



<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper presented at *22nd International Conference on Production Research, ICPR 2013; Parana; Brazil; 28 July 2013 through 1 August 2013.*

Citation for the original published paper:

Rastegari, A., Salonen, A., Bengtsson, M., Wiktorsson, M. (2013)
CONDITION BASED MAINTENANCE IN MANUFACTURING INDUSTRIES:
INTRODUCING CURRENT INDUSTRIAL PRACTICE AND CHALLENGES.
In: *22nd International Conference on Production Research, ICPR 2013*

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:mdh:diva-23287>

CONDITION BASED MAINTENANCE IN MANUFACTURING INDUSTRIES: INTRODUCING CURRENT INDUSTRIAL PRACTICE AND CHALLENGES

Ali Rastegari^{1,2}, Antti Salonen², Marcus Bengtsson², Magnus Wiktorsson²

¹Operation technical support, Volvo GTO, SE-731 80, Köping, Sweden

²School of Innovation, Design and Engineering, Mälardalen University, Box 325, 631 05, Eskilstuna, Sweden

Abstract

This paper presents an introductory review of CBM practice applied in manufacturing industry, focusing the technical constituents within condition monitoring. The empirical base for the study is a case study of two major manufacturing sites in Sweden, complemented with a brief benchmark of data from two reference manufacturing sites from France and Brazil. The data from the main studies were collected by interviews and document analysis. The result indicates that there is a wide range within current practice of applying CBM. The implementations are dependent on process type (machining, assembly or heat treatment) and product type. By analysing the empirical data, gaps and challenges for implementing CBM in industry are presented, primarily focusing condition monitoring within manufacturing industry. The paper concludes with a discussion on possible future trends and research areas, needed to increase the industrial use of CBM.

Keywords:

Condition based maintenance, Condition monitoring, Preventive maintenance

1 INTRODUCTION

In order to stay competitive, manufacturing companies need to continuously increase the effectiveness and efficiency of their production processes. Further, introducing lean manufacturing increases the concern about equipment availability. As a result, the demand for effective maintenance is significantly increased. Well-performed maintenance involves few corrective maintenance actions while performing as little preventive maintenance as possible [1].

During the past decades, strategies and concepts have evolved for support this ideal situation. One of these is condition based maintenance (CBM). Research in the CBM area has been of major interest from researchers over the years, resulting in a plethora of technical, organizational and process-based enabling constituents. The practical implementation of advanced maintenance technologies, such as CBM, in manufacturing industry is however more scarce [2].

The objective of this paper is to present an introductory review of CBM practice applied in industry, at this stage focusing the technical constituents within condition monitoring and its implementation.

2 PRODUCTION MAINTENANCE

The technical, administrative and managerial areas of maintenance are defined in e.g. the Swedish standard SS-EN 13306 [3]. Maintenance is here defined as “the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (function or a combination of functions of an item which are considered necessary to provide a given service).” [3], (p.7).

Khairy [4] describes the key objective of maintenance as “total asset life cycle optimization which means maximizing the availability and reliability of the assets and equipment to produce the desired quantity of products, with the required quality specifications, in a timely manner. Obviously, this objective must be attained in a cost-

effective way and in accordance with environmental and safety regulation.” (p.22).

2.1 Maintenance types

In order to assure this maximum availability and reliability of an asset, maintenance may be performed according to various actions. One classification of maintenance types and their relationship in the Swedish standard SS-EN 13306 [3], as shown in Figure 1.

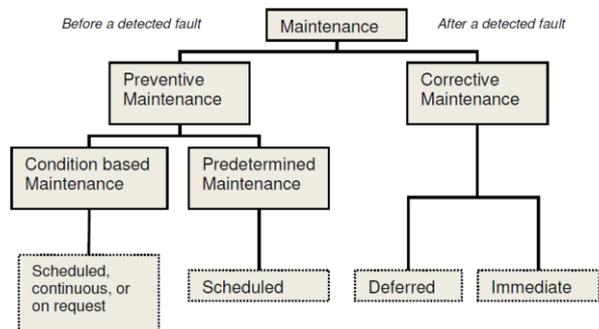


Figure 1: Overview of different maintenance types [3], (p.23)

Maintenance is in Figure 1 divided into two main actions: corrective maintenance (or break down maintenance), and preventive maintenance (PM), with PM being predetermined (periodic) maintenance or condition based maintenance (CBM).

2.2 Maintenance concepts

Various operational concepts have been developed to increase the effectiveness of maintenance and focus on the maintenance activities. The two more common concepts are Reliability Centred Maintenance (RCM), and Total Productive Maintenance (TPM).

- RCM: Moubray [5] defines RCM as “...a process used to determine what must be done to ensure that any physical asset continues to do what its user wants it to do in its present operating context.” (p.7).

- TPM: a Japanese concept for maintenance. According to Nakajima [6], who introduced the concept, TPM may be defined as “*Productive maintenance involving total participation*” (p.10). Several explanations of the definition may be found in literature.

More recently, various attempts such as Smith and Hawkins [7] have been made to introduce a Lean Maintenance concept, but this is still not unanimously defined.

2.3 Condition based maintenance

Condition based maintenance (or predictive maintenance) is carried out “...*following a forecast derived from the analysis and evaluation of significant parameters of the condition of the item.*” [8], (p.19). Condition-based maintenance is based on management and decisions through information collected through condition monitoring. Previous reviews describe CBM as consisting of three main steps: data acquisition, data processing and maintenance decision-making [2]. Swedish standard [3] defines condition based maintenance as “*preventive maintenance based on performance and/or parameter monitoring and the subsequent actions.*” (p.15). Performance and parameter monitoring may be scheduled, on-request or continuous.

For CBM, the core part is condition monitoring, which can be performed using various approaches and utilizing different levels of technology [2], and as presented in Figure 2. Monitoring is defined as: “*Activity performed either manually or automatically, intended to observe the actual state of an item.*” [3], (p.16). In on-line (or real-time) monitoring, one continuously monitors a machine and triggers a warning alarm whenever something wrong is detected. But two limitations of on-line monitoring are: (i) it is often expensive and (ii) to continuously monitor raw signals with noise produces inaccurate diagnostics information. In comparison, periodic monitoring is used due to its low cost and providing more accurate diagnostics using filtered and/or processed data. But, the risk of using periodic monitoring is the possibility of missing some failure events that occur between successive inspections [9].

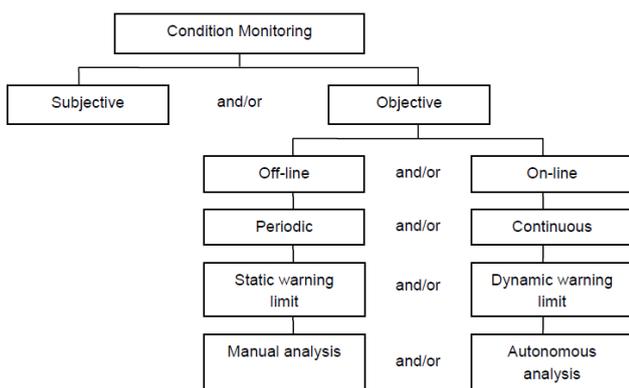


Figure 2: Different approaches to condition monitoring [10], (p.6)

In condition monitoring, the information must be obtained externally about internal effects while the machines are in operation [11]. According to Randall [11], the two principal techniques for obtaining information about internal conditions are vibration analysis and lubricant analysis. Machines are always generating vibrations. Many of these vibrations are linked to periodic events in the machine’s operation, such as rotating shafts, meshing gear teeth, rotating electric fields etc. Some vibrations are from events

that are not entirely phase locked to shaft rotations, for instance combustion in engines. Other vibrations are linked to fluid flow, as in pumps and gas turbines, and these also have particular or unique characteristics. A machine in standard condition has a certain vibration signature and fault growth changes that signature in a way that can be linked to the fault.

The lubricant also expresses information from the inside to the outside of operating machines in the form of wear particles, chemical contaminants etc. Its use is mainly confined to circulating oil lubricating systems. Moreover, some analysis can be carried out on grease lubricants [11].

For certain types of machines, performance analysis such as stage efficiency is an effective way to determine whether a machine is functioning correctly. Thermography is another technique. Sensitive instruments are presented for remotely measuring temperature changes in comparison with a standard condition. Thermography can be used principally in quasi static situations, such as electrical switchboards to detect local hot spots, and to detect faulty refractory linings in hot fluid containers [11].

2.4 Condition monitoring implementation in manufacturing industry

According to Walker [12], implementation of CBM strategy entails the use of condition monitoring technologies. Although, a large number of condition monitoring tools exist, they are scarcely ever used [12]. Walker [12] points out some of the more common reasons of why condition monitoring technologies are unsuccessful to stay effective in maintenance activities, including discrepancies in training, management direction, technology selection, user commitment and user competence.

Walker [12] proposes a process of condition monitoring development as an effective approach to present a CBM strategy to an industrial organization which includes:

1. Identify maintenance asset types by asset registration
2. Identify the ways in which these assets fail
3. Develop a process for evaluating these faults to see how they become apparent and whether they demonstrate symptoms which are detectable and measurable
4. Identify the appropriate techniques to detect fault symptoms to see if there are existing technologies that can detect and or measure such symptoms
5. Produce a selection process to determine the CBM strategy

The factors like the buying, training, application, data processing and management of condition monitoring technologies must be considered very wisely and a condition monitoring strategy developed before acquiring technologies [12].

3 METHOD AND MATERIAL

As concluded in the brief overview of CBM implementations in section 2, the practical implementation of advanced maintenance technologies, such as CBM, in industry is scarcely documented. As described in section 1, the objective of this paper is thus to present an introductory review of CBM practice applied in manufacturing industry.

The empirical base for the study is a case study of two major manufacturing sites in Sweden, complemented with a brief benchmark of data from reference manufacturing sites in France and Brazil. The data is collected by on-site interviews and document analysis from two manufacturing sites. Additional data from the two reference sites have been obtained by document analysis. Table 1 describes

the case companies, nature of study and data gathering techniques.

Table 1: Data sources

	Case company A	Case company B	Reference comp. C	Reference comp. D
Type of product	Engine	Gearbox	Engine	Engine
Volume per year	85 000	95 000	42 000	18 000
Processes	Casting, Machining and assembly	Machining, Heat treatment and Assembly	Stamping and Assembly	Machining, Assembly, Testing and Painting
Nature of study	Privileged observation	Non-participatory observation	Document analysis	Document analysis
Data sources	3 interviews with one maintenance manager and two CBM responsible people, Documents	3 interviews with two managers and one maintenance engineer, Documents	Forms and document	Forms and document

The interviews were semi-structured, with a set of predetermined questions listed in Table 2. In total were six interviews conducted on the two sites A and B. The interviewees were maintenance managers and maintenance engineers. Each interview lasted for about one hour. The interviews were recorded and notes were taken in order to strengthen the validity and reliability of the data. The interviews were transcribed by the interviewer.

Table 2: Interview guide

1. What is the role of CBM at your company? Do you see CBM as one important factor to implement?
2. Does maintenance management and top management see CBM strategically important factor in order to fulfil technical availability?
3. How is the competence level of your company in CBM? What is the reason of lacking knowledge?
4. How is the level of development of CBM tools at your company?
5. Do you have online condition monitoring? If yes, what type and in which areas (e.g.: machining)?
6. How do you choose the appropriate condition monitoring technique?
7. How do you communicate condition monitoring data?
8. What are the main challenges to implement CBM?
9. What are your future plans?

The data was collected in two formats:

- Interview protocol
- CBM implementation matrix.

The data analysis from the transcribed interviews was based on a clustering technique, where central themes were identified. The reason of selecting themes is to have a view on the current level of development in this area and making a guide for further research and development. Moreover, the matrixes were filled-in by the interviewer based on the answers from the respondents.

The following result presentation is focused on the CBM implementation matrixes from the case companies, while the later cross-case discussion is structured according to the key themes found in the interview protocols.

4 EMPIRICAL RESULTS

4.1 Case A

CBM has an important role at the company to provide management and maintenance responsible people with correct and reliable information. Without this information maintenance decisions are made by guessing. The maintenance responsible people have been guessing too much in the past and this experience makes the role of CBM even more important (e.g. important to understand where to invest money both in renovation process and early equipment management process while buying new equipment).

Previously, the management did not have a clear idea about CBM and therefore, CBM organization made efforts for a couple of years to convince the management that the company needs more reliable system for CBM, more resources and so on. Currently, the management is fully aware of the importance of CBM. In consequence, there is a good management support in the CBM area.

There was a CBM organization until five years ago, but after the downturn all the personnel except one were laid off. Then, for five years, the company had a CBM organization with only one person. Today, the company has just started up a new CBM organization with five employees. However, the company expresses an awareness that it takes a long time, many years, to be good in this area and before the paybacks can be expected. Moreover, the company believes that it is important to have a strategic maintenance to fulfil this long term goal.

The level of development of CBM tools is quite good and the company has invested in a lot of tools over the last two years (See table 3). They want to drive the development of tools. They worked hard to build the instruments and tools that are used for industry (many of these tools are made for laboratory or university environment and they are not effective in industry). The respondents argue that the tools must be fast and quicker. The company is trying to bring Bluetooth solutions to not have to be in the machine while measuring, because of safety.

The company has a few online systems in vibration monitoring, only in the foundry area for two critical places which are identified as essential for the foundry. These online systems work as safety systems, because it is dangerous for the staff to perform offline condition monitoring in this environment.

Table 3: CBM status map at case A

Product type	Process type	Production equipment type	Geometry analysis	Vibration analysis	Force control	Temperature/Thermography	Oil analysis	Application	
Engine	Machining	Processing machines	x					Positioning accuracy (by Laser interferometer)	
				x				Vibration and Balancing (by Micro log)	
		Rough-Finnish machining	x					Repeat accuracy (by Laser interferometer)	
			x					Stability or Milling test	
	Assembly	Automated assembly machines	x					Geometry check (by Laser tracker)	
				x				Rotation accuracy / Form fault and Temp. stability	
					x			Clamping forks and tool spindle	
							x		-
								x	Electrical cabinets
									x
All									

The company had an old online vibration monitoring system in the machining area but it has been taken out. The company does not see any need for the online system. The reasons they express are:

- No need to monitor that frequently.
- It is not worth the money.
- It is better to spend the money in other systems which can give more money back.
- The information collected from offline vibration monitoring is more useful than online monitoring. This due to the fact that the people are out in the machines and they can understand different problems. It is a big benefit.
- It could be a long time between offline detecting a problem until it becomes a real problem. So, it would be possible to prepare for reparation, renovation, change and so on.

However, the company has the interest of having mobile online system which can be located where there is a critical problem to monitor, maybe one or several machines continuously for a specific period of time. Then, it is possible to move the system to another location when it is needed for another problem. But there are some challenges to have this system, e.g. the investment cost. This system is also resource demanding and needs allocated people to track the information from the system. It may also take some production time in order to measure, due to; (1) it needs to have the same circumstances all the time while measuring vibration; (2) it needs specified tools to have specified details and (3) it has to be repetitive in order to trend the manual. In consequence, it is not so easy to build up this system.

The data collected from condition monitoring are analysed by the CBM organization which provides recommendations by sending reports directly to maintenance responsible people in different departments. All reports must be implemented as an order number in their CMMS. In addition, it is needed to set tolerances for all the machines in different departments and put the information in the system which requires a lot of work, and is especially hard for a new machine.

One of the main challenges to implement CBM at the company is management support. The management must comprehend the importance of the CBM's role at the company and provide the resources needed, etc. The other challenge is time. It takes time to educate both management and CBM responsible people and have a clear common objective. It needs to have a long term strategy to change the way of working from reactive maintenance to proactive maintenance. The company has been working with reactive maintenance for many years and it takes time to change this culture. In order to decrease maintenance cost, CBM can be a very good solution for mechanical wastes and increasing the productivity. The management looks at CBM as an advanced method and it is considered as the next step to take. Even simple condition monitoring methods for continuously measuring can be counted as CBM, and CBM does not need to be considered as an advanced method. There is also a need to standardize practices, methods and requirements.

Consequently, education and training is one of the main future plans of the company to increase the competence and certificate personnel in this area. Moreover, maintenance management wants to invest more resources in research (e.g. in new technologies) and to study the effect of new products on the machines. These are being formulated as a strategy for coming years in order to develop CBM and reach a certain level of competence.

4.2 Case B

Company B sees CBM as an important factor to implement but currently there is no CBM organization. Only in some small areas do the company has offline condition monitoring. Moreover, some measurements are being performed during the repairs. The management mentions the importance of CBM, but still the organization is not made for using CBM.

Currently, the company is using corrective maintenance to solve all kind of problems in workshop with a few preventive maintenance solutions. There is not time or resources within the new organization to work with CBM.

Table 4: CBM status map at case B

Product type	Process type	Production equipment type	Geometry analysis	Vibration analysis	Force control	Temperature/Thermography	Oil analysis	Application
Gearbox	Machining	Processing machines	x					Stone and gauges
				x				Only on some spindles
					x			Clamping chucks
						x		Cutting force monitoring
	Assembly	Automated assembly machines						-
	Heat treatment					x		Monitoring of the process in heat treatment
	All					x		Temp. stability in electrical cabinets and electrical components
							x	Analyse the oil features and measure the amount of particulars

The level of CBM competence at the company is quite low. The company is familiar with the tools and measurements but does not have time to learn how to work with CBM. In a respondent's view, maintenance responsible people need to work 50-75% of their working time with CBM to get the knowledge about it, not only measurement, but also how to use the data gathered. Also, the level of development of CBM tools is very low. The company has some tools, as shown in Table 4, but they are not used so frequently because there is no organization.

They do not apply online condition monitoring system, but the company has a plan to invest in having online condition monitoring in some of the critical machines.

The data collected from condition monitoring are gathered in a shared computer storage. Maintenance responsible people are doing some measurements and analyse the data directly to provide a maintenance plan.

The challenge for the company is to have a specific department to work with CBM. It needs to implement CBM

in most of the machines and also get fingerprint from the new machines. However, the company has invested in research in this area. There is a plan to implement CBM in a pilot study to have online condition monitoring. In addition, the management has a clear understanding about the importance of CBM practices and has interest to have further development in this area.

4.3 Reference company C

Company C has stamping machines, automated assembly machines and robots. CBM techniques such as vibration monitoring, oil analysis and thermography are being performed in product development activities and stamping activities, as shown in Table 5. In addition, the company uses a cracks detection technique in stamping activities as well as thermography in assembly activities.

The challenge ahead of the company is to apply CBM on the assembly line and select appropriate measurement equipment.

Table 5: CBM status map at case C

Product type	Process type	Production equipment type	Geometry analysis	Vibration analysis	Force control	Temperature/Thermography	Oil analysis	Application
Engine	Stamping	Stamping machines		x				-
						x		-
							x	-
	Assembly	Automated assembly machines				x		Thermal monitoring of the electrical cabinets

Table 6: CBM status map at reference company D

Product type	Process type	Production equipment type	Geometry analysis	Vibration analysis	Force control	Temperature/Thermography	Oil analysis	Application
	Machining	CNC machines	x					Dynamic Balance (Rotor of Exhaust System)
				x				Monitoring of bearing at the CNC machine (spindle, drive units, pumps and dynamometers, exhaust fan)
Engine	Assembly	Automated assembly machines			x			Measurement for machine tool spindles
	All					x		Check the overheat at the wires and components of the electrical cabinets
							x	Analyse the oil features and measure the amount of particulars

4.4 Reference company D

Company D has an organization of two technicians from maintenance engineering working part time on CBM activities. They are responsible for making the CBM yearly schedule, contract the CBM services, following the execution and analyse the reports in each field. The CBM organization started working some ten years ago with vibration analysis and is today executing thermography analysis, oil analysis and geometry analysis, as shown in Table 6. The thermography analysis and measurement machine tool spindle are executed by the company and other CBM activities are outsourced.

The company has also the knowledge of servo traces analysis from CNC. Through the graphics created by the CNC, the mechanical problems are being verified.

Servo trace provides functions with graphic user interface for checking and monitoring drive/servo signals and states. The units such as torque, velocity, amperage could be measured using the servo trace.

The company has CNC machines, assembly line, testing cell and painting. The challenges ahead of the company are to develop a team and an efficient CBM system to ensure the reliability of the equipment.

For future plans, the company is interested to know more about the CBM methods and how to define and set limits of CBM parameters. They want to develop the skills in geometry alignment and measurement as well as validation of vibration monitoring for using in predictive maintenance and autonomous maintenance approaches.

5 DISCUSSION

5.1 Enabling factors for CBM

A successful condition monitoring environment is an important enabling factor for CBM. In this regard, it is needed to have a clear condition monitoring strategy to manage the overall CBM strategy. The management support acts as an important role to make a strong organization in this area.

Several aspects as enabling factors should be in consideration while implementing condition monitoring. The techniques should be selected appropriately. The level of competence within CBM organization should be adequate to use the techniques effectively. It is required to have sufficient training and experience to become skilled in

the condition monitoring techniques. The level of complexity needed for the condition monitoring technologies and the degree of continuous use should be decided and responsible must be determined. It is necessary to have a plan for all purchases; to consider the cost before purchasing the technologies and determine who should provide the services.

A robust asset registration, asset fault's history and their symptoms as well as baseline data of the assets make the condition monitoring data easier to analyse and contributes to appropriate maintenance plans. However, there must be a way to follow up the application of condition monitoring technologies to control their effectiveness.

5.2 Criteria for selecting CBM technique

According to the case companies, five main techniques are found important to use which are mentioned in the matrixes, including; geometry analysis, vibration analysis, force control, thermography and oil analysis. The companies are selecting CBM techniques depending on the type of the problems that the machines have had. For instance, if a problem happened because of geometry alignment, the appropriate technique to choose is geometry analysis. Based on the empirics gathered from the case companies, usually in big size machines geometry analysis is applied. For the machines which are working in high speed, vibration analysis is an effective way to determine whether a machine is functioning correctly or not. Vibration analysis is carrying out to monitor rotating accuracy in the parts which are linked to vibration such as rotating shafts, spindle, bearing, drive units, fans and pumps. Force control is used for clamping spindle tools and so on. All of the case companies are using thermography technique to monitor the electrical cabinets. Also, for the companies which have thermal processes, thermography is used to monitor the heat treatment process. Finally in all of the case companies, oil analysis is carried out to analyse the oil features and measure the amount of particulars in order to ensure the quality of the oil and its function.

5.3 Cost and Value

Based on literature review and case study, there is no clear model for cost of maintenance that can compare production cost and maintenance cost. For instance, respondents in the case companies argued that having online condition monitoring needs to invest lots of money which is not financially justified. But still there is not clear

view that how much a breakdown can cost for production to compare this value with maintenance cost.

There are two views while investing condition based maintenance. In a view a company prefers to invest money to increase the number of resources and their competences in having offline condition monitoring besides having some online condition monitoring in more critical places which safety factor is also important. The other view is that a company prefers to invest money to have more online condition monitoring on the machines. Obviously, this company demands less resources but still needs resources to track the information collected from online system and some experts to analyse these data and make maintenance plan as well as other requirements.

Both of these two views are resource demanding and need to invest money for different factors such as tools and instruments, education and training, etc. It is important that the companies must be aware of the time while implementing CBM. According to the interviews, collected data and analysis in this research, it may take long time to get the paybacks from CBM system. The management must give this opportunity to CBM department to grow and earn sufficient knowledge before getting paybacks.

5.4 Witnessed main challenges in implementing CBM

Currently, the companies are attempting to apply the CBM techniques in most of their key machines, which demands increase in competences to use these techniques effectively. Nevertheless, management support is one of the main challenges. It is needed to change the culture of the companies from reactive to proactive strategies. The companies have been working with reactive strategies for many years and it needs time and of course more knowledge to change this perspective to a proactive strategy. In other words, it is necessary to convince the management and the maintenance responsible people that working with proactive maintenance tools such as CBM is a need for the companies' future success in the competitive environment.

5.5 Future plan for CBM at the case companies

The companies are trying to train their employees to increase their competence in this area which is one of the main challenges for the future. In addition to this, the companies have interest in having more advanced tools for CBM such as online mobile systems which can be located where there is a critical problem to monitor one or several machines continuously for a specific period of time. Then, it is possible to move the system to another location when it is needed for another problem.

The companies want to use CBM techniques to get fingerprint from new production equipment. Therefore, they can use this data to return the machines to the original setting when it is needed. Having further study on the effect of having new product on the machines is another action plan for the future. For instance, to see how the product's material can affect the production equipment and CBM techniques facilitate to have this analysis.

6 CONCLUSIONS

The study performed in this research relies on that CBM acts as a key role to provide management and maintenance responsible people correct and reliable data in order to prevent unplanned production stops.

All the companies in this study are more or less working with all CBM techniques, but on different levels. For those companies that have already had a specific organization for CBM, management support is one of the key factors to implement CBM. Their main concern is to have enough

resources and competences in this area to be good in condition monitoring both in offline and online. However, the rest of the companies that don't have a specific organization are also working with CBM tools and techniques. CBM is not always an advanced method and even a small offline condition monitoring is considered as CBM.

In order to select an appropriate CBM technique the companies are considering the problems that machines have already had. However, selecting appropriate measurement tools as well as increasing the competence in measurement skills and analysing the data, are some of the main challenges ahead of the companies to implement CBM.

6.1 Future research

The performed case study purposed to map the current CBM techniques applied in the manufacturing industry. Further research to continue this objective would be mapping the full process of CBM in the manufacturing industry including data processing and maintenance decision making.

Moreover, one of the case companies showed interest of having online condition monitoring. A prospective continuation of this research could be to follow and investigate in having online condition monitoring on some of the critical machines at the manufacturing company as a pilot study. The results from this pilot study can illustrate how much these practices are applicable and cost effective in the manufacturing industry and also it could be a good guide for further research and development in this area.

7 ACKNOWLEDGMENTS

The authors would like to thank the participating companies for their engagement in the case studies. The research work has been funded by the KK-foundation (within the INNOFACTURE research school), Volvo GTO and Mälardalen University. The research work is also a part of the initiative for Excellence in Production Research (XPRES) – one of two governmentally funded strategic initiatives for research excellence within Production Engineering in Sweden.

8 REFERENCES

- [1] Cooke, R. & Paulsen, J. (1997). Concepts for Measuring Maintenance Performance and Methods For Analysing Competing Failure Modes. *Reliability Engineering and System Safety*, 5(2), pp. 135-141.
- [2] Jardine AKS, Lin D, Banjevic D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing* ;20:1483–510.
- [3] Swedish Standards Institute (2001). Maintenance Terminology. SS-EN 13306, Swedish Standards Institute, Stockholm.
- [4] Khairy A., Kobbacy H. and Prabhakar Murthy D. N. (2008). *Complex System Maintenance Handbook*. Springer, New York.
- [5] Moubray, J. (1997) *Reliability-centered Maintenance*. Second Edition, Industrial Press Inc., New York.
- [6] Nakajima, S. (1988) *Introduction to TPM – Total Productive Maintenance*. Productivity Press, Cambridge.
- [7] Smith, R. & Hawkins, B. (2004). *Lean Maintenance*. USA: Butterworth-Heinemann.
- [8] Bengtsson M. (2004). *Condition Based Maintenance Systems – An Investigation of Technical Constituents*

and Organizational Aspects. Licentiate Thesis, Mälardalen University, Eskilstuna, Sweden

- [9] Goldman S. (1999). *Vibration spectrum analysis: a practical approach*. New York: Industrial Press.
- [10] Bengtsson, M. (2007). *Decision-Making During Condition Based Maintenance Implementation*. 20th International Conference on Condition Monitoring and Diagnostic Engineering Management, Faro, Portugal.
- [11] Randall, R.B. (2010). *Vibration-based Condition Monitoring : Industrial, Aerospace and Automotive Applications*. Hoboken: John Wiley & Sons, Ltd.
- [12] Walker, N. (2005). *The implementation of a condition based maintenance strategy*. COMADEM congress, Cranfield University, UK.