The growth of global competition has led to remarkable changes in the way manufacturing companies operate. These changes have affected maintenance and made its role even more crucial for business success. The introduction of lean manufacturing has increased concerns regarding equipment availability and the demand for effective maintenance. Despite the increasing demand for reliable production equipment, few manufacturing companies pursue the development of strategic maintenance. Moreover, traditional maintenance strategies, such as corrective maintenance, are no longer sufficient to satisfy industrial needs, such as reducing failures and the degradation of manufacturing systems to the greatest possible extent. The concept of maintenance has evolved over the last few decades from a corrective approach (maintenance actions after a failure) to a preventive approach (maintenance actions to prevent the failure). Strategies and concepts such as condition based maintenance (CBM) have thus evolved to support this ideal outcome. CBM is a set of maintenance actions based on the real-time or near real-time assessment of equipment conditions. CBM is increasingly recognized as the most efficient strategy for performing maintenance in a wide variety of industries. In addition, agendas such as “Industry 4.0” are promoting the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the internet. Thus, the natural link of CBM to cyber-physical systems (CPS) makes the role of CBM even more important in the fourth industrial revolution and digitalization. However, the practical implementation of advanced maintenance technologies, such as CBM, is relatively limited in the manufacturing industry.

The objective of this research is to provide frameworks and guidelines to support the development and implementation of condition based maintenance in manufacturing companies. This thesis will begin with an overall analysis of maintenance management to identify the necessary factors to strategically manage production maintenance and will continue with a focus on CBM to illustrate how CBM could be valued and implemented in manufacturing companies.

Ali Rastegari is an industrial PhD student at Mälardalen University and has been part of the INNOFACTURE Research School since September 2012. He is employed as a maintenance engineer at Volvo Group Trucks Operation. Ali received his M.Sc. from Mälardalen University in the field of Product and Process Development – Production and Logistics and his B.Sc. from Tehran Azad University in Mechanical Engineering. His background includes work as a mechanical and maintenance engineer in manufacturing industries.
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CONDITION BASED MAINTENANCE
IN THE MANUFACTURING INDUSTRY
FROM STRATEGY TO IMPLEMENTATION

Ali Rastegari
2017

School of Innovation, Design and Engineering
Abstract

The growth of global competition has led to remarkable changes in the way manufacturing companies operate. These changes have affected maintenance and made its role even more crucial for business success. To remain competitive, manufacturing companies must continuously increase the effectiveness and efficiency of their production processes. Furthermore, the introduction of lean manufacturing has increased concerns regarding equipment availability and, therefore, the demand for effective maintenance. That maintenance is becoming more important for the manufacturing industry is evident in current discussions on national industrialization agendas. Digitalization, the industrial internet of things (IoT) and their connections to sustainable production are identified as key enablers for increasing the number of jobs in industry. Agendas such as “Industry 4.0” in Germany and “Smart Industry” in Sweden are promoting the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the internet. Machines, systems, manufactured parts and humans will be closely interlinked to collaborative actions. Every physical object will formulate a cyber-physical system (CPS), and it will constantly be linked to its digital fingerprint and to intensive connection with the surrounding CPSs of its on-going processes.

That said, despite the increasing demand for reliable production equipment, few manufacturing companies pursue the development of strategic maintenance. Moreover, traditional maintenance strategies, such as corrective maintenance, are no longer sufficient to satisfy industrial needs, such as reducing failures and degradations of manufacturing systems to the greatest possible extent. The concept of maintenance has evolved over the last few decades from a corrective approach (maintenance actions after a failure) to a preventive approach (maintenance actions to prevent the failure). Strategies and concepts such as condition-based maintenance (CBM) have thus evolved to support this ideal outcome. CBM is a set of maintenance actions based on the real-time or near real-time assessment of equipment conditions, which is obtained from embedded sensors and/or external tests and measurements, taken by portable equipment and/or subjective condition monitoring. CBM is increasingly recognized as the most efficient strategy for performing maintenance in a wide variety of industries. However, the practical implementation of advanced maintenance technologies, such as CBM, is relatively limited in the manufacturing industry.

Based on the discussion above, the objective of this research is to provide frameworks and guidelines to support the development and implementation of condition-based maintenance in manufacturing companies. This thesis will begin with an overall analysis of maintenance management to identify factors needed to strategically manage production maintenance. It will continue with a focus on CBM to illustrate how CBM could be valued in manufacturing companies and what the influencing factors to implement CBM are. The data were collected through case studies, mainly at one major automotive manufacturing site in Sweden. The bulk of the data was collected during a pilot CBM implementation project. Following the findings from these efforts, a formulated maintenance strategy is developed and presented, and factors to evaluate CBM cost effectiveness are assessed. These factors indicate the benefits of CBM, mostly with regard to reducing the probability of experiencing maximal damage to production equipment and reducing production losses, particularly at high production volumes. Furthermore, a process of CBM implementation is presented. Some of the main elements in the process are the selection of the components to be monitored, the techniques and technologies for condition monitoring and their installation and, finally, the analysis of the results of condition monitoring. Furthermore, CBM of machine tools is presented and discussed in this thesis, focusing on the use of vibration monitoring technique to monitor the condition of machine tool spindle units.

Abstract

The growth of global competition has led to remarkable changes in the way manufacturing companies operate. These changes have affected maintenance and made its role even more crucial for business success. To remain competitive, manufacturing companies must continuously increase the effectiveness and efficiency of their production processes. Furthermore, the introduction of lean manufacturing has increased concerns regarding equipment availability and, therefore, the demand for effective maintenance. That maintenance is becoming more important for the manufacturing industry is evident in current discussions on national industrialization agendas. Digitalization, the industrial internet of things (IoT) and their connections to sustainable production are identified as key enablers for increasing the number of jobs in industry. Agendas such as “Industry 4.0” in Germany and “Smart Industry” in Sweden are promoting the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the internet. Machines, systems, manufactured parts and humans will be closely interlinked to collaborative actions. Every physical object will formulate a cyber-physical system (CPS), and it will constantly be linked to its digital fingerprint and to intensive connection with the surrounding CPSs of its on-going processes.

That said, despite the increasing demand for reliable production equipment, few manufacturing companies pursue the development of strategic maintenance. Moreover, traditional maintenance strategies, such as corrective maintenance, are no longer sufficient to satisfy industrial needs, such as reducing failures and degradations of manufacturing systems to the greatest possible extent. The concept of maintenance has evolved over the last few decades from a corrective approach (maintenance actions after a failure) to a preventive approach (maintenance actions to prevent the failure). Strategies and concepts such as condition-based maintenance (CBM) have thus evolved to support this ideal outcome. CBM is a set of maintenance actions based on the real-time or near real-time assessment of equipment conditions, which is obtained from embedded sensors and/or external tests and measurements, taken by portable equipment and/or subjective condition monitoring. CBM is increasingly recognized as the most efficient strategy for performing maintenance in a wide variety of industries. However, the practical implementation of advanced maintenance technologies, such as CBM, is relatively limited in the manufacturing industry.

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Ökad global konkurrens har lett till anmärkningsvärda förändringar av hur tillverkningsföretag bedriver sin verksamhet. Förändringarna har påverkat underhållet och gett ett ännu mer avgörande roll för en framgångsrik verksamhet. För att förbätta konkurrenskraftiga måste tillverkningsföretag hela tiden öka effektiviteten och ändamålsenligheten i sina produktionsprocesser. Införandet av produktionsindustrin framgår av aktuella diskussioner kring nationella industrialiseringsscenarier. Digitalisering, det industriella Internet of things (IoT) och deras kopplingar till häl粥 produktion identifieras som avgörande förutsättningar för att öka antalet jobb inom industrin. Agendor som "Industry 4.0" i Tyskland och "Smart industri" i Sverige främjar anslutningen av fysiska föremål, som sensorer, enheter och företags tillgångar, både till andra och till internet. Maskiner, system, tillverkade delar och människor kommer att vara nära kopplade till samarbetsgärder. Varje fysiskt objekt kommer att formulera ett cyber-physical system (system, CPS) och det kommer ständigt att vara kopplat till sitt digitala fingeravtryck och till intensiv anslutning till omgivande CPS i pågående processer.

Med detta sagt är det, trots det växande kravet på tillförlitlig produktionsutrustning, få tillverkningsföretag som arbetar med strategisk underhållsutveckling. Dessutom är traditionella underhållssystemer, såsom avhjälpande underhåll, idag inte längre tillräckliga för att i största möjliga utsträckning uppfylla de industriella behoven inom exempelvis minskning av fel och störningar av tillverkningsindustrin. Underhållsbegreppet har under de senaste årtiondena utvecklats från avhjälpande insatser (underhållssystemer efter fel) till förebyggande insatser (underhållssystemer avsedda att förebygga fel). Strategier och begrepp såsom tillståndsbaserat underhåll (TBU) har tagits fram för att stödja denna ideala situation. TBU är en uppsättning av möjliga utsträckningar av underhållsstrategier, såsom erhålls från inbyggda sensorer och/eller externa tester och mätningar utförda av bärbar utrustning och/eller genom subjektiv tillståndsovervakning. 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Ali
Eskilstuna, November 2017
Appended Papers

This thesis is based on the following papers, appended in their original format at the back of the thesis.

**Paper I**

**Paper II**

**Paper III**

**Paper IV**

**Paper V**

**Paper VI**

**Paper VII**

**Paper VIII**


Table of contents

1. Introduction .............................................................. 1
   1.1 Background .................................................... 1
   1.2 Problem statement ........................................... 2
   1.3 Research objective ......................................... 4
   1.4 Research questions .......................................... 4
   1.5 Scope and delimitations ..................................... 5
   1.6 Outline of the thesis .......................................... 5

2. Frame of reference .................................................. 7
   2.1 Maintenance types ........................................... 7
   2.2 Maintenance management .................................... 8
   2.3 Condition based maintenance (CBM) ....................... 13
   2.4 CBM of rotating machinery ................................ 17
   2.5 Concluding highlights from the frame of reference ... 22

3. Research methodology ............................................... 23
   3.1 Scientific approach ......................................... 23
   3.2 Research method ............................................ 24
   3.3 Research process ............................................ 24
   3.4 Research quality ............................................ 31

4. Summary of findings in research studies ......................... 33
   4.1 Strategic maintenance management: formulating a maintenance strategy ..... 33
   4.2 Maintenance decision-making model ......................... 38
   4.3 Cost effectiveness of implementing CBM in manufacturing companies .... 43
   4.4 Material efficiency through CBM ................................ 45
   4.5 Current industrial practices and challenges regarding the use of CBM in manufacturing companies .... 47
   4.6 Implementation of CBM in manufacturing companies .......... 49
   4.7 On-line condition monitoring of fans ....................... 54
   4.8 CBM of machine tools ....................................... 60

5. Discussion ................................................................. 69
   5.1 General discussion ........................................... 69
   5.2 Concluding highlights from the discussion ............... 72

6. Conclusions .................................................................. 73
   6.1 Discussion on the research objective and general conclusions ... 73
   6.2 Revisiting the research questions ........................... 74
   6.3 Research contributions ....................................... 75
   6.4 Quality of the research ...................................... 76
   6.5 Future research ................................................ 76

References ........................................................................ 79

Appendices ........................................................................ 87
1. Introduction
This chapter is intended to introduce the objective of this research. The background is discussed in detail. Based on the background, a research problem is formulated, and a research objective is defined. Next, the research questions and delimitations are presented. Finally, the thesis outline is specified.

1.1 Background
In recent decades, production maintenance has evolved into one of the most important areas of the business environment for companies aiming to have a competitive production system (Kutucuoglu et al., 2001; Salonen, 2011; Fraser et al., 2015). The growth of global competition has created remarkable changes in the way manufacturing companies operate. These changes have affected maintenance and made its role even more crucial for business success (Kutucuoglu et al., 2001). To remain competitive, manufacturing companies must continuously increase the effectiveness and efficiency of their production processes. Furthermore, the introduction of lean manufacturing increases concerns regarding equipment availability. As a result, the demand for effective maintenance has significantly increased (Salonen, 2011). Al-Najjar and Alysouf (2003) stated that the importance of the maintenance function has increased due to its role in sustaining and improving availability, product quality, safety requirements, and plant cost-effectiveness levels. Maintenance costs constitute an important part of the operating budget of manufacturing companies (Al-Najjar and Alysouf, 2003). According to Leger et al. (1999a), in most production units, improper maintenance can have serious consequences for product quality, equipment availability, the environment, and company competitiveness. Alysouf (2009) noted that proper maintenance practices can contribute to overall business performance through their impact on the quality, efficiency and effectiveness of a company’s operations. This can improve the company’s competitiveness, including productivity advantages, value advantages and long-term profitability (Alysouf, 2004). Consequently, proper maintenance can have positive effects for shareholders, customers, and society.

That maintenance is becoming more important for the manufacturing industry is evident in current discussions on national industrialization agendas. Digitalization, the increasing number of things and their connections to sustainable production are identified as key enablers for increasing the number of jobs in industry. Agenda such as “Industry 4.0” in Germany, “Factory 2050” in the UK, “Smart Industry” in Sweden, “Horizon 2020” in the EU, “Revitalize Manufacturing Plan” in the US, and the “4th Science and Technology Plan” in Japan are promoting the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the internet (Sipsas et al., 2016). Machines, systems, manufacturing parts and humans will be closely interlinked to collaborative actions. Every physical object will formulate a cyber-physical system (CPS), and it will constantly be linked to its digital fingerprint and to intensive connection with the surrounding CPs of its on-going processes (Monostori, 2014). Therefore, the role of condition based maintenance (CBM) and condition monitoring as a part of the CPS framework is increasingly important.

Given ever-increasing global competitive pressures, it is essential that companies gain a better understanding of maintenance management programs to optimize both overall equipment effectiveness (OEE) and productivity (Fraser et al., 2015). These pressures have given companies worldwide the motivation to explore and embrace proactive maintenance strategies in lieu of traditional reactive firefighting methods (Ahuja and Khamba, 2007; Sharma et al., 2005). Over the last few decades, maintenance functions have significantly evolved with the growth of technology (Rosmains and Kamaruddin, 2012). Traditional maintenance strategies such as corrective maintenance are no longer sufficient to satisfy the industrial need to reduce...
failures and degradation of manufacturing systems to the greatest extent possible (Leger et al., 1999b). Jantunen et al. (2014) suggest that the concept of maintenance has evolved over the last few decades from a corrective approach (maintenance actions after a failure) to a preventive approach (maintenance actions to prevent the failure). Strategies and concepts such as CBM have thus evolved to support this ideal outcome. CBM is a set of maintenance actions based on the real-time or near real-time assessment of equipment condition, which is obtained from embedded sensors and/or external tests and measurements, taken by portable equipment and/or subjective condition monitoring (Butcher, 2000). CBM is increasingly recognized as the most efficient strategy for performing maintenance in a wide variety of industries (Randall, 2011). Accordingly, CBM represents one means for manufacturing companies to remain competitive by increasing the availability of production equipment in a cost-effective manner.

Furthermore, machining systems (i.e., machine tools, processes, and their interaction) can only produce accurate parts if the degradation in their subsystems and components (e.g., feed-drive systems and spindle units) is identified, monitored, and controlled (Martin, 1994). Machine tool maintenance delays the possible deterioration in machines and reduces the machine downtime that leads to lower productivity and higher production cost. To be competitive, it is possible to reduce the fabrication downtime by applying CBM. On the other hand, measuring and monitoring machine tool accuracy and capability have become increasingly important because of increasingly stringent accuracy requirements for industrial products and the products’ functional and legislative requirements (Martin, 1994). The increased capabilities of manufacturing in measuring and monitoring will provide fewer machine breakdowns, smaller spare parts inventories, and reduced production and maintenance costs (Able et al., 2010).

1.2 Problem statement

Parida et al. (2015) argue that the largest problem in industry is that the OEE is low, being 15-25 percent below the targeted level. Ylipää et al. (2017) analyzed 94 empirical datasets from the manufacturing industry between 2006 and 2012 and found that the current handling of production disturbance within the manufacturing industry is not effective. The OEE figures have not increased over the last decades, rather slightly decreased, and maintenance workers are mostly working with reactive activities instead of preventive activities. These results provide further support of the difficulty in shifting from a reactive to a preventive mindset (Sandberg et al., 2014). Naturally, direct machine failures are a major reason for low OEE. Furthermore, having low OEE means that the utilization of current production resources is low; this leads to insufficient productivity and resource efficiency. These facts are problematic for current production in terms of economic and ecologic sustainability (Ylipää et al., 2017). Low OEE figures are also challenging for the expected increase of digitalization in production, where factories will be considerably more autonomous than today by implementing concepts such as Industry 4.0. “Digital production increases the level of complexity of production equipment and requires high availability and robustness to enable autonomous and highly automated production systems” (Ylipää et al., 2017, p.139). Therefore, it is crucial for future research activities to support maintenance and manufacturing organizations to achieve higher overall productivity and efficiency of the production system.

To utilize existing maintenance practices effectively, a new view on maintenance and a wider scope of maintenance activities is needed (Ylipää et al., 2017). Despite the importance of developing strategic maintenance, a large part of the manufacturing industry lacks clear maintenance strategies (Jonsson, 1997; Alyouf, 2009, Salomen, 2011). It is therefore difficult to develop maintenance work in accordance with the strategic goals of manufacturing companies. There are few models for formulating a maintenance strategy, and some proposed
models are quite resource demanding (Salonen, 2011). In addition, according to Ylipää et al. (2017), maintenance organizations are currently mainly experience-driven. Therefore, there is a general lack of analysis capability and fact-based decision support within maintenance organizations.

Well-performed maintenance involves few corrective maintenance actions while performing as little preventive maintenance as possible (Cooke and Paulsen, 1997). This is similar to the objective of CBM, which is an enabler for performing as little preventive maintenance as possible. Shin and Jun (2015) state that, first and foremost, CBM gives us prior warning of impending failure and increased precision in failure prediction. Thus, CBM can more effectively reduce failure than can other approaches. Moreover, a considerable body of evidence suggests that CBM confers economic advantages in most industries (Randall, 2011). Al-Najjar and Alyounf (2004) and Al-Najjar (2009) promote the idea that CBM can convert maintenance into a profit center. Sundin et al. (2007) document a number of cases of savings afforded by the use of CBM. A study by Rosmanni and Kamarudin (2012) suggests that the application of CBM is more beneficial than that of time-based maintenance (TBM) from a practical perspective. Furthermore, Skoogh et al. (2011) argue that 30 percent of the energy consumption in industry is wasted on machines in repair, idle, and stand-by states. Thus, CBM can have positive impacts in regard to preventing the related economic losses. The current evidence from the expert insight on failure incidences is that CBM has significant potential to bring substantial savings in different sectors, most typically in transport, such as aerospace and rail, but also in process and manufacturing industries (Bagle et al., 2016).

However, Bengtsson (2007a) and Ylipää et al. (2017) state that the practical implementation of advanced maintenance technologies, such as CBM, is relatively limited in the manufacturing industry. According to Trimble et al. (2004), who consider a number of industrial sectors, 60% of companies have basic skilled staff and follow a primarily reactive strategy, whereas only 10% use advanced maintenance techniques such as CBM. It is challenging for companies to switch focus from reactive maintenance activities to preventive activities (Sandberg et al., 2014). Walker (2005) identifies some of the more common reasons that CBM technologies are unsuccessful with respect to effective maintenance activities, including discrepancies in training, management direction, technology selection, user commitment and user competence. According to Starr (2000), it is important that CBM be applied to appropriate problems in a plant rather than as an overall policy; it would not be cost effective to use expensive techniques everywhere. Bengtsson (2007a) also emphasizes that an important aspect of or precondition for successful implementation is to implement the correct approach at the correct location in the correct manner. Carnero (2006) states, “The setting up of a predictive maintenance program is a strategic decision that until now has lacked analysis of questions related to its setting up, management and control” (p. 945).

According to Fraser et al. (2015), analysis of the research sectors indicates that manufacturing is the dominant sector for research. However, out of 82 empirical papers, only three have direct practical links to the automotive industry. Even when journals “dedicated to maintenance” are analyzed, a very high percentage of articles are purely theory based. Therefore, Fraser et al. (2015) emphasize the need for academia to be relevant to the needs of practitioners and for research academics be focused on solving “real world” problems.

Based on the above discussion, equipment failures and their rippling effects must be more effectively handled in future production. This required change is even more important because of the expected implementation of digital production in the fourth industrial revolution (Ylipää et al., 2017). In addition, the distribution of preventive maintenance activities compared to reactive activities is still not satisfactory in the manufacturing industry (Ylipää et al., 2017). The problem identified in this thesis is that CBM practices are not yet widely
utilized within manufacturing companies and that guidelines for organizationally and technically implementing CBM that can contribute to manufacturing companies’ business competitiveness are lacking.

1.3 Research objective

The overall purpose of this thesis is to increase productivity, sustainability and competitiveness; maintain quality; and improve the technical availability of the manufacturing industry through contributing to strategic maintenance development and to successful implementation of condition based maintenance. The main objective of this research is to provide frameworks and guidelines to support the development and implementation of condition based maintenance in manufacturing companies. Figure 1 indicates the main areas of interest in this research. CBM that is well developed in its technical, organizational and economic aspects can contribute to overall maintenance management and can consequently enhance companies’ competitiveness with respect to their production systems.

1.4 Research questions

To fulfill the research objective, the following research questions have been formulated.

RQ1 What are the necessary factors to strategically manage production maintenance in manufacturing companies?

Based on the background and problem statement above, manufacturing companies must have a clear maintenance strategy to lead them from a reactive approach toward a proactive approach, such as CBM, and to remain successful in the competitive environment. Therefore, this research question investigates the development of maintenance strategy and maintenance decision making within manufacturing companies. Thus, it aims to identify the necessary factors to strategically manage production maintenance in manufacturing companies.

RQ2 How could the cost effectiveness of CBM be valued in manufacturing companies?

Prior to implementation of CBM, it is essential to investigate whether implementing CBM would be cost effective for the company. As long as CBM technologies are costly, it is not cost effective to apply CBM where it is not needed. This research question investigates the cost effectiveness of implementing CBM in different applications in manufacturing companies.
RQ3: How could CBM be implemented in manufacturing companies?

Prior to implementation of CBM, it is necessary to understand the current industrial practices utilized to date within the manufacturing industry and the technological level to which they are utilized, as well as what challenges will be encountered in implementation. Based on the importance of a proper approach to ensure the successful implementation of CBM, this research question investigates how companies can implement CBM by analyzing the influencing factors that should be considered during implementation. Thus, this research question also introduces the organizational and technical factors that should be considered during implementation.

1.5 Scope and delimitations

This research includes studies conducted within automotive manufacturing companies. Machine tools are one of the substantial assets in the modern automotive manufacturing industry. Therefore, although CBM can be used in different applications, in this research, CBM was used as an approach for the maintenance of physical assets, including fans’ electric motors and machine tools (turning machines, milling machines, grinding machines, and machining centers) in the hardening and machining processes of manufacturing companies. As presented in section 2.3.1, CBM includes different type of condition monitoring techniques. However, this thesis mainly focuses on the use of the vibration analysis technique in manufacturing companies.

1.6 Outline of the thesis

Chapter 1 introduces the research by presenting the background, the problem statement, the research objective and the research questions, as well as the scope and the delimitations of this thesis. Chapter 2 presents the theoretical frame of reference on which the research was based. This chapter presents and summarizes the relevant literature, i.e., studies on maintenance types, maintenance management and CBM, as well as CBM of rotating machinery, including machine tools. Chapter 3 presents the research methodology applied in this research. It discusses relevant scientific approaches and research methods. Then, it describes the research process to illustrate how this research has been conducted. Finally, it presents a reflection on the quality of the research. Chapter 4 presents a summary of findings in research studies. The results will refer to the papers that have been published as part of this research. Chapter 5 presents a discussion on the results of the research. Chapter 6 presents the main conclusions with regard to the research objective and questions. Next, it presents the industrial and academic contributions of the research as well as the quality of the research and suggestions for future research. This chapter is followed by a list of all references used in the thesis, appendices and the appended papers on which this thesis is based.

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2. Frame of reference

This chapter presents the theoretical propositions that form the frame of reference for this research. To position this research and provide a platform to discuss its findings in relation to the relevant body of knowledge, this chapter covers theories and definitions in the fields of maintenance, maintenance management, condition based maintenance (CBM) and CBM of rotating machinery (i.e., machine tools) as well as the pertinent research that was previously conducted in these fields. The chapter concludes with several highlights from the theory described in the frame of reference.

2.1 Maintenance types

The term maintenance is defined in SS-EN 13306 (2010) 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” (p.5). Kobbacy and Murthy (2008) describe 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).

Maintenance may be performed through various actions, and there are various classifications of maintenance types (Shin and Jun, 2015). One classification of maintenance types and their relationships is indicated in SS-EN 13306 (2010), as shown in Figure 2. Maintenance is divided into two main actions, corrective and preventive. This broad classification of maintenance types is used in studies such as Duffuaa et al. (2001), in which CBM is below preventive maintenance. However, some studies, such as Shin and Jun (2015), classify maintenance into three types: corrective maintenance, preventive maintenance and CBM. In various studies in the maintenance literature, such as Shin and Jun (2015), Rosmani and Kamaruddin (2012), Erbe et al. (2005), Duffuaa et al. (2001) and Blanchard et al. (1995), the term “type” has been used similarly to other terms such as “approach”, “action”, “strategy” and “policy”.

Figure 2 - Overview of different maintenance types (SS-EN 13306, 2010, p.20)

One definition of corrective maintenance is the following: “Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function” (SS-EN 13306, 2010, p.13). It is sometimes used synonymously with breakdown maintenance (BM) or failure-based maintenance (FBM) (Shin and Jun, 2015 and Al-Najjar and Alyouf, 2003) or operation-to-failure (OTF) (Labib, 2004). Corrective maintenance is also known as run-to-failure or reactive maintenance and is a strategy used to restore (repair or replace) equipment to its required function after it has failed (Blanchard et al., 1995).
One definition of preventive maintenance is as follows: “Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item” (SS-EN 13306, 2010, p.12). The concept of preventive maintenance involves the performance of maintenance activities prior to the failure of equipment (Gertsbakh, 1977). Preventive maintenance can be predetermined (periodic) maintenance or CBM.

SS-EN 13306 (2010) defines predetermined maintenance as follows: “Preventive maintenance carried out in accordance with established intervals of time or number of units of use such as scheduled maintenance but without previous item condition investigation” (p.12). It is sometimes used synonymously with time-based maintenance (TBM) (Rosmaini and Kamaruddin, 2012), use-based maintenance (UBM) (Swanson, 2001) or fixed-time maintenance (FTM) (Labib, 2004). In the industry, application of TBM can be generally performed following either experience or original equipment manufacturer (OEM) recommendations and is based on a scientific approach (Rosmaini and Kamaruddin, 2012). The application of TBM through experience is a conventional preventive maintenance practice. In most cases, it is performed at regular time intervals (Canfield, 1986).

SS-EN 13306 (2010) defines CBM as “preventive maintenance which include a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuing maintenance actions” (p.12). The condition monitoring, inspection and/or testing may be scheduled; on-request or continuous. CBM is explained in greater detail in section 2.3. The term predictive maintenance is defined as follows: “Condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item” (SS-EN 13306, 2010, p.12). According to Kobbacy and Murthy (2008), design-out maintenance (DOM) can be considered as another maintenance type in which the focus is to improve the design of production equipment to make maintenance easier or even eliminate it. Ergonomic and reliability aspects are important in this policy. Labib (2004) considers skill-level upgrade (SLU) as another type for maintenance used to improve competence of operators.

In addition, various concepts have been developed to increase the effectiveness of maintenance and focus on maintenance activities. The two more common concepts are reliability-centered maintenance (RCM), and total productive maintenance (TPM). Moubray (1997) 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). A Japanese concept for maintenance, according to Nakajima (1988), who introduced the concept, TPM may be defined as “Productive maintenance involving total participation” (p.10).

### 2.2 Maintenance management

Kelly (2006) offers the following generic formulation of the objective of maintenance: “...to achieve the agreed plant operating pattern, availability and product quality within the accepted plant condition (for longevity) and safety standards, and at minimum resource cost” (p.26). Murthy et al. (2002) define the two key elements of the strategic maintenance management approach: “(1) maintenance management is a vital core business activity crucial for business survival and success, and as such it must be managed strategically. (2) Effective maintenance management needs to be based on quantitative business models that integrate maintenance with other decisions such as production, etc.” (p.290). They also note that maintenance is understood as a multi-disciplinary activity in the strategic maintenance management approach. It involves “(1) scientific understanding of degradation mechanisms and linking it with data collection and analysis to assess the state of equipment; (2) building quantitative models to...” (p.290).
predict the impact of different actions (maintenance and operations) on equipment degradation; and (3) managing maintenance from a strategic perspective (Murthy et al., 2002, p.200). Marquez and Gupta (2006) note that maintenance management must align with business activities at the strategic, tactical, and operational levels. The maintenance management process consists of the following factors: planning asset maintenance, scheduling maintenance operations, managing the execution of maintenance actions, assessing maintenance, and ensuring continuous improvement (Marquez, 2007).

Wienken et al. (2016) define the key elements that form the basis of maintenance management: "(1) a clear strategy; (2) policies to support the strategy; (3) procedures & processes to enable implementation of the strategy & policy; (4) tools to support this implementation; (5) a well-established Maintenance Business Process with checks and balances" (p.414).

2.2.1 Maintenance strategy

There is no consensus in the literature on the definition of maintenance strategy. Some authors (e.g., Zaim et al., 2012) define it as the choice among corrective maintenance and preventive maintenance actions. Other authors, such as Gullimore and Penleskey (1998), claim that it is the combination of reactive maintenance, regularly scheduled preventive maintenance, inspection, equipment back-up and equipment upgrades. The combination of these elements is specific to each facility and depends on the goals of the maintenance, the nature of the facility or equipment to be maintained, and the work environment.

According to Tsang (1998), a strategy reflects the organization’s conception of its intended long-term goal and the approach to achieving it. Because the strategy is often formulated at the senior management level, it is usually too abstract for line management personnel. As such, it becomes difficult to relate departmental and individual activities to the attainment of the strategic goal. Marquez and Gupta (2006) state that maintenance strategies are a means of transforming business priorities into maintenance priorities. By addressing current or potential gaps in maintenance performance, a generic maintenance plan can be developed.

Pinjala et al. (2006) discuss the relationship between business and maintenance strategies. They define a maintenance strategy as a "...coherent, unifying and integrative pattern of decisions in different maintenance strategy elements in congruence with manufacturing, corporate and business level strategies; determines and reveals the organizational purpose; defines the nature of economic and non-economic contributions it intends to make to the organization as a whole." (Pinjala et al., 2006, p.216).

There are few models for formulating maintenance strategies, and some of the proposed models are quite resource demanding (Salonen, 2011). The existing models are rather similar in their key elements. Authors such as Tsang (1998), Wilson (1999), Kelly (2006), Marquez (2007), and Salonen (2012) all emphasize the following steps in their models:

- Identify the strategic goals of all stakeholders.
- Identify the strategic goals for the maintenance department.
- Identify relevant key performance indicators (KPIs).
- Assess the current state of maintenance.
- Set goals for each KPI.
- Make an action plan.

Although these models share the presented steps, they have somewhat different approaches to achieving these steps. Figure 3 illustrates Salonen’s model for the formulation of maintenance strategies (Salonen, 2012).
As shown in Figure 3, the model includes all steps previously mentioned. Salonen and Bengtsson (2006) propose involving stakeholders in the identification of relevant KPIs for the maintenance department. For transformation of the identified gaps between the current and desired states, Salonen (2012) proposes the use of strengths, weaknesses, opportunities, and threats (SWOT) analysis. Furthermore, Salonen (2012) emphasizes the importance of documenting the strategy and the need for company management to approve the strategy to make it a steering document.

2.2.2 Maintenance decision making

According to SS-EN 13306 (2010), the maintenance plan consists of a “structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance” (p.5). The process of developing a plan consists of the following: identifying the maintenance task required, establishing the maintenance support and re-evaluating (Marquez, 2007). Maintenance planning means that one must “identify the asset, prioritize the asset according to maintenance strategy, identify its performance requirements according to strategy, evaluate the asset’s current performance, and plan for its maintenance” (Marquez, 2007, p.14).

Maintenance decision making involves assessing and selecting the most efficient maintenance approach (i.e., strategies, policies, methodology or philosophy) (Al-Najjar and Alsyouf, 2003). Maintenance decision making involves determining the most appropriate maintenance policy to take, such as corrective maintenance, TBM or CBM. The consequences of an inefficient maintenance policy go far beyond the direct costs of maintenance (Al-Najjar and Alsyouf, 2003). Therefore, companies can save more money through appropriate maintenance decision making.

Corrective maintenance is a strategy that could lead to high levels of machine downtime (production loss) and maintenance (repair or replacement) costs due to sudden failure (Tsang, 1995). A preventive maintenance strategy contributes to minimizing failure costs and machine downtime (production loss) and increasing product quality (Usher et al., 1998). However, the TBM practice is not usually applicable when attempting to minimize operation costs and maximize machine performance (Rosmann and Kamaruddin, 2012). Labib (2004) cites three reasons for this: (1) each machine works in a different environment and would therefore need different planned maintenance schedules; (2) machine designers often do not experience machine failures and have less knowledge of their prevention compared to those who operate and maintain such machines; and (3) OEM companies may have hidden agendas, that is, maximizing spare part replacement through frequent planned maintenance actions. Marquez (2007) also states that the maintenance plans provided by the equipment manufacturer are not...
completely reliable because they are not aware of “business-related consequences of failure, safety considerations, regulatory requirements, the use of condition monitoring techniques, availability of resources and unique environmental conditions” (p.16). This statement is supported by Tam et al. (2006), who note that planned maintenance intervals based on OEM recommendations may not be optimal because actual operating conditions may be very different from those considered by the OEM. As such, actual outcomes may not satisfy company requirements. In addition to corrective maintenance and TBM, according to Gupta and Lawririrat (2006), the main goal of CBM is to perform an assessment of equipment conditions to enable maintenance decisions to be made, consequently reducing unnecessary maintenance and related costs.

Labib (2004) proposes a model for maintenance decision making called the decision-making grid (DMG), which is based on the status of machines/components in accordance with the frequency of breakdowns, the downtime and the cost of repair. The achievement of more efficient maintenance depends on the capability of the implemented maintenance policy to effectively provide and employ relevant information concerning the factors that affect the life of the component/equipment in question (Al-Najar and Alsyouf, 2003). Providing more relevant information on component condition increases the ability (effectiveness) of a maintenance solution to avoid failures and to make the best possible use of the equipment/component’s effective life by performing replacements “just” before failure; thus, this information improves the maintenance policy’s accuracy (Al-Najar and Alsyouf, 2003). Jantunen et al. (2014) propose a guide for maintenance decision making based on component failure models. According to Figure 4, in case of wear models D, E and F, the use of CBM is not possible or sensible, as failures can occur without a warning being registered by the measuring signals. In such a case, the best solution is to run the component until failure occurs; hence, the optimal maintenance policy is corrective maintenance. When infant mortality is high (A and F), CBM is not an appropriate option. Cases A, B and C can be monitored, but it is not sensible to monitor the remaining three (D, E and F).

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Figure 4 - Failure models, adopted from Nowlan and Heap (1978)

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2.2.3 Maintenance performance measurement

According to Parida (2006), maintenance performance measurement can be defined as “the multi-disciplinary process of measuring and justifying the value created by maintenance investment, and taking care of the organization’s stakeholders’ requirements viewed strategically from the overall business perspective” (p.7). Maintenance performance measurement is required for measuring the value created by maintenance, to justify the investment made and revise the resource allocation, and to care for customers, health, safety and environmental issues while adapting to new trends in operation and maintenance strategy and organizational structural changes (Parida, 2006). According to Tsang (1998), because maintenance spending constitutes a large share of the operating budget for organizations with heavy investments in machinery and equipment, tracking the performance of maintenance operations in such organizations should be a key management issue. Another reason for linking the measurements to the organization’s strategy, according to Tsang (1998), is the influence of the applied performance measurements on employee behaviors. Wienker et al. (2016) argue that the greatest misunderstanding of the role of a CMMS is the belief that CMMS is the maintenance strategy itself, rather than being just a tool to support the existing maintenance strategy of an organization. “This belief that the CMMS will change maintenance in an organization from a reactive to a proactive approach is quite common and often results in poor usage of the available modules of such systems” (Wienker et al., 2016, p.416). Therefore, the incorrect use of these tools together with a lack of data implementation leads to the CMMS only being used as a “work order system”, without the analysis and reporting capability (Wienker et al., 2016).

OEE is a key measurement in TPM introduced by Nakajima (1988). The OEE measurement is becoming increasingly popular currently and is used as a standalone key performance measurement tool for productivity improvements (Ylipää et al., 2017). The OEE metric consists of six major losses, including equipment failures, setup and adjustments, idling and minor stoppages, reduced speed, defects in process, and reduced yield (Nakajima, 1988). A part of maintenance management is to interpret the data available and convert them into useful information in order to manage the equipment in the best possible way (Wienker et al., 2016). Therefore, the data must be gathered and analyzed in a structured manner to be able to be utilized effectively (Wienker et al., 2016). The increased amount of information available and a growing need to have this information at hand and in real time for decision making necessitates a computerized maintenance management system (CMMS) to aid maintenance management (Labib, 2004). Wienker et al. (2016) state that “Proactive world-class maintenance management is nearly impossible without computer-based support” (p.413).

Legacy maintenance systems with large batch reports in which the focus was on data throughput are being replaced by dynamic, on-line queries created on-the-fly with answers in seconds rather than days (Labib, 2004). The CMMS can achieve the following (Labib, 2004):

- Support CIMB.
- Track the movement of spare parts.
- Allow operators to report faults faster.
- Improve communication between operations and maintenance personnel.
- Provide historical information necessary for developing preventive maintenance schedules.
- Provide maintenance managers with information so that they have better control over their departments.
- Offer accountants information on machines to enable capital expenditure decisions to be made.

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According to Parida (2006), maintenance performance measurement can be defined as “the multi-disciplinary process of measuring and justifying the value created by maintenance...
2.3 Condition based maintenance (CBM)

CBM is a popular maintenance type discussed in the literature (Dieulle et al., 2001; Han and Song, 2003; Moya, 2004). Generally, CBM can be treated as a method to reduce the uncertainty of maintenance activities and is conducted according to the requirements indicated by the equipment’s condition (Peng et al., 2010). Hence, CBM enables us to identify and solve problems in advance before damage occurs. In industry systems, any damage can have serious consequences. In this respect, CBM is a very attractive method for an industry operating high-valued assets (Shin and Jun, 2015). In CBM, the lifetime (age) of the equipment is monitored through its operating condition, which can be measured based on monitoring parameters such as vibration, temperature, lubricating oil, contaminants, and noise levels (Jardine et al., 2006; Rosmaini and Kamaruddin, 2012). CBM identifies and prevents potential failures of a system, reduces the failure consequences of the system, and, as a result, ensures a lower life-cycle cost of the system (Greenough and Grubic, 2011). Therefore, CBM is needed to ensure equipment health management, lower life cycle cost, and avoid catastrophic failure (Rosmaini and Kamaruddin, 2012). According to Jardine et al. (2006), CBM is a maintenance program that recommends maintenance actions (decisions) based on the information collected through the condition monitoring process.

2.3.1 Condition monitoring

Condition monitoring is defined as an “activity performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the actual state of an item” (SS-EN 13306, 2010, p.14). Emerging technologies are expected to come into rapid use for gathering and monitoring the status data of assets during their usage period (Shin and Jun, 2015). Advancements in information technology have added accelerated growth in the area of CBM technology by enabling network bandwidth, data collection and retrieval, data analysis, and decision support capabilities for large sets of time series data (Prajapati et al., 2012).

The core aspect of CBM is condition monitoring, which can be performed using various approaches and employing different levels of technology (Jardine et al., 2006), as presented in Figure 5. Condition monitoring can be performed either periodically or continuously. Typically, periodic monitoring is conducted at certain intervals, such as every hour or at the end of every working shift, with the aid of portable indicators such as hand-held measurement instruments, acoustic emission units, and vibration pens. The condition monitoring process also includes evaluations based on human senses (subjective monitoring) to measure or evaluate equipment conditions, such as the degree of dirtiness and abnormal color (Rosmaini and Kamaruddin, 2012). In on-line (or real-time) monitoring, a machine is continuously monitored and a warning alarm triggered whenever an error is detected. However, there are two limitations of on-line monitoring in the literature: (1) it is often expensive, and (2) continuously monitoring raw signals with noise produces inaccurate diagnostic information (Jardine et al., 2006). In comparison, periodic monitoring is used due to its low cost and because it provides more accurate diagnostics using filtered and/or processed data. However, the risk of using periodic monitoring is the possibility of missing some failure events that occur between successive inspections (Goldman, 1999).
Various standards and guidelines have been issued for the condition monitoring and diagnostics of machines (ISO/TC 108/SC 5, 1993; ISO 13381-1, 1995). As Bloch and Geitner (1983) state, most equipment failures are preceded by certain signs, conditions, or indications (i.e., vibration, temperature, and noise) that such a failure was going to occur. In general, the purpose of the condition monitoring process is twofold. First, it collects the condition data (information) of the equipment. Second, it increases knowledge regarding the causes and effects of failure and the deterioration patterns of equipment (Rosmaini and Kamaruddin, 2012). In condition monitoring, information concerning internal effects must be obtained externally while the machines are in operation (Randall, 2011).

The most popular condition monitoring technique used in CBM, especially for rotating equipment (e.g., bearings and gearboxes), is vibration monitoring (Al-Najjar, 1997; Carnero, 2005; Higgs et al., 2004). Machines are constantly generating vibrations. Many of these vibrations are linked to periodic events in the machine’s operation, such as rotating shafts, meshing gear teeth, and rotating electric fields. Some vibrations are due to events that are not entirely phase locked to shaft rotations, such as combustion in engines. Other vibrations are linked to fluid flow, as in pumps and gas turbines, and these have particular or unique characteristics (Randall, 2011). 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.

Oil analysis is another principal technique for obtaining information on machine internal conditions. In oil analysis or lubricant monitoring, the condition (quality) of the oil is evaluated to determine whether the oil is suitable for further use (Rosmaini and Kamaruddin, 2012). Moreover, the results of oil analysis can show the wear conditions of internal oil-wetted components, such as engine shafts (Rosmaini and Kamaruddin, 2012). The lubricant transmits information from the inside to the outside of operating machines in the form of wear particles or chemical contaminants, for example. Its use is mainly confined to circulating-oil lubricating systems. Moreover, some analyses can be performed on grease lubricants (Randall, 2011).

For certain types of machines, such as turbines or compressors, performance analysis, for example of stage efficiency, is an effective way to determine whether the machine is functioning correctly. Thermography is another condition monitoring technique. Sensitive instruments are employed to remotely measure temperature changes in comparison with a standard condition. Thermography is principally applied in quasi-static situations, such as electrical switchboards, to detect local hot spots and faulty refractory linings in hot fluid containers (Randall, 2011). Sound or acoustic monitoring is another technique frequently used in CBM, especially for rotating equipment (e.g., bearings and gearboxes), is vibration monitoring (Al-Najjar, 1997; Carnero, 2005; Higgs et al., 2004). Machines are constantly generating vibrations. Many of these vibrations are linked to periodic events in the machine’s operation, such as rotating shafts, meshing gear teeth, and rotating electric fields. Some vibrations are due to events that are not entirely phase locked to shaft rotations, such as combustion in engines. Other vibrations are linked to fluid flow, as in pumps and gas turbines, and these have particular or unique characteristics (Randall, 2011). 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.

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in CBM; it has a strong relationship with the vibration monitoring technique. However, there is a fundamental difference between the two (Rosmaini and Kamaruddin, 2012). Whereas vibration sensors are rigidly mounted on the component involved to register local motions, acoustic sensors “listen” to the equipment. As in vibration monitoring, sound or acoustic monitoring is executed on-line, either in periodic or continuous manners (Rosmaini and Kamaruddin, 2012).

2.3.2 Cost effectiveness of CBM

According to Wienker et al. (2016), maintenance of equipment is a significant part of the total operating costs in most industry sectors. However, the real impact of maintenance is often under-estimated. As indicated in Figure 6, the iceberg model highlights the hidden cost impact of maintenance upon the business, which is far greater than just the direct costs associated with maintenance (Wienker et al., 2016). “For many companies, reducing these hidden costs requires a shift from the traditional reactive approach to a proactive reliability-based approach” (Wienker et al., 2016, p. 414).

For CBM investment and implementation to have total effectiveness, both direct maintenance costs and indirect maintenance costs must be taken into consideration. The cost effectiveness of CBM can be observed in various forms of potential savings, including reduced maintenance costs, damage limitation, and avoided production losses, which should be compared to the cost of CBM (setup cost and operation cost) (Starr, 2000). Starr (2000) divides cost effectiveness into costs and potential savings, where reduced maintenance costs (direct cost/savings), damage limitations (direct cost/savings), and avoided production losses (indirect maintenance cost/savings) are cited as potential savings, and setup costs (direct cost) and operations costs (cost of measurements/analysis) (direct costs) are the actual costs of CBM. These costs must be compared and analyzed before deciding where to implement CBM. Moreover, Hess et al. (2001) cite the importance of evaluating both potential savings and costs; they call this technology effectiveness evaluation and technology cost evaluation. Furthermore, they note that it is wise to prepare a business case with a return on investment (ROI) calculation and state that, as a rule of thumb, a one-year or less payback period should be achieved if the technology is to be implemented. In evaluating the use of CBM to make decisions according to measured data, the management’s function is to review the selection process, including routine monitoring, the selection of techniques, the selection of assets and cost effectiveness (Starr, 2000). Moore and Starr (2005) propose a model to evaluate the total

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cost of machine damage, considering the direct cost and indirect cost of maintenance, and Kerf (2006) proposes a practical model for calculating the financial return of predictive maintenance. Allwood et al. (2013) define the concept of material efficiency as: "to continue to provide the services delivered by materials, with a reduction in total production of new material" (p. 3). This definition refers to a holistic and general perspective of the entire supply chain and society. In addition, studies have shown that 30 percent of the energy consumption in industry is wasted on machines in repair, idle, and stand-by states (Skogeh et al., 2011). From the perspective of environmental sustainability (particularly material efficiency), CBM enables the early identification of problems with equipment to avoid product damage, scrap generation and extra energy consumption. As a result, CBM directly contributes to sustainable manufacturing (Garetti and Taisch, 2011), lower life-cycle costs and the avoidance of catastrophic failure (Rosmaini and Kamaruddin, 2012).

2.3.3 Implementation of CBM

According to Shin and Jun (2015), many manufacturing companies have recently initiated efforts to adopt new technologies and obtain more accurate real-time information on the asset status during the usage period of the asset. As diverse information becomes available, the CBM approach of using this information to prevent a critical failure or degradation in advance has been emphasized (Shin and Jun, 2015). Although most machine maintenance is still either purely reactive (fixing or replacing equipment after it fails) or blindly proactive, world-class companies are moving toward "predict-and-prevent" maintenance (Kobbacy and Murthy, 2008), which is very similar to the goal of CBM.

According to Walker (2005), the implementation of CBM entails the use of condition monitoring technologies. Although a large number of condition monitoring tools exist, they are rarely used. A proper approach to implementation, primarily during the early decision-making phase of implementation, can address some challenges and lead to a well-implemented and effective CBM. Below is a list of important steps to take or factors to consider in implementing CBM. These factors are adopted or reworked from Bengtsson (2007b), Starr (2000), and Walker (2005):

- Feasibility test.
- Assignment of responsibilities.
- Identification of maintenance assets.
- Failure analysis to determine the parameters to monitor.
- Selection of appropriate techniques to detect failures.
- Selection of technologies.
- Production of a selection process to determine the CBM strategy.
- Cost-effectiveness evaluation.
- Management evaluation.

In the early decision making concerning implementation, a company must decide whether CBM is suitable for its situation based on technical, organizational, and economic factors (Bengtsson, 2006). The first two steps for information gathering regarding plant selection are the determination of plant criticality and an audit of existing maintenance activities (Starr, 2000). The criticality of a plant can be based on safety, capital value, and influence on the value of production (Starr, 2000). Condition monitoring can be performed using different approaches and utilized by different levels of technology (Jardine et al., 2006). The techniques must be appropriate for the failure mode and sensitive enough to provide an early warning of a major group of failures with infrequent measuring (Starr, 2000). Hess et al. (2001) also underline that the selection of technologies is based on the capabilities of the cost of machine damage, considering the direct cost and indirect cost of maintenance, and Kerf (2006) proposes a practical model for calculating the financial return of predictive maintenance. Allwood et al. (2013) define the concept of material efficiency as: "to continue to provide the services delivered by materials, with a reduction in total production of new material" (p. 3). This definition refers to a holistic and general perspective of the entire supply chain and society. In addition, studies have shown that 30 percent of the energy consumption in industry is wasted on machines in repair, idle, and stand-by states (Skogeh et al., 2011). From the perspective of environmental sustainability (particularly material efficiency), CBM enables the early identification of problems with equipment to avoid product damage, scrap generation and extra energy consumption. As a result, CBM directly contributes to sustainable manufacturing (Garetti and Taisch, 2011), lower life-cycle costs and the avoidance of catastrophic failure (Rosmaini and Kamaruddin, 2012).

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technology to provide early detection of degraded performance with less concern about whether its use is necessary based on a business perspective. Factors such as the buying, training, application, data processing and management of condition monitoring technologies must be considered very judiciously, and a condition monitoring strategy must be developed before acquiring technologies (Walker, 2005).

2.4 CBM of rotating machinery

One of the most common concerns of rotating equipment is the bearing condition (Morando, 1996). Bearing failure can result in major damage to shafts, rotors, and housings (Starr, 2000). Randall and Antoni (2011) also state that rolling element bearings are one of the most widely used elements in machines and that their failure is one of the most frequent reasons for machine breakdown. A rolling bearing is a mechanical component that carries loads and eliminates sliding friction by placing rolling elements (i.e., balls or rollers) between two bearing rings (i.e., the outer and inner raceways). Depending on the internal design, rolling bearings may be classified as radial bearings (i.e., those that carry radial loads) or thrust bearings (i.e., those that carry axial loads) (El-Thalji and Jantunen, 2015). Nearly all rolling bearings consist of four basic parts: the inner ring, outer ring, rolling elements, and cage, as illustrated in Figure 7.

![Figure 7 - Elements of a rolling bearing](image)

The majority of bearings fail before the natural fatigue limit of the bearing steel has been reached. In most cases, such failure is due to insufficient lubricant film between rolling elements and raceways. Inappropriate mounting, electrical currents and machine vibrations are other explanations for decreased bearing life (Morando, 1996). The Mobius Institute (2016) also emphasizes the most common causes of bearing damage as inappropriate lubrication, fatigue due to normal and parasitic loads, poor installation, and contaminations. All machines with moving components generate forces from responding motion or defective balance. These forces, in response, act on the bearings, where rotation or sliding is supported on rolling surfaces. Extreme increases in forces due to component damage, overloading, or poor design are the basis for early failures in bearings. Bearing condition monitoring provides information about the condition of bearing lubrication, possible bearing damage, and the need for special maintenance or bearing replacement (Morando, 1996).

2.4.1 Maintenance of machine tools

A machine tool is used in industry to fabricate metal components by removing a specific part of the metal (Mobius Institute, 2014). The operational availability of machine tools is an essential precondition for the profitability of the manufacturing industry (Verel et al., 2009). Preventive maintenance is one of the most effective maintenance approaches that leads to reducing wear and disruption of a production facility (Tajadod et al., 2016). Preventive maintenance involves minor and medium repairs, along with major overhaul. It is reported in...
the literature that an effective preventive maintenance program includes an inspection frequency schedule, items identified to be considered in the maintenance program, and component personnel, among others (Yousuf and Hassan, 2008). An example of the preventive maintenance of machine tools is provided in Table 1.

<table>
<thead>
<tr>
<th>Table 1 - Preventive maintenance scheme of machine tools (Yousuf and Hassan, 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component name</td>
</tr>
<tr>
<td>Guide ways</td>
</tr>
<tr>
<td>Ball-screw, Bearings</td>
</tr>
<tr>
<td>Guide ways, Ball Screw</td>
</tr>
<tr>
<td>Covers</td>
</tr>
<tr>
<td>Motor-spool</td>
</tr>
</tbody>
</table>

CBM techniques, such as vibration monitoring, have become important for ensuring machine availability through timely maintenance actions and reducing breakdown maintenance (Goyal and Pabla, 2015). During operation, machine tools generate vibrations that result in their deterioration, eventually causing failure of some subsystems or the machine itself. Vibration analysis can be used to detect the nature and extent of any damage in machines and components or any maintenance decisions related to the machine (Goyal and Pabla, 2015). According to ISO/TR 230-8 (2009), machine tool vibration must be controlled to mitigate the
types of vibration that produce undesirable effects such as “unacceptable cutting performance with regard to surface finish and accuracy, premature wear or damage of machine components, reduced tool life, unacceptable noise level, physiological harm to operators” (p. vii). SS 728000-1 (2014) provides information on how to evaluate the severity of machine tool spindle unit vibrations measured on the spindle housing. The CBM of machine tools ensures the basic conditions to deliver the appropriate ability or capability of the relevant machine at the correct time (Youssef and Hassan, 2008).

2.4.2 Machine tool spindle units

The spindle system is one of the critical subsystems of a machine tool that supplies the necessary power to the cutting process (Abel et al., 2010). The spindle is a high-precision component that comprises several parts, e.g., the rotor shaft, bearings, and clamping system. The key components of the spindle are as follows: 1) the spindle design, i.e., belt driven or with an integral motor; 2) the bearing design, including the type, tolerance, and method of lubrication; 3) the motor design, which comprises the belt type, motor spindle, capacity, and kW rating; 4) the spindle shaft, which can be a tool retention drawback, and the tooling system used; and 5) the spindle being used, including the size, mounting style, and capacity (Mobius Institute, 2014). All these components need to be in a perfect balance to achieve the required high accuracy at elevated rotational speed and high material removal rate under stable conditions. Furthermore, forming the interface between the machine tool structure and the cutting tool, as well as the spindle dynamic characteristics play a critical role in machining centers (Li and Mobin, 2015). Spindle requirements include accuracy, speed range capability, high rigidity, high damping capacity, and stable operating temperature (Chang and Chen, 2009).

As explained above, the components of the spindle should be carefully selected. To have the required spindle speeds, many factors need to be taken into consideration, e.g., using a precision bearing, using an effective bearing lubrication system, and utilizing the most effective cooling and cleaning system (Mobius Institute, 2014). The literature demonstrates that the bearing has the most significant effect on the spindle design (Martin 1994). The spindle shaft should also be designed in a way that provides a strong motor and appropriate tooling retention system, along with stiffness without developing bearing problems when all rotating components are operating in a balanced condition (Mobius Institute, 2014, Chang and Chen, 2009). In addition, the spindle housing, which transfers all factors from the spindle to the machine tool, should be robust and stiff in a way that completely supports and accurately locates the bearing and provides the required utilities for the spindle system (Mobius Institute, 2014).

In summary, different factors can affect the speed of the spindle, such as the bearing size and type and precision tooling systems, among other factors. Stiffness can be increased when the preload and the number of tandem bearings increase; however, these variables will reduce the speed. Higher speeds require higher-precision tooling systems, better balance, and cleanliness to obtain the desired results (Mobius Institute, 2014).

In the majority of spindle units, high-precision bearings with built-in preloads are used to enhance the stiffness of the bearing arrangement and increase running accuracy. The spindle bearings operate without load, or under very light load, and at high speeds. In such cases, the preload in high-precision bearings serves to guarantee a minimum load on the bearings, prevents bearing damage resulting from sliding movements and prolongs service life (Skf, 2003). However, because the lifespan of spindle bearings is unknown for different machines and each machine is in a different work environment, it is difficult to plan for spindle renovation.

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2.4.3 Vibration analysis of rolling element bearings
Vibration analysis is a common bearing condition monitoring technique. In rotating equipment, vibration analysis can diagnose failures by measuring overall machine vibration or, more precisely, frequency analysis (Starr, 2000). The vibration signals generated by faults in rolling element bearings have been broadly studied, and very powerful diagnostic techniques are currently available (Randall and Antoni, 2011). Vibrations are measured with an accelerometer. The vibration velocity parameter is measured as the broadband vibration magnitude in mm/s rms (root mean square). The vibration acceleration parameter is measured in mm/s² rms. Vibration measurement can be performed either by portable analyzers or on-line continuous monitoring systems.

It is necessary to analyze spectrum and time waveforms when there is any suspicion of a fault condition. The spectrum is a summary of the vibration within the machine. The fast Fourier transform (FFT) uses the time waveform to calculate how much of each frequency is present and displays that as a line in the spectrum. The time waveform is a record of what occurred from moment to moment as the shaft turns, the gears mesh, and the rolling elements roll around the bearing. Each minute change that results from impacts, rubs, scrapes, rattles, surges, etc. is recorded in the time waveform and then summarized in the spectrum (Mobius institute, 2017). For example, if there is damage on the inner race of a bearing, there will be an impact each time the ball or roller comes into contact with the damaged area. It will be seen in the spectrum as harmonics of a frequency that is not a multiple of the shaft turning speed (non-synchronous harmonics) with sidebands. Impacts are also observable in the time waveform (Mobius institute, 2017). Figure 8 indicates typical acceleration signals generated by localized faults in the different components of a rolling element bearing and the corresponding envelope signals generated by amplitude demodulation (Randall and Antoni, 2011).

Figure 8 - Typical signals and envelope signals from local faults in rolling element bearings, adopted from Randall and Antoni (2011)
Ball pass frequency, inner race (BPFI) is the rate at which a ball or roller passes a point on the inner race of the bearing (Mobius institute, 2016). If there is damage on the inner race, a periodic pulse of vibration is observed at this rate. Ball pass frequency, outer race (BPOF) is the rate at which a ball or roller passes a point on the outer race of the bearing (Mobius institute, 2016). If there is damage on the outer race, a periodic pulse of vibration is observed at this rate. FTF is the fundamental train frequency, and BSF/RSF is the ball/roller spin frequency (Randall and Antoni, 2011).

Rolling bearing damage in the early stages can be detected by using high-frequency measuring methods for the analysis, such as enveloping or demodulation, the shock pulse method (SPM) and PeakVue. Enveloping and demodulation are two names referring to the same technique. These techniques use the high-frequency vibrations observed as bearing damage and make them available as low-frequency vibrations that can be analyzed (Mobius institute, 2016). SPM monitors and analyzes the high-frequency compression (shock) waves created by a rotating bearing (Morando, 1996). Damage to the bearing surface causes a significant increase in the shock pulse strength that can be seen by SPM. Shock pulses are measured with a transducer with a natural frequency of 32 (kHz) (Sundström, 2010). The PeakVue method uses a signal processing technique to detect signs of bearing wear using a technique similar to acceleration enveloping. It samples the vibration at a very high rate (102.4 kHz) to detect any short duration stress waves that occur in the earliest stage of bearing fault (Mobius institute, 2016). Similar to the enveloping technique, the PeakVue method involves a filter setting suitable for the application based on machine speed and type.

The bearing wear or failure process can be described in four stages (Sundström, 2013). At the first signs of minor bearing damage, the vibration amplitude will be very low. The vibration generated will be a very high frequency—possibly over 10 kHz. Vibration spectrum analysis and time waveform techniques will not detect the fault. Only the spectrum from the high frequencies will reveal a fault. High-frequency techniques such as enveloping, SPM, and PeakVue may detect the fault in stage one, but only if the filter is set correctly and the accelerometer or shock pulse sensor is properly mounted. As the bearing fault develops, high-frequency techniques will be more effective. However, it is questionable if a linear velocity spectrum will indicate the fault. The fault is more likely to be seen in the acceleration spectrum. The time waveform in units of acceleration will demonstrate signs of the defect, especially when applied to slow-speed machines (Mobius institute, 2017). At this stage, measurement should be planned more often. When the bearing fault reaches stage three, the damage is more severe and will be visible if the bearing is removed. The velocity spectrum can be used to detect the fault in addition to the time waveform (in velocity or acceleration units) and high-frequency techniques (Mobius institute, 2017). At this stage, replacement should be planned soon. Bearing damage at this stage in a spindle unit, for example, can affect the quality of the work piece, or it can cause damage to the other machine components such as the cutting tool. When the bearing fault reaches stage four, the bearing has major damage and should be replaced as soon as possible. As the condition deteriorates, high-frequency techniques become less effective. Vibration levels will increase, and the velocity spectrum will indicate the fault. Non-synchronous harmonics and sidebands will disappear in the spectrum, and the spectrum will be very noisy. As vibration becomes noisier, the waveform will become noisier and less effective (Mobius institute, 2017).
2.5 Concluding highlights from the frame of reference

The highlights of the literature study are summarized as follows:

- By simultaneously reducing operations costs and maintenance costs and increasing the performance and reliability of production equipment, an effective and efficient maintenance strategy can provide manufacturing companies with a competitive production system.
- Despite the importance of developing strategic maintenance, a large part of the manufacturing industry lacks clear maintenance strategies.
- Proposals for strategic approaches lack descriptions of how to formulate a maintenance strategy to support the company’s strategic goals.
- CBM is being used to plan for maintenance action based on the condition of the machines and to prevent failures by solving the problems in advance.
- Condition monitoring can play a key role in providing persons responsible for management and maintenance with correct and reliable data to prevent unplanned production stoppages.
- The actual impact of maintenance is often under-estimated. The hidden cost impact of maintenance upon the business is far greater than just the direct costs associated with maintenance. Reducing these hidden costs requires a shift from the traditional reactive approach to a proactive approach.
- The effect of CBM on scrap generation has been under-researched, and only limited related information is available.
- An appropriate approach for the implementation of CBM is needed.
- Some of the necessary factors to consider when deciding whether to implement CBM are training, management direction, technology selection, user commitment and user competence.
- Measuring and monitoring machine tool condition has become increasingly important due to the introduction of lean production, increased accuracy requirements for products and customers’ requirements for quality assurance.
- CBM techniques, such as vibration monitoring, are becoming very attractive for companies operating high-value machines and components.
- By increasing the knowledge in CBM of machine tools, companies can save money through fewer acute breakdowns, reductions in inventory cost, reductions in repair times, and an increase in the robustness of the manufacturing processes, leading to more predictable manufacturing.

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- CBM is being used to plan for maintenance action based on the condition of the machines and to prevent failures by solving the problems in advance.
- Condition monitoring can play a key role in providing persons responsible for management and maintenance with correct and reliable data to prevent unplanned production stoppages.
- The actual impact of maintenance is often under-estimated. The hidden cost impact of maintenance upon the business is far greater than just the direct costs associated with maintenance. Reducing these hidden costs requires a shift from the traditional reactive approach to a proactive approach.
- The effect of CBM on scrap generation has been under-researched, and only limited related information is available.
- An appropriate approach for the implementation of CBM is needed.
- Some of the necessary factors to consider when deciding whether to implement CBM are training, management direction, technology selection, user commitment and user competence.
- Measuring and monitoring machine tool condition has become increasingly important due to the introduction of lean production, increased accuracy requirements for products and customers’ requirements for quality assurance.
- CBM techniques, such as vibration monitoring, are becoming very attractive for companies operating high-value machines and components.
- By increasing the knowledge in CBM of machine tools, companies can save money through fewer acute breakdowns, reductions in inventory cost, reductions in repair times, and an increase in the robustness of the manufacturing processes, leading to more predictable manufacturing.
3. Research methodology

This chapter presents the scientific approach and research method used to conduct this research. The research process is discussed to show how the research was conducted. Finally, issues regarding the quality of the research are discussed.

3.1 Scientific approach

Research can be performed using various methodological approaches (Arbtor and Bjerke, 1994). The choice of methodology depends largely on the researcher’s view of knowledge, but it also depends on the nature of the research questions being asked (Merriam, 2009). The three main approaches, as described by Arbtor and Bjerke (1994), are the analytical approach, the actors approach and the system approach. The system approach considers reality to be objective and constructed in such a way that components are mutually dependent. The system approach explains (understands) the components based on the properties of the whole (Arbtor and Bjerke, 1994). The system approach has been applied in the research conducted as part of this research. The research considers different aspects of condition based maintenance (CBM), including its economic, technical and organizational aspects. From a system perspective, CBM is composed of components that have mutual requirements. In addition, the system approach holds that real life is arranged in such a way that the whole differs from the parts (Arbtor and Bjerke, 1994). It is not possible to isolate CBM from its surroundings, as it requires input from internal/external connected interfaces such as the overall maintenance management and production system.

Moreover, according to Dhawan (2010), there are two basic approaches to research, the quantitative approach and the qualitative approach. The former involves the generation of data in quantitative form that can be subjected to rigorous qualitative analysis in a formal and rigid fashion. Dhawan (2010) states that the qualitative approach to research is concerned with the subjective assessment of attitudes, opinions and behavior. Research in this approach is a function of the researcher’s insights and impressions. One way of differentiating qualitative research from quantitative research is that qualitative research is largely exploratory, whereas quantitative research is more focused and aims to test hypotheses (Glenn, 2010). The use of qualitative and quantitative data is fundamental to research design, and both types of data can be utilized for generating and testing theories (Saunders et al., 2012). Qualitative data are more suitable for studying complex phenomena (Alvesson and Sköldberg, 2008). A combination of qualitative and quantitative approaches has been used in the current research, although qualitative data were the primary means of achieving the research objective.

Karlsson (2009) states that exploring an area, building analytical models, and providing a set of guidelines may not be possible within a limited scope. Research should naturally explore the field before defining a field of knowledge, identify the constituents before understanding the relations, and identify the relations before predicting the effects (Karlsson, 2009). Hyde (2000) states that there are two general approaches to reasoning that may result in the acquisition of new knowledge, namely, inductive reasoning and deductive reasoning. Interpretative reasoning is a theory building process that begins with observation of specific instances, and seeks to establish generalizations. Deductive reasoning is a theory testing process that begins with an established theory or generalizations and determines if the theory applies to specific instances. Qualitative research often follows an inductive process. However, in most instances, theory developed from qualitative research is untested theory (Hyde, 2000). In this thesis, a combination of inductive and deductive approaches were used in the studies, with the theories used to understand the phenomena before performing the empirical studies; as a result, new theories were generated in the form of work processes, models, frameworks, and guidelines. The developed theories were also tested and validated in
the empirical studies. In addition, this thesis can be categorized as applied research, i.e., the knowledge produced in the research should not only be of scientific relevance but also of industrial usefulness.

3.2 Research method

Saunders et al. (2012) describe a research strategy as a plan created by the researcher to answer the research questions. A research strategy can be defined as a methodical link between the philosophy and subsequent choice of methods to collect and analyze the data. To address the research questions and the objective, the research strategy here has been to find a suitable context for data collection and to study the phenomena affecting the successful implementation of CBM. A case study (Yin, 2009) was chosen as the main research method for collecting empirical data in this research. A case study method provides the opportunity to use multiple sources of data and different data collection techniques (Yin, 2009). Moreover, the case study method enables the researcher to understand the empirical data, thereby allowing a suitable analysis of the phenomenon studied (Yin, 2009). Following Saunders et al. (2012) and Merriam (2009), the empirical data for the case studies presented in this research were mainly collected through observations, interviews, questionnaires and documents. The data collection process in each study is described in greater detail in section 3.3.

In addition, literature studies were performed throughout the research process. First, a general literature study was performed to clarify, map and obtain a clear perspective of the existing state of the research area of interest while the research questions were being formulated. As the papers were written, more focused literature studies were performed. The relevant literature was predominantly found in books (including licentiate and doctoral dissertations) and academic papers published in conference proceedings and journals. The databases and search engines employed in the study to find relevant studies were Ebrary, Google Scholar, IEEE Xplore, Scopus and ScienceDirect. The main search terms or topics used were the following: “condition based maintenance”, “condition based maintenance cost effectiveness”, “condition based maintenance implementation”, “condition based maintenance of machine tools”, “condition monitoring”, “condition monitoring implementation”, “maintenance development”, “maintenance management”, “maintenance strategy”, “maintenance strategy formulation”, “manufacturing industry”, “vibration analysis”, “vibration analysis of fans” and “vibration analysis of rolling element bearings”.

3.3 Research process

This section will explain the research process to illustrate how the research was performed. Three main study areas (comprised of eight individual studies) were investigated as part of this research, which also included a pilot project that was performed while conducting the other studies. In Figure 9, the various studies performed during the present research are plotted in time.
Table 3 reports the studies, research methods and data collection sources used in each study as well as the research questions and the appended papers with the highest correlation to each study.

<table>
<thead>
<tr>
<th>Study</th>
<th>Research method</th>
<th>Data collection sources</th>
<th>RQ</th>
<th>Paper No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Maintenance management</td>
<td>A. Formulating maintenance strategy</td>
<td>Single case study, Observations, Interviews, Documents</td>
<td>1</td>
<td>Paper I</td>
</tr>
<tr>
<td></td>
<td>B. Maintenance decision making</td>
<td>Single case study, Observations, Documents</td>
<td>1</td>
<td>Paper II</td>
</tr>
<tr>
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<td>2</td>
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<td></td>
<td>B. Material efficiency through CBM</td>
<td>Single case study, Observations, Interviews, Documents</td>
<td>2</td>
<td>Paper IV</td>
</tr>
<tr>
<td>III. CBM implementation</td>
<td>A. CBM industrial practices and challenges</td>
<td>Multiple case study, Interviews, Documents</td>
<td>3</td>
<td>Paper V</td>
</tr>
<tr>
<td></td>
<td>B. CBM implementation process</td>
<td>Single case study, Observations, Questionnaires, Documents</td>
<td>3</td>
<td>Paper VI</td>
</tr>
<tr>
<td></td>
<td>C. On-line condition monitoring of fans</td>
<td>Single case study, Observations, Documents</td>
<td>3</td>
<td>Paper VII</td>
</tr>
<tr>
<td></td>
<td>D. CBM of machine tools</td>
<td>Single case study, Observations, Documents</td>
<td>3</td>
<td>Paper VIII</td>
</tr>
</tbody>
</table>
The following is the case company introduction, a summary of the research studies and a description of the data analysis performed in the present research.

3.3.1 Case company
All the case studies were performed in a large automotive manufacturing company in Sweden. The company produces gearboxes for trucks, buses and heavy equipment, with a production volume of 95,000 to 135,000 pieces per year in the period of studies. The company includes three main production processes: machining, hardening and assembly. The company operates with approximately 800 medium-size CNC machine tools, such as turning machines, machining centers, milling machines, boring machines and grinding machines, as well as six furnaces in hardening.

3.3.2 Study I – Maintenance management

A. Formulating a maintenance strategy
The first study concerns strategic maintenance management and the formulation of a maintenance strategy. The main objective of this study was to define a process for formulating a maintenance strategy to facilitate maintenance management to further strategic development. The empirical basis for the study was a single case study. The main data source was participant observation. The observations were primarily obtained by observing the status of the company’s plant and, when possible, participating in maintenance-related meetings and in internal and external audits at the company. The data were also collected through on-site interviews and document analysis. The interviews were semi-structured using a set of predetermined questions listed in Appendix 1. In total, four interviews were conducted at the site. The interviewees were maintenance managers. Each interview lasted approximately one hour. The interviews were recorded, and notes were taken to strengthen the validity and reliability of the data. The interviews were transcribed by the interviewer. In addition, various documents, including maintenance strategies, maintenance audits, maintenance organization charts, and maintenance activities, were studied. Analysis of the empirical data provided the framework for formulating a maintenance strategy. The researcher then conducted several workshops with two maintenance managers to formulate the case company’s current maintenance strategy. Then, the maintenance strategy was provided and presented to the company.

B. Maintenance decision making
The purpose of this study was to provide models that can be linked to the CMMS in order to add value to data collected in the system by providing decision-making capability. The empirical basis for the study was a single case study. This study was conducted within a global project at the case company to provide a new CMMS. Therefore, the data were mainly collected by direct observation, including participation in project meetings. The data were also collected through document analysis complemented by discussions with maintenance engineers and managers at the case company to verify the data. Various documents, including the emergency work orders (EWO) database, maintenance audits, maintenance strategies and maintenance activities at the case company, were studied. Methods including a multiple criteria decision making (MCDM) technique called TOPSIS, the k-means clustering technique, and one decision-making model adopted from the literature were used. The results indicate the most appropriate maintenance decision for each of the selected machines/parts according to factors such as frequency of breakdowns, downtime, and cost of repair. It concludes with a comparison of results obtained from the different decision-making techniques and possible improvements needed to increase the capability of the maintenance decision-making models.

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3.3.3 Pilot study
To illustrate the extent to which advanced CBM practices are applicable and cost effective in a manufacturing company and serve as a guide for further research and development in this area, a pilot project was followed in real time. The pilot project was performed at the case company presented in section 3.3.1. The management team at the case company expressed interest in investing in and conducting this pilot study in its hardening and machining production processes. The purpose of the pilot project was to implement condition monitoring of gas circulation fan electric motors in hardening and machine tool spindle units in machining processes. The pilot project, which started with five fans and five machine tools, evolved into sixty machine tools.

The researcher’s ability to perform this pilot study in real time represented an excellent opportunity to collect valuable data to fulfill the research objective. The researcher played an active role in this project by cooperating with the maintenance managers and maintenance engineers at the case company as well as with the contact people from a condition monitoring supplier. Therefore, the researcher employed participant observation as the data source during the pilot study, and empirical data were collected during project meetings, workshops and informal discussions with the project members. The pilot project was conducted in parallel with the other studies in the present research. However, some of the data collected during the pilot study was used in study area II and study area III.

3.3.4 Study II – CBM cost effectiveness
A. CBM cost-effectiveness model
This study was performed to investigate the cost effectiveness of implementing CBM in the manufacturing industry. The empirical basis for the study was a single case study, complemented by a brief benchmark using data from a reference manufacturing site in Sweden. The main source of data was participant observations through the pilot project of implementing CBM at the case company. In the study, CBM was applied to five critical gas circulation fans in a furnace in the hardening area of the production facility, four turning machines and one grinding machine in the machining area. The data from the case study were collected through various workshops with different departments at the case company, primarily with maintenance engineers (see Table 4). For a suitable approach, the information regarding the parameters in the cost-effectiveness model was collected through questionnaires and discussed during the workshops (see Appendix 2).

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<th>Workshop</th>
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<tr>
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Table 4 - Workshops

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Analysis of the empirical data revealed the necessary factors to consider in analyzing the cost-effectiveness of CBM in the manufacturing industry. Consequently, the main benefits of implementing CBM at the company were identified and presented to the case company.

**B. Material efficiency through CBM**

The results presented in this study are primarily based on a single case study. The empirical data collection performed in this study was based on direct and participatory observations, semi-structured interviews and document reviews. The observations included the implementation of CBM at the case company, in which a total of eight critical gas circulation fans on two furnaces and one critical fan in a phosphating area were investigated. The objective of the CBM implementation was to implement on-line condition monitoring on the fans, to enable continuous monitoring of the condition of the fans and to trigger a warning upon any relevant change.

The document reviews included the review of historical data and reports on furnace breakdowns and maintenance activities as well as a cost-effectiveness evaluation of the implementation of CBM for the real-time cases of the electric motors of the monitored fans used in the phosphating and hardening processes. The document reviews complemented the empirical data collection by providing an overview of the manufacturing processes and an increased understanding of the historical maintenance activities and maintenance strategies.

Two maintenance engineers and two maintenance technicians responsible for the hardening and phosphating processes were interviewed in a semi-structured approach. These semi-structured interviews were primarily based on the CBM cost-effectiveness model proposed in study II-A, in which various costs related to production loss, quality loss, environmental loss, safety loss and customer satisfaction loss are estimated. This empirical study was then complemented with a literature study concerning CBM and material efficiency in the manufacturing context. The literature search included a keyword search of scientific data, and the selection method was based on both keywords and qualitative upstream and downstream searches for relevant references. By analyzing the empirical data, a real-time implementation of CBM at the case company from the perspective of material efficiency is evaluated.

### 3.3.5 Study III – CBM Implementation

**A. CBM industrial practices and challenges**

This study was performed to present an introductory review of CBM practices applied in the manufacturing industry. The empirical basis for the study was a multiple case study of two major manufacturing sites in Sweden, complemented by a brief benchmark using data from reference manufacturing sites in France and Brazil.

The data were collected through on-site interviews and document analysis from two manufacturing sites. Additional data from the two reference sites were obtained via document analysis. Table 5 describes the case companies and data collection techniques. The interviews were semi-structured using a set of predetermined questions listed in Appendix 3. In total, six interviews were conducted at the two sites A and B. The interviewees were maintenance managers and maintenance engineers. Each interview lasted approximately one hour. The interviews were recorded, and notes were taken to strengthen the validity and reliability of the data. The interviews were transcribed by the interviewer.

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implementing CBM at the manufacturing company was developed. Using this information, the process for implementing CBM at the manufacturing company was developed.

To strengthen the validity and reliability of the data, the information was documented in hand notes and interview protocols. The data from the case study were collected during project meetings, workshops and informal discussions with the project members, including maintenance engineers, maintenance managers, contact people from the condition monitoring supplier company, and industrial and academic supervisors. To ensure a suitable approach during discussions and to ensure that the pilot project could be pursued in a structured and manageable way at the company, a questionnaire was used during the decision-making phase of the pilot project. The questionnaire is shown in Appendix 4. In addition, various documents, including the project’s object specifications, the company’s project model, and information on condition monitoring technologies from the supplier company, were studied. To strengthen the validity and reliability of the data, the information was documented in hand notes and computer files during the implementation process. Using this information, the process for implementing CBM at the manufacturing company was developed.

**Table 6 - CBM implementation matrix framework**

<table>
<thead>
<tr>
<th>Product type</th>
<th>Process type</th>
<th>Asset type</th>
<th>CBM technique</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Geometry analysis</td>
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<td></td>
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<td>Force control</td>
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</tbody>
</table>

In addition, various documents were studied, including maintenance audits, maintenance organization charts and CBM maps at the case companies. By analyzing the empirical data, the current industrial practices regarding CBM in the manufacturing industry were mapped to the matrices. Furthermore, several issues regarding the implementation of CBM in the manufacturing industry were discussed.

**B. CBM implementation process**

This study was performed to provide a work process for implementing CBM in the manufacturing industry. The empirical basis for the study was a single case study. The main source of data was participant observations obtained during the pilot project implementing CBM at the case company. The data from the case study were collected during project meetings, workshops and informal discussions with the project members, including maintenance engineers, maintenance managers, contact people from the condition monitoring supplier company and industrial and academic supervisors. To ensure a suitable approach during discussions and to ensure that the pilot project could be pursued in a structured and manageable way at the company, a questionnaire was used during the decision-making phase of the pilot project; the questionnaire is shown in Appendix 4. In addition, various documents, including the project’s object specifications, the company’s project model, and information on condition monitoring technologies from the supplier company, were studied. To strengthen the validity and reliability of the data, the information was documented in hand notes and computer files during the implementation process. Using this information, the process for implementing CBM at the manufacturing company was developed.

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</table>

The data were collected in two formats: interview protocols and CBM implementation matrices. The framework in Table 6 was used for the matrices to present the current CBM practices at the case companies. The matrices were completed by the interviewer based on the answers from the respondents.
C. On-line condition monitoring of fans

As explained, one of the purposes of the pilot project was to implement on-line condition monitoring of five critical gas circulation fans in the hardening process of the case company. The empirical basis for this study is thus a case study, and the data were mainly collected by direct and participatory observations while performing the pilot project to implement on-line condition monitoring of the fans. In addition, various documents were reviewed, including the fan specifications, the historical data and reports of fan breakdowns and their maintenance plans, as well as information on condition monitoring technologies from the supplier company. Thus, CBM via on-line condition monitoring technology was implemented at the case company. The real-time cases from the industry are presented in this study, focusing on the use of vibration analysis to detect bearing damage. By analyzing the empirical data, guidelines to implement on-line condition monitoring on fans are provided, and the advantages of the on-line condition monitoring are discussed.

D. CBM of machine tools

Another purpose of the pilot project was to implement CBM on machine tool spindle units at the case company. Thus, CBM via the vibration monitoring technique was implemented on different types of machine tools, including turning machines, milling machines, grinding machines, and machining centers. The empirical basis for this study is thus a case study, and the data were mainly collected by direct and participatory observations while performing the pilot project to implement vibration monitoring of machine tool spindle units. In addition, to provide a more generic view of the area of the study, a similar manufacturing company, as a reference company, was visited, and an interview was carried out with three CBM specialists. Various documents were reviewed, including the machine specifications, the bearing catalogues, the historical data and reports of spindle failures and their maintenance plans, as well as information on condition monitoring technologies from the supplier company. The real-time cases from the industry are presented in this study, focusing on the use of vibration analysis of spindle units to detect bearing damages. By analyzing the empirical data, guidelines to implement vibration analysis of machine tool spindle units are provided, and the cost effectiveness of the implementation is discussed. The results can be used for both maintenance and production purposes; i.e., they can provide a strong base for preventive maintenance at the manufacturing company and can also be used to optimize a machine’s operations and quality of the products.

3.3.6 Data analysis

The data collected must be processed and analyzed to draw conclusions. Various approaches to analyzing data are described in the literature. The clustering method and pattern-matching logic were used for data analysis in the current research. In the clustering method, the researcher groups similar data into specific categories and then conceptually these categories to illustrate similar patterns or characteristics (Merriam, 1994). The data analysis of the observations, transcribed interviews, questionnaires and documents was based on the clustering method, where essential categories were identified. The categories were further developed to identify their relationships and patterns. The reason for selecting categories was to obtain a better understanding of the phenomenon and to better link the research findings.

In addition, pattern-matching logic was used when analyzing the empirical data in the case studies. Pattern-matching logic is a technique that essentially involves comparing empirically observed patterns with predicted ones (Yin, 2009). Pattern matching helps to ensure that there is a logical connection between the study results and existing theories within the field. Therefore, the empirical data from the case studies were continuously compared with the reviewed literature to find similarities and differences. For example, the interviews were
transcribed, and pattern-matching logic was applied to relate the empirical results to existing
theories within the context of the studies. In addition, the patterns and characteristics observed
among the empirical cases were also evaluated. Thus, the empirical findings from the various
resources, i.e., interviews, observations and documents, were continuously compared to
maintain the same data analysis quality.

However, all data analysis techniques are dependent on the researcher’s pre-understanding.
Some of the researcher’s previous work experiences in the research area affected the current
research. Therefore, efforts were made to involve maintenance engineers and managers at
the case company, researchers at conferences and academic supervisors to analyze the data in
each of the studies to reduce implications made by the researcher and prevent weakness due to
bias.

3.4 Research quality
Evaluating the quality of research is an important but difficult task, especially when, as in this
research, the results are based primarily on qualitative data (Corbin and Strauss, 2008). The
two most commonly used terms when judging the quality of research are validity and
reliability. According to Gummesson (2000), validity refers to “the extent to which
researchers are able to use their method to study what they had sought to study rather than
(often without being aware of it) studying something else” (p.91). When case studies are
employed, as in this research, Yin (2009) argues that the criteria for judging the quality of
research are construct validity, internal validity, external validity and reliability. These quality
measurements are described below.

3.4.1 Construct validity
Construct validity is concerned with the level of conformity between what is actually studied
and the intended subject of study (Saunders et al., 2012). Tactics that can be used to increase
construct validity include the use of multiple sources of evidence and a review of the draft
case study report by the key informant (Yin, 2012). In the case studies in this research, these
measures were considered to increase construct validity. Multiple data sources were used for
data collection in the case studies, including observations, interviews, questionnaires and
documents. The results were also triangulated using different data sources. In addition, the
participants in the case studies, particularly during the pilot project, reviewed and controlled
the findings across presentations of the results in different steps of the research process.

3.4.2 Internal validity
Internal validity concerns the question of how research findings match reality (Merriam,
2009). An example of a tactic that can be used to increase internal validity is pattern matching
(Yin, 2009). In the case studies included in this thesis, pattern matching was employed when
analyzing the empirical data to ensure that there was a logical connection between study
results and the existing theories within the field. Moreover, maintenance engineers and
managers at the case company, researchers at conferences and academic supervisors were
involved in each study to reduce the implications made by the researcher and prevent
vulnerability to bias.

3.4.3 External validity
External validity is concerned with the extent to which the findings of a study can be
generalized and are applicable to other relevant settings (Merriam, 2009). According to
Gummesson (2000), a common criticism of case studies as a scientific method is the inability
to generalize their results. He covers the difficulties of generalizing from a limited number of
cases and notes that generalizability is closely related to validity. Yin (2012) suggests using
theory in single case studies to secure external validity. In the case studies in this thesis, the
empirical findings were continuously compared with the reviewed literature to identify

justifying and contracting theories and to explain similarities and differences with theory. Moreover, multiple cases were selected for study in study III-A. While conducting the pilot project, the aim was to use various types of objects at the case company in studies II and III to ensure external validity.

3.4.4 Reliability
Reliability refers to the repeatability of research results. More precisely, the use of similar data collection and analysis techniques should lead to similar findings if a study is repeated or conducted by another researcher (Saunders et al., 2012). However, organizations and humans are subject to constant change, which means that it is infeasible to completely replicate studies (Merriam, 1998). As the research presented in this thesis was mainly qualitative, a recreation of the study conditions is not possible because it is very reliant on the researcher’s own understandings. According to Merriam (1994), independent of the type of research at hand, reliability can be strengthened through careful attention to the way that data and information are gathered, analyzed and interpreted. Therefore, to strengthen reliability, every step in the case studies was carefully documented, and the research methodology was described transparently. This was achieved by fully describing all steps in the process of collecting and analyzing data.

3.4.5 Role of the researcher
The researcher who conducted this research is an industrial PhD student at Mälardalen University and has been a part of the INNOFACTURE Research School since September 2012. He is also employed as a maintenance engineer at Volvo Group Trucks Operation (GTO). He has a master’s degree in product and process development – production and logistics – and a bachelor’s degree in mechanical engineering. The researcher’s background is in the manufacturing industry, where he has worked as a CAD designer in an R&D department and as the head of a preventive maintenance department in Iran. As the head of a preventive maintenance department, the researcher worked with tasks such as root cause analysis, maintenance planning, scheduling condition monitoring plans and developing CBM for the manufacturing company. Before becoming an industrial PhD student, the researcher worked at the case company as part of his master’s thesis in strategic maintenance development by formulating a maintenance strategy at the company.

The researcher has acquired knowledge in the field of production maintenance in a manufacturing context. The researcher’s background has provided information regarding which persons to contact to address various questions. As this research was conducted in the company in which the researcher was employed, the researcher adopted the role of an internal researcher (Saunders et al., 2012). Moreover, he played an active role in leading the pilot project at the case company. Therefore, he had considerable opportunity to access sources of data and communicate with the case company to verify and further extend the empirical findings. The research could thus have influenced the case company and the mindset of the members of the maintenance department and other participants in the case studies.

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4. Summary of findings in research studies

This chapter summarizes the findings obtained in research studies.

4.1 Strategic maintenance management: formulating a maintenance strategy

This research finding is based on study I-A and primarily addresses RQ1. Its main purpose is to define a process through which to formulate a maintenance strategy to facilitate further development in a strategic manner. The problem is investigated by means of a literature study and a case study at the case company, and a maintenance strategy is formulated and presented. The process used to formulate the maintenance strategy and the formulated maintenance strategy itself are the main findings of study I-A. In addition, a summary of the company’s view of strategic maintenance development as the result of the performed interviews is also presented. This is followed by a summary of the essential factors to formulate a maintenance strategy. The more detailed results of the study, in addition to the definitions and descriptions of the performance indicators and action plans used in this section, can be found in the appended paper I.

4.1.1 The proposed process of maintenance strategy formulation

One positive aspect of formulating a maintenance strategy for a company such as the case company is that the company’s business strategy had previously been formulated, and both the company and its maintenance department had clearly formulated visions and missions. Moreover, although there was not a clear maintenance strategy, some maintenance goals and activities had been identified in different managerial frameworks, such as “management by objectives”. These positive aspects of the case company enabled the formulation process to extend a step beyond other processes proposed in the literature. Figures 10 and 11 show different phases of maintenance strategy formulation and the factors that should be included in the maintenance strategy.

Figure 10 demonstrates that the work process begins by collecting data from the company, including different perspectives on maintenance strategies and the vision and mission of the company with regard to maintenance as well as maintenance activities, including “management by objectives” and “professional maintenance” within the “world class manufacturing (WCM) method” used by the company. Based on the information gathered, strategic objectives for maintenance and their relevant KPIs can be identified. In this step, a balanced scorecard is proposed to structure the maintenance strategy. Depending on the company’s objectives, targets for the next three years should be determined, and action plans to reach these targets and objectives should be established. Then, relevant measures indicating the status of the action plans should be classified.

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The main purpose of the maintenance strategy is to establish a relationship between the factors included and the objectives and action plans. This strategy includes more areas than the business strategy. However, the important element here is to establish a relationship between the factors included and the objectives and action plans.

The last phase involves establishing a clear link between the maintenance strategy and the strategic action plans. In this step, the maintenance strategy should be classified in the same areas as the business strategy, although in some cases, the maintenance strategy includes more areas than the business strategy. However, the important element here is to establish a relationship between the factors included and the objectives and action plans.

The main purpose of the maintenance strategy is to indicate a clear direction between activities and their results to help the company achieve its strategic goals.

In the next phase, the strategic action plans are classified into three levels: strategic, tactical, and operational (see Figure 11). The use of different levels of action plans allows factors such as responsibility and time to be more easily recognized. Furthermore, the maintenance manager and other personnel can obtain a more appropriate overview of the maintenance activities and ways to manage them.

The last phase involves establishing a clear link between the maintenance strategy and the company’s business strategy (see Figure 11). In this step, the maintenance strategy should be classified in the same areas as the business strategy, although in some cases, the maintenance strategy includes more areas than the business strategy. However, the important element here is to establish a relationship between the factors included and the objectives and action plans.

The main purpose of the maintenance strategy is to indicate a clear direction between activities and their results to help the company achieve its strategic goals.
4.1.2 Formulated maintenance strategy

The formulated maintenance strategy is divided into two parts that are each described in this section: strategic objectives and action plans.

Strategic objectives

The strategic objectives of maintenance are formulated and presented as illustrated in Figure 12. As described, a balanced scorecard is an appropriate manner in which to formulate the strategy that has been applied as a solution in this study. According to the case company’s business strategy, the strategic objectives of maintenance are classified into different areas, including safety/quality/environment, leadership, employeeshop, the organization and ways of working, competence, delivery, productivity and economy. Within these areas, the relevant objectives and their measures (KPIs) are set, as are the targets for the current and the coming three years.

<table>
<thead>
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<th>Strategic objectives</th>
<th>Measures (KPIs)</th>
<th>YTD 2012</th>
<th>Target 2013</th>
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Figure 12 - Strategic objectives
In the area of safety/quality/environment, an improved safety culture and reduced energy consumption are the strategic objectives for the maintenance department. The strategic objective for maintenance with regard to leadership is to reach the highest steps of professional maintenance within the WCM method. Therefore, the maintenance manager can provide proper supervision by measuring the defined KPIs for each step, such as the number of breakdowns for classified machines, reduced preventive maintenance (PM)-related costs and coverage of the components in the CMMS.

In the area of employment, there is a significant measurement for the manager, the Volvo group attitude survey (VGAS). The purpose of the VGAS is to continuously improve the working climate. Thus, the engagement of employees in this survey is important for the managers. The results can be calculated to include the employee engagement index (EEI). Improving SS in the working environment is also part of the strategic objectives of maintenance within employment and can be measured by its audit measurement.

An emergency work order (EWO) plays a key role in working with maintenance in the case company. A “right first time EWO” is a process implemented by the maintenance department to increase the efficiency of work orders, which can be measured by decidable EWOS per their total number. A dependability measurement that indicates the maintenance supportability of the organization is mean waiting time (MWT), which may include mean waiting time for spare parts (MWTISP). MWT can be improved by implementing Andon, and improving it is an important strategic objective for maintenance in the case company.

Mean time to repair (MTTR) is a dependability measurement that indicates maintainability and illustrates the competence of maintenance personnel in performing maintenance work. A decrease in MTTR is an important strategic objective for maintenance. A personal business plan (PBP) and an individual contribution plan (ICP) are two other competence indicators in this area, and the percentage of their completed activities is a strategic objective for maintenance.

With respect to delivery, increased technical availability is a strategic objective that can be measured by overall equipment availability (OEA). This is one of the most important objectives and indicates the extent to which the maintenance department delivers services to production.

Mean time between failures (MTBF) is a dependability measurement that indicates equipment reliability. MTBF, MWTISP and the capability for planned maintenance can indicate the productivity of maintenance. Therefore, these objectives are formulated in the productivity area.

One important aspect of maintenance that is frequently lacking in the formulation of a maintenance strategy is the financial aspect of maintenance (Salonen, 2011). The presence of a financial factor within a maintenance strategy can indicate how cost effective the maintenance work has been and can provide the maintenance manager with a better perspective regarding how to manage costs for effective and efficient maintenance. As an example, maintenance cost reduction per produced unit has been understood as a strategic objective in this area in the case company.

**Action plans**

In the formulated maintenance strategy, maintenance actions are classified into relevant areas linked to business strategy. In this way, the maintenance manager can clearly see which action plan is occurring in which area and can directly observe the results using defined KPIs. Figure 13 illustrates the formulated maintenance action plans in the different areas.

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The maintenance strategy’s action plans can be structured into three levels, strategic, tactical and operational. Therefore, appropriate responsibilities for each level and measures to follow up maintenance actions can be defined. Moreover, the maintenance manager can define the time or deadlines for action plans.

In this study, maintenance action plans are classified into the same areas as the strategic objectives of maintenance, related to the business strategy’s action plans. Furthermore, action plans are structured into levels according to organizational layers.

4.1.3 The case company’s view on strategic maintenance development

Part of the results of this study involves the case company’s view on strategic maintenance development, which is summarized as follows:

- The maintenance strategy was not clearly written and was not well aligned with the company’s business strategy.
- The company used KPIs for control of the strategic, as well as the tactical and operational, levels.
- The company worked to continuously improve its maintenance activities.
- The company implemented a lean concept within maintenance by adding activities such as Kaizen.

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- The company worked to continuously improve its maintenance activities.
- The company implemented a lean concept within maintenance by adding activities such as Kaizen.
• The company has begun to work with a newer CMMS with more attention to collecting valuable data to contribute to maintenance planning.
• Top-down management and the maintenance managers shared the view that maintenance is a strategically important function.
• The manufacturing company in this study showed considerable potential within the maintenance department by increasing interest in proactive tools and methods, such as condition based maintenance (CBM), to develop maintenance management that can fulfill the company’s overall goals in a lean environment. Therefore, an action plan to be included in the maintenance strategy is to develop and implement CBM to reach the highest possible level of proactive maintenance.

### 4.1.4 Essential results – Formulating a maintenance strategy

The necessary factors to be considered to formulate a maintenance strategy are summarized as follows:

- The main purpose of a maintenance strategy is to indicate a clear direction between activities and their results to help the company achieve its strategic goals.
- It is important to establish a clear link between the maintenance strategy and the company’s business strategy.
- The company and its maintenance department should clearly formulate their visions and missions.
- Maintenance goals and activities should be identified and settled in different managerial frameworks.
- A balanced scorecard can be used to structure the maintenance strategy.
- Strategic objectives for maintenance and their relevant KPIs should be identified.
- The strategic objectives of maintenance can be classified into different areas, including safety/quality/environment, leadership, employee, the organization and ways of working, competence, delivery, productivity and economy.
- The presence of a financial factor within a maintenance strategy can indicate how cost effective the maintenance work has been and can provide the maintenance manager with a better perspective regarding how to manage costs for effective and efficient maintenance.
- Depending on the company’s objectives, targets for the next three years should be determined, and action plans to reach these targets and objectives should be established.
- Relevant measures indicating the status of the action plans should be classified into relevant areas linked to business strategy.
- The maintenance strategy’s action plans can be structured into three levels: strategic, tactical and operational.

### 4.2 Maintenance decision-making model

This research finding is based on study I B and primarily addresses RQ1. The purpose of this study was to provide models that can be linked to the CMMS in order to add value to data collected in the system by providing decision-making capability. The empirical basis for the study was a single case study at the case company. Methods including decision-making grid (DMG), technique for order of preference by similarity to ideal solution (TOPSIS) and clustering techniques adopted from the literature were used in the case company. As a result of this study, the information required for proper maintenance decision making and the decision-making models are identified, and the details on how they were utilized are described. The results indicate the most appropriate maintenance decision that suits each of the selected machines according to factors that include frequency of breakdowns, production downtime, and cost of repair. The results together with the proposed models are presented in

- The company has begun to work with a newer CMMS with more attention to collecting valuable data to contribute to maintenance planning.
- Top-down management and the maintenance managers shared the view that maintenance is a strategically important function.
- The manufacturing company in this study showed considerable potential within the maintenance department by increasing interest in proactive tools and methods, such as condition based maintenance (CBM), to develop maintenance management that can fulfill the company’s overall goals in a lean environment. Therefore, an action plan to be included in the maintenance strategy is to develop and implement CBM to reach the highest possible level of proactive maintenance.

### 4.1.4 Essential results – Formulating a maintenance strategy

The necessary factors to be considered to formulate a maintenance strategy are summarized as follows:

- The main purpose of a maintenance strategy is to indicate a clear direction between activities and their results to help the company achieve its strategic goals.
- It is important to establish a clear link between the maintenance strategy and the company’s business strategy.
- The company and its maintenance department should clearly formulate their visions and missions.
- Maintenance goals and activities should be identified and settled in different managerial frameworks.
- A balanced scorecard can be used to structure the maintenance strategy.
- Strategic objectives for maintenance and their relevant KPIs should be identified.
- The strategic objectives of maintenance can be classified into different areas, including safety/quality/environment, leadership, employee, the organization and ways of working, competence, delivery, productivity and economy.
- The presence of a financial factor within a maintenance strategy can indicate how cost effective the maintenance work has been and can provide the maintenance manager with a better perspective regarding how to manage costs for effective and efficient maintenance.
- Depending on the company’s objectives, targets for the next three years should be determined, and action plans to reach these targets and objectives should be established.
- Relevant measures indicating the status of the action plans should be classified into relevant areas linked to business strategy.
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this section. This is followed by a presentation of the relevant items for the maintenance decision making. The results can be found in more detail in the appended paper II.

4.2.1 Application of maintenance decision-making grid in the case company

The model proposed by Labib (2004), the DMG, is used in this study. The model is based on identifying the criteria of importance, including downtime, frequency of failures and cost. The DMG then proposes different maintenance policies based on the state in the grid, which is indicated in Figure 14. Maintenance policies are described in greater detail in section 2.1.

The first step that must be taken to obtain a DMG is criteria analysis (Labib, 2004). The aim of this phase is to establish a Pareto analysis of two important criteria: downtime and frequency of breakdowns. Downtime and frequency of breakdowns can be substituted by MTTR and MTBF. The purpose is to assess how bad the worst performing machines are for a certain period of time.

To establish equipment criticality, manufacturing companies in Sweden mainly use an ABC-type classification (Gopalakrishnan et al., 2015). The machines at the case company are therefore classified into AA, A, B and C levels. In this classification, AA machines are the most important machines. Appendix 5 includes criteria analysis on data collected from the EWO database for AA machines at the case company. The analysis shows that 53 percent of the total downtime of the company during the six months of the year, in addition to 54 percent of the number of breakdowns, is caused by failures of AA machines. The worst performing machines in both criteria are sorted and grouped into high, medium, and low sub-groups. It is obvious that machine numbers 8527784 and 87843 are the worst machines in that they have the highest downtime and frequency of breakdowns. However, performance of criteria analysis requires consideration of different aspects such as the analytic hierarchy process of faults related to the machine system and components, as well as the performance of more mathematical analysis to reach an accurate scope for each level.

The next step is to place the machines in the DMG (Figure 14) to recommend asset management decisions (Labib, 2004). By locating machines in the DMG (decision mapping), the model indicates which maintenance policy should be selected for each machine (Figure 15). For instance, machine number 87843, which has the highest downtime and the highest frequency of failure, in the top-right region, is the worst performing machine, and the action to implement, or the rule that applies, is DOM; accordingly, the machine design should be modified. On the other side, in the bottom-left region, machine number 8528622, which has the lowest downtime and frequency of failures, can work until a failure occurs (BM). In the top-left region, SLU is the most appropriate policy; the high frequency of breakdowns with low downtime show that a machine has been stopped many times for limited periods of time. Therefore, maintaining this machine is a rather easy task that can be performed by operators after upgrading their skill levels. The machines with performances located in the bottom-right region are problematic machines. The low frequency of breakdowns shows that the machines do not breakdown often, but their high downtime shows that each breakdown can last for a
long time due to a large failure. Therefore, the appropriate action for these machines is CBM to analyze the breakdowns and monitor the machines’ conditions. If a machine is located in a region with a medium downtime or a medium frequency, the appropriate policy to take is TBM. However, sometimes two machines are exactly the same, and they are doing the same work in the same environment but are located in different grids. Maintenance engineers should therefore perform more analysis according to maintenance concepts such as TPM and RCM in order to select the appropriate maintenance policy. In addition, in some cases, two machines are located near or at the border of two different grids. Maintenance concepts can be helpful in deciding which decision to make in these cases. For example, when downtime is high but the frequency of failure is low, performing some analysis such as RCM can be considered to decrease downtime.

The model proposed in this section can be a solution to provide decision-making analysis capability for the system by adding value to data collected in the CMMS. To obtain a more logical model and use data for selecting maintenance policy, a cost function must be considered. For this reason, the company needs to have historical cost data, such as cost of failures for production and cost of maintenance. By considering cost and performing criteria analysis, the model will have three dimensions on a fuzzy surface, with each region indicating which maintenance policy should be selected (Figure 16). In this model, the assumption is that the cost function of maintenance policies is linear and obeys the following relationship: DOM > CBM > SLU > TBM > BM.

Figure 15 - DMG for AA machines at the case company

Figure 16 - The fuzzy decision surface showing the regions of different maintenance policies, adopted from Labib (2004)
In addition, the criteria analysis that has been performed in this section is at the machine level. To obtain a more accurate decision-making model, this criteria analysis should be performed at the component level. Furthermore, the level of fault in the analytical hierarchy process (AHP) should be prioritized and analyzed according to the components.

4.2.2 Application of MCDM and clustering technique in the case company

The logic of the DMG (in Figure 14) is adopted from Labib (2004) and is used in combination with two mathematical methods to rank and categorize the case company’s machines and parts in their relevant maintenance policy groups.

**TOPSIS**

The most widely used MCDM tool called TOPSIS (Hwang and Masud, 1979) is used in this section to rank the machines and parts. The basic mechanism of this approach is to calculate the distance from each alternative to a positive-ideal solution (PIS) and a negative-ideal solution (NIS), which are defined in n-dimensional space, where “n” represents the number of criterion in the decision problem. The chosen alternative should have the smallest vector distance from the PIS and the greatest from the NIS. The TOPSIS algorithm presented in Mobin et al. (2014) and Salmon et al. (2015) is utilized in this study. Using the TOPSIS method, machines are ranked based on three criteria, including downtime, cost and frequency of failures. Based on the TOPSIS method, the ranked machines are divided into five categories and are presented in Figure 17 for visualization purposes. According to these categories, five different maintenance policies can be considered. The configurations of each category are summarized in Appendix 6. The total number of machines is equal to 540.

![Figure 17 - Ranked machines based on TOPSIS using 3 criteria](image)

To perform more investigations on the data, the parts are also ranked based on three criteria as mentioned above. Applying the TOPSIS method with equal weights for the criteria, the ranks of parts are obtained (summarized in Appendix 7). All parts are divided into five categories as presented in Figure 18. Based on the category of the machines and parts, maintenance engineers or managers can more easily decide which decision is the most appropriate. For example, a machine in the first rank that has the highest downtime with the highest frequency and cost is a problematic machine. Therefore, CBM can be a good action to take. However, it still requires more analysis, such as failure analysis, before implementation.

In addition, the criteria analysis that has been performed in this section is at the machine level. To obtain a more accurate decision-making model, this criteria analysis should be performed at the component level. Furthermore, the level of fault in the analytical hierarchy process (AHP) should be prioritized and analyzed according to the components.

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The k-means clustering technique (Dash et al., 2010) is used to cluster the machines based on three criteria. The algorithm was run for a number of different means, and the optimal number of clusters was determined to be five according to the calculated silhouette index (Mokhtarpour and Stracener, 2014). Each cluster is represented by a single representative, which reflects the characteristics of the cluster. The representatives (centroids) are obtained from the data based on two criteria of different maintenance policies (Figure 14) (Labib, 2004). Based on Figure 14, the data for machines are divided into five categories as presented in Table 7.

The cost criterion is also considered in the clustering algorithm, which is assumed as the average cost of machines in each cluster. The representatives of each cluster are presented in Table 8.

The result of the clustering technique is presented in Figure 18. This figure indicates that each cluster can be assigned to a specific maintenance policy.

K-means clustering technique

The k-means clustering technique (Dash et al., 2010) is used to cluster the machines based on three criteria. The algorithm was run for a number of different means, and the optimal number of clusters was determined to be five according to the calculated silhouette index (Mokhtarpour and Stracener, 2014). Each cluster is represented by a single representative, which reflects the characteristics of the cluster. The representatives (centroids) are obtained from the data based on two criteria of different maintenance policies (Figure 14) (Labib, 2004). Based on Figure 14, the data for machines are divided into five categories as presented in Table 7.

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The result of the clustering technique is presented in Figure 19. This figure indicates that each cluster can be assigned to a specific maintenance policy.
4.2.3 Essential results – Maintenance decision making

The following items are relevant for maintenance decision making:

- Three important factors for maintenance decision making are the frequency of breakdowns, the production downtime, and the cost of repair.
- The proposed maintenance decision-making models can be feasible and applicable practically.
- The models and inspiration from the studied case can be used for maintenance engineers and managers to make more appropriate maintenance decisions.
- The decision-making models cannot autonomously be used; rather, they should be further analyzed.
- The use of models increases the decision analysis capability of CMMSs.

4.3 Cost effectiveness of implementing CBM in manufacturing companies

This research finding is based on study II-A and primarily addresses RQ2. The study proposes a guide for analysis of the costs and benefits of implementing CBM in manufacturing industry. The guide is exemplified using case study results from real CBM implementation in hardening and machining processes in the pilot project at the case company. The results reveal the factors that should be considered to evaluate both the costs and benefits of implementing CBM. Therefore, a CBM cost-effectiveness model is presented as one of the main findings of this study. This section also presents a summary of the essential results with regard to the case study.

4.3.1 CBM cost-effectiveness model

To illustrate the difference between annual maintenance costs with and without CBM, a model for CBM cost effectiveness is presented below. This model is based on a combination of two cost models from the literature (Moore and Starr, 2005), (Kerf, 2006).

\[
L_{tot} = L_C + L_P + L_Q + L_S + L_{E} + L_{CS}
\]

(1)

- \(L_C\): Safety loss
- \(L_P\): Production loss
- \(L_Q\): Quality loss
- \(L_S\): Safety loss
- \(L_{CS}\): Customer satisfaction loss
- \(L_{E}\): Environmental loss

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- \(L_P\): Production loss
- \(L_Q\): Quality loss
- \(L_S\): Safety loss
- \(L_{CS}\): Customer satisfaction loss
- \(L_{E}\): Environmental loss
\( I_o = (\text{MTTR} \times C_L) + C_s + C_p \)  \( (2) \)

MTTR: Mean time to repair
C_L: Labor rate
C_s: Mean spare cost
C_p: Secondary damage cost

The labor rate (C_L) has almost the same values with or without CBM. Therefore, there is no need to consider it.

\( \Delta K_{\text{max}} = \frac{\Delta K_{\text{max}} \times \Delta K_{\text{max}} \times \text{Inv}}{\text{MTBR}} \)  \( (3) \)

\( f_{\text{max}} = e^{-\frac{\text{Inv}}{\text{MTBR}}} \)  \( (4) \)

\( \Delta K_{\text{max}} \): Damage reduction value with CBM
\( \Delta K_{\text{max}} \): Time of expected operation
\( \text{Inv} \): Current value of investment in equipment

MTBF: Mean time between failures

MTBR: Mean time between repairs

In equation 3, the cost of damage is defined as the cost of the spares. Labor cost is excluded because the costs of cleaning, disassembly, assembly and transportation are almost equal in the cases of minimal and maximal damage. The maximal damage cost includes the spare cost as well as the secondary damage cost. Secondary damage is damage caused to one asset based on the failure of another.

MTBF can be calculated as the manufacturing runtime divided by the number of failures of certain manufacturing equipment. MTBR is the runtime between scheduled maintenance actions.

\[ \Sigma \Delta K_{\text{max}} = \frac{\Delta K_{\text{max}} \times \Delta K_{\text{max}} \times \text{Inv}}{\text{MTBR}} \]  \( (5) \)

\( \Sigma \Delta K_{\text{max}} \): Damage reduction with CBM for all machines in the same group

\( L_o = \text{MTTR} \times P_s \times R_p \)  \( (6) \)

\( P_s \): Mean product price
\( R_p \): Mean production rate

The production rate \( (R_p) \) is the number of products processed by a single production process per hour.

\( L_o = \text{MTTR} \times R_p \times P_s \)  \( (7) \)

\( R_p \): Reduction in product price

\( L_s = C_p + C_s \)  \( (8) \)

\( C_p \): Cost of fines for breaches of regulations when an asset failure injures an employee
\( C_s \): Cost of compensation for an injured employee

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\( C_p \): Cost of fines for breaches of regulations when an asset failure injures an employee
\( C_s \): Cost of compensation for an injured employee
Environmental loss ($L_F$) is the cost of energy loss regarding damage.

4.3.2 Essential results – CBM cost effectiveness in hardening and machining processes

As discussed in chapter 3, the main part of the data from study II-A was collected at different workshops with employees within different departments at the case company, mainly with maintenance engineers. The purpose of these workshops was to investigate the difference between annual maintenance costs with and without CBM. Some of the main results of the workshops are presented as follows:

- In the hardening area, the objects of the study were five mounted fans on top of a 920°C furnace that runs constantly. The expected running time for a fan is 12 months. However, the history of the fan has shown different working times. The earliest breakdown of the fan was recorded after approximately eight months of working time. Each breakdown of these fans involves 20-22 hours of downtime. Therefore, the resulting production loss due to breakdown of fans is costly for the company. By using CBM to predict the failure of certain fans, it is possible to schedule their replacement in a manner that does not affect production.

- In the machining area, the objects of the study were four turning machines from two different types, two with a motor spindle and two with a spindle and a pulley system, in addition to a grinding machine. The turning machines worked two by two in parallel. A breakdown in any of the machine tool spindle units is estimated to involve 5-8 days of downtime, which can also involve the risk of resulting loss and late delivery. With CBM, the time to repair can be reduced to one day. Therefore, it is possible to save production losses. Reducing the downtime can also decrease extra costs for the transportation of spare and extra labor costs. In addition, CBM reduces the risk of secondary damage in the machines. CBM thus contributes to reduce the cost of maintenance. There are few quality losses due to machine failures. Therefore, using CBM to prevent machine failures can also increase or maintain the quality of the products.

These results and the collected quantitative data from the workshops were used in the model presented in section 4.3.1. These results illustrate one-year payback time of investing money into implementing CBM on five gas circulation fans and five machine tools at the case company. The results of the workshops and the CBM cost-effectiveness calculations can be found in greater detail in the appended paper III.

4.4 Material efficiency through CBM

This research finding is based on study II-B and primarily addresses RQ2. It addresses the controversial gap between the environmental perspective and the cost perspective in a manufacturing context. This section presents the empirical data from the studied cases, including eight fans mounted over furnaces and a fan used in the phosphating process. The empirical results from the interviews, documents and observations are presented and analyzed based on the necessary factors for the cost evaluation of the CBM implementation, which are presented in section 4.3. Based on the empirical data, the essential results regarding the material efficiency through CBM are discussed. Further details on the results of this study can be found in paper IV.

Environmental loss ($L_F$) is the cost of energy loss regarding damage.
4.4.1 Empirical findings from the studied cases

The studied fans in hardening and phosphating processes operate 24 hours per day and 7 days per week, with an estimated lifespan of one year. Historically, the fans have had at least one breakdown per year before CBM was implemented to monitor the fans condition. The root causes of fan breakdown in the studied cases are as follows: a lack of lubrication; fatigue in the blades and shafts; imbalance; and particles that build up in the production processes and adhere to the impeller.

In case of breakdown in the fans, the entire process of fan replacement requires between 8 to 24 hours, causing an equivalent stop in the production time. Therefore, the production loss incurred as a result of breakdown of a fan in the studied cases is equal to the loss of approximately 8 to 24 hours of production capacity. However, there are scheduled maintenance shutdowns in hardening and phosphating processes. In the case that an impending failure in the fan is detected through the implementation of CBM, such as vibration monitoring, it is possible to schedule the fan replacement within such a planned stop time; such a scheduled replacement does not affect production and thus prevents production loss. CBM can therefore have a beneficial effect if a failure prediction arises near a scheduled maintenance time.

The fan breakdown can rarely cause a late delivery to the subsequent production processes. Therefore, if the production department is regarded as the customer for the hardening and phosphating processes, breakdowns can sometimes cause dissatisfaction, particularly when production is already behind the schedule of the primary production plan or the stock level is low. The cost related to this issue has never been calculated at the case company though. However, fan breakdown does not cause late delivery of the final products to external customers and never puts the case company at risk of business loss.

The maintenance cost includes the costs of spare parts, human resources and transportation. A major breakdown that affects the entire fan package costs at least two times more than minor fan damage. CBM, by providing the early damage warning, prevents the occurrence of major fan damage and therefore can reduce the cost of maintenance.

No safety issue has been reported as related to fan breakdowns or fan replacements. However, safety issues are a major concern regarding the replacement of the fans, and the stress factor plays an important role in determining how the maintenance work is performed in the hardening and phosphating processes. In addition, the maintenance work must be performed by highly skilled personnel to reduce the risk of safety issues. In the case of either scheduled maintenance guided by CBM techniques or a replacement service caused by a breakdown, the maintenance work must be performed at a high temperature in the hardening process. Thus, there is a high safety risk either with or without CBM. However, a scheduled maintenance guided by CBM can reduce the stress in determining how the maintenance work should be performed.

Sometimes fan breakdown causes product quality issues. The affected products are sometimes spared or reworked, depending on their quality, or, in the worst cases, they are scrapped. The company thus incurs additional costs because of quality losses; however, it is challenging for the case company to estimate these losses. In the phosphating process, the scrap products cannot be reworked; hence, a new order is placed in production to manufacture the same products again. The scrapped products also incur an environmental cost because of the waste of the materials used, the chemicals and other consumable materials used during fabrication, the additional internal transportation to mixed metal containers and the external transportation to the recycling.
company, and the eventual environmental cost related to the recycling of the scraps (which could be prevented if no scraps were ever generated).

4.4.2 Essential results – Material efficiency through CBM

Previous study, presented in section 4.3, has revealed several factors that must be considered to evaluate the cost effectiveness of CBM implementation and its benefits. Based on the proposed model, the total cost incurred as a result of machine damage is equal to the sum of the direct cost of maintenance (capital loss, which is the machine repair cost) and the indirect maintenance cost (production loss, quality loss, safety loss, customer satisfaction loss and environmental loss). However, focus has typically been placed on ensuring CBM cost effectiveness by reducing production losses and the probability of maximal damage to the equipment. In this study, other potential savings/indirect costs of maintenance due to breakdown were addressed. These losses are predominantly the consequences of the occurrence of maximal damage to the equipment that causes products to require rework or to be scrapped, which is primarily regarded as quality loss. These losses thus refer to lost opportunities and delays in production caused by unplanned stop times due to breakdown and quality failures, which impose an additional cost that the company must pay for reworking the products or disposing of the material wastes in any internal and external transportation of the scrapped products. Furthermore, machine damage may also cause additional costs in cases of safety issues, customer dissatisfaction and environmental accidents.

Environmental loss is related to environmental damage caused by a breakdown; for the context considered in this study, such damage can be reported in the form of global warming, greenhouse gas emission (primarily CO2), waste generation, energy consumption and air pollution, among other impacts. Components that are scrapped because of breakdowns in the hardening and phosphating processes can have major environmental effects, such as the energy consumption and carbon dioxide generation associated with the additional transportation of scrap, the energy consumption for the recycling of scrapped materials, the degradation of the materials, and the waste of productive and auxiliary materials. Usually metals, particularly ferrous metals such as steel and iron, which are lower in value, are sufficiently resilient that they can be recycled many times. However, this is not true for alloys. Kühne et al. (2011) present a waste hierarchy that illustrates the major environmental impacts of scrap generation at the various levels. According to the waste hierarchy, the prevention of scrap generation is the best option from both the economic and environmental perspectives, followed by the reduction of scrap. Both prevention and reduction have high environmental and economic benefits for manufacturers and society. CBM contributes to waste management by enabling companies to move up the waste hierarchy, from material recycling and reuse of scrapped products toward the reduction and prevention of scrap generation. Therefore, reductions in the waste of auxiliary materials that occur in the production of scrap, the degradation of material, the waste of the original value of productive materials and the energy consumption required for various processes are the main contributions of CBM to material efficiency and sustainable manufacturing.

4.5 Current industrial practices and challenges regarding the use of CBM in manufacturing companies

This research finding is based on study III-A and primarily addresses RQ3. It presents an introductory review of CBM practice as applied in the manufacturing industry, focusing on the organizational aspects and technical constituents of monitoring asset condition. The empirical basis for the study is a case study of two major manufacturing sites in Sweden, complemented by a brief benchmark of data from two reference manufacturing sites located in France and Brazil. By analyzing the empirical data, the gaps and challenges in company, and the eventual environmental cost related to the recycling of the scraps (which could be prevented if no scraps were ever generated).
implementing CBM in the industry are presented, primarily focusing on monitoring asset conditions within the manufacturing industry. This section presents the summarized explanations of some of the main findings of this study. The results can be found in greater detail in paper V.

4.5.1 Criteria for selecting the CBM technique

Based on the case companies in study III-A, five main condition monitoring techniques are found to be important, including geometry analysis, vibration analysis, force control, thermography and oil analysis. Companies select CBM techniques based on the types of problems the assets have had and the types of parameters and/or failure indicators. For instance, if a problem occurred due to geometric misalignment, the appropriate technique to choose would be geometry analysis. Based on the empirical data gathered from the case companies, geometry analysis is typically applied to large machines. For machines that work at high speeds, vibration analysis is an effective way to determine whether a machine is functioning correctly. Vibration analysis is conducted to monitor the rotating accuracy of the parts that are linked to vibration, such as rotating shafts, spindle units, bearings, drive units, fans and pumps. Force control is used for clamping spindle tools and similar parts. All the case companies use thermography techniques to monitor electrical cabinets. Additionally, for companies with thermal processes, thermography is used to monitor the heat treatment process. Finally, in all the case companies, oil analysis is conducted to analyze oil features and measure the amount of particles to ensure the quality and function of the oil.

4.5.2 Cost and value

Based on the literature study and the case study, there is no clear model for maintenance cost to compare production and maintenance costs. For instance, respondents in the case companies argued that on-line condition monitoring is not justified financially. However, there is still no clear consensus on how to determine the cost of a breakdown to production to compare it with the cost of maintenance.

The empirical data indicate two perspectives regarding investment in CBM. In the first, a company prefers to invest money to increase the amount of resources and its competence in off-line condition monitoring in addition to having some on-line condition monitoring of more critical places where safety is an important factor. In the other perspective, a company prefers to simply invest money to have more on-line condition monitoring for the machines. Obviously, this latter perspective demands fewer resources but still requires some resources to track the information collected from the on-line monitoring system and experts to analyze these data and develop maintenance plans as well as other requirements.

Each of these views demands resources and requires investment in tools and instruments as well as in education and training. The companies must understand the time required to implement CBM. The interviews, data and analyses in this study indicate that it may take substantial time to achieve valuable results from a CBM system. Management must provide CBM the opportunity to grow and acquire sufficient knowledge before expecting return on its investment.

4.5.3 Main challenges in implementing CBM

Currently, the case companies are attempting to apply CBM techniques in most of their key assets, but increased competencies are required to use these techniques effectively. Management support is one of the main challenges in this regard and is necessary to change the culture of the companies from incorporating reactive strategies to incorporating proactive strategies. These companies have employed reactive strategies for many years, and time and additional knowledge are needed to transform the culture to utilizing proactive strategies. In other words, it is necessary to convince management and those responsible for maintenance implementing CBM in the industry are presented, primarily focusing on monitoring asset conditions within the manufacturing industry. This section presents the summarized explanations of some of the main findings of this study. The results can be found in greater detail in paper V.

4.5.1 Criteria for selecting the CBM technique

Based on the case companies in study III-A, five main condition monitoring techniques are found to be important, including geometry analysis, vibration analysis, force control, thermography and oil analysis. Companies select CBM techniques based on the types of problems the assets have had and the types of parameters and/or failure indicators. For instance, if a problem occurred due to geometric misalignment, the appropriate technique to choose would be geometry analysis. Based on the empirical data gathered from the case companies, geometry analysis is typically applied to large machines. For machines that work at high speeds, vibration analysis is an effective way to determine whether a machine is functioning correctly. Vibration analysis is conducted to monitor the rotating accuracy of the parts that are linked to vibration, such as rotating shafts, spindle units, bearings, drive units, fans and pumps. Force control is used for clamping spindle tools and similar parts. All the case companies use thermography techniques to monitor electrical cabinets. Additionally, for companies with thermal processes, thermography is used to monitor the heat treatment process. Finally, in all the case companies, oil analysis is conducted to analyze oil features and measure the amount of particles to ensure the quality and function of the oil.

4.5.2 Cost and value

Based on the literature study and the case study, there is no clear model for maintenance cost to compare production and maintenance costs. For instance, respondents in the case companies argued that on-line condition monitoring is not justified financially. However, there is still no clear consensus on how to determine the cost of a breakdown to production to compare it with the cost of maintenance.

The empirical data indicate two perspectives regarding investment in CBM. In the first, a company prefers to invest money to increase the amount of resources and its competence in off-line condition monitoring in addition to having some on-line condition monitoring of more critical places where safety is an important factor. In the other perspective, a company prefers to simply invest money to have more on-line condition monitoring for the machines. Obviously, this latter perspective demands fewer resources but still requires some resources to track the information collected from the on-line monitoring system and experts to analyze these data and develop maintenance plans as well as other requirements.

Each of these views demands resources and requires investment in tools and instruments as well as in education and training. The companies must understand the time required to implement CBM. The interviews, data and analyses in this study indicate that it may take substantial time to achieve valuable results from a CBM system. Management must provide CBM the opportunity to grow and acquire sufficient knowledge before expecting return on its investment.

4.5.3 Main challenges in implementing CBM

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that working with proactive maintenance tools such as CBM is necessary for the companies’ future success in a competitive environment.

4.5.4 Future plan for CBM at the case companies

The case companies are attempting to train their employees to increase their competence in this area, which is one of the main challenges for the future. Furthermore, the companies have an interest in more advanced tools for CBM, such as on-line mobile systems, which can be located where there are critical problems to monitor one or several machines continuously for a specific period of time. 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 obtain fingerprints from new production equipment so that they can use these data to return the machines to their original settings when needed. Further study of the effects of new products on the machines is another action plan for the future. This analysis may be facilitated by implementation of CBM techniques to determine how a product’s material can affect production equipment.

4.5.5 Essential results – Enabling factors for CBM

A successful environment in which to monitor asset conditions is an important enabling factor for CBM. In this regard, there must be a clear condition monitoring strategy to manage the overall CBM strategy. Management support plays an important role in creating a strong organization in this area.

Several enabling factors should be considered during the implementation of condition monitoring. The techniques should be selected appropriately. The level of competence within the CBM organization should be high enough to use the techniques effectively. Sufficient training and experience are necessary to become skilled in the techniques associated with condition monitoring. The level of complexity required for the condition monitoring technologies and their degree of continuous use must be resolved, and resources must be determined. It is necessary to have a plan for all purchases, to consider the cost before purchasing the technologies and to determine who should provide the services.

A robust asset registration system, asset failure histories and symptoms, and baseline data on the assets make asset condition monitoring data easier to analyze and contribute to appropriate maintenance plans. However, there must be a means of following up on the application of the technologies involved in monitoring the condition of assets to control their effectiveness.

4.6 Implementation of CBM in manufacturing companies

This research finding is based on study III-B and primarily addresses RQ3. It presents a guide to implement CBM in a manufacturing industry and considers the technical constituents and organizational elements when implementing CBM. Its empirical basis is a single case study. The data were collected during the pilot project to implement CBM at the case company. This section presents the proposed work process of CBM implementation, followed by a summary of the main implementation factors. The results can be found in more detail in the appended paper VI.

4.6.1 Work process of CBM implementation

One of the main findings involves the CBM implementation process that is generated and validated while implementing CBM at the case company. The proposed work process of CBM implementation is presented in Figure 20. The steps to be taken in the process are discussed in the following.
In implementing CBM, the case company should consider different aspects in its early phases to estimate its feasibility. These aspects are classified as organizational, economic, and technical.

In the organizational aspect, evaluating the cultural needs and competence within the organization is necessary to assess whether CBM is feasible and what types of technologies are appropriate to use. A SWOT analysis and maintenance audits of the company’s maintenance activities can also provide useful information to investigate whether implementing CBM is proper. It should be determined whether CBM can improve the work environment, such as by reducing the number of unscheduled corrective actions and increasing OEA by decreasing the number of unexpected breakdowns. The safety factor should be assessed regarding both environmental and personnel safety. The company should decide whether to develop in-house expertise in condition monitoring or whether to use external condition monitoring contractors. In this regard, the factors used to choose a proper condition monitoring supplier must be assessed, such as the type of technologies that can be provided, ease of access and appropriate support in the future.

Regarding the economic aspect, financial issues cannot be precisely calculated at this early stage. Nevertheless, a list of requirements can be proposed to evaluate whether implementing CBM will be cost effective. Therefore, the possible size of the investment cost should be estimated, such as the cost of purchasing the condition monitoring equipment and its installation. The cost of maintenance and production loss per breakdown should also be estimated to provide a pre-estimation of the implementation cost as well as the returns on CBM implementation.
A criticality analysis and a maintenance audit can help assess the technical feasibility of implementing CBM. It should be determined whether the criticality of the failure is known and whether there are appropriate indicators for failure criticality. If so, are there proper tools or techniques to detect the failures? Importantly, in predicting failures, is it possible to prevent major damage and plan for maintenance at a time that does not affect production to reduce maintenance costs and production losses?

A variety of tools and methods are available to conduct feasibility tests, including reliability centered maintenance (RCM) tools such as failure mode and effect analysis (FMEA) to perform estimates regarding technology. The choice of suitable tools and methods should be in accordance with the tools and methods that the company normally employs. However, in the early decision-making phase of implementation, light versions of tools and methods can be used to gain sufficient information for an appropriate feasibility test. Moreover, qualitative methods such as benchmarking against other companies, mapping current knowledge within the organization and interviews can be used in the early phase of the implementation process.

Experiences from the concept study illustrate the relevance of pursuing a CBM implementation process. More accurate assessments and calculations should be made later in the process.

**Defining responsibilities**

For a more structured implementation, responsibilities in the early phases of implementation must be defined. Early in the decision-making phase, the topics of implementation, development requirements, and selection of the equipment, techniques and technologies can be discussed among the managers and engineers in the maintenance and production departments. However, after the early decision-making phase, responsibilities may shift to smaller groups based on the selected equipment areas and the need to follow the implementation process.

**Selection of assets**

The selection of machines or components is a vital aspect to make the implementation manageable and cost effective. A criticality analysis of production assets can be an effective guide to selecting the proper objects for implementation. This criticality analysis can be based on existing data and previous experience with the assets at the company. Additionally, tools and methods such as RCM or FMEA can be used with more precision at this stage. The choice of tools and methods depends on what the company is accustomed to using. The use of tools and methods helps to structure the information while assessing the criticality of the assets. To perform a criticality analysis, the assets and their functional specifications should be identified, and a failure analysis should be performed using different levels of failure.

**Selection of techniques and technologies**

By deciding which assets to monitor and their failure types, the types of parameters and/or failure indicators can be determined. The parameters determined can lead to decisions regarding which techniques to use. The parameters are dependent on the production equipment type; for example, for a bearing failure in an electric motor, vibration can be one of the main failure indicators. In selecting the techniques, several factors should be considered, including the availability of the technology to monitor the parameters, the competence and manpower required to use the technology and the cost effectiveness of applying the techniques.

The condition monitoring techniques can be performed using different levels of technology. The choice among technologies should be based on organizational, economic and technical aspects. Condition monitoring can be performed by humans (monitoring using their senses) or

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by using measuring systems. The measuring systems can be applied either on-line or off-line. On-line measuring systems can provide continuous monitoring of the assets and trigger warnings. The analysis can be performed automatically or manually to determine the time between detecting a fault and failure. This decision can be made depending on the asset type and based on the length of the interval between the fault and the failure of the asset; although on-line systems may be more costly in certain aspects, they may require fewer human resources. Moreover, different technologies require different types of knowledge within the organization. Of course, technologies that are more effective at lower cost would be the best choice.

Although the same process of implementation can be applied to hand-held condition monitoring (off-line), the descriptions of the following steps are more relevant to implementing on-line condition monitoring based on the studied case.

**Installation**

In on-line technologies, the installation of condition monitoring tools can be performed by personnel from the supplier companies of condition monitoring technologies. However, there are several factors that should be addressed in the decision-making phase. Some factors to be considered are the positioning of the sensors and the placement of the sensors, cables, measuring units and database.

Measuring points should be carefully selected and set to ensure that future analyses will be valuable. Machine specifications can be used to identify the location and design of bearings. For instance, to select a measuring point for vibration measurement, the signal path should only have one mechanical interface between the bearing and the bearing housing. It is essential that the signal path between the measuring point and the bearing in its the loaded area of the bearing housing and must also be solid and straight.

The direction of the sensors’ positions should be determined: horizontal, vertical or axial. There are several ways to mount the sensors to the objects using steel screws, insulated screws, magnets, thin layers of wax, glue or three axis mounting brackets.

It should be determined how to pass cables through the equipment to use shorter lengths of cable and to avoid disturbing operation of the equipment while also considering safety issues. The cables should be installed in good condition and should not be damaged. The measurement system unit that collects data should be located in a place that is easy to access and accessible by the power units. The company should be able to provide the units with the required power. The units can be connected to the company’s local area network (Ethernet) to transfer the data to a database. A desktop or laptop computer can act as the database. The supplier companies provide customers with computer software products that can be installed on a desktop or laptop computer to collect and analyze the data.

**Data handling**

In the case study, one challenge to implementing on-line condition monitoring systems is connecting to the company’s IT server to collect the data in the database. Supplier companies should have access to the database to provide support to their customers, although some companies are restricted from providing this access to the IT server. Thus, it can take time to find a solution that is appropriate for both the supplier and the customer. Supplier companies can also recommend a proper solution to more readily accomplish this task. Another solution is to use 3G modems without connecting to the company’s IT server. In this case, the information is collected in the supplier’s database, but the customer may not have access to the data all the time, which makes it more difficult to perform the subsequent analysis.

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An advantage of on-line systems in connecting to the company’s IT server is the ability to connect to the company’s CMMS. Thus, the company could provide maintenance work orders based on its CBM system. In addition, the gathered data can be used in the form of big data sets for further decision-making analysis.

Training
Different technologies require different training and skills. The people responsible for using CBM must be trained to become familiar with the condition monitoring system and to be able to analyze the data from monitoring the asset condition. More advanced skills are required for advanced data analysis techniques, such as frequency analysis. The data from condition monitoring can be either raw information, such as information on vibration, or analyzed data that can be observed as trends. Raw vibration information can be analyzed by programming and simulation computer software, such as MATLAB. Most computer software products developed by condition monitoring suppliers are able to analyze the data and show the results as graphs in an automated analysis. Thus, suppliers can provide their customers with training courses for their condition monitoring applications and products.

Measurement and setting baseline data
Depending on the type of technology, measurements should be undertaken either on-line (in real time) or off-line (by handheld instrument). An early use of the measurement data is to set the baseline data as a fingerprint for the production equipment. This information documents the normal condition of the equipment. Warning limits can be set for the equipment using the baseline data. The on-line condition monitoring technologies can trigger warnings when a change is detected in the values compared with the baseline data.

Data analysis
The level of the data analysis depends on the type of technologies used. Some monitoring systems provide direct condition monitoring by performing green-yellow-red condition analysis, which can provide data on the lubrication and surface condition of a bearing. The data from these types of condition monitoring systems can be analyzed in a simple manner by examining the graphs provided by the computer software and analyzing the trends presented therein. Data analysis can be performed through a more specific frequency analysis at a more advanced level, which can provide more accurate and reliable data on the conditions of the bearings.

If a fault is detected, various factors can be analyzed, such as the time necessary for the fault to turn into a failure and when subjective factors, such as extra noise, will occur on the object. If there is a failure of the object, performing a failure analysis can indicate whether the results from the condition monitoring analysis are similar to the reason for the failure. The data analysis should lead to the establishment of more accurate warnings and a plan for maintenance activities that are more appropriately timed.

Evaluation
An important phase of the implementation process is to evaluate whether the implementation has been appropriately performed and whether it can provide the desired outputs. Some factors can be considered in this regard, such as the type of sensors, the positioning of the sensors and success factors such as cost and the time between the detection of a fault and failure. This data analysis can be used to examine whether the type of sensor is sensitive enough for the type of application to extract useful data. The same examination can be performed for the positioning of the sensors and the manner in which they are installed on the equipment. Furthermore, it may be necessary to add other sensors on different axes to extract more appropriate data.

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Regarding cost, as discussed above in this section, implementation should begin with an estimation of cost. However, after implementation, there is a clearer picture of cost, particularly for the cost of condition monitoring tools. At this point, whether implementation has been performed in a cost-effective manner can be determined.

An important success factor for implementation is to determine the most precise interval time between detecting a fault and failure. Perhaps the best situation for the manufacturing company is to have sufficient time after detecting a fault to plan for a maintenance activity before failure.

**Improvement**

Logically, the results from the evaluation phase are used to improve implementation. Some technical examples of improvement are to change the type of sensors, the positioning of the sensors and the number of sensors. Furthermore, the organization should follow up on the activities, increase competence to analyze the data and use CBM effectively; however, management support will still be required.

The decision-making parts of the implementation process, including the selection of the assets, the techniques and the technologies, can be reviewed more generally at this stage. The company should establish routine monitoring. It should be clear what must be measured and when. More accurate warning limits will be set by repeated measurements. The techniques should also be used to detect the most common failure modes, and the most important assets should be covered by these techniques.

### 4.6.2 Essential results – CBM implementation

The necessary factors to be considered for CBM implementation can be summarized as follows:

- The company’s cultural needs and competence within the organization.
- Cost-effectiveness analysis; the possible size of investment compared with the size of potential savings.
- In-house expertise in condition monitoring or use of external condition monitoring contractors.
- The criticality analysis of the production assets: Is the failure known? Are there indicators for the failure? Are there proper techniques to monitor the indicators? Can major damages be prevented?
- Availability of the technology and competence to use the technology, humans or measuring systems, and off-line or on-line.
- Use of the most appropriate sensors and condition monitoring tools in accordance with the type of application, and ensuring an appropriate installation.
- Transferring the data to the IT network; use of a company’s local area network (Ethernet) or 3G modem, etc.
- Data handling and analysis.
- Increase of competence within the organization.
- Use of baseline data as fingerprints, and setting warning limits based on the fingerprints.
- Evaluation of the interval time between detection of a fault and failure.

### 4.7 On-line condition monitoring of fans

This research finding is based on study III-C and primarily addresses RQ3. The data were mainly collected by direct and participatory observations during the pilot project. The idea of implementing CBM at the case company was included in several discussions among the maintenance management teams and engineering teams. During these discussions, the company is to have sufficient time after detecting a fault to plan for a maintenance activity before failure.

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technical, organizational and economic aspects of implementation were discussed. Investigations were undertaken to determine whether there is existing competence in this area within the organization to provide the necessary knowledge. The following presentation of results focuses on the on-line condition monitoring of the fans for a period of three years, followed by a discussion of the results. The results can be found in more detail in the appended paper VII.

4.7.1 Implementation of on-line condition monitoring of fans
The asset objects selected for study are five gas circulation fans mounted on top of a furnace in the hardening area (Figure 21). The fans are running 24 hours per day and 7 days per week to maintain the gas atmosphere of cracked methanol and nitrogen as smooth and steady. According to the information collected regarding the fans’ replacements and breakdowns, the expected running time for a fan is 12 months. However, the history of the fans, before implementing on-line condition monitoring, has shown different working times. The earliest breakdown of the fan has been recorded after approximately eight months of working time. In addition, the entire fan replacement process takes approximately 20 to 22 hours of production time. However, because there are scheduled maintenance shutdowns, in the case that an impending failure is detected, it is possible to schedule the replacement for a time that does not affect production.

Figure 21 - Gas circulation fan mounted on furnace
The gas circulation fan is attached to a 4 kW electric motor. The bearing in the electric motor is exposed to a high load owing to the extra-long motor shaft and a relatively large impeller. Therefore, it is of great importance that the balanced unit of the electric motor and the impeller be precisely balanced. Obviously, imbalances can cause a failure in the electric motor’s bearing. Owing to the working conditions of 920°C in the furnace, the motor shaft and the impeller are exposed to a high wear due to material fatigue/metal dusting, which causes imbalance, and, in the long run, vibration, which places an extra and rough load on the electric motor’s bearing. In addition, the furnace in its processes creates some degree of particles. These particles gradually build up and stick to the wings of the impeller, which can contribute to the vibrations.

An imbalance in a fan and an electric motor or a fault in a bearing results in extra vibrations and noise. These parameters can be failure indicators for the fans’ electric motors, which are measurable by vibration analysis. These techniques can be applied either on-line or off-line with handheld tools. In this study, on-line condition monitoring was selected to continuously monitor the vibrations from the fans and to trigger a warning alarm when an error was detected. Measuring points for a vibration sensor (accelerometer) and a shock pulse transducer should be carefully selected and set to ensure the value of future analyses. Machine

55
specifications can be used to identify the location of bearings and their construction. The sensors can be installed using glue or a steel screw, although a steel screw can give a better result. In this study, a shock pulse transducer and one vibration sensor were glued to the drive side of the electric motor, and a shock pulse transducer was installed to the non-drive side of the electric motor using steel screw (Figure 22).

The reason for not using a screw to install the sensors was the lack of access to drill for the fan mounted on the furnace. However, spare fans were later drilled to mount the sensors by using a steel screw. The sensitivity of the vibration sensor is 100 mV/g, which is appropriate for the 945 rpm speed of the fan. The sensors are connected to a measurement system unit/analyzer by cables. Depending on the type of the unit, the system can have several channels for vibration and shock pulse. The condition monitoring data are collected on an SD card in the unit. The data from the unit are transferred to a computer database using either the company's local area network (Ethernet) or 3G modem. Using computer software provided by a condition monitoring supplier, the data are analyzed automatically. The computer software is also able to trigger warnings. Hence, the early measurements from the objects can be used as the baseline data, and warning limits can be set based on the standards (ISO 10816-3, 2009; ISO 7919-3, 2009). The employees responsible for using CBM should thus be trained and able to analyze the results. Figure 23 shows a schematic view of the on-line condition monitoring of a gas circulation fan.

Figure 22 - Location of shock pulse and vibration sensors

Figure 23 - Schematic view of on-line vibration monitoring of a gas circulation fan
4.7.2 Results of condition monitoring

By implementing on-line condition monitoring with a time interval of one hour, two breakdowns on two fans were observed at the beginning of the measurement. In the first case, as illustrated in Figure 24, the vibration trend was unstable for a long period of time and was at a higher level compared with the other fans. However, the significant increase in the vibration trend occurred in a very short time before breakdown, approximately 12 hours. In the second case, there was also a rapid increase in vibration in a short time, beginning three days earlier and ending with an extensive vibration (Figure 25). In the latest time before failure, extra noise in the fan was observed as strong shock pulses in the shock pulse measurement in a very short period of time, almost 20 hours (Figure 26). However, the shock pulses were at a high level approximately 23 days before the failure. The alert and alarm values are indicated by yellow and red colors in the figures.
After experiencing these two breakdowns, the result indicates no fan breakdown in the furnace since the implementation of on-line condition monitoring for a period of three years. Five fans were replaced owing to high vibration and shock pulses. In one of the cases, illustrated in Figure 27, an increase in the vibration value by more than 30 percent indicates a variation in the bearing condition or a fault in the bearing. Therefore, the fan was replaced. In the five cases, planned maintenance was too far ahead, so replacements were performed before the planned furnace shutdown. In some cases, when the faults were diagnosed near the time of planned maintenance, extra lubrication was applied to the bearing to extend its lifetime (Figure 28 shows an example). Therefore, it was possible to replace the fan in the planned time for maintenance without affecting production time.

As an extension of the previous analysis, further analysis has been performed by using high-frequency methods. The frequency range of measurements varies for different rotational speeds, bearing types, and measuring methods used for the analysis. The vibration velocity parameter can be measured within a frequency range of 100 times the operational speed frequency (e.g., a fan with an operational speed of 1200 rpm and 20 Hz can be measured in the frequency range of 10-2000 Hz). However, measuring methods such as demodulation or enveloping techniques use different and higher frequency ranges for detecting rolling bearing damage (i.e., 0.5-10 kHz and 5-40 kHz frequency ranges are used to detect bearing damage).

In one of the studied cases, as illustrated in Figure 29, damage to the inner race of a ball bearing was found two months earlier than the occurrence of failure by using the enveloping technique over a frequency range of 5-40 kHz. As shown in the figure, the higher peaks in the spectrum correspond to the bearing damage frequencies in the inner race (BPFI). Furthermore, as illustrated in Figure 30, the bearing damage both in the inner and outer races was observed clearly one month before the failure, using the enveloping technique with a frequency range of 0.5-10 kHz. As shown in the figure, the bearing damage frequencies in the outer race are indicated as the BPFO in the spectrum.

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**Figure 27 - Vibration measurement of the fan 18 days before replacement**

**Figure 28 - Shock pulse measurement of the fan two months before planned maintenance**

### 4.7.3 High-frequency analysis

As an extension of the previous analysis, further analysis has been performed by using high-frequency methods. The frequency range of measurements varies for different rotational speeds, bearing types, and measuring methods used for the analysis. The vibration velocity parameter can be measured within a frequency range of 100 times the operational speed frequency (i.e., a fan with an operational speed of 1200 rpm and 20 Hz can be measured in the frequency range of 10-2000 Hz). However, measuring methods such as demodulation or enveloping techniques use different and higher frequency ranges for detecting rolling bearing damage (i.e., 0.5-10 kHz and 5-40 kHz frequency ranges are used to detect bearing damage).

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By considering these analyses in addition to performing trend analysis (Figure 31), the fault was successfully diagnosed, and the fan replacement was performed without having a breakdown or disturbing the production time.

4.7.4 Bearing damage analysis

Given the observed breakdowns of the fans, one of the main issues to be discussed was the reason for the late warnings before breakdowns. Obviously, late warnings do not allow the company to schedule maintenance work outside production time to reduce production losses.
Therefore, some factors have been reconsidered in implementation, such as the type of sensors and their positioning and placement. Furthermore, failure analysis was performed on one of the broken fans, and the results showed that the grease in the bearing was burnt since it was blackened and contaminated with metal particles (Figure 32), which might be related to factors such as heat in the operational environment of the system. Based on this experience, better control of the condition of the fans was implemented by altering the warning limits, shortening the measurement intervals and better controlling the bearing lubrication. Therefore, the bearing failures were predicted, and they did not cause any breakdown.

4.7.5 Essential results – On-line condition monitoring
The on-line condition monitoring of the fans for a period of three years resulted in having no fan breakdown in the furnace in this period, except for the two observed breakdowns at the start of the measurements. Five fan replacements were performed due to the high value of vibration. Therefore, five breakdowns were also prevented. In some cases where faults were diagnosed close to the planned time for maintenance, extra lubrication of bearings was performed to extend the bearing lifetime and reach the planned maintenance. By assuming that a fan breakdown takes approximately 20 hours of production time, the case company, by preventing the breakdowns on the fans, saved a large amount of money through increased productivity, shorter maintenance cycles, reduced downtime, no catastrophic failures, no secondary damage, reduced parts inventory and increased process quality.

4.8 CBM of machine tools
This research finding is based on study III-D and primarily addresses RQ3. The data were mainly collected by direct and participatory observations during the pilot project at the case company. The purpose was to address CBM implementation in manufacturing industries, focusing on the use of the vibration monitoring technique to monitor the condition of the machine tool spindle units. Part of the results of the studies, including implementation of vibration analysis on machine tool spindle units and its results and cost effectiveness, are presented in this section. The results can be found in greater detail in the appended paper VIII.

4.8.1 Implementation of vibration analysis on machine tool spindle units
A number of standards typically involve vibration-related parameters. Larger companies often have their own standards that define what is good and bad, which are designed according to their own experiences. In this study, the Swedish standard for machine tool spindle vibrations by measurement on the spindle housing (SS 728000-1, 2014), was used. Some of the important factors of the vibration measurement of spindle units are summarized in Table 9.

Therefore, some factors have been reconsidered in implementation, such as the type of sensors and their positioning and placement. Furthermore, failure analysis was performed on one of the broken fans, and the results showed that the grease in the bearing was burnt since it was blackened and contaminated with metal particles (Figure 32), which might be related to factors such as heat in the operational environment of the system. Based on this experience, better control of the condition of the fans was implemented by altering the warning limits, shortening the measurement intervals and better controlling the bearing lubrication. Therefore, the bearing failures were predicted, and they did not cause any breakdown.
The following items are relevant for the implementation:

- Measurement points should be selected and prepared carefully to ensure that future readings are repeatable. The signal path between the bearing and the measurement point should be in the loaded region of the bearing housing. Machine specifications should be used to identify the location of bearings and their construction. The types of the bearings should be known in order to facilitate the finding of bearing damage.
- If the machine is in the warrantee period, the machine manufacturer should be informed of any change in the machine for measurement.
- To install the sensors in radial directions, measurement points should be selected according to the axes of movement of the machine tool such as X and Y. A single tri-axial sensor can also be used. Figure 33 shows installed vibration sensors in the radial and axial directions on a turning machine spindle housing. Sensors are mounted with glue.

Table 9 - Implementation factors of vibration measurement of spindle units

<table>
<thead>
<tr>
<th>Implementation factor</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration sensor type</td>
<td>Vibration accelerometer with a sensitivity of 100 mV/g for spindles with an operating speed between 60 and 30,000 rpm.</td>
</tr>
<tr>
<td>Sensor installation</td>
<td>In radial and axial directions at the front and back ends of the spindle housing, as close to the bearing as possible with the use of threaded fittings, chemical bonding wax or a magnetic base.</td>
</tr>
<tr>
<td>Machine loading condition for measurement</td>
<td>No-load conditions (cutting, grinding, or milling) either with a tool clamped or no tool in the machine.</td>
</tr>
<tr>
<td>Machine rotational speed for measurement</td>
<td>The machine’s operational speed, to avoid resonance frequencies.</td>
</tr>
<tr>
<td>Measurement frequency range</td>
<td>Varies for different spindle speeds, bearing types and numbers of gear teeth and use of different measuring methods for the analyses.</td>
</tr>
<tr>
<td>Automatic or manual measurement</td>
<td>Using handheld vibration instruments or on-line vibration measuring units (analyzers).</td>
</tr>
<tr>
<td>Alert and alarm limits</td>
<td>The alert value is set to 50% higher than the baseline value and the alarm value to 150% higher than the baseline value.</td>
</tr>
<tr>
<td>Measurement strategy and measurement interval</td>
<td>Different measurement time intervals depending on types and criticality of the machine.</td>
</tr>
</tbody>
</table>

Figure 33 - Vibration sensors installed on a turning machine spindle housing

The following items are relevant for the implementation:

- Measurement points should be selected and prepared carefully to ensure that future readings are repeatable. The signal path between the bearing and the measurement point should be in the loaded region of the bearing housing. Machine specifications should be used to identify the location of bearings and their construction. The types of the bearings should be known in order to facilitate the finding of bearing damage.
- If the machine is in the warrantee period, the machine manufacturer should be informed of any change in the machine for measurement.
- To install the sensors in radial directions, measurement points should be selected according to the axes of movement of the machine tool such as X and Y. A single tri-axial sensor can also be used. Figure 33 shows installed vibration sensors in the radial and axial directions on a turning machine spindle housing. Sensors are mounted with glue.
The sensors should be calibrated after five years of use to ensure that they function properly. Consider using close contact to install sensors in a wet condition. The spindle chuck mechanical settings should be recorded, such as clamped and unclamped positions. It should be recorded whether a tool is used during the measurements because of the imbalance in the tool.

Increasing or decreasing of the spindle speeds should permit 10 seconds of constant speed at each such selected speed before starting the measurement. Therefore, the spindle speed changes in such a way that a steady state of vibration is achieved before recording the measurements.

Techniques such as the bump test can be used to find the resonance areas to avoid measuring machine vibrations in the resonance areas. It is best to measure at the machine’s operational speed to avoid resonance frequencies. Background vibrations should be removed while measuring. Background vibrations can emanate from nearby machines.

The frequency range of measurements varies for different spindle speeds, bearing types, numbers of gear teeth and measuring methods for the analysis. Vibration velocity parameters can be measured within a frequency range of 100 times the operational speed frequency (e.g., a spindle with an operational speed of 3000 rpm and 50 Hz can be measured in the frequency range of 10 Hz-5000 Hz). However, high-frequency techniques, such as enveloping, use filter settings to detect bearing damages, i.e., frequency ranges of 0.5-10 kHz and 5-40 kHz are used in the enveloping technique.

Alarm values can be subject to agreement between the machine manufacturer or supplier and the user. The values should normally be set relative to a baseline value determined from experience for the measurement position and direction for that particular machine type. According to SS 728000-1 (2014), the alert value can be set to 1.4 to 2.0 times the established baseline value, and the general recommendation is to set alarm values to values exceeding the spindle baseline values by a factor of 3.

To obtain the best possible effect from vibration monitoring and thus be cost effective, there must be a strategy for how and where to perform vibration monitoring. Different types of machines with different criticalities should be measured at different time intervals, i.e., slow-moving machines only measured once a month. Very fast machines and the most important machines should be measured more often or be provided with on-line vibration monitoring. The strategy is also coupled to the rate at which the failure is developing as well as to how severe an error it is if it occurs. For example, if the spindle breaks, the whole work piece needs to be scrapped.

All measurements should be documented, and a trend analysis should be performed. In the case of unacceptable vibration levels, the cause must be found immediately by using, for instance, spectrum analysis and time waveform analysis with different methods such as high-frequency methods. If available, an FFT analyzer or a machine analyzer should be used. For the more complex problems or if there is a complete lack of the necessary analytical instruments, expert assistance must be requested.

Some examples of machine vibration measurements

Figure 34 represents the vibration measurement of a multi-task milling machine spindle at different speeds. The alarm boundaries are also shown by yellow and red lines in the figure. The maximal operational speed of the spindle is 12,000 rpm. As illustrated, the value of vibration velocity is significantly increased at the highest speeds and in the speeds close to the spindle maximum speed (14,000 rpm). The variation in amplitude can be explained by local resonances in the machine tool including the spindle unit.

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The data are then analyzed automatically by computer software. The computer software is also able to trigger warnings (i.e., via email). The data from the units are transferred to a computer as a database by using the company’s local area network (Ethernet) or using a 3G modem. The computer software is also able to trigger warnings (i.e., via email). Depending on the type of measuring units and number of its input channels, several machines can be connected to a single measuring unit. The machine should be programmed to run the measurement according to the required factors such as a constant spindle running speed and the no-load condition. As the schematic view in Figure 36 shows, the sensor/sensors are connected to a measuring unit by cables. The data from the units are transferred to a computer as a database by using the company’s local area network (Ethernet) or using a 3G modem. The computer software is also able to trigger warnings (i.e., via email).

4.8.2 On-line/automatic vibration monitoring of machine tool spindle units

The study showed that the on-line/automatic condition monitoring of spindle units using measuring units is challenging because machine tools operate at different speeds. The vibratory condition is dependent on both the spindle speed and the frequency response function (FRF) in the region of the work area. Therefore, different values will be measured at different speeds. In addition, as was explained, vibration measurement should be performed in an unloaded condition or not during a cutting operation, e.g., milling.

In on-line measurement, a measurement system unit/analyzer should be installed on the machine, and the machine should be programmed to activate the measuring unit to start and stop the measurement at a specific interval, after a specific number of work pieces. Depending on the type of measuring units and number of its input channels, several machines can be connected to a single measuring unit. The machine should be programmed to run the measurement according to the required factors such as a constant spindle running speed and the no-load condition. As the schematic view in Figure 36 shows, the sensor/sensors are connected to a measuring unit by cables. The data from the units are transferred to a computer as a database by using the company’s local area network (Ethernet) or using a 3G modem. The computer software is also able to trigger warnings (i.e., via email).
By using on-line vibration monitoring of machine tool spindle units, maintenance personnel spend less time performing the measurements by hand. There is no need for machine operator assistance to perform the measurements. The measurements can be performed in more accurate intervals. The on-line measurement takes approximately 85% less time compared to the measurement by portable instruments. Thus, it results in increased technical availability.

4.8.3 Vibration analysis of a machine tool spindle unit with bearing damage

By performing vibration analysis on a hard-turning machine’s spindle with integral drive, damage was found in an N1018 bearing at the non-drive end of the spindle. As indicated in Figure 37, an accelerometer was installed in the axial direction on the spindle housing close to the bearing location.

The spindle has an operational speed of 1100 rpm and 18.33 Hz that was measured in the frequency range of 5 Hz-2500 Hz. Figure 38 shows the spectrum analysis of the vibration velocity and acceleration parameters of the spindle. In the spectra, non-synchronous harmonics and shaft-rate sidebands are seen. The higher peaks in the spectrum correspond with the BPFI, which equals 253.08 Hz and 13.80 orders for the N1018 bearing. Since periodic pulses of vibration are observed at this rate, there is damage on the inner race because the impact harmonics of the BPFI are seen in the spectrum.
Since a spall travels around the bearing once per revolution, the impacts will not be equal in amplitude. Therefore, in an inner race defect, there are shaft-rate sidebands in the spectrum, as indicated in Figure 39.

By observing the damage in the velocity spectrum, the possible actions are to plan for spindle replacement and, in the meantime, monitor more frequently.

The damage was clearly observed using high-frequency techniques, including enveloping, SPM and PeakVue. As shown in Figure 40 and Figure 41, the non-synchronous harmonics in the spectra clearly correspond with the BPFI.
As indicated in Figure 42, the time waveform also shows inner race damage with a clear impact. The typical pattern in the time domain is a result of the damage on the inner race entering and leaving the loaded zone. The pattern in the time domain is repeated for every revolution (B2-B1); the distance between the small peaks equals the BPFI (A2-A1). The carrier frequency is the BPFI, and it is modulated by the shaft turning speed.

Bearing damage and failure analysis

By considering these analyses, the spindle bearing fault was successfully diagnosed, and the spindle was replaced. In addition, the bearing was removed from the spindle for further analysis. Figure 43 shows the damage on the inner race of the bearing in the rolling element contact area.

The early diagnosis was false brinelling damage due to vibrations during standstill. This occurs when vibrations from nearby machines travel through the bearing of the stationary machine and damage it. However, the machine does not have long enough stops for this type of damage. Therefore, further analysis shows that the root cause of the damage was that the spindle had the same start and stop geometry position. This means that the spindle has always...
been stopping in the same position when changing the work piece. The spindle bearing has also been stopping in the same place. At the same time, due to the oscillation of the spindle, the bearing lacks lubrication, which it causes metal to metal contact in the bearing. This is the root cause for wear on the inner race in the rolling element contact areas. The recommended action was to re-program the machine to have different stopping positions for the spindle.

### 4.8.4 Essential results – Cost effectiveness of vibration analysis of machine tool spindle units

The initial reason for troubleshooting the machine presented in section 4.8.3 was a quality issue, which caused an extra 10 seconds for each work piece. Therefore, other actions were taken to fix the problem with the machine, such as changing the ball screws and pulleys at a cost of 150 KSEK. These actions required 50 hours of production time with the loss of at least 50 KSEK for production. However, the main issue with the machine was not solved. Vibration analysis was then performed, and the bearing damage was found in the spindle. The spindle was replaced, and the root cause of the bearing damage was eliminated. Therefore, the probability of the same problem occurring in the spindle is quite low, and the company can avoid a 350 KSEK cost for spindle renovation in the near future. As a result, the cost avoidance with vibration analysis is estimated as at least 550 KSEK in this case. The results presented in section 4.3.1 show other indirect costs that are not considered in this estimation such as quality loss. Production time is reduced by 10 seconds per work piece, and tool life is increased; these are not estimated in the cost avoidance. In addition to the presented case, it was also observed that a turning machine spindle remained operating for approximately 70,000 hours without any bearing failure. It was however recommended to replace the spindle after 10,000 operating hours by the machine manufacturer. By considering a 200 KSEK total cost of spindle replacement in this case, the saving for the case company can be estimated as 1200 KSEK. This result indicates that there is a large potential saving by performing vibration monitoring of spindle units and replacing them when needed, instead of replacing them via a planned maintenance based on the machine manufacturer’s recommendations. The cost effectiveness of vibration analysis of spindle units in general is considered in the following objectives: reduced risk of safety issues, reduced risk of scrap or low-quality products, increased tool life, reduced costs for troubleshooting, reduced costs of spare spindle units in the warehouse, reduced downtime due to acute breakdowns, and use of the maximum life length of the spindle unit instead of replacing it via planned maintenance when it is not needed. Vibration analysis can also be very cost effective for machines that "cannot/do not have to" have unplanned stops in the production line due to high production volume. Machines should be measured and analyzed before being entered into service. In the case of identified deviations, the machine users can demand actions by the machine manufacturers, such as free machine renovation, free warrants/upgrades for some years and prolonged guarantees.

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5. Discussion
This chapter discusses the research studies and their results. The chapter concludes with several highlights from the described discussion.

5.1 General discussion
Based on the theoretical review and the empirical results (in chapters 2 and 4), the following areas have been identified as important and relevant in relation to the objective and research questions.

5.1.1 Strategic maintenance management
In study I-A, a process for formulating maintenance strategy was presented and tested through the case study presented in the previous chapter (section 4.1). The study indicated that a non-resource-demanding process may be used to formulate a maintenance strategy aligned with a company’s overall strategic goals. A formulated strategy can be based on a set of aspects that companies consider strategically important for their maintenance development. In other words, the proper goals of maintenance and the factors that should be developed to facilitate the strategic contribution of maintenance programs should be identified in a maintenance strategy. Some participants in the case company remarked that the formulated strategy not only can indicate the factors to improve but also can be viewed as a map to observe all maintenance-related activities and their influencing factors.

By establishing a well-formulated strategy for maintenance management, companies can achieve their strategic goals. One benefit of a formulated strategy is to reach an agreement with companies' maintenance provider on the strategic goals of maintenance. A formulated strategy helps companies obtain a clear picture of what deliveries they must achieve to reach their strategic goals. Furthermore, a formulated strategy aims to identify the relevant performance measures to use for maintenance activities. For instance, using financial KPIs for strategic maintenance goals makes it easier to determine the clear influence of strategic maintenance development on finances and the difference in cost between a planned and an unplanned stop. Finally, because the strategy is signed and approved at the board level, it acts as a management document.

A well-formulated maintenance strategy that is clearly linked to a company’s overall goals can motivate the implementation of preventive maintenance, such as condition-based maintenance (CBM), in the production schedule and can increase operators’ and production managers’ awareness to the benefits. Although maintenance is a cost center, as is any other production support function, identifying the strategic goals of maintenance and implementing a well-formulated strategy can enhance returns on the investment made in maintenance.

5.1.2 Maintenance decision making
As presented in section 4.2, preparing the decision-making models for the case company through the use of collected data from the CMMs in study I-B indicated that the models can be feasibly and practically applied. Comparing the results with maintenance engineers’ ideas revealed that utilizing various mathematical decision-making tools increases the decision analysis capability by helping maintenance engineers and managers to make more appropriate maintenance decisions. However, the suggested tools require further practical testing in different potential applications. Based on the empirical findings, it can also be concluded that the results of the decision-making models cannot be autonomously used; rather, they should be further analyzed in terms of prioritizations and characterization of different failure types and main contributing components.

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5.1.3 Cost effectiveness of implementing CBM

Study II-A was conducted to investigate the potential savings of implementing CBM in hardening and machining processes. Two cost models from the literature were combined and used to illustrate the difference between annual maintenance costs with and without CBM and were presented in the previous chapter (section 4.3). The results showed that reducing the probability of maximal damage in production equipment and reducing production losses, particularly in high production volumes, are two potentially significant benefits of CBM. Although reducing maximal damage in a single application might not seem to result in substantial savings in numbers for a company, it is logical to believe that a company can gain more benefits with a greater number of successful CBM applications for different types of production equipment. Furthermore, although a large part of the savings of CBM implementation should be related to preventing production losses, it seems difficult to gather this type of information in practice. This study has shown that the indirect maintenance costs, such as the cost of production loss, quality loss, safety loss or late delivery, are a substantial part of indirect maintenance costs. However, the companies in this study seem to have considerable difficulty calculating these costs. Although applying CBM is costly, a cost-effectiveness analysis for implementation can contribute to success and returns from CBM.

5.1.4 Material efficiency through CBM

Study II-B indicates that material efficiency is an important factor to consider when implementing CBM in the manufacturing industry, especially during the early decision-making phases. The analysis of the cost effectiveness and material efficiency of the implementation of CBM by the case company – in the presented cases (in section 4.4), for the hardening and phosphating processes – indicates that this approach contributes to cost savings by preventing production losses, reducing equipment downtime, achieving more efficient use of resources (spare parts, maintenance personnel and tools) and avoiding the generation of scrap and material wastage. As presented, many of the fan breakdowns experienced in the hardening and phosphating processes do not require the company to scrap the affected products. However, there is still the possibility of catastrophic failures that may incur high costs because of the scrapping of products (quality loss). In these cases, CBM can be an attractive solution, particularly for companies that produce high-value products. As a result, companies not only gain benefits from reducing equipment damage and production losses but also cut unnecessary costs associated with the scrapping of products. CBM is thus required to manage the health of equipment, prevent catastrophic failures and lower costs by reducing production losses and scrap-related costs.

5.1.5 Main practices and challenges to implement CBM

Study III-A relies on the notion that CBM plays a key role in providing management and people responsible for maintenance with correct and reliable data to prevent unplanned production stoppages. All the companies in the study – presented in section 4.5 – including those that do not have a specific organization for CBM, are more or less working with all CBM techniques but on different levels. To select an appropriate CBM technique, the companies consider the problems that machines have previously had. One of the main concerns is the presence of sufficient resources and competences in this area to effectively perform both off-line and on-line condition monitoring.

For companies that have worked with reactive maintenance strategies for many years, one of the main challenges in implementing proactive maintenance strategies (such as CBM) is transforming the culture of the company. Selecting the appropriate CBM techniques and technologies and increasing competence in measurement skills and data analysis are some of the main challenges in implementing CBM. Management support can therefore act as a key ingredient in transforming the culture of the company. Selecting the appropriate CBM techniques and technologies and increasing competence in measurement skills and data analysis are some of the main challenges in implementing CBM. Management support can therefore act as a key ingredient in transforming the culture of the company.
Detecting faults or damage via vibration monitoring of complex structures, such as spindle measurement routine, warning limits, and data handling and measuring tools and technologies, automatic or manual running of measurement, spindle rotational speed during the measurements, measurement condition, including the no-load condition with a tool clamped or without a tool, measuring tools and technologies, automatic or manual running of measurement, measurement routine, warning limits, and data handling and analysis, among other factors. Detecting faults or damage via vibration monitoring of complex structures, such as spindle in different directions, positioning of the vibration accelerometers, frequency range to be measured, resonance frequency, spindle rotational speed during the measurements, measurement condition, including the no-load condition with a tool clamped or without a tool, measuring tools and technologies, automatic or manual running of measurement, measurement routine, warning limits, and data handling and analysis, among other factors. Detecting faults or damage via vibration monitoring of complex structures, such as spindle

5.1.6 Successful implementation of CBM

According to study III-B, the process of implementing CBM must consider different aspects in the decision making and the implementation phases of CBM, as presented in the previous chapter (section 4.6). Several organizational, economic and technical aspects should be considered successful. The implementation process can also be a good guide when implementing CBM in manufacturing companies without previous experience in CBM. Examining the process will provide experience that can be used to facilitate future work. However, performing the implementation process in a sequential order is sometimes difficult or impossible. Therefore, decisions and actions can be re-arranged in a different order based on particular needs. Based on the discussion above and given that applying CBM is costly, an appropriate approach to implementation can help companies to succeed and achieve good returns on investment in CBM. The condition monitoring supplier company should be selected wisely. The presence of sufficient resources and competence within the organization to analyze the data and follow up on the activities is important for continuous improvement. It is important to involve the management in the implementation and budget for human resources and tools to be able to run a successful CBM.

5.1.7 On-line condition monitoring

Using on-line condition monitoring in study III-C – presented in section 4.7 – has shown several advantages compared with off-line monitoring; on-line condition monitoring is useful in difficult operational environments such as hardening processes. Therefore, the risk of safety issues is low compared with off-line monitoring by portable instruments. Furthermore, the risk of missing some failure events that occur between inspections is low with on-line monitoring. Therefore, by preventing the failure at the right time, the risk of major damage occurring in the equipment is low. In addition, CBM enables the identification and prediction of failure before breakdown occurs. It can thus prevent the consequences of a breakdown, such as production loss and extra cost for transportation of spare parts. According to a comparison of the cost of investment in on-line monitoring with the reduced cost of production losses and maintenance cost, such as the labor cost of off-line monitoring, on-line condition monitoring is a cost-effective way of working, if applied correctly.

However, to obtain more accurate results from condition monitoring to predict failure, more advanced frequency analysis must be carried out in addition to trend analysis. Increasing knowledge in performing advanced vibration analysis, such as high-frequency analysis, can provide a strong basis for preventive maintenance. Therefore, responsibilities should be defined, and the competent responsible people should always be ready to take proper action in any type of cases.

5.1.8 CBM of machine tools

According to study III-D, presented in section 4.8, several factors should be taken into consideration to perform vibration monitoring of a machine tool spindle. Some of these factors are as follows: the sensor type/sensitivity, number of sensors to be installed on the spindle in different directions, positioning of the vibration accelerometers, frequency range to be measured, resonance frequency, spindle rotational speed during the measurements, measurement condition, including the no-load condition with a tool clamped or without a tool, measuring tools and technologies, automatic or manual running of measurement, measurement routine, warning limits, and data handling and analysis, among other factors. Detecting faults or damage via vibration monitoring of complex structures, such as spindle
units, is challenging because there are different sources of frequencies from spindle bearings, gearboxes, gear meshes, etc. However, with the help of advanced vibration analysis, such as high-frequency measuring methods, it is possible to detect bearing damage in spindle units from a very early stage of the damage.

Only checking the vibration levels of machines that are already suspected to have a failure cannot be considered a feasible strategy. Vibration monitoring is aimed at finding problems long before they lead to failing components. However, more advanced vibration analysis should be used to determine the exact problems with the machine. It has been proven in the literature, as well as in the performed case studies, that regularly checking the vibration levels of machines is a major step forward in preventive maintenance of machine tools. Measuring a number of points on each machine every two weeks and ensuring that no elevated vibration levels are developing cost relatively little, but this approach is very good insurance against acute breakdowns. This results in shorter maintenance cycles and lower costs because of lower downtime, lower catastrophic failures, lower secondary damage and reduced parts inventory.

By increasing competence in this area, it is expected that machine condition monitoring systems that use vibration analysis will enable companies to reduce the uncertainty of maintenance activities, increase productivity, maintain quality and improve technical availability.

5.2 Concluding highlights from the discussion

The highlights of the discussion are summarized as follows:

- A well-formulated maintenance strategy that is clearly linked to a company’s overall goals can motivate the implementation of preventive maintenance such as CBM in the production schedule and can increase awareness of its benefits.

- The utilization of various mathematical decision-making tools increases the decision analysis capability by helping maintenance engineers and managers to make more appropriate maintenance decisions.

- Reducing the probability of maximal damage in production equipment and reducing production losses, particularly in high production volumes, are two potentially significant benefits of CBM.

- It is challenging to calculate the indirect maintenance costs, such as the cost of production loss, quality loss, safety loss or late delivery. However, they are a considerable part of maintenance costs.

- CBM can result in a more efficient use of resources (spare parts, maintenance personnel and tools) and avoid the generation of scraps and material wastage.

- Culture transformation, adequate competence within organization and management support are the main challenges to implement CBM.

- An appropriate approach to implementation can help companies to succeed and achieve good returns on investment in CBM.

- On-line condition monitoring is useful in difficult operational environments due to reducing the risk of safety issues. The measurement intervals are more accurate and more often. Therefore, the risk of missing some failure events that occur between inspections with on-line condition monitoring is low.

- It is possible, although still challenging, to detect bearing damage in machine tool spindle units with the help of advanced vibration analysis, such as high-frequency measuring methods.

- Machine condition monitoring systems will enable companies to ensure machine health management and thus improve technical availability, maintain quality and increase productivity.
6. Conclusions

This chapter begins with a discussion regarding the research objective and general conclusions as well as the fulfillment of the research questions. The research contribution is then presented, followed by an assessment of the quality of the research. The chapter ends by proposing topics for future research.

6.1 Discussion on the research objective and general conclusions

This research is based on the problems presented in the discussion in chapter 1. The overall purpose of this thesis is to increase productivity, sustainability and competitiveness; maintain quality; and improve the technical availability of the manufacturing industry through contributing to strategic maintenance development and to successful implementation of condition based maintenance (CBM). The main objective of this research is to provide frameworks and guidelines to support the development and implementation of CBM in manufacturing companies. A theoretical frame of reference has been presented to provide a theoretical foundation for the research. Furthermore, eight empirical studies were conducted at a major automotive manufacturing site to investigate the overall maintenance strategy and to determine the factors required to successfully implement CBM. In the case studies, the empirical findings were continuously compared with the reviewed literature to identify justifying and contrasting theories and to explain similarities and differences with theory. Therefore, the findings of the studies are applicable to other relevant settings.

The research introduces current industrial practices and challenges of implementing CBM – including cost effectiveness – and provides a guide for the organizational and technical implementation of CBM in the manufacturing industry. A work process for formulating a maintenance strategy, from company goals to maintenance actions, is generated. This is followed by a discussion on the decision-making models to increase the decision support capability of maintenance systems. A model for calculating the value of using CBM is proposed in addition to exemplified values of CBM. Challenges and enabling factors for the implementation of CBM are listed. A work process for implementing CBM in the manufacturing industry is generated. This is followed by example implementations of CBM for fan electric motors and machine tool spindle units.

Throughout the research, working with proactive maintenance strategies such as CBM has been understood as necessary for manufacturing companies’ future success in a competitive environment. Maintenance has an impact on the OEE and productivity of manufacturing companies. The importance of maintenance is increasing due to the growth of global competition, the introduction of lean manufacturing and the fourth industrial revolution. CBM is increasingly recognized as the most efficient strategy for performing maintenance in a wide variety of industries. It is being used to plan for maintenance action based on the condition of the machines and to prevent failures by solving the problems in advance. Therefore, it aims for companies to save money through fewer acute breakdowns, reductions in inventory cost, reductions in repair times, and an increase in the robustness of the manufacturing processes leading to more predictable manufacturing. Agendas such as “Industry 4.0” are promoting the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the internet. The natural link of CBM to cyber-physical systems (CPS) makes the role of CBM even more important in the fourth industrial revolution and digitalization. It is, however, important to start CBM implementation from a strategic perspective. It is challenging but important to calculate the possible value of CBM implementation. The research indicates that there is a potential to reduce costs and increase productivity when implementing CBM. The guidelines and inspiration from the studied cases in this research can be used when implementing CBM.

6. Conclusions

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6.2 Revisiting the research questions

To describe the research findings in a structured manner, the research questions are reviewed below, followed by a brief description of how they are answered within the research. Thus, the three research questions formulated in chapter 1 can be answered as follows:

**RQ1 What are the necessary factors to strategically manage production maintenance in manufacturing companies?**

This research question was formulated to investigate the need to manage production maintenance in a strategic manner. Two case studies were performed to answer this research question, and relevant evidence was collected to describe the current situation of the studied phenomenon. As a result, a work process for formulating a maintenance strategy was suggested, and the feasibility of this process was tested in cooperation with the maintenance managers at the case company. For instance, the company’s overall goals were considered and translated into the strategic objective of maintenance. Moreover, a balanced score card was used as a tool to provide a framework for maintenance strategy. Additionally, the results indicate that the maintenance strategy can contribute to the company’s business goals. Therefore, the formulated maintenance strategy, including the strategic objectives and their relative action plans, illustrates the factors that must be considered to strategically manage production maintenance based on the company’s overall strategy. However, these factors differ for different industries and companies based on their needs and possibilities. Section 4.1.4 summarizes the necessary factors to be considered to formulate a maintenance strategy. Furthermore, the influencing factors, including frequency of breakdowns, downtime, and cost of repair, were identified and used in maintenance decision-making models in order to provide decision-making capability for a maintenance management system. The decision-making models can act as further assistance for maintenance managers and engineers to determine which maintenance policy is appropriate for the type of component. Section 4.2.3 summarizes the relevant items regarding the utilization of maintenance decision-making models.

**RQ2 How could the cost effectiveness of CBM be valued in manufacturing companies?**

This research question was formulated to investigate the cost effectiveness of implementing CBM in the manufacturing industry. Two case studies were performed to answer this question. A cost model was developed and tested in the case company to evaluate the cost effectiveness of implementing CBM on fan electric motors and machine tool spindle units in the case company’s hardening and machining processes. Reducing the probability of maximal damage in production equipment and reducing production losses, particularly regarding high production volumes, were two potentially significant benefits of CBM in manufacturing companies. The results of the evaluation of the cost effectiveness of implementing CBM on fans and machine tools are presented in section 4.3.2, 4.7.5 and 4.8.4. In addition, the results of the empirical studies indicate that implementing CBM contributes not only to cost savings by preventing production losses and reducing equipment downtime but also to a more efficient use of resources by avoiding the generation of scraps and material wastage. Section 4.4.4 summarizes the main contributions of CBM to material efficiency and sustainable manufacturing.

**RQ3 How could CBM be implemented in manufacturing companies?**

Although advanced maintenance strategies such as CBM are considered promising ways to convert maintenance to a profit center, few manufacturing companies are employing these strategies to their highest potential. Therefore, this research question was formulated to investigate the current industrial practices and challenges of implementing CBM and how CBM can successfully be implemented in the manufacturing industry. Hence, some of the
main current challenges to implement CBM in the manufacturing industry – as a result of a multiple case study – have been identified, including management support, competence within the organization to use CBM effectively and company culture. The enabling factors for successfully implementing CBM include a clear condition monitoring strategy, management support, appropriate selection of techniques, adequate competence within the organization, determination of the level of technological complexity, the degree of continuous use and responsibility, consideration of the cost and supplier of the technologies and robust asset registration and asset failure history and symptoms. In addition, three case studies were undertaken by performing a pilot project at the case company to implement on-line and off-line condition monitoring on some of the case company’s critical components, including fans and machine tool spindle units. As a result, a work process for implementing CBM that focuses on its technical and organizational aspects is proposed and used in the case company. Section 4.6.2 summarizes the necessary factors to be considered for a CBM implementation. Furthermore, the organizational and technical factors of implementing CBM via the vibration monitoring technique on rotating machinery – including fans and machine tool spindle units – were identified. Section 4.8.1 summarizes the implementation factors of vibration monitoring of machine tool spindle units, such as sensor installation, machine loading condition for measurement, machine rotational speed for measurement, measurement frequency range, alarm limits and measurement strategy.

6.3 Research contributions

This research makes both scientific and industrial contributions. Based on the defined purpose and objective, this research contributes to the scientific community in terms of increasing practical and theoretical knowledge in the field of strategic maintenance development, focusing on the use of CBM in manufacturing companies. In addition, by performing a pilot project to implement CBM from the early phases of the research, this study provides relevant knowledge to the industry.

Scientific contribution

The main scientific contributions are summarized as follows:
1. Presenting the influencing factors that should be included in the maintenance strategy.
2. Introducing maintenance decision-making models using different methods or techniques, such as a maintenance decision-making grid, MCDM and clustering.
3. Identifying how one can value the financial implications of CBM in manufacturing companies.
4. Introducing the current industrial practices and challenges of implementing CBM in manufacturing companies.
5. Identifying the influencing factors to implement CBM in manufacturing companies.

Industrial contribution

The main industrial contributions are summarized as follows:
1. Providing a work process for formulating a maintenance strategy as well as providing the factors that should be included in the maintenance strategy.
2. Providing a cost model to analyze the cost effectiveness of implementing CBM.
3. Providing a process for implementing CBM by considering its organizational and technical aspects.
4. Providing guidelines to implement on-line condition monitoring.
5. Providing guidelines to implement vibration analysis on machine tool spindle units.
6.4 Quality of the research

Various aspects of the presented research quality were discussed in section 3.4. The methodological approach presented in chapter 3 was followed to ensure and improve the quality of the research. However, the researcher’s background and previous knowledge influenced the research process. For example, the researcher’s background has provided information regarding which persons to contact to address various questions. In addition, the researcher’s previous knowledge of the manufacturing industry and the criticality of its production assets assisted the researcher in defining the research problem and designing the research studies. Furthermore, the researcher’s ability to perform a real pilot project and to play an active role in the case company provided an excellent opportunity to understand the phenomenon and to collect reliable data as well as to strengthen the study’s contribution to both academia and industry. Reflective discussions were held continuously during the project with the researcher and project members in addition to discussions between the researcher and academic and industrial supervisors to align the research results.

6.5 Future research

Based on the performed research, because of the growth of global competition and implementation of concepts, such as Industry 4.0 and digitalization, it is crucial for future research activities to support maintenance and manufacturing organizations to achieve a higher overall productivity and efficiency of the production system. During the research process, several potential areas for future research work were identified. None of these areas are described below.

Additional studies on the implementation of maintenance strategies

Part of this research focused on maintenance strategy formulation. A possible continuation of the research could be to follow and investigate the implementation. A number of forces and obstacles that influence maintenance must be defined during implementation. The results of such an implementation investigation may demonstrate the importance of a well-formulated maintenance strategy and may motivate the management team toward further developments in maintenance.

Additional investigation on CBM cost effectiveness

In study II-A, a cost model was developed using theoretical evidence by performing a pilot project at the case company, and the factors were investigated in workshops. In addition, the cost effectiveness of a real-time implementation of on-line condition monitoring of fans and vibration monitoring of machine tool spindle units were investigated in study III-C and study III-D. The recommended tools and methods for the cost-effectiveness analysis require further practical testing in different potential applications.

Additional studies on different CBM techniques for different types of applications

A number of CBM techniques are explained briefly in section 2.3.1. However, the vibration analysis technique has mainly been the focus of the research studies in this thesis. Further research can be performed on the other CBM techniques for different types of applications such as circularity testing of machine tools, condition monitoring of rotating machinery with acoustic emission and on-line oil analysis of gearboxes.

Additional studies on vibration analysis for fault diagnostics

To obtain more accurate results from vibration monitoring, trend analysis by computer software is not the only solution. More specific frequency analysis should also be conducted. More knowledge regarding the performance of advanced vibration analysis measuring

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To obtain more accurate results from vibration monitoring, trend analysis by computer software is not the only solution. More specific frequency analysis should also be conducted. More knowledge regarding the performance of advanced vibration analysis measuring
methods, such as high-frequency analysis, can provide a strong basis for preventive maintenance. Therefore, further studies should be performed in this area.

Further investigation on the implementation and development of on-line vibration monitoring of machine tool spindle units

One of the important findings of the research studies was the development and implementation of on-line vibration monitoring of machine tool spindle units. Through this approach, it is expected for maintenance personnel to spend less time performing the measurements. In addition, there is also no need for operator assistance to perform the measurements. The data are then analyzed automatically by computer software. The computer software is also able to trigger warnings. It is therefore necessary to perform more investigations on the results of the implementations and more studies to achieve further development in this area. This can be one step forward to obtain a link between CBM and the concepts such as digitalization and IoT.

Research on big data analytics for maintenance purposes

Another interesting area in this field is to investigate the use of CBM in predictive analysis and/or prognostic fault analysis. For this purpose, CBM can be linked to concepts such as big data analytics to obtain fault prediction models for different types of applications. Because a part of the research studies performed in this thesis concerned on-line condition monitoring of rotating machinery, further studies can be performed to make use of existing data (i.e., real-time analysis of big data sets) to obtain predictive analytics models.


Hyde, K. F. (2000), "Recognising deductive processes in qualitative research", Qualitative market research: An international journal, 3(2), 82-90.

Industrie 4.0 Platform, VDMA, presentation, 2014


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Appendices

Appendix 1 - Interview guide for formulating maintenance strategy, adopted from Salonen (2011)

1. Is there a maintenance strategy?
2. Is it written or oral?
3. Is it clearly tied to the business strategy?
4. How do you formulate the strategy (a team effort/ the maintenance manager/ other)?
5. Who approves the strategy (the company’s board)?
6. Which components/aspects are/should be included in a maintenance strategy?
   - Maintenance organization
   - Control (maintenance control/ planning, spare parts planning, CMMS)
   - Policies/ concept (corrective maintenance/preventive maintenance, TPM/ RCM)
   - Material resources (tools, machinery, etc.)
   - Technological resources (condition monitoring, etc.)
   - Economy (do you consider the financial effect of maintenance?)
   - Personnel (number, competences)
   - Work hours (shifts, on-call duty)
   - Technological skills
   - Are all departments served?
   - Focus areas
   - Spare parts management
   - Education and training
   - Others
7. Are responsibilities defined in the strategy?
8. Is the strategy communicated (to whom, how)?


<table>
<thead>
<tr>
<th>Type of loss</th>
<th>List of needed data for evaluating the losses due to damage</th>
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| Capital loss | • Current value of the equipment investment
               • Maximal damage cost (as a percentage of the current value of the equipment investment)
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               • Probability of maximal damage with CBM (as a percentage)
               • MTBF (Mean Time Between Failures) = runtime/no. of failures
               • Runtime
               • Number of failures
               • MTBR (Mean Time Between Repairs) |
| Production loss | • MTTR (Mean Time To Repair)
                • Mean product price
                • Mean production rate = batch size/time that the batch is in the machine
                • Batch size
                • The time that the batch is in the machine |
| Quality loss | • Cost of fines for a breach of regulation (in the event that an asset failure injures an employee)
           • Cost of compensation for an injured employee |
| Safety loss | • Cost of fines for a breach of regulation (in the event that an asset failure injures an employee)
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| Environmental loss | • Cost of energy loss due to damage |
| Customer satisfaction loss | • Fines for late delivery
                     • Lost business to a competitor due to late orders |

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| Environmental loss | • Cost of energy loss due to damage |
| Customer satisfaction loss | • Fines for late delivery
                     • Lost business to a competitor due to late orders |
Appendix 3 - Interview guide for companies’ views on practices and challenges of CBM

1. What is the role of CBM at your company? Do you see CBM as an important factor to implement?
2. Do maintenance management and top management see CBM as a strategically important factor to realize technical availability?
3. What is the competence level of your company in CBM? What is the reason for a lack of knowledge?
4. What is the level of development of CBM tools at your company?
5. Do you have on-line condition monitoring? If yes, what type and in which production processes (i.e., 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 in implementing CBM in your company?
9. What are your future plans?

Appendix 4 - Questionnaire for selecting the pilot project objects

1. What are the specifications of the selected object? (including any pictures and drawings)
2. What were the main factors for selecting this object?
3. What is the most critical component of this object?
4. How does failure occur in this object?
5. Are there any data that can be found from EWOs, including MTBF, MTR, and MWT?
6. What is the expected running time for the object?
7. How many breakdowns has the object had? How frequently?
8. Are there similar objects in the factory? How many breakdowns have they had?
9. In the event of breakdowns, what maintenance tasks are performed on the object? Replacement? (A description of maintenance tasks that have been performed after each breakdown.)
10. When was the last replacement?
11. Is there any scheduled maintenance for the replacement?
12. What conditions should be provided for the replacement?
13. How many hours are required to perform the replacement?
14. Do the breakdowns halt the entire production process? (How much production loss is estimated?)
15. Do the breakdowns cause “quality” issues for the products?
16. Do the breakdowns cause “safety” issues?
17. How often should the object be lubricated?
18. Are there any data or estimates concerning the cost of the breakdowns, at least for maintenance costs?
19. Did you have condition monitoring on this object before? If yes, how frequently? Which tools have you been using (if any)? On-line or off-line monitoring?
20. Regarding predicting the failure time through on-line condition monitoring, is it possible to schedule the maintenance for a time that does not affect production (during non-production time)? Or is there a possibility of having a buffer in production?
Appendix 5 - Criteria analysis on data collected from the EWO database

<table>
<thead>
<tr>
<th>Category</th>
<th>Rank</th>
<th>DT (hrs)</th>
<th>Cost (Fr.)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
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Appendix 6 - Summary of the categories of machines

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<tr>
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Appendix 7 - Summary of the categories of parts

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<th>Cost (Fr.)</th>
<th>Percentage</th>
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