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van de Kerkhof, R.M.; Akkermans, Henk; Noorderhaven, Niels

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CBM Maturity Model (CBM^3) for asset owners in the process industry

Roland van de Kerkhof (r.m.vdkerkhof@tilburguniversity.edu)
Tilburg School of Economics and Management, Tilburg University

Henk Akkermans
Tilburg School of Economics and Management, Tilburg University

Niels Noorderhaven
Tilburg School of Economics and Management, Tilburg University

Abstract

While the attention for Condition-Based Maintenance (CBM) has been growing, both academically and in practice, many organizations are struggling with the adoption and deployment of advanced condition monitoring technologies. The purpose of this research is to develop a CBM Maturity Model and CBM Maturity Assessment that can aid asset owners and maintenance managers in the development of their CBM practices. The maturity model, assessment instrument and assessment procedure have been developed with and tested at two large asset owners in the Dutch process industry following the design science methodology.

Keywords: Condition-Based Maintenance, Maturity model

Introduction

Condition-Based Maintenance (CBM) is one of the means to optimize the utilization and useful lifetime of our current asset base and thereby, to make our industries more sustainable. CBM aims to predict future malfunction of an asset by monitoring several conditions (e.g., temperature, vibrations), so maintenance can be executed at "just the right time" (Jardine, Lin & Banjevic, 2006).

In recent surveys in northwest Europe up to 60% of organizations indicated they have concrete plans or intentions to use predictive maintenance in the near future (PwC & Mainnovation, 2018). In those same surveys, only 11% of organizations indicated they are already employing predictive maintenance practices. In reality, many organizations are struggling with adopting advanced condition monitoring (CM) technologies (PwC & Mainnovation, 2018) and, when adopted, with fully diffusing these technologies throughout the organisation (Van de Kerkhof, Akkermans & Noorderhaven, 2016). Unfortunately, there is a lack of relevant, actionable guidance for industrial maintenance organizations to meet their maintenance ambitions (Bokrantz, Skoogh, Berlin & Stahre, 2017), as well as a lack of understanding of what optimal usage of CBM entails for maintenance organizations (Tiddens, 2018).

Maturity models are helpful tools for addressing these issues (Wendler et al., 2012). Based on the assumption of predictable patterns, maturity models represent theories about how organizational capabilities evolve in a stage-by-stage manner along an anticipated, desired, or logical maturation path (Pöppelbuß & Röglinger, 2011). In general, the term 'maturity' refers to a state of being complete, perfect, or ready (Schumacher et al., 2016). The main purpose of maturity models is to help an organization or entity reach a more sophisticated maturity level (Mittal et al., 2018), by enabling the organization to assess the as-is situation, by picturing the desired 'final' stage of maturity and by providing guidance on how to improve (Wendler et al., 2012).

Although the maturity concept emerged out of quality management (Shewhart, 1931), the first instruments with maturity stages building on each other were developed by Crosby (1979: quality management process maturity grid) and Nolan (1979: maturation of data processing). The development of maturity models really took off since the Software Engineering Institute introduced the Capability Maturity Model (Paulk, Curtis, Chrissis & Weber, 1993). Since then, the maturity concept has been widely applied across many domains, such as software development (e.g., Haase, 1996; Subramanian, Jiang & Klein, 2007), project management (e.g., Kerzner, 2002; Hilson, 2003; Pennypacker & Grant, 2003), knowledge management (e.g., Hsieh, Lin & Lin, 2009; Khatibian, Hasan & Abedi, 2010), and many more (see Wendler et al., 2012 for an overview). Recently some maturity models have also been developed in fields that are related to CBM, such as digitalized manufacturing (e.g., Mittal, Khan, Romero & Wuest, 2018), big data (e.g., Comuzzi & Patel, 2016), asset management (The IAM, 2016), and reliability-centred maintenance (Hauge & Mercier, 2003). Yet, an actual CBM maturity model is still missing.

In this paper we aim to develop a descriptive maturity model (Pöppelbuß & Röglinger, 2011) for the deployment of Condition-Based Maintenance by (the maintenance organizations of) asset owners in the process industry. The main purpose of this descriptive maturity model is to enable asset owners and their maintenance managers to assess their current practices and capabilities. The outcomes of these assessments can then be used to create improvement plans. To achieve these objectives, the maturity model (the reference model) is translated into an assessment instrument and accompanied by an assessment procedure. Hereby we answer the call for relevant, actionable guidance for industrial maintenance organizations (Bokrantz et al., 2017).

Methodology

We have adopted the design science paradigm (Hevner, March, Park & Ram, 2004) for developing and evaluating the maturity model, the assessment instrument and the assessment procedure. Typically, design science research seeks to create innovative artefacts that are useful for coping with human and organizational challenges by following an iterative process of development and testing (Hevner et al., 2004). Our methodology, as depicted in Table 1, is based on the procedure of Becker et al. (2009), who have translated the design science principles into a dedicated procedure for the development of maturity models. Following the recommendations of Wendler et al. (2012), we have applied a combination of multiple methods in different research states to evaluate the maturity model's completeness, validity, usefulness and ease of use. Specifically, the study has been performed in three consecutive phases: (1) scoping, (2) development and testing of the maturity model, and (3) development and testing of the assessment instrument and assessment procedure.

Table 1 – Methodology

Phase	Activity	How
1. Scope	a. Identify need	Based on literature review and practitioners' request
	b. Define problem, design requirements and development strategy of maturity model	Based on focus group session with future users and domain experts
2. Iterative development of maturity model	a. Design first version of maturity model	Based on literature review and interviews with domain experts
	b. Evaluate first version of maturity model	Domain expert evaluation: focus groups and in-depth interviews
	c. Design second version of maturity model	Incorporate feedback from first evaluation
	d. Evaluate second version of maturity model	Domain expert evaluation: survey
3. Development of assessment method	a. Design assessment instrument	Based on maturity assessment instruments in industry
	b. Design assessment procedure	Based on maturity assessment procedures in industry
	c. Evaluate assessment instrument & procedure	Practical setting evaluation: test at multiple facilities and survey participants

The maturity model and assessment method are developed in cooperation with two large asset owners in the Dutch process industry: Tata Steel and BP. Seeing practice impact in new ways, we followed a leading pathway (Simsek, Bansal, Shaw, Heugens & Smith, 2018), working with Tata Steel's central domain expert to establish the research design, as well as the first version of the maturity model, the assessment instrument and the assessment procedure. Most focus group sessions, as well as the practical setting evaluation, have been held with domain experts from these organizations. To safeguard the external validity of the developed maturity model, additional focus group sessions have been held with domain experts from other asset owners and knowledge institutes in the Netherlands.

Scope

In the first phase, scoping, we evaluated the practical and theoretical need for the development of a new maturity model. The theoretical need was assessed by identifying calls for research and guidelines (Bokrantz et al., 2017; Tiddens, 2018) and by reviewing existing maturity models – no maturity model yet existed for the usage of CBM. The practical need was assessed by interviewing managers and domain experts from the organizations involved in our research program, asking whether or not and how a maturity model would aid them in improving their CBM practices. The results from both endeavours confirmed the need for a CBM maturity model.

Then a focus group session was held with maturity model experts and domain experts from Tata Steel to define the problem, the design requirements, the development strategy, and the future user group.

Development of maturity model

The maturity model has been developed in four consecutive steps. First, we have reviewed the structure and content of existing and accessible maturity models – from scientific journals, conference proceedings, and knowledge institutes, as well as Tata Steel's prior developed maturity models – to identify what structure best fits the application of CBM by asset owners and to ensure a structural fit with Tata Steel's maintenance related maturity models. The content of the maturity model was developed first and foremost by studying scientific literature and reports, books and guidelines from knowledge institutes, and by reviewing interviews with domain experts that had been held before within the research program (139 at Tata Steel, 154 at BP, 32 with other asset owners and service providers). The few gaps that initially remained were closed by performing (5) additional interviews with domain experts.

After the first version of the maturity model had been developed, 12 focus group sessions were scheduled with domain experts from the two asset owners and two knowledge institutes (see Table 2). The participants for the sessions were selected as such that, as a whole, their knowledge covered all maintenance disciplines and all types of CM technologies, and the key stakeholders within the organisation were represented (maintenance, operations, projects, IT, R&D).

During these sessions participants were asked to evaluate the maturity levels (would you add/remove levels, would you adjust the description of levels? If yes, why and what/how?), the categories (would you add/remove/adjust categories? If yes, why and what/how?), and the description of each category-level combination (would you adjust the description? If yes, why and how?), based on the evaluation template of Salah et al. (2014). All sessions were recorded and transcribed.

Table 2 – Focus group sessions

	Focus groups	**Total participants**	**Length of each focus group**
Tata Steel	3	17	1-2 hours
BP	7	18	1-2.5 hours
Other	2	4	1.5 hours

After the sessions the written feedback was aggregated per maturity level, category and description. All feedback that was considered relevant was used to adapt the first version of the maturity model into the second version. This was done primarily by the main researcher, in accordance with Tata Steel's central domain expert.

As the final step, a survey was sent to all participants of the focus group sessions to evaluate the maturity model's relevance (the elements are relevant to CBM maturity), comprehensiveness (all elements are included), accuracy (elements are correctly assigned to maturity levels) and mutual exclusiveness (elements are clearly distinct), following the evaluation format of Salah et al. (2014).

Development of assessment method

The assessment method consists of an assessment instrument and an assessment procedure that describes how the instrument should be used. The design specifications for both were determined in focus group sessions with future users at Tata Steel and BP. As Tata Steel's central asset management department had over 10 years of experience with developing maturity models and performing maturity assessments, we could build on their instruments and procedures for designing the CBM Maturity Assessment.

After development, two assessments were performed to test the usefulness and ease of use of the assessment instrument and procedure, one at Tata Steel and one at BP. In these assessments we followed the prescribed procedure. Both sessions lasted 2 hours. At the end of each session, the participants received a survey to evaluate the usefulness and ease of use of the assessment instrument and procedure, following the evaluation format of Salah et al. (2014).

Findings

We define CBM maturity as a state in which a 'facility' (an organizational subunit) makes optimal usage of CBM. In particular, when a facility has reached CBM maturity, the facility applies the optimal combination of CM technologies (that are currently available) to all assets that could benefit from CBM and optimally uses the information provided by these CM technologies.

According to the domain experts, a facility is the most meaningful unit of analysis in the process industry: for most sites the entire production process is too large to manage by a single production and maintenance department, thus the organization is divided into smaller teams, each responsible for a subset of the asset base. A facility is the organizational unit that is responsible for managing their subset of the asset base, such as a production line or cracker unit. Each facility has their own production teams, maintenance team(s) and management.

It should be noted that the exact features of the optimal state of a facility are likely to differ per facility and change over time. First, the applicability and usefulness of CBM is dependent upon the characteristics of the assets (e.g., degradation mechanisms) and the production process (e.g., consequences of breakdown). Secondly, new CM technologies and the capabilities of existing CM technologies are still being developed. To stay mature, the organization thus needs to keep track of changes in their asset base and innovations in CM technologies, and adapt their CM technology portfolio accordingly.

CBM Maturity Model

In our observations of CBM practices and in line with maintenance (e.g., Macchi & Fumagalli, 2013; Hauge & Mercier, 2003) and asset management maturity models (e.g., The IAM, 2016; Volker, Van der Lei & Ligtvoet, 2011), we identified five logical states of using CBM. In the first state, CBM is not used, for example because assets are not maintained. In the second state, CBM is used reactively. None of the assets are monitored structurally, but when an operator or a maintenance technician encounters an anomaly with an asset, an external CM service provider is asked to properly investigate the asset in order to better prepare maintenance activities.

In the third state, CBM is used structurally and planned, mainly to improve the efficiency of maintenance. In this state, the organization has built some internal capabilities with easy-to-learn and easy-to-use CM technologies (Nicholas, 2016) and uses CBM to reduce corrective and periodic maintenance activities.

In the fourth state, CBM is used proactively to increase the reliability and productivity of (mainly important) assets. Here the organization has decided to invest more heavily in CBM and has started experimenting with multiple hard-to-learn, hard-to-use and specific CM technologies, for example in a dedicated Condition Monitoring Program. Better equipped CM specialists have become important partners in reliability improvement initiatives, as insight into the assets' condition aids in identifying why the assets failed. In this state, the higher costs for CBM are justified by even higher gains from reliability and asset productivity improvements.

In the fifth state, CBM is used optimally, or World Class, to increase the value realised from the asset base. Here the facility has ramped up all successful CM technologies, while maintaining the exploration for new CM technologies. The facility has embraced asset management (as described in ISO 55.000) and information about the assets' condition has become an essential component of many asset management decision processes, including optimization of production, inventory management, project prioritization, and designing new assets. Because processes become more stable and predictable now, the facility starts actively reducing buffers, such as redundancy and stocks. To facilitate this, CM teams have gained a central position in the organization and have become well-connected to knowledge institutes, equipment and CM technology manufacturers and specialist CM service providers.

Through our studying of the diffusion of CBM practices (Van de Kerkhof et al., 2016), a literature review and additional interviews at Tata Steel and BP, we distilled twelve categories of elements that are required to perform CBM successfully. These categories describe characteristics of the technology, the organization or the people involved.

In the technological realm, five categories were relevant. First, the category *CM technologies* describes what CM technologies are used by the organization and how they are used, starting off with ad hoc and infrequent inspections and moving towards high-frequent and automated measurements. Second, the category *Assets* describes to what assets CBM is applied, starting with the assets that are easy to monitor, but incorporating more and more assets for which the highest value of monitoring can be attained towards higher maturity levels. The third category, *Decisions*, describes what decisions are (also) based on information about the assets' condition, starting with maintenance decisions only, but moving gradually towards other asset management decisions as well. The fourth category, *Data*, describes what data are needed to be able to perform the CM analyses and make the decisions thereafter, including for example master data, financial data, failure data, production data, and environmental data. The fifth and last technological category, *IT-infrastructure*, describes the characteristics of the IT-infrastructure, starting with stand-alone systems for each CM technology, but moving towards a standardized IT-infrastructure that enables smooth ramping up of successful CM technologies.

Also in the organizational realm, we identified five main categories. The category *Strategy and goals* describes the strategy of the organization (or facility) and the main KPIs for the facility, moving from minimizing maintenance costs to improving reliability, production and the value realised from assets. The category *Structure* describes how the monitoring is organized, first relying mostly on external CM service providers, but moving towards a structure in which centralized and decentralized CM teams work in close cooperation with specialist external CM service providers. The category *Budget and capacity* describes what budgets and capacities are reserved for condition monitoring, CBM, experimenting with new CM technologies and maintaining adopted CM technologies, moving from no or very limited budget and capacity to structural and dedicated budget and capacity for each of these purposes. The category *Processes and documentation* describes the processes and documentation that are used for the CBM practices, gradually defining processes and documentation for monitoring and decision-making, for experimenting with and implementing new CM technologies, and for evaluating and managing the CM technology portfolio. Important documentation includes standard CM reports, maintenance concepts, CM concepts (how an asset type is monitored), a list of critical assets, and an overview of what CM technologies are applied to each asset. The final organizational category, *Governance*, describes how the CBM practices are governed, including defined procedures, specified acceptance criteria, certification of CM specialists, formal agreements about data rights and responsibilities, and obligations for project managers to consider CM technologies in their projects.

Finally, we classified two categories that focus on the characteristics of the people involved in the CBM practices. First, the *Knowledge, skills and abilities* of those people is one of the key determinants of the success of a CBM practice. Specifically, domain knowledge about the asset and its (production) context – what is 'normal', how can it fail, what influences degradation, how does degradation influence production – and proficiency with CM technologies are determining the quality of analyses and decisions. Second, the *Culture* of the organization has to match the CBM practices for the practice to be sustainable. Typically organizations progress from a firefighting culture towards a bureaucratic culture, after which the organization can transition to a reliability and asset management culture.

In addition, multiple maintenance managers indicated during the domain expert evaluation that the rationale was lacking in the first version of the CBM Maturity Model: "why should our facility aim pursuing a higher maturity level?" Therefore we added one category to the maturity model: *Value*. This category describes the primary gains that can be realised at each maturity level, going from better and more efficient maintenance to increased productivity and return on assets. The design for the CBM Maturity Model is shown in Table 3.

Table 3 – CBM Maturity Model design

		Level 1: No CBM	**Level 2: Reactiv e CBM**	**Level 3: Planned CBM**	**Level 4: Proacti ve CBM**	**Level 5: World Class CBM**
Value	Value					
Technology	CM technologies					
	Assets					
	Decisions					
	Data					
	IT-infrastructure					
Organization	Strategy & goals					
	Structure					
	Budget & capacity					
	Processes & documentation					
	Governance					
People	Knowledge, skills & abilities					
	Culture					

CBM Maturity Assessment

The assessment instrument and procedure are designed as such that they can be integrated in Tata Steel's assessment program. This program focuses on facilitated and self-assessments to aid facilities in improving their asset management practices. Specifically, the assessments help in understanding how well a facility performs certain asset management practices, in identifying gaps, in creating improvement plans, and in transferring knowledge between facilities.

The design of the assessment instrument is displayed in Figure 1. For each of the twelve categories, the assessment group can assign the best fitting maturity level (score and description). When selecting a score, the group has to present evidence that supports their choice, such as data or references to documentation, interviews or observations. If the maturity level's description doesn't perfectly match their current situation, they can outline the differences in the comments. The scores are automatically converted into a vertical spider diagram, making it easy to see what categories are at a lower-than-desired maturity level.

Category		Score	Description	Evidence of score	Comments with score
Technology	CM technologies	4			
	Assets	3			
	Decision	3			
	Data	3			
	IT-infrastructure	4			
Organisation	Strategy & goals	2			
	Structure	3			
	Budget & capacity	2			
	Processes & documentation	3			
	Governance	2			
People	Knowledge, skills & abilities	3			
	Culture	3			

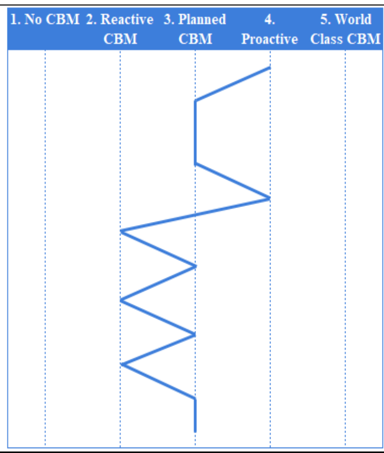

Figure 1 – Design CBM Maturity Assessment instrument

In the practical setting evaluation it was confirmed that the assessment can best be performed with an independent facilitator who understands the CBM Maturity Model, clarifies descriptions with examples, and challenges the participants to get a shared and correct view of the situation.

The assessment procedure consists of six steps. First, the facilitator and the facility's initiator (often a management position) agree on a plan for carrying out the assessment, including the date, who is going to participate, and whether or not a preparatory session is required. If so, a brief CBM awareness session is held for the assessment's participants two weeks prior to the assessment. Then, secondly, the CBM Maturity Model is shared with the participants about one week prior to the assessment. This gets the participants thinking about the topic and their maturity already, and it speeds up the introduction during the assessment session.

The third step is the assessment itself, guided by the facilitator. The ambition is to get a common shared view on the maturity of each element in the assessment. If the group does not reach a consensus or the score is in between two scores, the lowest score is to be selected. In these cases, the comments box is used to explain the score. It was noted by the practitioners that low scores are at least as valuable as high scores, since these provide opportunities for improvement. These scores were supported by comments as well, so that it was easier to define the steps to improve the maturity in the next step.

In the fourth step, the facility's management translates the assessment results into an improvement plan. At this stage it is sufficient to have a prioritised list of improvement areas, rather than a detailed plan. If needed, the facilitator can support in this step, but the facility's management should take responsibility for drafting and executing the improvement plan. Then, in the fifth step, the facilitator and facility's management decide upon a realistic timescale for re-assessing, dependent on the planned improvement process.

Lastly, after each assessment process, the facilitator reviews the assessment process and communicates learning points to the people who were involved in conducting the assessment and to the people who will be involved in setting up and facilitating future assessment sessions.

Conclusion

The CBM Maturity Model provides scholars with more insight into the multi-faceted nature of CBM and, when used by practitioners, shows the areas asset owners have most difficulties with. This can guide future (practice-oriented) research. Managers from asset owners can use the CBM Maturity Model's assessment instrument and assessment procedure to assess their as-is situation and derive opportunities for improvement.

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