Knowledge Lost in Data: Organizational Impediments to Condition-Based Maintenance in the Process Industry

Robert M. van de Kerkhof, Henk A. Akkermans and Nils G. Noorderhaven

Abstract In this chapter we report on a pilot study of Condition-Based Maintenance (CBM) in the process industries, such as the steelmaking- and chemical industries, and propose a diagnostic instrument for systematically analysing the challenges to the successful implementation and execution of a CBM program. Although the field of predictive maintenance is growing and considerable research effort has been targeted to the technical aspects of CBM, we observe that many firms in the process industry do not yet systematically use advanced CBM approaches. This research therefore aims to contribute to our understanding of the contextual barriers (beyond the technical issues) that hinder organisations from employing condition-based maintenance programs to improve their asset management.

Keywords Condition-based maintenance · Inter-organizational collaboration · Organizational design · Maintenance strategy

1 Introduction

For many complex capital goods, the costs of maintenance represent a large fraction of the Total Cost of Ownership. Additionally, with the rapid development of modern technology, products have become more and more complex while better quality and higher reliability are required. Given this it is not surprising that in the Netherlands and in Europe the field of maintenance, repair and overhaul (MRO) is growing in importance (Verbraeken 2015). In the field of maintenance it is essential to develop strategies that minimize cost whilst maximizing the availability and safety of assets (Garg and Deshmukh 2006). One promising approach to boost

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R.M. van de Kerkhof (✉) · H.A. Akkermans · N.G. Noorderhaven
Tilburg School of Economics and Management, Tilburg University, Tilburg 5037 AB,
The Netherlands
e-mail: r.m.vdkerkhof@tilburguniversity.edu

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maintenance productivity is Condition-Based Maintenance (CBM); a pro-active maintenance program that aims at predicting the time of a future malfunction by monitoring several conditions (e.g., temperature, vibrations), so the maintenance can be executed at 'just the right time' (Jardine et al. 2006). Multiple studies have empirically found that CBM results in a substantial reduction of the equipment's downtime and total maintenance costs compared to other maintenance strategies (see Jardine et al. 2006; Veldman et al. 2011), particularly when CBM activities can be clustered with scheduled maintenance activities.

Considerable research effort has been expended on the technical aspects of CBM, driven by the development of hardware technology, remote condition monitoring instrumentation, data mining ('big data') and data analysis techniques (e.g., Aggarwal 2013; Peng et al. 2010; Panagiotidou and Tagaras 2010; Heng et al. 2009). At the same time, firms in the process industry work with high capital investments, large expenses for downtime and high safety requirements, which puts pressure on the maintenance function and causes a need for advanced maintenance technology and practice (Arts et al. 1998; Tan and Kramer 1997). However, in contrast to our expectations, we observe that many firms in the process industry apply CBM approaches in general, and data-driven prognostics in particular, only to a very limited extent.

Perhaps even more surprising is how little attention this gap between state of the art and general practice has yet received in the literature. This raises the question: why do many asset owners within these industries struggle when trying to successfully set up and execute systematic CBM approaches, either by themselves or in collaboration with third parties? Apparently, studying technical factors alone is insufficient to answer this question, as technical solutions can rarely solve an organizational or a cultural problem. As yet, however, hardly any empirical evidence on the organizational aspects of designing and implementing condition-based maintenance approaches has been published (Veldman et al. 2011).

Hence we propose that there is a need to increase our understanding of the contextual barriers (beyond the technical issues) that hinder organisations from employing condition-based maintenance programs to improve their asset management. In time this understanding will be transformed into practical guidelines for the implementation of intra- and inter-organisational collaborative CBM activities and data sharing. Given that the asset owners do not have sufficient resources to set up the CBM programs by themselves, the aim is to contribute to the optimal design of condition-based maintenance relations, based on both general knowledge on inter-organisational relations and experiences acquired in the research.

The chapter begins with a brief description of condition-based maintenance and its applications in the process industry. Then we provide a diagnostic framework for analysing the contextual barriers to the implementation and execution of a CBM program, after which we discuss the initial findings of a pilot study we have conducted in the Dutch process industry. Here we have included several empirical examples (in grey boxes), in order to make the discussed concepts more tangible. The pilot study involved interviews with Maintenance-, Process-, and Reliability engineers, Inspectors and Operators, as well as plant tours and observations of maintenance-related meetings. This pilot study is part of the larger research program CAMPI, a collaborative effort of the University of Groningen, Tilburg University, Eindhoven University of Technology, and Dinalog.

2 Condition-Based Maintenance

2.1 Maintenance Strategies

A prevalent taxonomy of maintenance strategies (Fig. 1) distinguishes between reactive and proactive maintenance, in which the asset is replaced or repaired either after or before breakdown, respectively (Kothamasu et al. 2006). In the proactive maintenance category we can further distinguish between preventive maintenance, which sets a predetermined periodic interval to perform maintenance (regardless of the physical status of the asset), and predictive maintenance, which recommends maintenance actions based on the actual status of the asset. Since reactive maintenance is (by definition) unplanned and frequently involves collateral damage, the costs of breakdown (especially of critical equipment) are expected to be higher than in the case of proactive maintenance. Ideally, one would want to conduct maintenance shortly before the asset will fail, not too early, but not too late either. By monitoring the state of the asset and basing the maintenance decision on its current condition, the number of (unplanned) breakdowns and the number of unnecessary scheduled preventive maintenance operations can be reduced (Tsang 1995).

Jardine et al. (2006) describe CBM as “a maintenance program that recommends maintenance actions based on the information collected through condition monitoring.” According to this definition, CBM contains a large range of predictive maintenance activities, such as a visual inspection of the tires of a car, vibration

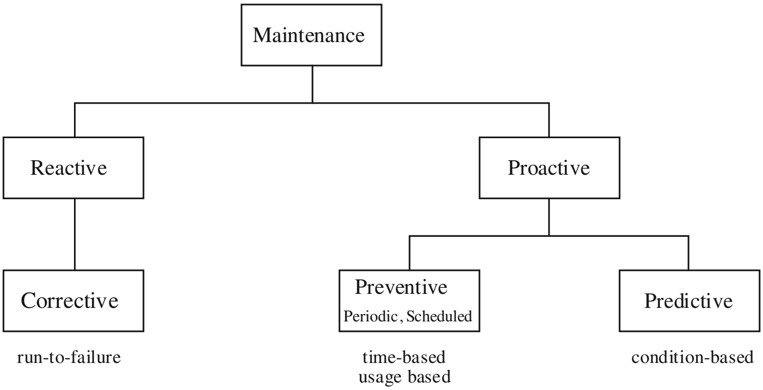

Fig. 1 Categorization of maintenance strategies

analyses of rotating equipment (tool-driven techniques) and fully automated approaches for hard-to-reach assets, in which many conditions are remotely and continuously monitored, stored in large data bases (for data mining purposes) and used in one or multiple prognostic modelling techniques (data-driven techniques). Over the years many specialized tools and sensors have been developed to monitor specific degradation processes (see for example Moubray 1997) and technological progress has enabled the more automated data-driven techniques. Each of these approaches varies in their Technology Readiness Level (TRL) and requirements for the IT-infrastructure, but also (and most importantly) in their monitoring sensitivity and predictive accuracy.

To illustrate the general rationale behind CBM, the degradation process of an asset is depicted in Fig. 2, a so-called P-F curve (Moubray 1997). Within this curve two states are prevalent: (1) a functional failure, entailing the inability of the equipment to meet a specified performance standard, and (2) a potential failure, entailing an identifiable condition that indicates that a functional failure is imminent (early signal). Note that the several early signals indicating the degradation of the asset are likely to be received by people within different departments. In this fictional example, the reduced pressure (P_1) can for instance be noted by an operations engineer, the decreased quality of output (P_2) by a quality inspector and the audible noise (P_3) by a maintenance engineer. Whenever proactive maintenance is desired, the P-F interval (i.e. the interval between the first signal indicating a possible degradation and the functional failure, see Fig. 2) can be used to determine the optimal inspection interval for periodically measured conditions.

Three observations are important here. First, the earlier one detects the asset's degradation (which requires more sensitive monitoring equipment), the more time is available to schedule and prepare the maintenance. Second, in reality the degradation process is often much less 'smooth' than the function depicted in Fig. 2

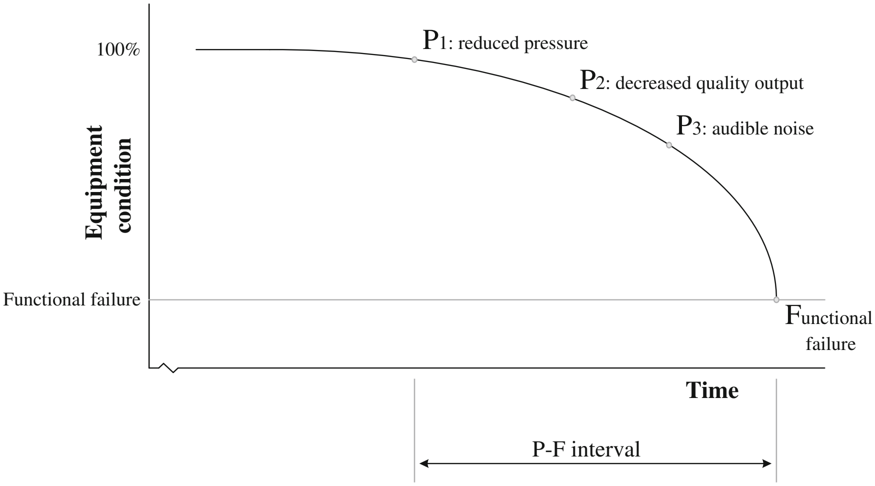

Fig. 2 P-F curve

and the actual timing of the functional failure might be earlier or (much) later than predicted (partly due to the fact that most machines have multiple failure modes). Third, accurately predicting the downtime of a complete unit (i.e., a system of connected machines) requires predictions about each (non-redundant) equipment's failure timing and is therefore in many cases (very) hard.

In essence every CBM program consists of three key steps (Jardine et al. 2006): (1) data acquisition, (2) data processing, and (3) maintenance decision-making. Data acquisition is the process of collecting and storing useful information, such as process and event data, preferably in a centrally accessible system. Before the data can be analysed with a variety of models and algorithms (for a review, see Jardine et al. 2006), the data should be cleaned, involving the removal of human entry errors and accounting for irregularities arising by start-ups and sensor faults. Finally, the techniques for maintenance decision support can be divided in either of two categories: diagnosis and prognosis. Fault diagnostics focuses on detection (i.e., whether something goes wrong), isolation (i.e., where it goes wrong) and identification (i.e., what goes wrong) of faults when they occur. Prognostics on the other hand deals with fault prediction before it occurs, providing an estimation of either the remaining useful life time or the probability that the equipment operates faultlessly until the next inspection (thereby determining the condition monitoring interval).

2.2 CBM in the Process Industry

The process industries are industries in which the primary production processes are either continuous or occur on repeated batches, such as the food, chemical and pharmaceutical industries. In the pilot study we have mainly focused on the chemical-, refinery and steelmaking industries, which are characterized by large multinational asset owners, high capital investments, complex processes within complex installations and high financial and safety risks connected with breakdown. Therefore the maintenance function is of crucial importance.

At the same time, most of the processes in these industries are continuous, which limits the ability to inspect the equipment, and dynamic, which makes it harder to analyse trends. Since a large portion of the equipment is custom-made and every context is slightly different, data gathered from one unit is not directly transferable to other units. Also, because most assets have a relatively long life-span and are replaced preventively before breakdown, limited failure data is available. Furthermore, a trend of outsourcing of specialized maintenance activities has led to the dispersion of data and expertise (Garg and Deshmukh 2006; Tsang et al. 2006) and increased the need for collaboration and coordination to minimize downtime.

Some trends relevant to maintenance are worth mentioning as well. Over the years the governmental and media attention on these industries has risen, fueled by several incidents all around the world (in which people were fatally wounded and major damage was inflicted to the environment). As a result the level of governmental and internal regulation has steadily increased, leading to the establishment of new procedures to 'guarantee' a quality of work and more bureaucracy. At the same time, the '*don't fix it when it ain't broken*' culture of the '90s turned gradually into a safety culture (Guldenmund 2000), in which new procedures had to safeguard against mistakes previously made. Although the once prevalent reactive culture is slowly diminishing, many of the asset owners are still primarily trained in performing corrective maintenance. A real "data culture" has not yet been established, although reliability engineers and asset management advocates are pushing in this direction.

Through conversations with several disciplines, we realized however that (somewhat to our surprise) a lot of data is gathered and stored already, though for different *purposes*. For example, Optimization continually monitors and stores the process data (input data, output data, operational data), Inspection periodically assesses the quality of the products and the integrity of the assets, and Maintenance generally records the failure data (failure mode). When combined these data contain a lot of information about the current functioning of the asset, common failure modes and trends, but to date this potential has remained largely untapped.

2.3 Adoption of CBM

In the current state the asset owners neither possess sufficient resources nor have sufficient knowledge to execute advanced prognostic CBM activities by themselves. Therefore asset owners have to make use of third parties for specialized condition-based maintenance tasks (Veldman et al. 2011). Three general stakeholders can be identified for the use and provision of CBM, which together have the capabilities to successfully set up a CBM program: the asset owner, the original equipment manufacturer (OEM), and maintenance contractors specialized in condition monitoring and/or data analysis. The potential values each of these stakeholders can derive from engaging in CBM are listed in Table 1. Recently OEM's have started exploiting remote monitoring tasks in their service offering and explored possibilities for 'leasing' their equipment, a trend called 'servitization' (Persona et al. 2007; Veldman et al. 2011).

Table 1 is based on Zaki and Neely's (2014) overview of values and benefits for condition monitoring services in asset-heavy organizations.

Although these potential values seem promising, it is important to realize that each of them can only be realised if the right processes are in place. Minimizing downtime for example requires the asset owner to accurately and timely predict the timing of an impending failure, schedule the maintenance (preferably during an already planned periodic maintenance stop), prepare the maintenance and execute the maintenance as planned. In the same line of reasoning, reducing safety hazards requires the asset's health assessment to be translated into adjusted operational guidelines and enhancing the product's quality requires the OEM to access and gather the data (in the right format), and to analyse and translate them into an improved product design.

Table 1 Value of using/providing CBM for the main stakeholders

User	Asset owner	–	Decrease total cost of ownership
		–	Maximize asset productivity
		–	Minimize downtime
		–	Extend effective life of asset
		–	Reduce long-term cost of maintenance
		–	Reduce safety hazards
		–	Facilitate certification and reports for legislative bodies
Provider	OEM	–	Grow spare parts and repairs business
		–	Strengthen relationship with asset owners
		–	Understand equipment behaviour
		–	Build dataset of equipment in different contexts
		–	Improve product quality
		–	Identify and leverage best practices
	Maintenance contractor	–	Increase the value of the contract
		–	Improve and leverage algorithms
		–	Gain access to data; pooling
		–	Collaborate with and learn from engineers

3 A Diagnostic Instrument

The factors explaining the relative absence of advanced CBM programs in the process industry can be grossly subdivided in one of three categories: technical, organizational and cultural. Given the current technological capabilities, we expect that a large fraction of the absence of CBM can be explained from (1) organizational and cultural factors, and (2) the interaction between the three categories (e.g., different technological designs synergize better with specific organizations and cultures).

The waterfall diagram, as depicted in Fig. 3, provides a diagnostic framework for systematically analysing the organisational and cultural barriers to CBM. The purpose is to uncover *why* a certain critical equipment is *not* maintained predictively; what contextual barriers hinder the successful execution of the CBM program? Only if all contextual barriers are dealt with, the CBM program can and will be executed successfully. Since we are primarily interested in the organisational impediments, we will not consider equipment that is impossible to maintain through CBM due to technological or legal impediments.

Reading from left to right, the first block contains all critical equipment for which CBM is technologically and legally possible. The block in the middle contains all critical equipment for which CBM is selected as the maintenance strategy (which is a subset of the requipment referred to in the first block) and for which the required CBM technology such as the monitoring equipment, a data platform and specialized prognostic software is in place. The final block on the right

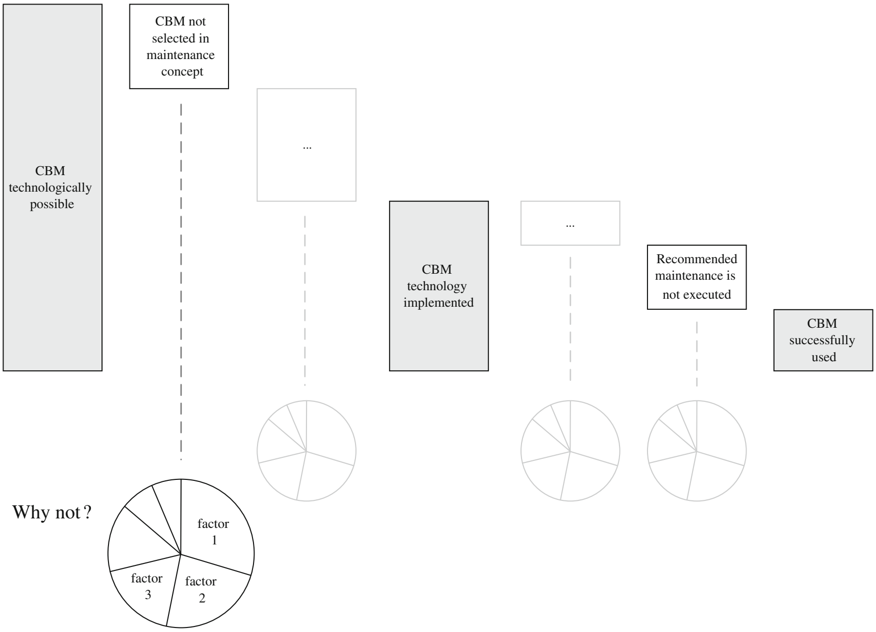

Fig. 3 Systematic (and truncated) presentation of organizational impediments to CBM

contains all critical equipment for which CBM is successfully implemented and used. (Note: although not shown in Fig. 3, we also keep a list of equipment for which CBM is unsuccessfully used, or delivers unsatisfactory results). Thus, some equipment can be found in all three blocks, while others ‘do not make it’ to the second or third block; these are stopped in between by a contextual barrier.

In between the three blocks are smaller rectangles, containing broad categories of contextual barriers to either the implementation or the execution of CBM programmes. These are for example “CBM is not in the maintenance concept” or “the recommended maintenance is not executed”. The final components of the waterfall diagram are the pie diagrams at the bottom, one for each broad category of contextual barriers. This is the part in which we are particularly interested; the pie diagram contains the arguments *why* a certain critical equipment could not pass the barrier. For example, CBM is not in the maintenance concept, because (1) this year’s budget did not allow it, (2) the equipment was identified as not critical, (3) the engineers responsible for the maintenance concept were not aware of the technological monitoring possibilities for this type of equipment, (4) the engineers responsible for the maintenance concept had a bad experience with previous CBM activities, etc.

4 Organizational Impediments

Lastly we report on several common organisational barriers, combining a theoretical and empirical perspective. These are selected based on their frequent occurrence in interviews in the pilot study. The aim of this section is to provide a first exploration of important contextual barriers to collaborative CBM activities and data sharing within the chemical-, refinery and steelmaking industry (and is not intended to be exhaustive). An effective (collaborative) condition-based maintenance program needs to be designed and managed in such a way that these barriers can be overcome.

4.1 Barriers to the Implementation of CBM

Most organizations in the process industry work with a so-called ‘maintenance concept’ (that specifies for each equipment what type of maintenance activities will be performed, as well as its frequency) and a ‘maintenance plan’ (that specifies how these activities will be performed; with what tools and by whom the data will be collected, processed and analysed). Thus, a CBM program is considered to be ‘implemented’ when CBM is selected in the maintenance concept, specified in the maintenance plan, when the tools are purchased and installed and when the engineers are trained to work with these tools. Within this context, multiple barriers have been identified that refrain CBM from being implemented.

The first draft of the maintenance concept is often constructed with a multidisciplinary team that consists of one or multiple reliability engineers, maintenance engineers and operators. Together this team decides on the maintenance strategy and control measures for each type of equipment, based on the criticality and the known failure modes and effects (FMEA) and (sometimes) an estimation of the Life-Cycle Costs (LCC). A potential *lack of knowledge of this team* is thus the first barrier and limiting factor. From observations and interviews we derive that its decisions are mainly driven by (1) expertise and experience of the engineers and (2) the attached manual of the OEM. However, we’ve also observed that (a) most of the engineers in the team have been working in the industry for a long time and are not familiar with state of the art condition monitoring techniques, (b) it requires a lot of time to comprehend the manual of the OEM, which often recommends more preventive maintenance than actually needed, (c) none of the teams contained condition monitoring specialists or data experts, and (d) the teams didn’t have access to an internal library of best practices or condition monitoring techniques.

Then, the initial draft of the maintenance concept is discussed with the maintenance managers (who are responsible for the maintenance budget), after which the maintenance manager decides what maintenance activities will be executed and how they will be performed (including what activities will be outsourced). These decisions are mainly based on the *yearly maintenance budget*, in which corrective and legally obliged preventive maintenance activities get priority. Since many of the advanced CBM techniques require a significant initial investment (for the purchasing and installation of sensors, the IT-infrastructure and data-processing software, the training of engineers and the validation of the prognostic models) and are only profitable in the long run, the maintenance manager is more likely to remove these activities from the maintenance concept (Marginson and McAulay 2008). Note that the initial investment is even larger for techniques which are still under development (TRL of 5, 6 or 7; such as big data analytics) and the returns are more uncertain. Unfortunately, most of the advanced CBM techniques to date are not yet readily applicable in practice, as the models lack specificity to the assets in question and many algorithms require a large amount of historic data, resulting in a long learning time (Peng et al. 2010). This is especially true for companies in the process industry that deal with dynamic processes (which makes it harder to develop accurate prognostic models) and custom-made assets, each operating in its own context (which limits the possibilities for leveraging prognostic models to similar assets).

Although these first organisational barriers are not exhaustive, they contain an important lesson: *people* decide what maintenance strategy will be adopted (and consequently design the CBM process, buy and install the monitoring equipment, etc.). We have limited mental capabilities, limited time and are susceptible to local incentives. Thus, any organisation that aims to adopt CBM on a larger scale should attempt to enable the involved people to make well-informed decisions and encourage them to make the decisions that are most profitable for the entire organisation.

A positive note: enablers. While discussing the barriers that hinder the implementation of CBM, the interviewees identified multiple enablers of the implementation process. The absence of these factors doesn't make it impossible to implement CBM, but the presence of these factors certainly speeds up the process. Some examples are:

- visionary managers that prioritize reliability over short-term profits and free up resources for innovation (e.g., time, money);
- engaged plant managers that believe in the potential of CBM;
- an internal knowledge team with condition monitoring specialists and data experts;
- an internal knowledge base that captures best practices with proven technologies and contains an overview of the existing condition monitoring techniques (and for which type of equipment they are suited);
- standards for data collection and storage (based on for example the ISO 14.224 standard);
- a wall of fame, that spreads success stories of previous CBM activities, and;
- strategic partnerships with innovative OEMs or maintenance contractors (who share their knowledge, sell and use their tools, have built a trustful relationship over time and don't charge high initial investments).

4.2 Barriers to a Successful Execution of the CBM Program

The next stage is the execution of the CBM program, which can be organized in many different ways. In essence three sub processes can be identified: (1) the condition monitoring process, in which the data requirements are determined, after which the data is (continuously or periodically) monitored and stored, (2) the condition-based maintenance process, in which the data is processed and analysed, the equipment's remaining life-span is predicted, proactive maintenance decisions are made and the maintenance is scheduled and executed, and (3) the failure elimination process, in which recurring failures are eliminated through root-cause analyses (RCAs) and consequent changes in procedures or the equipment's design. How these processes are designed depends on the requirements of the CBM program, the in-house knowledge and capabilities and the availability of capable partners. Note that the value and predictive power of the CBM program diminishes significantly if the effort into one of the process' steps is abandoned at any moment in time (Braaksma et al. 2011).

Due to the specificity of the techniques and knowledge needed for effective condition-based maintenance in the process industry, effective condition-based maintenance activities often require the asset owner, the original equipment manufacturer (OEM) and specialized maintenance contractors to work together closely and share their data (Veldman et al. 2011), even though their *organisational incentives* to do so are initially *misaligned*. Within these complex, multi-party and multi-phased transactions, formal agreements as such are likely to be insufficient to solve the contracting problems (Henisz et al. 2012), as can be seen in Box 1.1.

Box 1.1 Asset owner and Maintenance contractor

Consider the case in which an asset owner has decided to outsource the condition monitoring and maintenance execution to a specific maintenance contractor. This scenario typically leads to multiple conflicts of interests. By nature, an asset owner benefits from a maximized uptime of the asset and minimized maintenance costs, while the maintenance contractor generally benefits from more maintenance actions. Also the question arises who is responsible for breakdowns and additional costs: the party performing the maintenance or the party operating the asset?

Clever design of the formal agreements can to some extent align the interests of both parties, but the asset owner will always remain legally responsible for safety and environmental incidents.

Failure to recognise and acknowledge these differences of interests is likely to ultimately result in abandonment of the CBM program. Therefore the organisation of any successful CBM program has to be designed in such a way that the interests of these direct stakeholders are either (1) aligned, or (2) met separately (Parmigiani and Rivera-Santos 2011). In case the interests cannot be aligned perfectly, bonding, collaborative problem solving, open communication and trust (relational contracting; Ring and Van de Ven 1994) may complement the formal agreements, such that the collaboration (and the CBM program) is sustained and strengthened over time (see e.g., Autry and Golicic 2010; Krishnan et al. 2006; Narayandas and Rangan 2007). For improving collaboration under these difficult conditions the concept of 'partnering' has been developed and implemented, in particular in the construction industry (Gadde and Dubois 2010). Partnering emphasises trust building, transparency, and the construction of shared goals, and has been proposed also in the context of maintenance relationships (Olsson and Espling 2004). The relationship is strengthened by building value together, by engaging in inter-organisational learning processes (Akkermans et al. 2004; Laan et al. 2011) or by integrating the supply chain (Prajogo and Olhager 2012). Also building and maintaining understanding for each other's processes (with each new successor) enhances mutual trust and reduces conflicts (Akkermans et al. 2004; Johnston et al. 2004). That trust is essential for a successful CBM collaboration is underscored in the example in Box 1.2.

Box 1.2 Maintenance scoping by a maintenance contractor
Instead of hiring and training an internal vibration monitoring specialist, some asset owners have decided to outsource the periodic vibration analyses to a specialized maintenance contractor. In discussion with the vibration expert, he identified that he adds value for his clients if and only if:

- he has access to the client's data (process data, machine archive, etc.) and is allowed to do a visual inspection upfront
- he has the opportunity to use high-end tools (i.e., no minimal budget) and is allocated the time to perform extensive analyses
- the internal knowledge and experience (of the engineers from the maintenance contractor) is up to date and they maintain a customer-oriented attitude
- (most importantly,) the client trust his recommendations. According to him, this trust is a product of the client's trust in the tool, the maintenance contractor and (mainly) in the vibration expert himself. Without trust, the client is very unlikely to perform the recommended actions.

Additional challenges with the successful execution of a CBM program are (1) the continuous collection and sharing of high-quality data, which requires time from engineers who do not themselves directly benefit from the data collection, (2) the recognition of weak and ambiguous signals, which requires sensitive monitoring equipment and well-trained engineers, (3) the processing and analysis of large piles of data, which requires fast computers, decision-support tools and well-trained engineers (data-overload impending), (4) proactive and collaborative decision-making, which requires well-trained engineers to get together and invest time (without a direct sense of emergency), (5) the increased variability in the plant's maintenance (and production) planning, which is particularly bothersome if the maintenance is executed by external maintenance contractors, etc. All of these activities require time from the engineers and well-structured processes which are challenging when spanning multiple departments and even more challenging when spanning multiple organisations (Paulraj et al. 2008). Moreover, many asset owners have indicated that they struggle with measuring and proving that the CBM program is actually an improvement over the previous maintenance policy, since "we'll never know what would have happened to the equipment if we hadn't preventively maintained it" (Carnero 2006). This puts even more pressure on inter-organisational relationships, as can be seen in the final example in Box 1.3.

Box 1.3 External monitoring

The developments in remote monitoring technology gave rise to contractors that offer to 'monitor the health of your asset' and predict impending failures with clever algorithms. Although the services of these specialized monitoring organisations seems promising, it turned out to be hard to establish such functions in the past. In one representative example, the contractor was challenged with:

1. *providing valid alarms*. Although the contractor was specialized in data processing, they lacked the specific engineering and situational knowledge to determine all failure mechanisms and relevant indicators (a list of 'usual suspects' was the best possible result);
2. *providing valid alarms, in time*. Many of the alarms given were 'too late' (i.e., the issues were already spotted by an operator or a maintenance engineer), limiting the direct added value of the contractor, and;
3. *proving your worth, continuously*. The contractor had to prove his added value year after year, particularly when previous stakeholders of the collaboration changed positions within the organisation;

Recently, the contract was terminated after 5 years of collaboration, right after the former manager of the contract moved to a different position.

5 Conclusion

In this chapter we have discussed the condition-based maintenance strategy and its implication in the process industry and proposed a diagnostic instrument for identifying the organizational impediments to CBM. Although considerable research effort has been expended on developing the technical aspects of CBM programs, our pilot study indicates that many firms in the process industry struggle with systematically employing CBM activities in general and prognostic CBM approaches in particular. Therefore this research aims to contribute to our understanding of the contextual barriers that hinder organisations to adopt condition-based maintenance programs to improve their asset management. We hope to contribute to the establishment of a safe, more sustainable future, in which advanced maintenance approaches enhance the machines' uptime and reduce unnecessary waste. We believe that this is only possible by taking the evident organisational challenges into account and therefore encourage both scholars and engineers to further explore the organisational conditions that enable the successful execution of collaborative CBM activities.

As a final note; while data gathering can be done by machines, analytics is about people (Zaki and Neely 2014). No matter how advanced the technologies, transforming data into information and information into knowledge and action requires an equal investment in the people handling these technologies.

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