares need to be transported to the location where the maintenance activities have to be executed. This can be done in, e.g., a van or a vessel. Such means of transportation often have limited space available to carry the required men, tools, and spares. Priority rules are thus required to decide in advance how to allocate this space. An example can be found in a repair center for, e.g., copiers. These copiers are typically located in various offices, and are collected by a repairman using a van. Another example concerns a repairman who visits customers with a van with the required tools and parts. Specific maintenance jobs require specific tools or spares, but the repairman usually does not know in advance which jobs need to be performed. Also this type of resource dependence is not yet studied in a CBM setting.

2.4.5. Budget restrictions

Apart from the resources considered so far, related to the actual execution of maintenance activities, a monetary budget is required for the latter. Many different types of budget restrictions can be found in practice, varying from lumpy sum type of budgets for a complete year up to monthly budgets for each of the resources discussed in this section. As far as we know, no attention has been paid to this important resource limitation in the context of CBM.

2.5. Economic dependence

Given the structural, stochastic, and resource dependencies between components, the next step is to schedule the maintenance actions. The costs related to a certain maintenance policy can thereby be influenced by the degree of economic dependence. Economic dependence means that combining maintenance on multiple components is either more expensive (*negative economic dependence*) or less expensive (*positive economic dependence*) than maintaining each component separately. Below, we discuss the different ways in which negative and positive economic dependence are currently implemented in the CBM policy literature.

2.5.1. Negative economic dependence

A system is subject to negative economic dependence when maintaining several components simultaneously leads to higher costs than maintaining them separately. According to [6], such negative economic dependence can be present in systems with manpower restrictions, safety requirements, or production-loss, which is usually incorporated by imposing restrictions in the maintenance model. However, such restrictions are examples of *structural dependence* or *resource dependence*, as discussed in Sections 2.2 and 2.4, respectively. A suitable example of negative economic dependence is given by a company that needs to (temporarily) hire additional staff or rent additional tools to simultaneously maintain multiple components. The maintenance costs can then be incorporated as a convex function of the number of components that receive maintenance. Another example where negative economic dependence occurs in practice, is when multiple maintenance workers need to operate in a limited space. They will start blocking and irritating each other, thereby increasing the probability of human errors. This problem, among others, arises in turn-arounds, where numerous maintenance jobs are performed simultaneously. To the best of our knowledge, however, negative economic dependence has not yet been studied in a CBM setting.

2.5.2. Positive economic dependence

Positive economic dependence occurs for example when high costs are involved in traveling to the location where maintenance activities have to be executed (think of windmills at sea), or shutting down and restarting an oil refinery to perform maintenance. In the maintenance literature, this dependence is often modeled as a set-up cost that needs to be paid once if maintenance is performed, independent of the number of components that receive maintenance. Typically, this set-up cost is independent of the system structure, the type of maintenance that is performed, and time. However, when a system consists of several subsystems or component types, a distinction can be made by including multiple set-up costs. In [64, 65], for example, a system set-up cost is included along with a separate set-up cost for each component type or subsystem, respectively. This case is also referred to as a *hierarchy of set-ups* [6]. Similarly, a distinction can be made between the type of maintenance that is performed. An inspection, a preventive replacement, and a corrective replacement could for example each incur a different set-up cost. This distinction between maintenance activities is made in [21, 28, 37, 43, 44]. Furthermore, although the set-up cost is generally assumed to be time-independent, this is not necessarily the case in practice. For example, set-up costs for maintenance on a hydro-generating unit in a deregulated power system can be time-dependent due to fluctuations in the monthly electricity price [36]. For that reason, a (single) time-dependent set-up cost is introduced in [36].

Alternatively, positive economic dependence can be incorporated by including a set-up cost that is a concave function of (for example) the number of components that receive maintenance. This case is also known as *economies of scale* [6]. Although one could argue that a single set-up cost can be viewed as such a concave function, more complicated set-up cost function structures have not yet been studied under a CBM regime.

A positive economic dependence between components forms an incentive to combine (or *cluster*) maintenance actions. Optimizing the maintenance decisions for each component separately will therefore not result in an optimal policy at the system level. Instead, the maintenance policy should allow for clustering opportunities. Whereas in Section 2.2, we observed that some technical dependencies can force certain components to be replaced together, we now consider optional clustering for non-technical reasons, with the sole intention to save costs. Intuitively, maintenance actions are combined more often under stronger positive economic dependence. This property of the maintenance policy can be incorporated in different ways. Below, we provide an overview of the contributions on CBM with positive economic dependence, divided into different ways to achieve maintenance clustering.

Complete clustering The simplest form of maintenance clustering is a maintenance policy in which all maintenance actions are clustered. We refer to this case as complete clustering. Table 2.4 lists the contributions that apply complete clustering in a CBM setting for a system subject to economic dependence. A combination of CBM and ABM is studied by [43, 44]. Under these policies, a complete system replacement is initiated as soon as one component requires maintenance. This can be based upon a component failure, a component's deterioration level exceeding its preventive replacement threshold, or upon reaching a certain age. Both the preventive replacement threshold and the replacement age are decision variables, which are responsive to the set-up costs for the different maintenance actions. Although significant cost savings are reported by [43, 44] compared to (for example) an individual CBM optimization for each component, these models are not completely responsive to the degree of economic dependence. Typically, clustering all maintenance actions is only optimal in a system subject to very strong economic dependence (i.e., a very high set-up cost). For a weaker form of

Table 2.4. Summary of contributions that cluster all CBM activities for systems subject to economic dependence.

Contribution	Positive economic dependence: set-up cost for	CBM policy structure	Decision moments
[43]	Preventive replacement (age-based), preventive replacement (condition-based), and corrective replacement	Threshold for preventive replacement (combined with ABM)	Continuously
[44]	Preventive replacement (age-based), preventive replacement (condition-based), and corrective replacement	Threshold for preventive replacement (combined with ABM)	Continuously

economic dependence, maintenance is performed too often under this type of policy.

Inspection-driven clustering CBM is regularly implemented by using a threshold. Under such a policy, inspections are performed that reveal the condition, or deterioration level, of each component. A component is preventively replaced if an inspection reveals that its degradation exceeds a certain deterioration threshold, or when its reliability (or failure risk) drops below (exceeds) a certain threshold. Although it appears that maintenance is only clustered by chance if multiple components exceed their (individual) threshold at the same time, clustering possibilities can be incorporated by varying the inspection interval. By considering a larger inspection interval, the probability that multiple components have reached their preventive replacement threshold increases, and thus maintenance actions are clustered more often. A stronger economic dependence will thus lead to an increased inspection interval. Table 2.5 summarizes the contributions that apply this way of clustering for systems subject to economic dependence. Note that the inspection interval is optimized for each component separately in [46], and thus additional probability thresholds are used to decide which components are clustered. In [10, 28, 34, 66], both the preventive replacement threshold and the inspection interval are optimized. Results indicate that a larger set-up cost for maintenance will indeed increase the optimal inspection interval. To compensate for the resulting increased failure risk, the maintenance thresholds will be decreased. An alternative way to deal with the increased failure risk resulting from

Table 2.5. Summary of contributions on CBM that apply inspection-driven clustering to systems subject to economic dependence.

Contribution	Positive economic dependence: set-up cost for	CBM policy structure: threshold for	Decision moments
[28]	Preventive replacement and corrective replacement	Preventive replacement	Periodic: optimize interval, or inspect each time unit
[34]	Any replacement	Preventive replacement	Periodic: optimize interval
[10]	Any replacement	Preventive replacement	Periodic: optimize interval
[41]	Any replacement	Preventive replacement (fixed)	Aperiodic: find near-optimal inspection moments
[66]	Any replacement	Preventive replacement	Periodic: optimize interval
[46]	Any replacement	Preventive replacement, and probability thresholds for grouping replacements	Periodic: optimize interval for each component separately

such an increased, static inspection interval is provided by [41]. An aperiodic, dynamic inspection schedule is optimized, for which inspections can be scheduled more frequently when a component is approaching the end of its life. However, the preventive replacement threshold is fixed and therefore not optimized, despite its influence on the cost rate.

Opportunistic clustering Whereas the inspection-driven clustering approach relies on the assumption that the decision moments can be internally decided, many process industries deal with externally determined inspection or decision moments (e.g., legally forced inspections). In such cases, clustering can be achieved by using additional thresholds to facilitate opportunistic replacements. As opposed to inspection-based clustering, this approach can also be applied to a continuously monitored system. Maintenance is initiated upon reaching a certain threshold, but additional components can be replaced opportunistically according to their additional, opportunistic thresholds. In case of internally decided decision moments, the inspection interval can be optimized as well. Table 2.6 summarizes the contributions that apply such opportunistic clustering for systems subject to economic dependence. We remark that a maintenance strategy is proposed for a system with positive economic dependence by [67], but not applied.

From Table 2.6, we observe that the most common approach is to include both a preventive replacement threshold and an opportunistic replacement threshold. Under the resulting policy, a component is preventively replaced upon reaching its preventive replacement threshold, independent of the states of the other components. Additionally, provided that at least one component receives a corrective or preventive replacement, the other components are replaced upon reaching their opportunistic replacement threshold. A lower opportunistic replacement threshold results in more frequently clustered maintenance actions. This type of opportunistic clustering is considered by [15, 23, 26, 27, 30, 35–37, 42, 45, 56, 64, 65, 67–70] (see also Chapters 3 and 4). Results indicate that a strong economic dependence reduces the opportunistic replacement threshold to better facilitate maintenance clustering. A time-dependent set-up cost, along with time-dependent thresholds, is considered in [36]. Results indicate that a high set-up cost at some point in time increases the corresponding maintenance thresholds, to prevent expensive replacements. Furthermore, a distinction is made in [64] between a set-up cost for the system and one for each component type. Two types of clustering opportunities can thus arise: at the system-level (due to maintenance on a component of another type), or at the component-type level (due to maintenance

Table 2.6. Summary of contributions on CBM that apply opportunistic clustering to systems subject to economic dependence.

Contribution	Positive economic dependence: set-up cost for	CBM policy structure: threshold for	Decision moments
[64]	Any replacement: for system and component type	Opportunistic replacement (on system), opportunistic replacement (on component type), and preventive replacement	Periodic: fixed
[15]	Any replacement	Opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[65]	Preventive replacement	Opportunistic replacement and preventive replacement	Periodic: fixed
[21]	Any replacement: for system, and prev. replacement (if no corr. replacements): for subsystem	Maintenance initiation and maintenance ceasing on subsystem	Periodic: fixed
[68]	Preventive replacement (if no corrective replacements)	Opportunistic replacement and preventive replacement	Periodic: fixed
[23]	Any replacement	Opportunistic replacement and preventive replacement	Continuously
[26]	Any replacement	Opportunistic replacement and preventive replacement	Periodic: optimize interval
[27]	Any replacement	Opportunistic replacement (fixed) and preventive replacement	Continuously
[30]	Any replacement	Opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[35]	Any replacement	Opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[36]	Any replacement: time-dependent	Opportunistic replacement and preventive replacement (time-dependent)	Periodic: fixed
[69]	Any replacement	Opportunistic replacement and preventive replacement	Periodic: fixed
[37]	Inspection, preventive replacement, and corrective replacement	Opportunistic replacement and preventive replacement	Periodic: optimize interval
[40]	Any replacement	Maintenance initiation, opportunistic replacement, and preventive replacement	Periodic: optimize interval
[11]	Any replacement	Maintenance initiation, then determine group to replace	Periodic: optimize interval
[42]	Any replacement	Opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[67]	Not specified	Opportunistic replacement and preventive replacement	Periodic: fixed

Continued on next page

Table 2.6 – continued from previous page

Contribution	Positive economic dependence: set-up cost for	CBM policy structure: threshold for	Decision moments
[56]	Any replacement	Opportunistic replacement and preventive replacement	Continuously
[45]	Any replacement	Opportunistic imperfect repairs (restoring to different states) and preventive replacement	Periodic: fixed
[70]	Any replacement	Opportunistic replacement and preventive replacement	Continuously

of a component of the same type). For both levels, a threshold is included. Finally, opportunistic imperfect repairs are considered in [45], which can restore a component to different states. For each degree of repair, an opportunistic threshold is included.

Similarly to the inspection-driven clustering opportunities, the inspection interval is optimized as well in [11, 26, 37, 40], whereas aperiodic inspection moments are incorporated in [15, 30, 35, 42] by using deterioration thresholds to decide on the next inspection moment (see also Chapters 3 and 4). CBM models with periodic inspections (of which the periodicity is either fixed or optimized) can be seen as special cases of such an aperiodic inspection scheme.

Alternatively, a threshold for the system failure risk or reliability is used in [11, 21, 40] to decide whether maintenance should be initiated. In [40], opportunistic and preventive replacement thresholds are used for deciding which components to replace, while in [21], enough components are replaced to let the system risk drop below a second threshold. A cost-based group improvement factor is used in [11] to decide on which components to replace. Although clustering possibilities are included in these approaches, they are mainly developed to deal with the structural dependence that is also present in these contributions. Nevertheless, an advantage of these approaches is that, in addition to minimizing the costs, one can control the performance of the system in terms of reliability. This is more difficult to achieve with deterioration thresholds.

Optimal clustering The different ways to incorporate clustering possibilities described so far are all subject to a predetermined policy structure, such as thresholds. However, such a policy structure is not necessarily optimal. In Table 2.7, we list all contributions that allow any group of maintenance actions to be clustered. The performances of the models developed by [9, 25, 47, 48] are compared with

Table 2.7. Summary of contributions that allow any CBM actions to be clustered for systems subject to economic dependence.

Contribution	Positive economic dependence: set-up cost for	CBM policy compared with	Decision moments
[12]	Preventive replacement		Periodic: fixed
[9]	Any replacement	Risk threshold for preventive replacement	Periodic: fixed
[71]	Any replacement		Periodic: fixed
[22]	Any replacement		Periodic: fixed
[25]	Any replacement	Deterioration threshold for preventive replacement	Aperiodic: optimize next inspection moment
[53]	Any replacement		Periodic: fixed
[47]	Any replacement	Deterioration threshold(s) for (opportunistic replacement and) preventive replacement	Periodic: fixed
[48]	Any replacement	Deterioration threshold for preventive replacement	Periodic: fixed

those of a CBM policy where a threshold is used to schedule preventive replacements (see also Chapter 6). Results indicate that the use of thresholds limits the benefit of CBM, and that significant cost savings can be obtained by allowing any policy structure. In addition, the results of [47] are compared with a policy with thresholds for both opportunistic and preventive replacements. Results indicate that also this multi-threshold policy can be significantly more expensive than the optimal CBM policy, although it does outperform the threshold policy with a single (preventive replacement) threshold (see also Chapter 5).

2.6. Multiple types of dependencies

When a system is subject to more than one type of dependence, the effects of these dependencies on the optimal policy structure can be heavily intertwined. Table 2.8 shows the contributions on CBM that consider at least two types of dependencies. Below, we discuss the influence on the policy structure of multiple types of dependencies. We observe that all contributions incorporate positive economic dependence and/or structural dependence through system performance. For that reason, we distinguish three cases: where either economic dependence or structural dependence through system performance is incorporated, or both.

Table 2.8. Summary of contributions on CBM that consider multiple types of dependencies.

Contribution	Structural dependence			Stochastic dependence			Resource dependence		Economic dependence
	Maintenance	*Usage*	*Performance*	*Failure-induced damage*	*Load sharing*	*Common-mode deterioration*	*Workers*	*Spares*	*Positive*
[12]			✓						✓
[14]			✓		✓		✓		
[15]			✓						✓
[9]	✓							✓	✓
[20]			✓				✓		
[21]			✓						✓
[22]			✓						✓
[23]			✓						✓
[24]			✓			✓			
[25]			✓						✓
[26]			✓						✓
[27]			✓				✓		✓
[28]			✓	✓					✓
[30]			✓						✓
[31]			✓			✓			
[33]			✓				✓		
[34]			✓			✓			✓
[10]		✓	✓						✓
[35]			✓						✓
[36]			✓						✓
[53]					✓				✓
[37]			✓		✓				✓
[38]			✓			✓			
[39]			✓			✓			
[40]			✓						✓
[41]			✓						✓
[11]		✓	✓						✓
[42]			✓						✓
[43]			✓						✓
[44]			✓						✓
[56]					✓				✓
[45]			✓						✓
[46]			✓			✓			✓
[47]			✓						✓
[48]			✓		✓				✓

Table 2.9. Summary of contributions on CBM that consider economic dependence but no structural dependence through system performance.

Contribution	CBM policy structure	Decision moments
[9]	No predetermined structure (compared with threshold for preventive replacement)	Periodic: fixed
[53]	No predetermined structure	Periodic: fixed
[56]	Thresholds for opportunistic replacement and preventive replacement	Continuously

2.6.1. Economic dependence without performance dependence

In Table 2.9, we summarize all contributions that consider economic dependence, but do not consider structural dependence through performance. As explained in Section 2.5, a strong degree of economic dependence causes maintenance actions to be clustered more frequently. In [9], both maintenance restrictions (structural dependence) and a shared set of resources (resource dependence) are considered besides the economic dependence. Whereas the maintenance restrictions are implemented through a penalty cost structure, the shared set of resources is implemented by restricting the set of possible maintenance actions. The joint effects of the different dependencies are not investigated. In [53, 56], load sharing (stochastic dependence) is considered in addition to economic dependence, as explained in Section 2.3.2. However, neither investigate the joint effects of the different dependencies.

2.6.2. Performance dependence without economic dependence

Table 2.10 lists all contributions that consider structural dependence through performance, but do not consider economic dependence. As explained in Section 2.2, different system structures can have different influences on the optimal policy structure. In principle, a series configuration will require preventive maintenance to be performed at a relatively early stage, whereas in systems with redundancy (such as a k-out-of-N system) preventive maintenance can be performed somewhat later. This can for example be achieved by decreasing or increasing the maintenance thresholds, respectively.

In [24, 31, 38, 39], common-mode deterioration (stochastic dependence) is considered in addition to the structural dependence through performance. Both series and parallel configurations are considered in [24, 31]. Whereas the joint effects of the system structure and the stochastic dependence are not investigated by [24], a parallel system is found to be much more affected by changes in the degree

Table 2.10. Summary of contributions on CBM that consider structural dependence through system performance but no economic dependence.

Contribution	System structure	CBM policy structure	Decision moments
[14]	Series-parallel-series	Threshold for preventive imperfect repair	Continuously
[20]	Cold standby	Threshold for preventive imperfect repair (fixed, combined with BR)	Continuously
[24]	Series or parallel	Threshold for preventive replacement	Continuously
[31]	Series or parallel	Threshold for preventive replacement (fixed)	Periodic: optimize interval
[33]	Series-parallel	Threshold for maintenance initiation, use yield-cost importance measure to decide on which components to replace	Continuously
[39]	Series	Threshold for preventive replacement	Periodic: optimize interval
[38]	Series	Threshold for preventive replacement (fixed)	Periodic: optimize interval

of stochastic dependence than a series system in [31]. No insights are provided on the effects on the preventive replacement threshold, as this threshold is fixed in advance. In [38, 39], a series system is considered, but no insights are provided on the joint effects of this structure and the common-mode deterioration.

A single maintenance worker (resource dependence) is considered for a cold standby system by [20] and for a series-parallel system by [33]. As explained in Section 2.4.1, CBM is implemented on a two-component system using a preventive replacement threshold in [20]. If a component reaches this threshold and the maintenance worker is not available (i.e., is working on the other component), the system becomes unavailable until maintenance on the other component is completed. Through this policy structure, the single maintenance worker increases the downtime resulting from the cold-standby configuration. Alternatively, maintenance is performed sequentially rather than simultaneously in [33] because of the single maintenance worker. In this case, the effects of the series-parallel setting (structural dependence) and the single maintenance worker (resource dependence) are independent. A set of multiple maintenance workers is considered for a series-parallel-series system by [14], where maintenance is postponed if no maintenance worker is available. In addition, stochastic dependence is implemented through load sharing. In the numerical experiments, a subsystem consisting of three components in parallel is considered, which are subject to load sharing and a shared pool of two maintenance workers. Although load sharing typically forms an incentive to perform maintenance at a relatively early stage, the results indicate that preventive maintenance is performed as rarely as possible for these components. This is caused by the parallel setting, which allows components to fail without causing immediate unavailability of the system, and the limited number of maintenance workers, which can cause downtime if components are waiting for maintenance. Maintenance is now only performed if strictly necessary. We thus conclude that the effects of the system structure, the load sharing, and the limited number of maintenance workers are certainly correlated.

2.6.3. Both economic dependence and performance dependence

In Table 2.11, we summarize all contributions that consider both positive economic dependence and structural dependence through system performance. In Section 2.5, we found that positive economic dependence forms an incentive to cluster maintenance activities, whereas Section 2.2 revealed that different system structures can have different influences on the optimal policy structure. When combining these types of dependencies, two interesting situations can occur in which the effects of the dependencies are intertwined.

The first case concerns a series configuration, where non-negligible maintenance durations are considered. For such systems, we observed in Section 2.5 that the implications on the resulting policy structure can be two-fold. Both a failure and a maintenance activity on a single component can shut down the complete system and thus lead to high unavailability costs. Downtime can be reduced by performing preventive maintenance at a relatively early stage and by clustering maintenance activities. In case of negligible maintenance durations, the latter property disappears, and the two types of dependencies become independent of each other. From Table 2.11, we observe that the majority of the contributions consider a series configuration, where non-negligible maintenance durations are only considered by [23, 27, 28]. In [28], the maintenance cost is used as the performance criterion, and the non-zero maintenance durations are included in the set-up cost. In this way, the effects of the downtime resulting from maintenance are incorporated in the (stronger) economic dependence, thereby reinforcing the importance of clustering. Multiple performance criteria are considered in [23, 27], such as system availability and maintenance costs. Both contributions assume that the system needs to be shut down for a fixed period of time to perform maintenance activities, independent of the number of activities to be executed. Although the maintenance durations do not affect the maintenance costs, they do

Table 2.11. Summary of contributions on CBM that consider both economic dependence and structural dependence through system performance.

Contribution	System structure	CBM policy structure	Decision moments
[12]	Series	No predetermined structure	Periodic: fixed
[15]	Series	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[21]	Subsystems in series	Thresholds for maintenance initiation and maintenance ceasing on subsystem	Periodic: fixed
[22]	Series	No predetermined structure	Periodic: fixed
[23]	Series	Thresholds for opportunistic replacement and preventive replacement	Continuously
[25]	Series	No predetermined structure (compared with threshold for preventive replacement)	Aperiodic: optimize next inspection moment
[26]	k-out-of-N	Thresholds for opportunistic replacement and preventive replacement	Periodic: optimize interval
[27]	Series or parallel	Thresholds for opportunistic replacement (fixed) and preventive replacement	Continuously
[28]	Series	Threshold for preventive replacement	Periodic: optimize interval, or inspect each time unit
[30]	Series-parallel	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[34]	Series or parallel	Threshold for preventive replacement	Periodic: optimize interval
[10]	Arbitrary structure	Threshold for preventive replacement	Periodic: optimize interval
[35]	Series	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[36]	Series	Thresholds for opportunistic replacement and preventive replacement (time-dependent)	Periodic: fixed
[37]	Series	Thresholds for opportunistic replacement and preventive replacement	Periodic: optimize interval
[40]	k-out-of-N	Thresholds for maintenance initiation, opportunistic replacement, and preventive replacement	Periodic: optimize interval

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Table 2.11 – continued from previous page

Contribution	System structure	CBM policy structure	Decision moments
[41]	Series	Threshold for preventive replacement (fixed)	Aperiodic: find near-optimal inspection moments
[11]	Arbitrary structure	Threshold for maintenance initiation, then determine group to replace	Periodic: optimize interval
[42]	Parallel	Thresholds for opportunistic replacement and preventive replacement	Aperiodic: deterioration thresholds
[43]	Series	Threshold for preventive replacement (combined with ABM)	Continuously
[44]	Series	Threshold for preventive replacement (combined with ABM)	Continuously
[45]	Series-parallel	Thresholds for opportunistic imperfect repairs (restoring to different states) and preventive replacement	Periodic: fixed
[46]	Parallel	Threshold for preventive replacement and probability thresholds for grouping replacements	Periodic: optimize interval for each component separately
[47]	k-out-of-N	No predetermined structure (compared with threshold(s) for (opportunistic replacement and) preventive replacement)	Periodic: fixed
[48]	Parallel	No predetermined structure (compared with threshold for preventive replacement)	Periodic: fixed

affect the availability. Results indicate that maintenance clustering can reduce costs due to the economic dependence, but also increase availability due to the series configuration.

The second case concerns system structures where some type of redundancy is incorporated by installing more components than strictly necessary, such as a k-out-of-N system. In practice, a component is typically replaced immediately upon failure, independent of the states of the other components. For systems with redundancy, however, the system can still be functioning after a certain component failed. Postponing the corrective maintenance to allow maintenance actions to be clustered can be cost-efficient due to the economic dependence. This property is not included in the CBM policy structure when thresholds are used for opportunistic or preventive maintenance actions. Table 2.11 shows that the majority of the contributions with some type of redundancy do implement CBM through thresholds. In [11, 40], corrective maintenance is allowed to be postponed by using a threshold for maintenance initiation. In this way, maintenance is only performed if the system reliability drops below a certain threshold. The optimal maintenance actions are found for any possible system state in [47, 48], without using thresholds to define the policy (see also Chapters 5 and 6). Results indicate that corrective maintenance is sometimes postponed to allow for maintenance clustering. In addition, when corrective maintenance is more expensive than preventive maintenance, non-monotonic behavior of the optimal policy is observed. In certain states, a component is preventively replaced solely to prevent a more expensive corrective replacement, whereas a corrective replacement on that same component would be postponed to allow for clustering. Such behavior cannot be captured by thresholds.

Combinations with other types of dependencies Additionally, two types of structural dependence are considered in [10, 11], through performance and usage as discussed in Sections 2.2.1 and 2.2.2. Complex system structures are considered, where some components can become idle upon failure of other components, while the system keeps functioning. Although not investigated in these contributions, postponing corrective maintenance can become more rewarding. Not only will this allow maintenance to be clustered, but postponing corrective maintenance will also prevent the idle components from deteriorating for a while. Since a reliability threshold for maintenance initiation is used in [11], while only a preventive replacement threshold is used in [10], the former study is better able to capture this property.

In [28, 34, 37, 46, 48], stochastic dependence is considered in addition to the economic and structural dependence. Recall that stochastic dependence can occur in three different ways: through failure-induced damage, load sharing, or common-mode deterioration. First, the case where a component failure can cause other components to fail as well is considered in [28]. As explained in Section 2.3.1, the influence of this type of dependence on the policy structure is not investigated, but we expect that preventive replacements are performed at a relatively early stage to prevent failures. This type of dependence appears to be independent of the economic and structural dependence. Second, stochastic dependence through load sharing is considered in [37, 48], as discussed in Section 2.3.2. Failure-based load sharing is considered by [48] (see also Chapter 6). Whereas the economic dependence in a system with redundancy encourages the postponement of corrective maintenance, this type of load sharing provides an incentive to perform corrective maintenance as soon as possible. Results indicate that this trade-off cannot be captured by thresholds, but that a custom-fit CBM policy is required. Degradation-based load sharing is considered by [37], which forms an incentive to perform preventive maintenance at a relatively early stage. Although not investigated, this will allow more maintenance activities to be clustered in the series system. Third, common-mode deterioration is studied by [34, 46], as discussed in Section 2.3.3. Although the performance of the series system in [34] is not comparable under different degrees of stochastic dependence, the components in [46] are more often replaced simultaneously under strong stochastic dependence.

In [27], resource dependence is considered through a shared pool of maintenance workers. In case only a single maintenance worker is available, maintenance actions can still be clustered, but will be executed sequentially rather than simultaneously [27]. Furthermore, the response time for external maintenance workers by assumption only applies for corrective maintenance. As corrective maintenance can also be combined with preventive maintenance, for which no response time is required, this restriction does not significantly affect the cost.

2.7. Conclusion and future research directions

In this chapter, we reviewed CBM policies for multi-component systems subject to dependencies. We noticed that the current division of dependencies in the literature (economic, structural, and stochastic) is no longer sufficient. For that reason, we proposed a new, more complete classification of dependencies. We introduced resource dependence as a new type of dependence, where multiple components are connected through a shared set of resources such as spares, tools, or maintenance workers. In addition, we extended the notion of structural dependence to cover also the case in which the system performance depends on the structure of the components (such as series, parallel, or k-out-of-N). For each type of dependence, we provided several examples from practice, while we also investigated the influence of the dependence on the structure of the CBM policy.

A number of lessons can be learned from past research, of which the majority is centered around the effects of a single type of dependence. From a technical point of view, structural dependence can impose a restriction on the possible maintenance actions, for example when certain components cannot be maintained simultaneously. Ignoring these restrictions can lead to infeasible maintenance policies. From a performance point of view, preventive maintenance should be performed at a relatively early stage for systems with a series configuration, but can be performed at a relatively late stage for systems which incorporate redundancy. Similarly, we found that preventive maintenance should be performed at an early stage for systems subject to failure-induced damage or load sharing (examples of stochastic dependence), and that resource dependence through a shared set of maintenance workers or spares can also impose a restriction on the possible maintenance actions. Another important lesson is that positive economic dependence provides an incentive to combine (or cluster) maintenance actions. Maintenance clustering can also be beneficial for systems with a series structure, when non-negligible maintenance durations are considered. In the literature, maintenance actions are for example clustered by varying the inspection interval or by using thresholds to indicate when maintenance should be performed. However, these strategies do not necessarily result in a close-to-optimal policy. It has been shown that ignoring economic (or stochastic) dependence can result in sub-optimal policies, which can be significantly more expensive than necessary.

Despite these lessons learned, our review also highlighted some important research gaps. Some types of dependencies have not been investigated in a CBM setting yet, despite their practical relevance. For example, the case where maintenance on a certain component requires maintenance on other components as well (an example of structural dependence on a technical level) has not yet been investigated under a CBM regime. Furthermore, resource dependence is still ill-researched. For instance, all existing research on sharing a pool of maintenance workers assume constant availability over time. In practice, however, it could well be that more maintenance workers are available during working days than during the weekend. Additionally, certain maintenance activities could require more maintenance workers than others, but also this case has not been considered. Resource dependence can also arise through a shared set of tools, which has not yet received any attention in the literature, although several interesting scenarios exist. Maintenance on a certain component can for example require a specific combination of tools. Moreover, the cases where maintenance workers have limited space in their van or vessel to store tools and spares, and thus need to decide in advance how to allocate this space, has not been studied yet for CBM. The case where failed components can be overhauled also needs further attention. Negative economic dependence has not yet been incorporated. Such negative economic dependence can arise when companies have to (temporarily) hire additional staff if many components require maintenance at the same time. This imposes an incentive to perform maintenance sequentially rather than simultaneously. We remark that most existing research on CBM assumes negligible maintenance durations. Under this assumption, the cases where several components cannot be maintained together (e.g., due to structural dependence on a technical level or due to negative economic dependence) do not impose a realistic restriction on the maintenance policy. Besides investigating new types of dependencies, including non-negligible replacement times is thus also a relevant field of future research.

It also transpired that certain types of dependencies have been considered, but without clarifying the effects on the optimal CBM policy structure. This holds for example for the case where the unavailability of a certain component (due to failure or maintenance) causes other components to be idle as well (structural dependence on a technical level). When ignoring the fact that certain components can be idle (and therefore not subject to deterioration), one can overestimate the deterioration levels, and thus schedule CBM more often than necessary. The extent to which this influences the optimal policy requires further research.

Whereas the previous observations highlight that knowledge gaps still remain for isolated types of dependencies, this is even more so for combinations of several types of dependencies. Most existing research considers just one type of dependence. Moreover, the majority of contributions that do consider more than one type are centered around positive economic dependence and structural dependence through performance. Our review reveals that the effects of these two types of dependencies are largely independent, unless they apply to a series system with non-negligible maintenance durations (which leads to an increased incentive to cluster maintenance actions) or to a system with redundancy (where corrective maintenance can be postponed to enable maintenance clustering). Significantly less attention has been paid to the joint effects of other types of dependencies. In fact, if we leave out the positive economic dependence and the structural dependence through performance, we observe that only two contributions remain. In [14], load sharing (stochastic dependence) is investigated along with a fixed number of maintenance workers (resource dependence), whereas maintenance restrictions (structural dependence) are considered in [9] along with a shared set of spares (resource dependence). We can thus conclude that much more research is needed on the joint effects of different types of dependencies on the optimal CBM policy structure.

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