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ON CONDITION BASED MAINTENANCE AND ITS IMPLEMENTATION IN INDUSTRIAL SETTINGS

Marcus Bengtsson

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Akademisk avhandling

som för avläggande av Teknologie doktorsexamen i Innovation och design vid Institutionen för innovation, design och produktutveckling kommer att offentligen försvaras fredagen, 9:e november, 2007, 10.00 i Filen, Verktyget, Smedjegatan 37.

Fakultetsopponent: Professor Bengt Klefsjö, Industriell ekonomi och samhällsvetenskap, Luleå Tekniska Universitet, Sverige.

Institutionen för innovation, design och produktutveckling

Abstract

In order to stay competitive, it is necessary for companies to continuously increase the effectiveness and efficiency of their production processes. High availability has, thus, increased in importance. Therefore, maintenance has gained in importance as a support function for ensuring, e.g., quality products and on-time deliveries. Maintenance, though, is a costly support function. It has been reported that as much as 70% of the total production cost can be spent on maintenance. Further, as much as one-third of the cost of maintenance is incurred unnecessarily due to bad planning, overtime cost, limited or misused preventive maintenance, and so on. In so, condition based maintenance is introduced as one solution for a more effective maintenance.

In condition based maintenance, critical item characteristics are monitored in order to gain early indications of an incipient failure. Research, though, has shown that condition based maintenance has not been implemented on a wide basis. Therefore, the purpose of this research is to investigate how a condition based maintenance approach can be implemented in an industrial setting, and to develop a method that can assist companies in their implementation efforts. Further, the research has been divided in three research questions. They focus on: constituents of a condition based maintenance approach, decision-making prior implementation of condition based maintenance, and finally, the implementation of condition based maintenance in a company.

By using a systems approach and a case study process, how condition based maintenance can be implemented as a routine has been investigated. The result is an implementation method in which four suggested phases are presented. The method starts with a feasibility test. It then continues with an analysis phase, an implementation phase, and an assessment phase. The conclusions can be summarized as follows: implementing condition based maintenance consists of many general enabling factors, including management support, education and training, good communication, and motivation etc.

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Abstract

In order to stay competitive, it is necessary for companies to continuously increase the effectiveness and efficiency of their production processes. Production strategies such as Just-in-Time and Lean Production demand high availability of production equipment in order to meet customer satisfaction. Therefore, maintenance has gained in importance as a support function for ensuring equipment availability, quality products, on-time deliveries, and plant safety. Maintenance, though, is a costly support function. It has been reported that as much as 70% of the total production cost can be spent on maintenance. Further, as much as one-third of the cost of maintenance is incurred unnecessarily due to bad planning, overtime cost, limited or misused preventive maintenance, and so on.

Well-performed maintenance implies seeing as few corrective maintenance actions as possible while performing as little preventive maintenance as possible. This might seem as a utopia, but during the past decades strategies and concepts have evolved for support. One of these is condition based maintenance. In condition based maintenance, critical item characteristics are monitored (through, for example, vibration or temperature monitoring) in order to gain early indications of an incipient failure. Research, though, has shown that condition based maintenance has not been implemented on a wide basis. Therefore, the purpose of this research is to investigate how a condition based maintenance approach can be implemented in an industrial setting, and to develop a method that can assist companies in their implementation efforts. Further, the research has been divided in three research questions. The first focuses on condition based maintenance as an approach; seeking constituents essential to take into consideration when implementing the approach. The second focuses on the decision-making process prior an implementation can commence. Finally, the third focuses on the implementation of the condition based maintenance approach in a company.

By using a systems approach and a case study process, how condition based maintenance can be implemented as a routine has been investigated. The result is an implementation method in which four suggested phases are presented. The method starts with a feasibility test. It then continues with an analysis phase, an implementation phase, and an assessment phase. These steps are taken in order, for example, to invest in the proper condition based maintenance approach and to implement it gradually. The conclusions can be summarized as follows: implementing condition based maintenance consists of many general enabling factors, including management support, education and training, good communication, and motivation etc.

Keywords: Condition based maintenance, condition monitoring, production systems, change management, implementation, case study, and decision-making.

Sammanfattning

För att vara fortsatt konkurrenskraftig och nå framgång på den globala marknad som råder krävs effektivare produktionsprocesser. Produktionsstrategier som Just-in-time och Lean produktion kräver produktion med hög tillgänglighet för att kunna möta kunders förväntningar. Underhåll av produktionsutrustning har därför på senare år fått en ökad betydelse som supportfunktion med syfte att säkra tillgänglighet och därigenom produktkvalitet, säkerhet och leveranser på utsatt tid osv. Forskning har dock visat att underhåll ses som en särdeles dyr supportfunktion. Underhållskostnaden kan vara så hög som 70% av produktionskostnaden. Det har även framkommit att så mycket som en tredjedel av de medel som läggs på underhåll spenderas i onödan, detta beror bland annat på dålig planering, övertidskostnader, samt begränsad eller felaktigt utfört förebyggande underhåll.

Ett väl utfört underhåll har definierats som då så få avhjälpande underhållsåtgärder som möjligt utförs samt då så lite förebyggande underhåll som möjligt genomförs. Detta kan ses som en omöjlig balansgång, men över de senaste decennierna har strategier och koncept utvecklas för att stödja denna syn. Ett utav dessa är tillståndsbaserat underhåll. Med tillståndsbaserat underhåll tillståndsövervakar man kritiska komponenter i en produktionsprocess med bland annat vibrations- och temperaturmätningar, för att få en tidig indikation då ett begynnande fel är nära förestående. Tillståndsbaserat underhåll har därför på senare år seglat upp som en av de effektivaste formerna av underhåll. Undersökningar har dock visat att tillståndsbaserat underhåll inte har implementeras i den utsträckning som förväntats. Den här forskningen har sökt orsaker och lösningar till detta problem.

Forskningsprojektet har med ett systemsynsätt och genom fallstudier, genomförda i olika industrier, undersökt hur tillståndsbaserat underhåll kan implementeras som ett dagligt arbetssätt. Resultatet av projektet blir således en implementeringsmetod där fyra föreslagna faser presenteras. Metoden tar sin början i ett lämplighetstest och fortsätter i en analysfas, en implementeringsfas, samt en utvärderingsfas, allt för att fatta korrekta beslut och implementera stegvis. Slutsatserna i forskningsprojektet kan sammanfattas som att implementering av tillståndsbaserat underhåll består av många generella framgångsfaktorer som till exempel ledningens stöd, utbildning och träning, god kommunikation och motivation.

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I am grateful to have been given the opportunity to share the office space with the staff from the Department of Innovation, Design, and Product Development. It has been a great workplace for the past five years. I am eager to, specifically, send my gratitude to the PhD-students: Antti Salonen, Mikael Hedelind, Joakim Eriksson, Anette Brannemo, Anna Pettersson, Yuji Yamamoto, Andreas Ask, and, of course, Carina Andersson, for interesting collaboration, fruitful discussions, and great friendship. Further, but certainly not the least, I would like to thank, the nowadays PhD's, Sofi Elfving and Rolf Olsson for support, fruitful discussions, and great friendship. Thank you, Juliana Cucu, and other staff at the Mälardalen University Library, your service and great knowledge has been invaluable during the process.

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Eskilstuna, October 2007
Marcus Bengtsson

Publications

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

Paper I Bengtsson, M. & Jackson, M. (2004). *Important Aspects To Take Into Consideration When Deciding to Implement Condition Based Maintenance*. 17th International Conference of Condition Monitoring and Diagnostic Engineering Management, Cambridge, UK.

Paper II Bengtsson, M. (2006). *The Possibilities of Condition Based Maintenance on the Main Battle Tank 122*. Technical report, Mälardalen University: Department of Innovation, Design and Product Development, Eskilstuna, Sweden.

Paper III Bengtsson, M. (2006*). Decision and Development Support When Implementing a Condition Based Maintenance Strategy – A Proposed Process Improvement Model.* 19th International Conference of Condition Monitoring and Diagnostic Engineering Management, Luleå, Sweden.

Paper IV Bengtsson, M. (2007). Supporting Implementation of Condition Based Maintenance: Highlighting the Interplay Between Technical Constituents and Human & Organizational Factors. *Accepted for publication in the International Journal of Technology and Human Interaction.*

Paper V Andersson, C. & Bengtsson, M. (2007). Essential Information Forms in a Condition Monitoring Context. *To be* s*ubmitted for publication.*

Paper VI Bengtsson, M. (2007). *Decision-Making During Condition Based Maintenance Implementation*. 20th International Conference of Condition Monitoring and Diagnostic Engineering Management, Coimbra, Portugal.

Additional publications not included in the thesis:

Bengtsson, M., Elfving, S., & Jackson, M. (2007). Maintenance as an Enabler of Production System Concepts – The Factory-in-a-Box Concept. *Submitted to the Journal of Quality in Maintenance Engineering.*

Funk, P., Olsson, E., Bengtsson, M., & Xiong, N. (2006). *Case-Based Experience Reuse and Agents for Efficient Health Monitoring, Preventive, and Corrective Actions.* 19th International Conference of Condition Monitoring and Diagnostic Engineering Management, Luleå, Sweden.

Bengtsson, M., Elfving, S., & Jackson, M. (2006). *The Factory-in-a-Box Concept and Its Maintenance Application.* 19th International Conference of Condition Monitoring and Diagnostic Engineering Management, Luleå, Sweden.

Bengtsson, M. (2006). *Ideas, Views, and Experiences On How To Implement A Condition Based Maintenance Strategy.* 10th International Conference of Maintenance and Reliability, Knoxville, Tennessee, USA.

Bengtsson, M. (2006). *Ideas and Views On How To Technically and Organizationally Implement Condition Based Maintenance.* 18th International Conference of Euromaintenance, Basel, Switzerland.

Bengtsson, M. (2004). *Condition Based Maintenance Systems – An Investigation of Technical Constituents and Organizational Aspects.* Licentiate Thesis, Mälardalen University, Eskilstuna Sweden.

Olsson, E., Funk, P., & Bengtsson, M. (2004). *Fault Diagnosis of Industrial Robots Using Acoustic Signals and Case-Based Reasoning.* 7th European Conference on Case-Based Reasoning, Madrid, Spain.

Bengtsson, M., Olsson, E., Funk, P., & Jackson, M. (2004). *Technical Design of Condition Based Maintenance System – A Case Study Using Sound Analysis and Case-Based Reasoning.* 8th International Conference of Maintenance and Reliability, Knoxville, Tennessee, USA.

Bengtsson, M. (2004). *Condition Based Maintenance System Technology – Where Is Development Heading?* 17th International Conference of Euromaintenance, Barcelona, Spain.

Bengtsson, M. (2003). *Standardization Issue in Condition Based Maintenance.* 16th International Conference of Condition Monitoring and Diagnostic Engineering Management, Växjö, Sweden.

List of definitions

Term	Description	Reference
Asset	A formally accountable item.	SS-EN 13306, 2001
Condition based maintenance	Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. NOTE: Performance and parameter monitoring may be scheduled, on request, or continuous.	SS-EN 13306, 2001
Condition based maintenance system	A system that uses condition based maintenance to determine and schedule predictive maintenance actions autonomously or in interactions with other systems or humans.	Bengtsson, 2004b
Conditional probability of failure	The probability that a failure will occur in a specific period provided that the item concerned has survived to the beginning of that period.	Moubray, 1997
Corrective maintenance	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, 2001
Diagnosis	Fault recognition and identification.	Lewis and Edwards, 1997
Failure	Termination of the ability of an item to perform a required function. NOTE1: After failure, the item has a fault, which may be complete or partial. NOTE2: “Failure” is an event, as distinguished from “fault”, which is a state.	SS-EN 13306, 2001
Failure consequence	The way (or ways) in which a failure mode or a multiple failure matters.	Moubray, 1997
Failure effect	What happens when a failure mode occurs.	Moubray, 1997
Failure mode	A single event that causes a functional failure	Moubray, 1997
Fault	State of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources.	SS-EN 13306, 2001
Function	The normal or characteristic actions of an item, sometimes defined in terms of performance capabilities.	Nowlan & Heap, 1978
Functional failure	A functional failure is the inability of an item (or the equipment containing it) to meet a specified performance standard.	Nowlan & Heap, 1978

Item	Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered. NOTE: A number of items (e.g. a population of items) or a sample may itself be considered as an item.	SS-EN 13306, 2001
Maintenance	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.	SS-EN 13306, 2001
Maintenance concepts	The set of various maintenance interventions (corrective, preventive, condition-based, etc.), and the general structure in which these interventions are brought together.	Pintelon et al., 1999
Manufacturing system	…a collection of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts.	Groover, 2001
Monitoring	Activity, performed either manually or automatically, intended to observe the actual state of an item. NOTE1: Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameter of the item with time. NOTE2: Monitoring may be continuous, over a time interval, or after a given number of operations. NOTE3: Monitoring is usually carried out in the operating state.	SS-EN 13306, 2001
On-condition task	A scheduled task used to determine whether a potential failure has occurred.	Moubray, 1997
P-F interval	The interval between the point at which a potential failure becomes detectable and the point at which it degrades into a functional failure (also known as ‘failure development period’ or ‘lead time to failure’).	Moubray, 1997
Potential failure	A potential failure is an identifiable physical condition which indicates a functional failure is imminent.	Nowlan & Heap, 1978
Predetermined maintenance	Preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation.	SS-EN 13306, 2001

Predictive maintenance	Condition based maintenance carried out following a forecast derived from the analysis and evaluation of significant parameters of the condition of the item.	Bengtsson, 2004b
Preventive maintenance	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, 2001
Production system	…the people, equipment, and procedures that are organized for the combination of materials and processes that comprise a company's manufacturing operations. /…/ Production systems include not only the groups of machines and workstations in the factory but also support procedures that make them work.	Groover, 2001
Prognosis	Prediction of when a failure may occur.	Lewis and Edwards, 1997
System	…a group of objects that are joined together in some regular interaction or interdependence towards the accomplishment of some purpose.	Banks et al., 1996

Contents

1 Introduction

This chapter presents the background of, and the problem connected to, the research that is the basis for the purposes of the research and the research questions. The chapter also presents the expected industrial results, delimitations, and the structure of the thesis.

1.1 Background

Increased productivity is a key issue for manufacturing companies to stay competitive on a global market. Success, and even survival, in manufacturing requires continuous development and improvement in the way products are being produced (Jackson and Petersson, 1999). Just-in-time, supply chain management, lean manufacturing, capacity assurance, flexible and agile manufacturing, to name a few, are strategies in which it is essential that production capacity is available in order to meet customer demand (Desirey, 2000; Gits, 1994; Luxhøj et al., 1997; Riis et al., 1997). Maintenance as a form of production support has thus become increasingly important to ensure equipment availability, quality products, on-time deliveries, and plant safety (Bevilacqua and Braglia, 2000; Luxhøj et al., 1997; Riis et al., 1997). Even so, maintenance is still considered a cost center in many companies (Alsyouf, 2004).

However, as Jonsson (1999) states, improper maintenance and unavailable equipment often limit the effectiveness of manufacturing. Wireman (1990) states that as much as one-third of the total maintenance cost is spent unnecessarily because of circumstances such as bad planning, overtime costs, poor usage of work order systems, and limited or misuse of preventive maintenance. There is also no doubt that maintenance is a costly support function. McKone and Weiss (1998) state that a company can spend as much as its net income on maintenance. Maggard and Rhyne (1992) state that maintenance expenses on a yearly basis usually range between 15 and 40% of the total production cost. Coetzee (2004) states it can be as much as 15 to 50%, and Bevilacqua and Braglia (2000) declare that maintenance cost can represent as much as 15 to 70% of the total production cost. A consensus of the above-mentioned percentages is, thus, that maintenance costs represent 15% or higher of the total production cost. Given Wireman's (1990) statement - that one-third of the maintenance is waste - it becomes clear that about 5% or more of the total production cost is spent unnecessarily due to bad maintenance. Several studies have also visualized that industry is far from utilizing production equipment to its full potential (Ahlmann, 2002; Ljungberg, 1998; Nord and Johansson, 1997). A study performed in ten Swedish manufacturing companies revealed that operative utilization of production equipment, on average, was as low as 59%. Of the unavailable time, 39% was spent on maintenance (Ericsson, 1997). Thus, there is truly untapped potential in industry today, parts of which can be realized through maintenance management development.

On a theoretical note, good maintenance has been defined as when very few corrective maintenance actions are undertaken and when as little preventive maintenance as possible is performed (Cooke & Paulsen, 1997). This demands great skills in planning proper preventive maintenance intervals and tasks. When as few corrective maintenance actions as possible should take place, it can be seen as good to perform as much preventive maintenance as possible. Continuous maintenance would, of course, lead to decreased availability and high direct maintenance costs in terms of, for example, labor and spare parts. The preventive maintenance should, for the most effective execution, be planned for when an item's pre-set normal condition is exceeded. In some cases, a machine can actually be run until just before failure (Al-Najjar, 1997). Al-Najjar (1997) continues by stating "The needs for increased plant productivity and safety, and reduced maintenance costs, have led to an increasing interest in methods for condition monitoring, (CM), of mechanical systems." (p.8).

The need for condition based maintenance was revealed as early as in the 1960's through a study performed during the development of the preventive maintenance program for the Boeing 747. The study's purpose was to determine the failure characteristics of aircraft components (Overman, 2002). The study was, at the request of the Department of Defense (USA), documented and published by Nowlan and Heap in 1978. It was found that a relatively small part of all components (11%) had clear ageing characteristics, which enables a schedule overhaul (that is predetermined maintenance). The rest of the components (89%) did not show such ageing characteristics (that is, they were more or less random failures) and consequently not applicable to schedule overhauls (Nowlan & Heap, 1978). Page (2002) presents similar conditional-probability curves within the manufacturing industry. He states that only 30% of all components have clear ageing characteristics, and that this percentage decreases as complexity and technology increases. Evidently, the ageing feature of a component is not the best approach, and in some applications not even possible, when planning appropriate maintenance schedules. This fact introduces condition based maintenance and condition monitoring as one solution to the issue.

1.2 Problem discussion

Independent investigations reveal that condition based maintenance is not utilized to a large extent. An investigation performed by Jonsson (1997), surveying 284 relevant respondent answers in the manufacturing industry of Sweden, reveals that only two-fifths of maintenance time is spent on preventive or condition based maintenance. In maintenance techniques, the use of objective condition monitoring is valued low in comparison to human senses, corrective maintenance, and other preventive techniques. Statistical testing visualized that large companies to a greater extent utilized condition monitoring than small- and medium-sized companies did. Alsyouf (2004) presents another investigation within Swedish industry placing condition based maintenance in second place, tied with corrective maintenance, as the most frequently used maintenance approach. Predetermined maintenance was reported to be the most frequently used. However, the condition monitoring tools reported as having been used in the same investigation were of quite low-tech art. A third investigation performed by Bengtsson (2004a) reports that condition based maintenance, as a maintenance approach, is only utilized in 10% of all maintenance activities. The investigation came to the same conclusions as Alsyouf's concerning the use of condition monitoring tools (in other words, they were generally of quite low-tech art). An industrial problem is thus that condition based maintenance, and in particular the technical advantages, are not utilized to their full potential.

Condition monitoring tools have been used and developed for many decades. However, according to the investigations above, the majority of Swedish industry has not started to utilize the technical advantage of these tools. When surveying published research within condition based maintenance and condition monitoring, most papers and books deal with the technical aspects, and less with organizational aspects. Pengxiang et al. (2005) state that most research within condition based maintenance and condition monitoring in the power industry is more or less devoted to the technical aspects. It does not bestow much attention on how the power utilities should carry out condition based maintenance and what strategies they should apply. Moya (2003) goes as far as stating that there is no international standard on managing a predictive maintenance program. McKone and Weiss (2002) state: "Although predictive maintenance technology has tremendous potential, most managerial practices have evolved by trial and error." (p.111). Moubray (1997) declares that a challenge nowadays for maintenance departments is not only to know what new techniques can do, but also to choose the correct one for their organization. Walker (2005) states that many implementation efforts fail, three (of many) reasons being inappropriate selection of condition monitoring, technology inappropriately applied, and no condition monitoring implementation strategy. Kotter (1996) argues that there are always barriers working against change in an organization, and that these, with the help of a method, can be overcome.

Within other maintenance approaches and philosophies, such as total productive maintenance, more research has been performed on the topics of organizational aspects and implementation methods (see Chand & Shirvani, 2000; Cigolini & Turco, 1997; Cooke, 2000; Eti et al., 2004; Lycke, 2000; Nakajima, 1988; Sun et al., 2003; Tsang & Chan, 2000; Wireman, 1991).

1.3 Purposes

The problem discussion indicates that there is a need for additional research within the area of implementing condition based maintenance. This, partly in order to raise the awareness of its incentives as well as giving companies a head-start in the implementation phase. There is a need to collect data from successful implementations of the approach, as well as experiences and views from experts, in order to develop implementation procedures for companies to use so that they do not suffer the effects of trial-and-error approaches.

Maxwell (1996) distinguishes between three different purposes of performing a study: personal, practical, and research purposes. Personal purposes are the ones that motivate a researcher to perform a study, it or perhaps they can come from different aspects such as political passions, curiosity, desire, or as simple as to advance in career. The practical purpose is focused on accomplishing something (in other words, to meet a need, to change a situation, or to achieve an operational goal). Finally, the research purpose is focused on understanding something, to gain insights into what is going on, and why. Indeed, this research has, as Maxwell (1996) suggests, three purposes. The personal purpose is two-fold: to qualify for a doctoral degree through the acquisition of deeper knowledge within the academic subject Innovation & Design (and in particular maintenance technology) and to acquire practical research experience in change management in industry (and in particular the implementation of condition based maintenance). The practical purpose of this research has an industrial focus: to facilitate the implementation of condition based maintenance in companies, where applicable. Finally, the research purpose can be formulated as:

The research purpose of this research project is to investigate how a condition based maintenance approach can be implemented in an industrial setting, and to develop a method that can assist companies in their implementation efforts.

1.4 Research questions

Three research questions have been formulated based on the problem discussion and the research purpose. The focus of the questions is on the implementation of condition based maintenance, although they take on a wide scope of the implementation process. The first question sets out to investigate the phenomena of condition based maintenance. This is performed in order to highlight constituents that influence a condition based maintenance approach. The second question sets out to investigate the decision-making process necessary to reflect upon before implementation can commence. The third and final question sets out to investigate the implementation process itself; how a condition based maintenance approach can be implemented in a company. The research questions are formulated as follows:

RQ1. Which are the constituents of a condition based maintenance approach?

Prior to an implementation of condition based maintenance, it is essential to understand and have knowledge in what a condition based maintenance approach is all about. As mentioned above, the technology in condition based maintenance is in strong focus. It is possible that other or additional constituents, besides technological, are important to focus on in order to achieve a successful implementation result. This research question sets out to investigate and highlight the constituents of a condition based maintenance approach.

RQ2. Which essential decisions should be made, before implementing a condition based maintenance approach?

It is essential to analyze the current situation a company is operating in today in order to implement a new system. How is the current maintenance strategy formulated, if it even exists? What are the current maintenance costs, and how well does the outcome of it reflect the goals? Questions like these and probably many more need to be answered in order to conclude whether a condition based maintenance approach can be an integral part of achieving the maintenance goals of a company. If it is concluded that condition based maintenance can be an applicable solution for a company, additional decisions lie ahead. Condition based maintenance is not to be used as an overall policy. Therefore, decisions on assets to be a part of the monitoring program need to be considered carefully. Also, condition based maintenance and condition monitoring comes in a variety of different techniques and technologies, to decide what to monitor and how on a trial-and-error or an ad-hoc basis can be a risky approach. This research question sets out to investigate the decision-making process necessary to reflect upon before implementation of condition based maintenance can start.

RQ3. How can a condition based maintenance approach be implemented, and which enabling factors are essential to focus on in the process?

There are many barriers for change. Kotter (1996) names a few. They are inwardly focused cultures, paralyzing bureaucracy, parochial politics, a low level of trust, a lack of teamwork, arrogant attitudes, a lack of leadership in middle management, and the general human fear of the unknown. These are just a few factors that may need to be overcome in order to be successful in the implementation of a condition based maintenance approach. This research question sets out to investigate how companies successfully have implemented, or successfully can implement, a condition based maintenance approach, and to visualize enabling factors essential to focus upon in an implementation effort.

1.5 Expected industrial results

The expected industrial results of the research are two-fold: first, a practical method companies will be able to use in implementing a condition based maintenance approach, and second, an investigation of how industrial companies have succeeded with an implementation process. In this research, a 'method' is treated as "a systematic procedure in order to achieve a specific result." Further, it will consist of different tools, guidelines, and models with a suggested sequential arrangement of use. The method, with its accompanying parts, is to be developed using data from several industrial cases and literature.

1.6 Delimitations

Even though condition based maintenance could be used for virtually any process or product, it will, in this research, be treated in relation to physical assets, such as motors, machines, pumps, and the like (in other words, assets that can be found within the ordinary manufacturing industry and in larger systems). Software, buildings, and services are excluded.

The case studies performed within the research have focused on companies in Sweden and the Swedish manufacturing- and process industry. The type of and sizes of companies, as well as the type of industry included in the case studies, have been spread over a wide range. This was done in order to collect data from several different settings, thereby increasing the generalizability of the results.

Condition based maintenance systems, and within diagnosis, prognosis, and decision support processes, in particular, analysis techniques and methods (such as mathematical modeling and different artificial intelligence techniques, to name two) might possibly be needed. This research acknowledges as much. However, the research does not have the objective of performing research within these specified issues; the research purposes has been formulated to approach the problem statement in a more comprehensive manner.

In implementing a new system and/or a new way of working it often takes a long time before the change is absorbed in the company. Changing an organization and the culture therein can sometimes take several years. As an example, Nakajima (1988) states that it takes approximately three years to implement total productive maintenance. One of the most important aspects in an implementation is to validate that the change has actually occurred and that the organizational culture has changed. This research acknowledges this but has focused more on the parts that comes before the validation phase. No case studies has been performed on the topic of validating an implementation of condition based maintenance simply because the approach for such a study would imply that a company and its implementation effort would have to be followed during many years and this has unfortunately not been a possibility between the licentiate- and the doctoral thesis.

1.7 Structure of the thesis

The thesis is divided into eight chapters (see Figure 1). Chapter 1 contains the introduction, with a background and problem discussion, followed by the purposes of the research as well as research questions. The first chapter ends with a discussion of the expected results and delimitations of the thesis. Chapters 2 and 3 contain a theoretical framework. Chapter 2 introduces maintenance as a vital support function in production systems. Meanwhile, Chapter 3 introduces condition based maintenance as one part of successful maintenance, and addresses the problems associated with its implementation. The research is thus not based on theory found within a certain theoretical setting; instead, a rather horizontal perspective has been applied, as the issue of implementing condition based maintenance is a holistic phenomenon. Chapter 4 presents the research methods used throughout the research. Chapter 5 then presents the results, divided in five parts, describing the cases. Later, Chapter 6 presents the suggested implementation method. Chapter 7 presents a discussion of the conclusions and suggestions on future research. Finally, chapter 8 lists the references used.

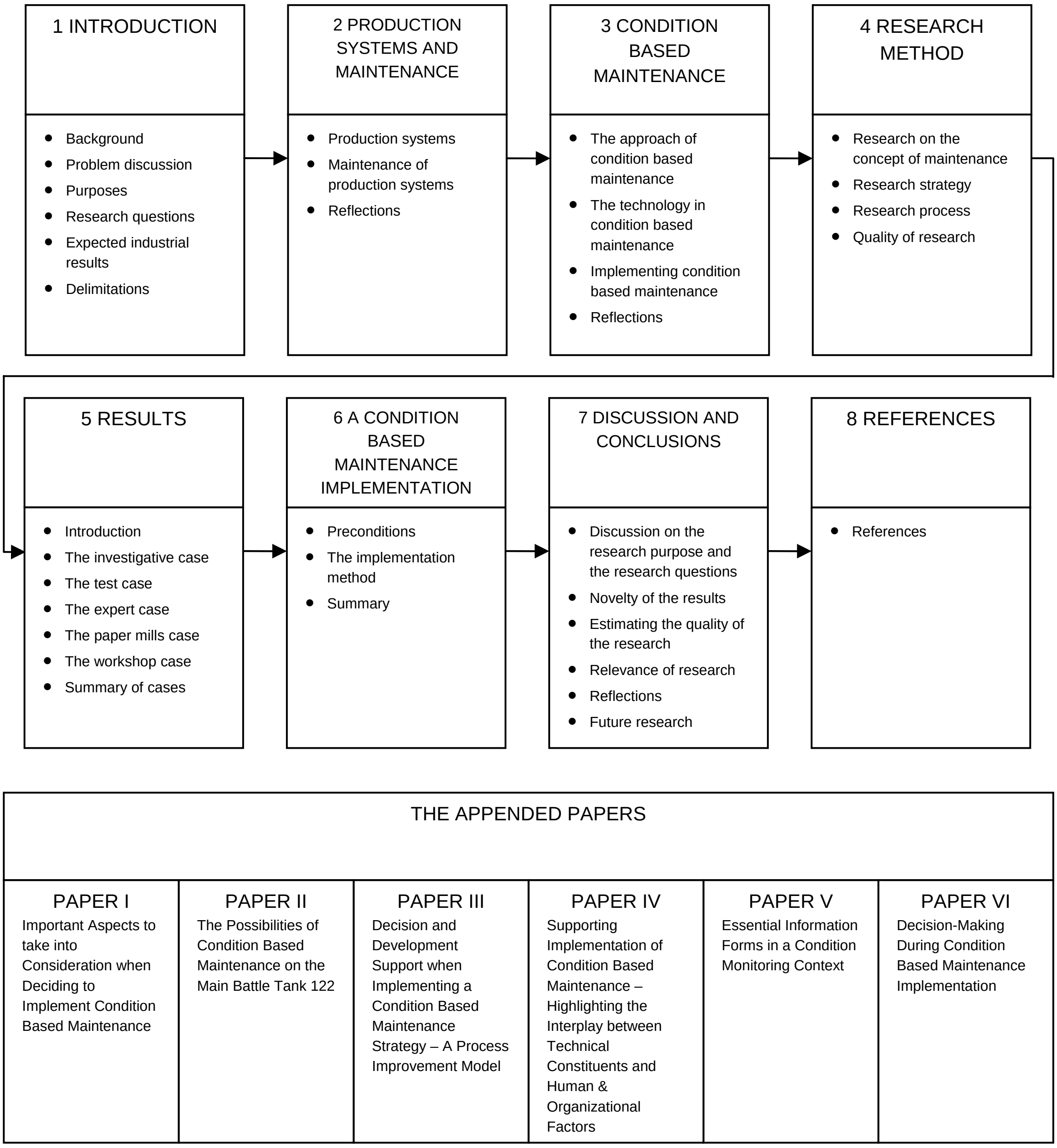

Figure 1. The structure of the thesis.

2 Production systems and maintenance

This chapter presents theory and definitions regarding production and manufacturing systems, failure and faults, and maintenance. The chapter aims at presenting the theories in a descending order, from the comprehensive production system to the consequences of, and some solutions to, its failures, and finally introducing the subject of maintenance. The chapter ends in a reflection that will argue in favor of condition based maintenance as one solution to failures in production systems.

2.1 Production systems

There are many definitions of production and manufacturing systems. In an attempt to clarify, a production system is, for the purposes of this research, defined as: "…the people, equipment, and procedures that are organized for the combination of materials and processes that comprise a company's manufacturing operations. /…/ Production systems include not only the groups of machines and workstations in the factory but also support procedures that make them work." (Groover, 2001, p.78). A manufacturing system, on the other hand, is defined as: "…a collection of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts." (Groover, 2001, p.375). This view positions the manufacturing system in a factory as a component in the larger production system. Goldman et al. (1995) share this view, stating that production includes everything it takes to create and distribute products.

Hubka and Eder (1988) present a model of a transformation system that visualizes a production system (see Figure 2). The technical system, humans, and the active environment all affect the technical process it takes to transform an operand (Od) (for example, a raw material) from an initial to a completed stage.

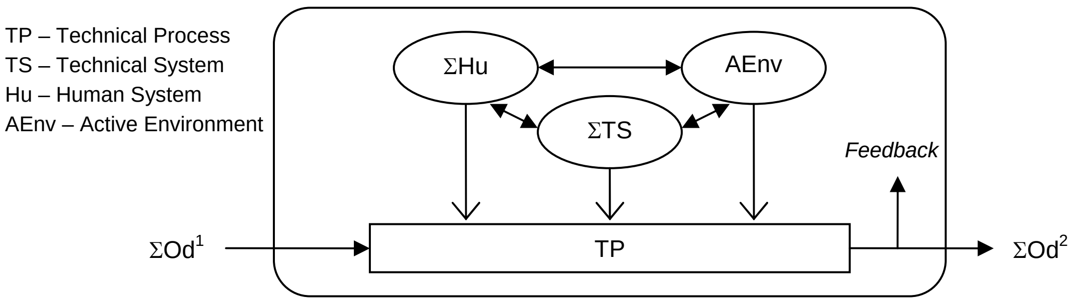

Figure 2. A model of a transformation system, the closed arrows symbolize input/output and the open arrows symbolize effect, Od is short for operand (Hubka & Eder, 1988, p.23).

The production systems of today are often guided by a complex production strategy. With strategies such as: just-in-time, supply chain management, lean manufacturing, capacity assurance, and others, it is increasingly important that production is available to meet customer demand (Desirey, 2000). As the trends of the new production strategies also imply working with fewer inventories, the production systems become even more vulnerable to unplanned unavailability (Gits, 1994).

Availability, though, can be seen as only one out of three dimensions of effectiveness of production equipment, the other two being the performance rate and the quality rate (Ljungberg, 1998). Multiplied, the three dimensions form the product of overall equipment effectiveness, OEE (Nakajima, 1988). Nakajima (1988) explains that in order to achieve a high OEE, the six big losses need to be eliminated. The six big losses are the following: down time in the form of equipment failure and setup and adjustments, speed losses in the form of idling and minor stoppages and reduced speed, and defects in the form of process defects and reduced yield (Nakajima, 1988). The downtime of production equipment is of course related to the availability of the production equipment. An OEE level of 85% has been viewed as a world-class target (Nakajima, 1988).

There is thus much that affects the effectiveness of production systems. Nord et al. (1997) add ten further losses, also taking into account human effectiveness. Below, failures and fault in production systems will be further explained as a major influence on effectiveness.

2.1.1 Failures and faults in production systems

Much has been written on failures, potential failures, faults, etc. According to Söderholm (2005), the literature within the area is not stringent; below an attempt to clarify the view within this research will be provided. A failure is defined as: "Termination of the ability of an item to perform a required function." (SS-EN 13306, 2001, p.11). A fault, on the other hand, is defined as: "State of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources." (SS-EN 13306, 2001, p.12). Thus, a failure is an event, while a fault is a state.

Nowlan and Heap (1978) instead define two types of failures: "A functional failure is the inability of an item (or the equipment containing it) to meet a specified performance standard." (p.18), and "A potential failure is an identifiable physical condition which indicates a functional failure is imminent." (p.19). A functional failure and a potential failure as defined by Nowlan and Heap (1978) correspond to the definitions (SS-EN 13306, 2001) of fault and failure, respectively.

Nowlan and Heap (1978) present a study of conditional-probability curves of United Airlines aircraft components. The results of the study visualized that the conditional-probability curves fell into six different patterns (see Figure 3), where only 4% of the components fell into the commonly known bathtub curve. Further, it visualized that only a total of 6% of the components had a well-defined wear-out region. Another 5% had no well-defined wear-out region, but it was visible that the probability of failure was higher as age increased. This implies that 89% of the tested components had no wear-out region; therefore, the performance of these components could not be improved by the introduction of an age limit. Nowlan and Heap (1978) also conclude that the failure rate of a component is not a very important characteristic within maintenance programs; although a good figure for setting up maintenance intervals, "…it tells us nothing about what tasks are appropriate or the consequences that dictate their objective." (p.48). Page (2002) presents corresponding conditional-probability curves within the manufacturing industry, and states that only 30% of all components have clear ageing characteristics, and that this percentage decreases as complexity and technology increases.

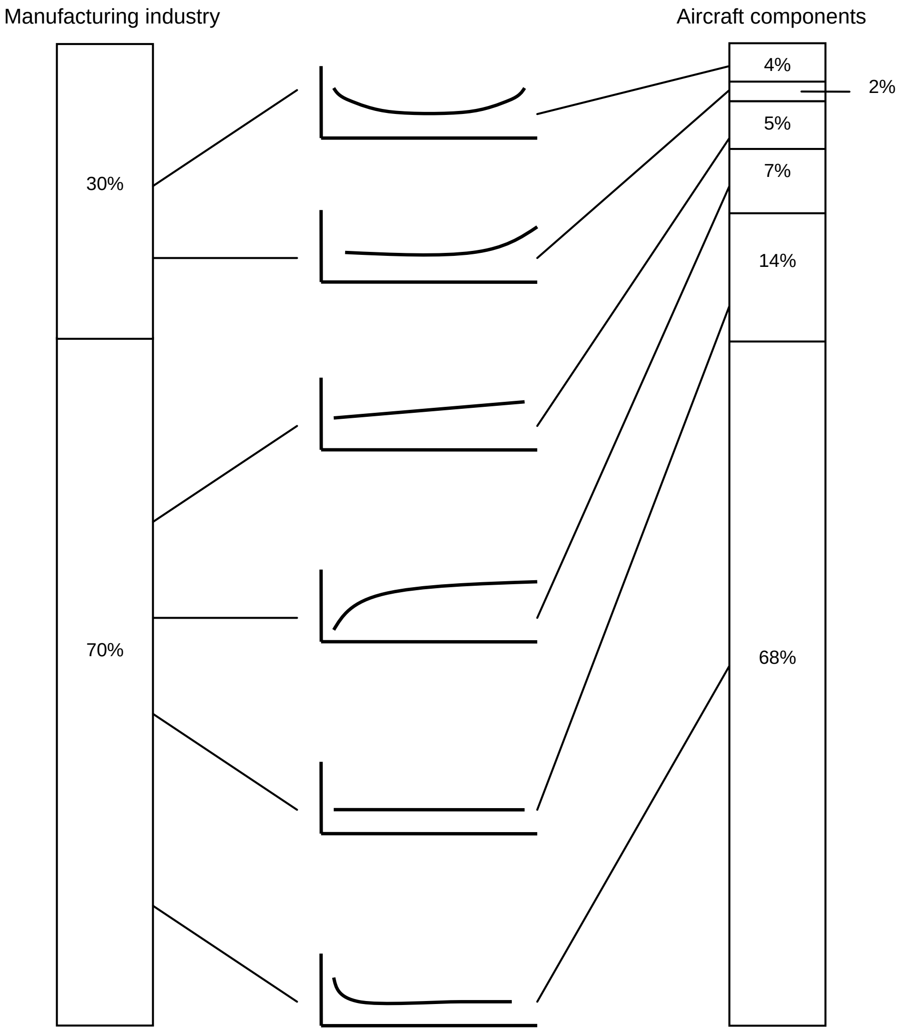

Figure 3. The six age-reliability patterns as presented by Nowlan and Heap (1978) and Page (2002). The vertical axes represent the conditional probability of failure, and the horizontal axes represent operating age since manufacture, overhaul, or repair. The percentages to the right of the curves correspond to the Nowlan & Heap (1978) study, performed on aircraft components. The percentages to the left of the curves correspond to the distribution of failure patterns within the manufacturing industry as presented by Page (2002).

As discussed above, planning maintenance intervals based on age are not always the best approach; other alternatives should then be consulted. Although many failures are not related to age, most of them give incipient warnings that they are in the process of failing (Moubray, 1997). This is termed the potential failure to failure curve, P-F curve (see Figure 4). Consulting the P-F curve for a particular failure mode can give indications as to what type of on-condition task is appropriate. Obviously, in order to be effective, on-condition tasks must be performed in intervals shorter than the P-F interval. Moubray (1997) defines an on-condition task as: “A scheduled task used to determine whether a potential failure has occurred." (p.413), and further divides the on-condition techniques into four categories:

- condition monitoring technologies,
- techniques based on product quality,
- primary effects monitoring techniques, and
- inspection techniques based on the human senses.

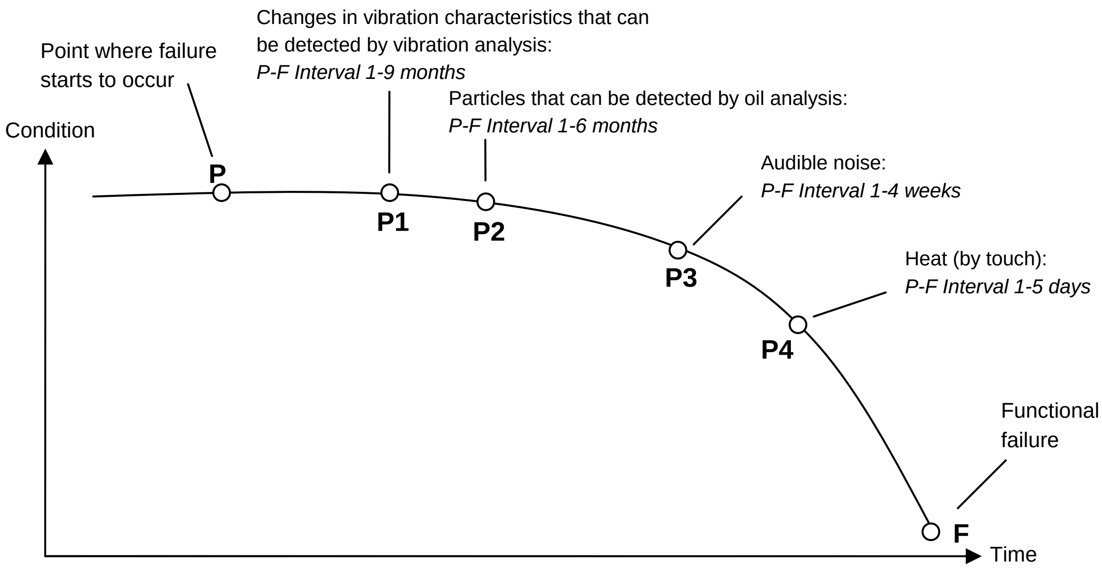

Figure 4. The potential failure to failure curve of a ball bearing (Moubray, 1997, p.144).

Often, different potential failure conditions can precede a failure mode. The P-F interval of these potential failure conditions can vary a great deal, choosing more than one potential failure condition as a warning can be a good idea. As an example, an incipient ball bearing failure might start with changes in high frequency vibration characteristics, followed by increasing particle content in lubricating oil, audible noise, and, finally, heat build up in the bearing caps (see Figure 4) (Moubray, 1997; Tsang, 1995).

Moubray (1997) mentions five possibilities for determining the P-F interval: continuous observation, start with a short interval and gradually extend it, arbitrary intervals, research, and a rational approach. However, Moubray (1997) states that only the last two have any merits. Research, such as laboratory testing, is considered the best approach, but is most often expensive and time consuming. Taking a rational approach and asking the right questions (for example, how rapid the failure process is) to the right people (for example, the operators and maintainers with experience) and concentrating on one failure mode at a time is, according to Moubray (1997), a surprisingly accurate approach for determining the interval.

In addition, Moubray (1997) claims that four criteria must be met in order for an on-condition task to be technically feasible (p.149):

- It is possible to define a clear potential failure condition.
- The P-F interval is reasonably consistent.
- It is practical to monitor the item at intervals less than the P-F interval.
- The nett P-F interval is long enough to be of some use (in other words, long enough for action to be taken to reduce or eliminate the consequences of the functional failure).

Tsang (1995) defines the time between potential failure and catastrophic breakdown *T,* and states that the inspection interval should not exceed one half of *T*. The uncertainty in the estimation of *T* does in many cases complicate setting up a proper interval. Moubray (1997) also concludes that it usually is sufficient to select a monitoring frequency equal to half of the P-F interval. However, Moubray (1997) also introduces the *nett* P-F interval as the "…minimum interval likely to elapse between the discovery of a potential failure and occurrence of the functional failure." (p.146). As indicated in Figure 5, the P-F intervals are the same. However, monitoring is carried out once a month in the top interval, while monitoring is carried out only every sixth month in the bottom interval. For the bottom, the nett P-F interval will be three months. The top one will be as much as eight months, although monitoring must be carried out six times more often. The benefits of monitoring often (and thus having a longer nett P-F interval) are several: decreased downtime (in that it enables better planning); decreased repair costs (in that secondary damage might be avoided easier); and, increased safety.

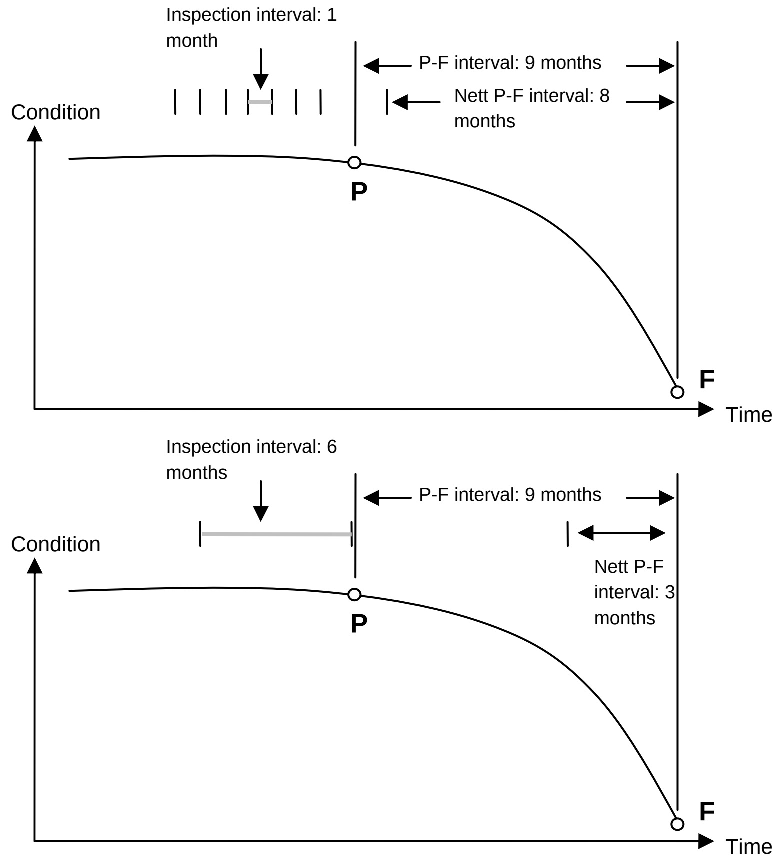

Figure 5. Examples of two different nett P-F intervals, but with similar P-F intervals (Moubray, 1997, pp.146-147).

2.1.2 Consequences and solutions to failures and faults in production systems

Failures in production systems can create many inconveniences. Todinov (2006) lists possible problems resulting from system failure, all of which can incur massive costs:

- lost production time,
- volume of lost production,
- mass of harmful chemicals into the environment,
- lost customers,
- warranty payments,
- cost of mobilization of emergency resources, and
- insurance cost

A production system generates value when being utilized productively, and obviously costs money in an unproductive state. Ericsson (1997) presents a study conducted at ten companies within the Swedish industry, where only 59% of the planned production time was used for operative production. Ljungberg (1998) presents a study placing the average of 23 machine systems on an overall equipment efficiency, OEE, of 55% (although he feels that the figure might be a little low, as many of the machines in this particular study were in a late running-in phase). Ahlmann (2002) presents a study of random Swedish engineering companies that places the OEE at 60%. Finally, Kinnander and Almström (2006) present a study in which OEE measurements had been performed at 11 companies within the Swedish industry, the average value of the study being 66%. However, they also state that the companies in the study reported the OEE measures of machines that had high priority for the production, implying that it might be higher than an average of all machines. In concluding, the OEE levels of Swedish industry, reported on in the studies above, have increased some during the past ten years. Nonetheless, they are far from what is considered world-class. That is, there is still an untapped potential in Swedish industry.

Mitigating unproductive time and system failure can and should be performed using different approaches on various levels. Techniques, tools, methods to increase maintainability (see Akersten, 1979; Markeset & Kumar, 2001; Blanchard et al., 1995), reliability (see Bergman & Klefsjö, 2001; Høyland & Rausand, 1994), production system robustness (see Bellgran & Säfsten, 2005; Bergman & Klefsjö, 2001), and so on have been developed through many years.

2.2 Maintenance of production systems

Maintenance as a support function in production systems has been valued as a critical role (Cholasuke et al., 2004) and even as a prerequisite (Starr, 1997) (see Figure 6). This, of course, also implies that maintenance must be performed effectively, in other words, the correct maintenance action should be taken at the proper time. Inadequate maintenance, on the other hand, can result in increased costs due to the following (Moore and Starr, 2006):

- lost production,
- rework,
- scrap,
- labor,
- spare parts,
- fines for late orders, and
- lost orders due to unsatisfied customers.

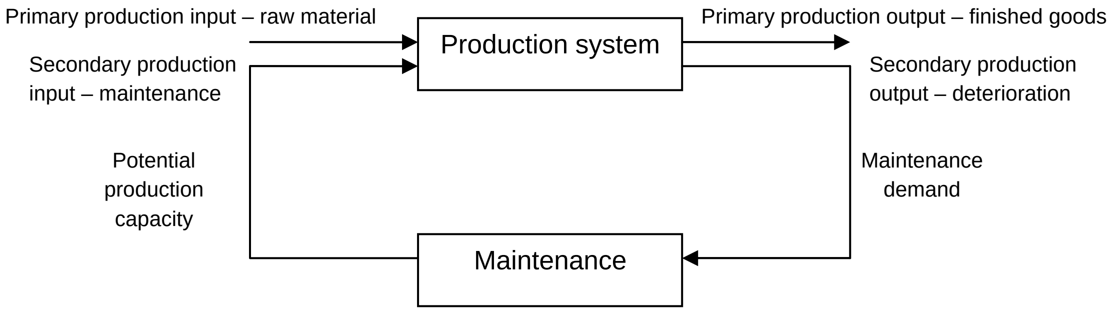

Figure 6. The need and affect of maintenance on a production system, adapted after Gits (1994). Obviously, additional support functions are necessary in order to run a production system. However, as the Figure visualizes, maintenance plays a vital role in upholding production capacity.

According to Simeu-Abazi and Sassine (2001), the prime target of maintenance should be to ensure the system function of production equipment. Further, maintenance should provide the right parameters of: cost, reliability, maintainability, and productivity, for any automated manufacturing system (Simeu-Abazi & Sassine, 2001). Coetzee (2004) shares this view on maintenance objective, stating that: "It is the task of the maintenance function to support the production process with adequate levels of availability, reliability and operability at an acceptable cost" (p.24). Various approaches to performing maintenance exist. Also, various definitions of maintenance have been suggested through the years, the common point being that they have moved away from the traditional perception of maintenance, as explained by Tsang et al. (1999), to repair broken items. Maintenance is defined as a: "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." (SS-EN 13306, 2001, p.7).

When focusing on "…retain it in, or restore it to…" in the definition of maintenance, it becomes evident that maintenance can be performed in two major types: corrective maintenance and preventive maintenance (see Figure 7). Both of the traditional maintenance types are widely used in practically all industrial sectors (Starr, 1997).

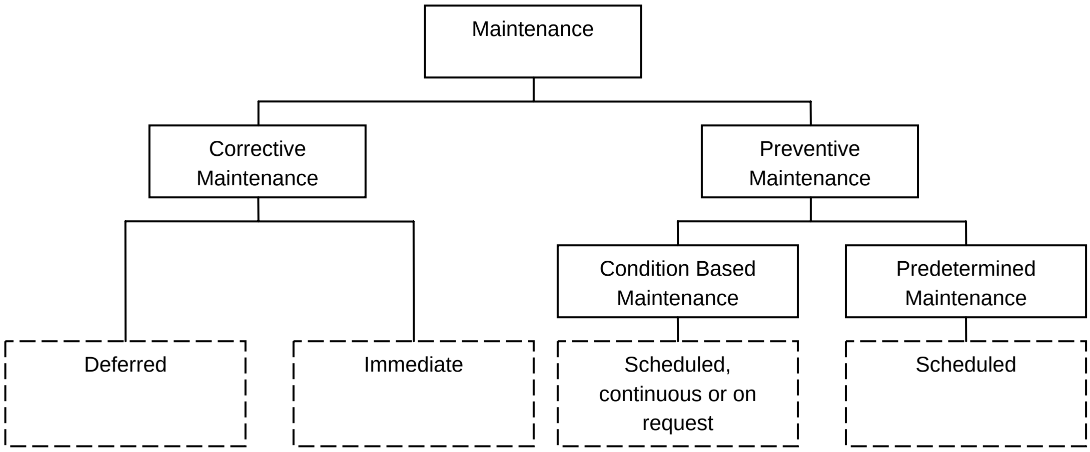

Figure 7. Overview of different maintenance types (adapted from SS-EN 13306, 2001, p.23).

Corrective maintenance, similar to repair work, is undertaken after a breakdown or when obvious failure has been located. Corrective maintenance is defined as: "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, 2001, p.15). For repair work, some modeling approaches are available. With minimal repair, the failed item is only restored to its functioning state and the item continues as if nothing has happened. The likelihood of a failure (i.e. the failure rate) stays the same as it was immediately before the failure. Using the minimal repair approach means that the item is only restored to an "as bad as old" condition (Høyland & Rausand, 1994). Minimal repair can be executed for various reasons, such as lack of time, spare parts, competence, and so on. If the item instead is replaced by a new component of the same type, or if it is restored to an "as good as new" condition, the failure rate will decrease to the level of when the item was just put into use. This is called a renewal process or sometimes a maximal repair. According to Høyland and Rausand (1994), these types of repairs are the extremes of repair work. Accordingly, most repair actions are located somewhere in between, and are often called imperfect repair (Bergman and Klefsjö, 1996).

For failures on critical functions, corrective maintenance has to be performed immediately. However, for failures that have no or little consequence on the comprehensive system function, the maintenance can be deferred in time to a better-suited occasion. Starr (1997), however, means that corrective maintenance at its best should only be utilized on non-critical areas where: capital costs are small, consequences of failure are slight, no safety risks are immediate, and quick failure identification and rapid failure repair are possible. Starr (1997) also means that companies by default often adopt corrective maintenance inappropriately, which in the long run can become costly. Corrective maintenance is sometimes referred to as: breakdown maintenance (Starr, 1997), failure-driven maintenance (Yam et al., 2001), failure-based maintenance (Alsyouf, 2004), and run-to-failure maintenance (Starr, 1997; Yam et al., 2001).

Preventive maintenance has been defined as: "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, 2001, p.14) Preventive maintenance is divided into two types, predetermined maintenance and condition based maintenance (SS-EN 13306, 2001). Predetermined maintenance is scheduled and planned without the occurrence of any monitoring activities. The scheduling can be based on the number of hours in use, the number of times an item has been used; the number of kilometers the items has been used, according to prescribed dates, and so on. Predetermined maintenance is best suited to an item that has a visible age or wear-out characteristic and where maintenance tasks can be made at a time that for sure will prevent a failure from occurring (Starr, 1997). Predetermined maintenance is sometimes referred to as time-based maintenance (Yam et al., 2001) and planned preventive maintenance (Starr, 1997).

The other preventive maintenance type, condition based maintenance, does not utilize predetermined intervals and schedules. Instead, it monitors the condition of items in order to decide on a dynamic preventive schedule. More on condition based maintenance and monitoring can be found in Chapter 3.

2.2.1 A historic perspective on maintenance

Maintenance as a discipline has evolved immensely over the past decades. According to Moubray (1997), it is possible to divide the changes into three generations. The first generation reaches up to the Second World War, the second generation spans from the Second World War until the mid-seventies, and the third generation spans from the mid-seventies until today. During the first generation, not much focus was directed towards maintenance. The manufacturing of goods was not highly mechanized, and the equipment was relatively simple (in many cases even over-designed). This gave little or no need for maintenance other than simple cleaning, servicing, and lubrication. In the second generation, increased demand on goods and decreased number of manpower, both due to war, led to increased mechanization. Thus, downtime came into a clearer focus. This led to the concept of preventive maintenance in the form of overhauls performed at fixed intervals. Of course, with this approach, maintenance costs increased, leading to the development and use of maintenance planning and control systems. However, new expectations, new research, and new techniques, somewhere in the mid-seventies, started to push maintenance into the third generation. As the manufacturing equipment evolved and became increasingly complex, the expectations on maintenance increased as well. Higher reliability and availability, higher levels of safety, longer equipment lifetime, increased demands on cost-effectiveness, among others, are expectations that in recent years have become quite common for maintenance departments in virtually all sectors. New research has also visualized that failures do not occur as earlier thought. As discussed above (see Figure 3), ageing characteristics are much more complex than believed in the first two generations. As manufacturing equipment has increased in complexity, so have also maintenance equipment and concepts (see Figure 8). According to Moubray (1997), a major challenge nowadays for maintenance departments is not only to know what the new techniques can do, but also to choose the proper one for their organization. However, still today, many companies adopt corrective maintenance by default in areas which are not appropriate (Starr, 1997).

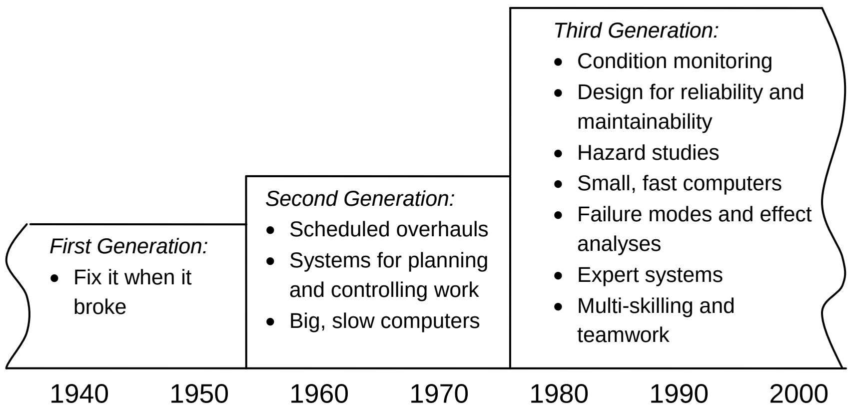

Figure 8. New expectation, new research and, as the figure visualizes, new techniques have since the end of the Second World War pushed maintenance into the third generation. According to Moubray (1997) the problem for companies nowadays is to choose the proper techniques for their organization, figure from Moubray (1997, p.5).

2.2.2 Different maintenance concepts

In order to achieve an effective maintenance execution, it is important to focus ones maintenance intentions. Utilizing some sort of maintenance concept can be an approach to this. Jonsson (1997) mentions maintenance management concepts such as: Total Productive Maintenance (TPM), terotechnology, Reliability-Centered Maintenance (RCM), asset management, integrated logistics support (ILS), and life cycle cost/profit (LCC/LCP). Some of these will be briefly explained below.

Total productive maintenance

Total Productive Maintenance, generally referred to as TPM, is a maintenance concept that heavily rests on employee participation, from the top management to shop floor personnel. TPM was born in Japan, and sprung from the preventive maintenance developed in the USA following the Second World War (Nakajima, 1988). TPM strives to maximize equipment effectiveness by first eliminating the "six big losses": equipment failure, setup and adjustment, idling and minor stoppages, reduced speed, process defects, and reduced yield. Elimination of the six big losses should be followed by: autonomous maintenance program, a scheduled maintenance program for the maintenance department, increased skills of operations and maintenance personnel, and an initial equipment management program (Nakajima, 1988). The goal of TPM is hence zero breakdowns and zero defects (Nakajima, 1988). TPM has, during the past decades, been widely spread across the world and successfully implemented in different industries (see Chand & Shirvani, 2000; Cigolini & Turco, 1997; Cooke, 2000; Eti et al., 2004; Sun et al., 2003; Tsang & Chan, 2000).

Reliability-Centered Maintenance

Reliability-Centered Maintenance, generally referred to as RCM, is a structured approach to setting up a maintenance program. It is sprung from the airline industry, and dates back to the early 1960´s (Overman, 2002). 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 users want it to do in its present operating context." (p.7).

Moubray (1997, p.7) describes the RCM process as answering seven questions about selected assets:

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfill its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

When correctly applied, RCM can achieve much and mitigate problems such as: higher levels of safety and environmental integrity, improved operating performance, better maintenance cost-effectiveness, longer useful life of expensive items, a comprehensive database, greater motivation of individuals, and better teamwork (Moubray, 1997). Backlund (2003) provides a comprehensive discussion of the benefits, as well as lifting the introduction issue.

Lean maintenance

Smith and Hawkins (2004) define lean manufacturing as: "…the practice of eliminating waste in every area of production including customer relations (sales, delivery, billing, service and product satisfaction), product design, supplier networks, production flow, maintenance, engineering, quality assurance and factory management. Its goal is to utilize less human effort, less inventory, less time to respond to customer demand, less time to develop products and less space to produce top quality products in the most efficient and economical manner possible." (p.16). Lean manufacturing or lean production thus strives to remove all non-value adding activity, such as waste (*muda*). According to Ohno (1988), seven wastes exist: overproduction, waiting, unnecessary motions, transporting, over processing, unnecessary inventory, and defects. Bicheno (2004) adds five additional wastes: the waste of making the wrong product efficiently, the waste of untapped human potential, the waste of inappropriate systems, wasted energy and water, and wasted materials.

Smith and Hawkins (2004) mean that a TPM program is the foundation of lean maintenance. Further, they find implementing lean maintenance without such a foundation difficult (see Figure 9). According to the authors, other maintenance "bricks" include: planning and scheduling, documentation, work order system, the use of a computerized maintenance management system, CMMS, predictive maintenance[1], and root cause failure analysis.

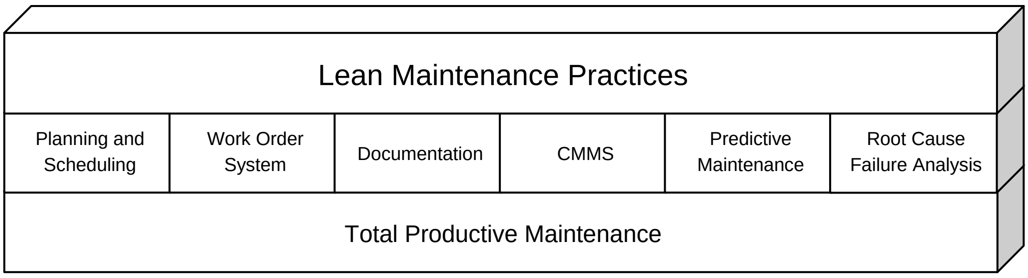

Figure 9. Lean maintenance practices, as visualized by Smith and Hawkins (2004, p.14). Total productive maintenance is the foundation, and six "bricks" achieve lean maintenance. CMMS is an abbreviation for computerized maintenance management.

[1] Predictive maintenance is defined as: "Condition based maintenance carried out following a forecast derived from the analysis and evaluation of significant parameters of the condition of the item." (Bengtsson, 2004b). It is sometimes used synonymously with condition based maintenance.

2.3 Reflections

New production system strategies that expect higher utilization grades using fewer inventories have put increased pressure on availability. Shown through the studies presented above, the OEE levels of the Swedish industry have not improved immensely over the past years. Failures in production systems incur massive costs. As a result, various techniques, tools, and methods to prevent or mitigate failures have been developed through the years.

Maintenance is one of the functions that have become increasingly important in production, especially in production systems with high capital investments. As described above, new expectations, new research, and new techniques have pushed maintenance from the traditional "fix-it-when-it-breaks" mentality to a more sophisticated view. Still to this day, though, many companies and industries apply a corrective maintenance approach by default.

Comparing the list of possible problems resulting from system failure (Todinov, 2006) with the list of reasons for increased costs from inadequate maintenance (Moore and Starr, 2006) presented above, the resemblance is strikingly similar. It becomes clear that maintenance, and the proper maintenance indeed, is truly a prerequisite for a successful production result.

What is proper maintenance then? Cooke and Paulsen (1997) define *good* maintenance as: "…seeing very few corrective maintenance events; while performing as little preventive maintenance as possible." (p.136). Further, they state that, ideally, preventive maintenance should be performed just before a component fails. The conditional-probability curves presented above visualize that finding out this point in time through the use of statistics can be a troublesome activity. Condition based maintenance is thus introduced as one possible solution to the issue.

3 Condition based maintenance

This chapter presents theories on condition based maintenance. First, the approach of the maintenance type is briefly introduced. The technology and the implementation of the maintenance type are also introduced.

3.1 The approach of condition based maintenance

As stated in Chapter 2, many components do not have a clear and visible wear-out region and are thus not applicable for scheduled overhauls (Nowlan & Heap, 1978; Page, 2002). Condition based maintenance, with on-condition tasks and condition monitoring in particular, are introduced as one solution for some of these potential failures (Moubray, 1997; Nowlan & Heap, 1978).

As discussed above, condition based maintenance is a preventive maintenance type utilized in order to dynamically plan maintenance. Condition based maintenance is defined as: "Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions." (SS-EN 13306, 2001, p.15). It is thus a maintenance type that utilizes on-condition tasks in order to monitor the condition over time and usage. This is done in order to give input to decide maintenance actions dynamically. According to Mobley (2002), condition based maintenance is performed to serve the following two purposes:

- to determine if a problem exists in the monitored item, how serious it is, and how long the item can be run before failure, and
- to detect and identify specific components in the items that are degrading and diagnose the problem.

A central part of condition based maintenance is thus monitoring, often called condition monitoring. Monitoring is defined as: "Activity, performed either manually or automatically, intended to observe the actual state of an item." (SS-EN 13306, 2001, p.16). Condition monitoring can be performed using a number of various approaches and utilizing different levels of technology (see Figure 10), the common point being that the activity is normally performed in an operating state.

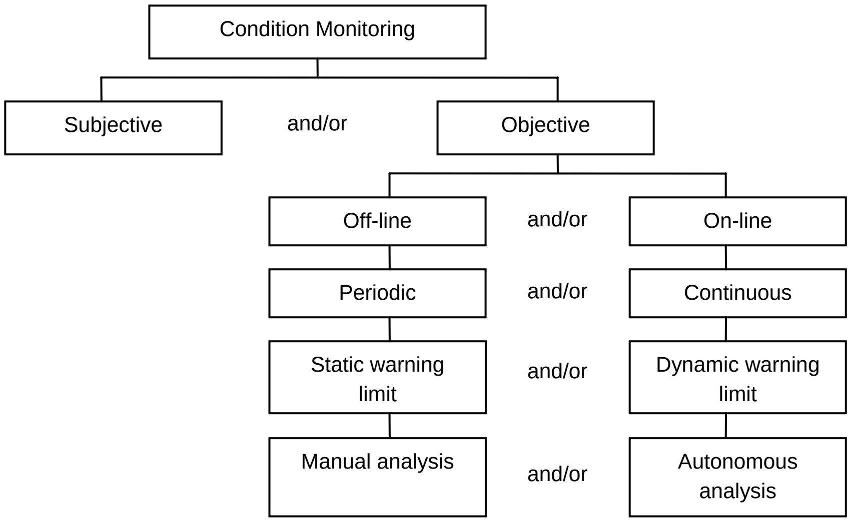

Figure 10. Different approaches to condition monitoring (Bengtsson, 2007).

The purpose of monitoring the condition of an item is to collect condition data to make it possible to detect incipient failure so that maintenance tasks can be planned at a proper time. Another purpose of condition monitoring is to increase the knowledge of failure cause and effect and deterioration pattern.

A number of different techniques exist to measure the condition of an item. Depending on the type of potential failure condition one is set out to measure, one or more techniques can be utilized. Moubray (1997) and Tsang (1995) classify condition monitoring techniques according to the symptoms they are designed to detect:

- dynamic effects, such as vibration and sound,
- particles released into the environment,
- chemicals released into the environment,
- physical effects, such as cracks, fractures, wear, and deformation,
- temperature rises in the equipment, and
- electrical effects, such as resistance, conductivity, dielectric strength, etc.

To mention a few of all the condition monitoring parameters/techniques, one can say that vibration monitoring is one of the most commonly used (see e.g. Al-Najjar 1997; Higgs et al., 2004). In addition, oil-analysis or lubricant monitoring (see e.g. Newell, 1999; Raadnui, 2007; Yan et al., 2005), shock pulse method analysis (see e.g. Eriksson, 2003), sound analysis (see Bengtsson et al., 2004; Olsson, 2005); temperature/infrared monitoring (see e.g. Livshitz et al., 2005), and subjective/visual monitoring (Johansson, 1993) are common parameters/techniques used in industries today.

The condition based maintenance approach thus implies utilizing the results of the monitoring activities (i.e. the potential failures found) and further analyzing them. This implies diagnosing the potential failures and prognosticating the components' remaining useful life. This together is used in order to plan the most effective maintenance task possible.

Moubray (1997), like Starr (1997) however, points out that condition monitoring techniques are effective where appropriate, but a deep disappointment where not. Moubray (1997) concludes that condition monitoring is only technically feasible for about 20% of all failure modes and worth doing in less than half of those cases. All on-condition tasks included increase this figure to about 25-35% of all failure modes. However, Starr (1997) also points out that by implementing a condition based maintenance approach, there is much to gain in the form of:

- Reduced maintenance costs, less unnecessary repairs and replacements saving labor, spare parts, and unavailability.
- Damage limitation, incipient failures are easier to repair than breakdowns, also less secondary damage is at stake.
- Eliminated production losses.

3.2 The technology in condition based maintenance

The comprehensive technology in condition based maintenance can be visualized as a condition based maintenance system (see Figure 11). A condition based maintenance system is defined as: "A system that uses condition based maintenance to determine and schedule predictive maintenance actions autonomously or in interaction with other systems or humans." (Bengtsson, 2004b, p.19). Illustrated by, for example, Thurston (2001) and Lebold et al. (2003), a condition based maintenance system contains seven modules/activities: data acquisition (sensors), signal processing, condition monitoring, health assessment (diagnosis), prognostics, decision support, and presentation.

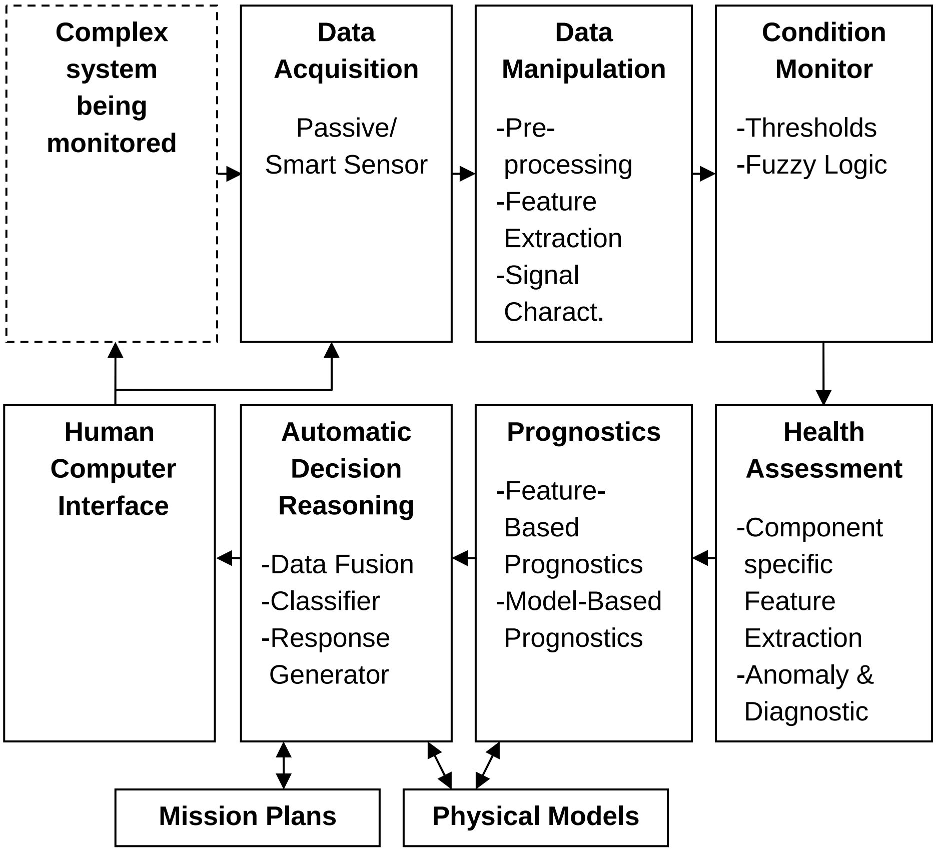

Figure 11. The seven modules in a condition based maintenance system, as presented in Lebold et al. (2003).

Data acquisition is thus the first component. Normally, when used in an objective context, sensors are components of the data acquisition and considered parts of a condition monitor module. Fraden (1996) defines sensors as: "a device that receives a signal and responds with an electrical signal." (p. 3). It is thus the equipment that captures the dynamic effect caused by the incipient failure. The purpose of the signal processors is, according to Bengtsson et al. (2004), three-fold: (1) to remove distortions and restore the signal to its original shape, (2) to remove irrelevant sensor data for diagnostics or prognostics, and (3) to transform the signal to make relevant features more explicit. In the condition monitoring module, the measured data is compared to normal data with either threshold values or other techniques such as artificial intelligence. If normal levels are exceeded or other unnatural phenomenon occur, such as sudden increases or decreases in the level (but still not exceeding normal levels), the data needs to be diagnosed. Warning limits can be established that are either static or dynamic (Tsang, 1995). Static warning limits utilize pre-determined threshold values. An example of such limits is the ISO, which has produced vibration severity charts for specific types of applications. According to Tsang (1995), static warning limits are more easily administered than dynamic ones. Nonetheless, they lack diagnostic power for predicting when the alarm will be reached. Tsang (1995) continues, stating that: "Dynamic limits, …, are used to monitor the rate of change of the measured parameter. If a CBM[2] procedure uses dynamic warning limits, the rate of change of the measured parameter is considered more important than the actual value." (p.14). According to Yam et al. (2001), diagnoses in condition based maintenance can be divided into three categories: (1) rule-based diagnostics, (2) case-based diagnostics, and (3) model-based diagnostics (for more information, see Bengtsson et al. (2004)). Following a diagnosis, the system now has knowledge as to something being unnatural in the condition, where it is unnatural, and what is causing the unnatural measurements; it now needs to be prognosticated. How long can the item operate before it is necessary to perform maintenance in order to prevent a breakdown? Prognostics can be performed as the diagnostics module, through different techniques of artificial intelligence, such as recurrent neural networks (Yam et al., 2001) and dynamic wavelet neural networks (Vachtsevanos & Wang, 2001), etc. Jardine et al. (2006) present an extensive review of diagnostics and prognostics within condition based maintenance. The major difference in prognosis compared to diagnosis is that a number of additional parameters need to be taken into consideration. Thurston and Lebold (2001) present a proposal for a generic prognostic module in which input requirements cover historic data in the form of health, failures, mission, maintenance history, model information, and spare part assets, for example. Output requirements cover information regarding the current health, along with remaining useful life with confidence levels on the prediction, requirements that are needed in the last activity. The last step in the condition based maintenance system process is to make a decision concerning what maintenance actions to perform and when. All the previous activities should of course be integrated into a decision support for the best possible solution for this particular event. Here, additional information that has been recovered through this system should be applied, such as production scheduling and labor. This decision can be totally autonomous, but other systems and/or humans will most likely guide it (Jiang et al., 2002).

Of course, condition based maintenance and condition based maintenance systems can have different levels of automation, stretching from humans performing all the tasks of the modules to, as explained above, hardware and software performing all those tasks. In Table 1, Granell (2007) presents nine levels of automation that can be used to explain different levels of automation in condition based maintenance. Imagining a condition based maintenance system as a computerized operation, the level of automation can, as the table depicts below, range from humans generating

[2] CBM is an abbreviation for condition based maintenance.

all the tasks, deciding one or more, and executing the option(s) to a computer suggesting and executing one option.

Table 1. LoA, level of automation, divided in nine levels as explained by Granell (2007, p.53). The computerized/cognitive tasks/activities can be used to explain that condition based maintenance systems as well can have different levels of automation.

LoA	Computerized/Cognitive Tasks/Activities	Mechanized/Physical Tasks/Activities
1	The human generates the options, decides and executes the option without any assistance from the computer.	Entirely manual physical work; no physical tools are used, only human muscular strength.
2	The computer presents all suitable options; the human can then choose and execute one of the options.	Manual physical work supported by a static hand tool.
3	The computer suggests a number of options; the human can then choose and execute one of the options.	Manual physical work supported by a dynamic hand tool.
4	The computer generates a number of options and recommends one of them; the human can then choose to execute that option.	Manual physical work supported by an automated hand tool.
5	The computer suggests one option; the human can then decide, and the computer executes the decision.	Human control of machine/robot on site that executes the task.
6	The computer suggests one option, decides and executes the option; the human is always informed.	Supervision of machine/robot on site that executes the task.
7	The computer suggests one option, decides and executes the option; the human is always informed if the human demands information.	Supervision and control of one or many machines/robots from a central control room.
8	The computer suggests one option, decides and executes the option; the human is only informed if the computer demands that the human should be informed.	Automated physical work by machine/robot; the human is only involved when the machine needs assistance.
9	The computer suggests one option, decides and executes the option without any assistance from the human.	Entirely automated physical work; the machine/robot solves problems by itself when they emerge. The human is never involved.

3.3 Implementing condition based maintenance

In many cases, the implementation of a condition based maintenance approach implies that an entire company needs to be involved and old routines need to be changed into new. Below, general implementation and change management has been included to move outside the box of maintenance and look at the implementation of condition based maintenance from a broader perspective.

3.3.1 General implementation and change management

Much research has been devoted to change management and how to effectively implement change in an organization. Many researchers have published change programs in the form of structured processes, with different numbers of actions to undertake to be successful in change; many of which are developed from others (see Garvin, 2000; Jick, 1991; Kotter, 1996; Mento et al., 2002; Vandermerwe & Vandermerwe, 1991; Vrakking, 1995). Other researchers have published keywords or rules to focus on in change efforts. Examples include pain, process, politics, payoff, and persistence (McAllaster, 2004) (in addition, see Denton, 1996; Mercer, 2001; and Sirkin et al., 2005).

Kotter (1996) states that successful implementation of change in organizations has to follow two important patterns: first, the change has to follow a multi-step process that creates power and motivation to overwhelm the reactionaries, and second, the process has to be driven by a strong leadership. Kotter (1996) derives this process in an eight-stage process: (1) establishing a sense of urgency, (2) creating the guiding coalition, (3) developing a vision and strategy, (4) communicating the change vision, (5) empowering broad-based action, (6) generating short-term wins, (7) consolidating gains and producing more change, and (8) anchoring the approaches in the culture.

To be successful, the organizational change needs a well-organized implementation strategy. Vrakking (1995) states that the success of the implementation of an innovation relates to the time elapsed between the generation of the innovation and its implementation. Success, claims Vrakking, is achieved if this time is kept to a minimum. Vrakking argues that such implementation is only successful in companies that follow a very strict implementation strategy. Vrakking (1995) presents eleven practical tips regarding implementation. They are the following: good communication and information, training, learning process, top-down and bottom-up communication, project approach, powerful leaders, support from opinion leaders, prevent "group think", create support, implementation is not separate from the design process, prevent resistance (if possible), and line management must support the change.

3.3.2 Implementation of condition based maintenance

As presented above, condition based maintenance with the use of condition monitoring can involve various parameters, techniques, and technologies. As such, many decisions need to be taken. The technology, even though properly chosen, is not a guarantee for a successful result. The technology needs to be introduced and integrated in a company and its ordinary everyday work.

Decision support

According to Simon (1997), the task of making a decision involves three steps: (1) listing all alternative strategies, (2) evaluating all consequences that follow every strategy, and (3) evaluating the consequences. According to Simon (1997), the use of the term "all" should be taken lightly. Obviously, it is impossible to know all the alternatives. Simon (1997) also highlights communication in the process of decision-making. Further, Simon (1997) means that, it is unnecessary to communicate an entire plan to everybody if each individual knows what he or she is to do.

Both Moubray (1997) and Starr (1997) point out that it is important that condition based maintenance is applied where it is appropriate, not as an overall policy. This is because many techniques are expensive, and it would not be cost effective. Hess et al. (2001) declare that the selection of condition based maintenance technologies has predominantly been based on the technical capabilities to provide early detection with little or no evidence of business case. According to the authors, this has resulted in large and costly condition based maintenance programs. Parida (2007) states that there is a tendency that industrial companies measure what is easy to measure, not what is required, and means that it is important for industrial companies to decide the relevant measurements. This implies that a rigorous decision-making process is necessary in order to not suffer the effects of a trial-and-error or ad-hoc approach.

Much has been published about various strategies regarding how to select maintenance strategies and techniques. Alsyouf et al. (2004) in Alsyouf (2004) present a survey in the Swedish industry stating that 81% of the companies in the survey use the company's own experience and knowledge when selecting maintenance strategy. Also, it was shown that 31% used some kind of modeling on the time to failure and/or optimization when selecting maintenance strategy, 10% used a Failure Mode Effect and Criticality Analysis, FMECA, or decision trees (more on decision trees can be found in Smith & Hinchcliffe, 2004), and 2% used Multiple Criteria Decision Making, MCDM (more on MCDM can be found in Alsyouf, 2004). Finally, 6% used other methods such as: monthly lists, documentation and experience, major overhauls twice a year, maintenance costs, manufacturer recommendations, risk analysis, and own databases. Several companies, 30%, mentioned that they used more than one method. Many decisions are thus taken based on experience.

Moubray (1997) presents how to choose proper on-condition task within the framework of RCM. Tsang (1995) lists three decisions necessary to undertake when implementing condition based maintenance: (1) selecting the parameters to be monitored, (2) determining the inspection frequency, and (3) establishing the warning limit (trigger). Starr (1997) presents a decision algorithm meant to be used to select proper assets to monitor using the proper technique. The algorithm starts with an overall criticality survey, using tools such as: Fault Tree Analysis (FTA), FMECA, and RCM. A maintenance audit is followed which prioritizes the areas where cost savings are most significant. The next step selects the units to be monitored on the basis of the first two steps (i.e. criticality and expenditure). The failure modes detected in the criticality analysis are then matched to a suitable technique, and routine monitoring can commence. The program, later, needs to be evaluated. Starr (1997) suggests four review areas: (1) frequency of measurements and alarm levels, (2) the selection of technique, (3) the selection of units, and (4) the cost effectiveness. Alsyouf (2004) and De Kerf (2006) present models for the calculation of the financial return on investment of condition based maintenance implementation. Hess et al. (2001) present an evaluation method that assesses potential technology compared to the two key parameters: cost and effectiveness.

IEEE (IEEE, 2001) presents a guide for the selection of monitoring of circuit breakers in a three-stage process. The first stage is divided into two: perform an FMECA and determine the monitoring options. The second stage, also divided into two, involves performing a risk and a cost-benefit analysis. In the third stage, a decision on implementing continuous or periodic monitoring should be performed using the previously acquired knowledge. As the FMECA methodology is rather common (see, for example, McDermott et al., 1996), it will not be explained in detail. The risk analysis is quite straightforward, defining risk as the probability of an event occurring multiplied by the consequences if that event occurs. The cost-benefit analysis includes looking at both direct cost and reduced costs.

Implementation

Spare (2001) states that condition based maintenance programs should be designed and implemented through: "Well-defined goals and a cost-effective investment strategy..." (p. 954). Reichard et al. (2000) provide a more technically-oriented aspect by stating that: "The implementation of such systems [intelligent monitoring system] requires a combination of sensor data fusion, feature extraction, classification, and prediction algorithms." (p. 329). Jiang et al. (2002) point out that the human aspect cannot be forgotten in a condition based maintenance approach by stating: "Correct analysis and diagnosis based on the collected information is essential for right maintenance decisions: when, where, and what maintenance actions should be carried out for a specific piece of equipment. Obviously, participation and intervention of the human experts are necessary for all these activities." (p. 1957). These statements visualize that several factors are important in an implementation context.

Both theoretical and case study references can be found in relation to the implementation of condition based maintenance. Mobley (2002) presents how a Predictive Maintenance (PdM) program could be established, focusing on: (1) goals, objectives, and benefits, (2) functional requirements, (3) selling predictive maintenance programs, (4) selecting a predictive maintenance system, (5) database development, and (6) getting started. Mitchell and Murry (1995) present how a Predictive Maintenance (PdM) program was implemented at the United States Department of Energy Strategic Petroleum Reserve. The program was composed of five major elements: tests and exercises, condition monitoring, data storage and retrieval, training, and program goals and reports. The PdM program consisted of eight logical steps: (1) development of PdM policy and program plan, (2) assignments of responsibilities, (3) definition and specification of required equipment, (4) purchasing of equipment, (5) development of implementation procedures, (6) training of employees, (7) implementation of program, and (8) reporting of results and assessing of program effectiveness. Mitchell and Murry (1995) also present a few suggestions and actions regarding what they would do differently if they had to go through the implementation process again:

- do a complete analysis and definition of the project needs, tailor the program,
- ensure that support from management, clients, and budget is available before the implementation process starts,
- be clear that the process takes time, a satisfactory database can take 18-24 months to build, additional manpower is required,
- involve affected groups early; maintenance, engineering, and operation; and develop a project team,
- be early in the procurement of equipment and services, be sure potential products have been developed, debugged, and proven to work in applications in environments similar to your own,
- implement in a phased approach, stay small, do not incorporate the whole program in the first phase, and
- keep management and clients informed; publicize any success no matter how small in the early phases of the implementation.

Higgs et al. (2004) present a survey that targeted six areas within condition based maintenance applications. One area focused on implementation issues associated with the respondents' condition based maintenance system. The survey revealed, amongst other things, that 45% of the respondents used a mixture of resources consisting of internal company expertise, external consultants, and external vendors in implementing the system, while 36% used only their internal company expertise. Open comments provided by the respondents include (Higgs et al., 2004):

- The implementation depends heavily on the skills of the technicians. Needs a lot of support in the initial introduction.
- It is important that you use a technique that is suitable for the monitoring. The collection of data can be routine, but turning the data into information on the condition may not be possible.
- It can be hard to get through to some engineers, especially the older generation.
- It might be hard to establish condition based maintenance all at once, it is then better to start with what you have and move forward.
- Management support is important in succeeding with condition based maintenance.
- Experiences of difficulties in gaining maintenance personnel acceptance and support.
- The technology is easy, but managing the wide changes in established practices is considered extremely slow, hard, and sometimes painful.

The survey (Higgs et al., 2004) leads to a four-point implementation guideline aimed at assisting a smoother introduction of condition based maintenance into an organization:

- top management support,
- reassess the organizations entire maintenance approach in every affected department,
- select proper system while taking into account the organizations resources and the level of employee expertise, and
- train and educate employees to appreciate the idea of condition based maintenance.

While not performing the study within condition based maintenance, but within Total Quality Management, TPM, and RCM, Hansson et al. (2003) identify similarities in managing commitment between the different concepts. The categories found, important for management to focus upon in order to promote employee commitment, were the following: leadership and support, strategic planning, training and education, monitoring and evaluation, buying-in and empowerment, and information and communication. Trodd (1998) gives a practical discussion of the implementation of a predictive maintenance program at a pulp mill operation. Further, Trodd (1998) states that the ultimate keys to the successful implementation of predictive maintenance are: clear goals and objectives, careful planning, constant assessment, and hard work. The hard work includes dedication and determination of all involved in the program including the software suppliers. Key areas to focus upon in order to reach the objectives were: safety, quality, productivity, environmental concerns, human resources, and cost control. Trodd (1998) concludes by stating that: "Having the best, latest, greatest technology won't on its own ensure a successful program." (p.35).

3.4 Reflections

Coetzee (1999) states that a typical approach towards increasing maintenance efficiency is to implement some highly publicized philosophy or maintenance technique, such as: RCM, TPM, CBM, CMMS, auditing system, etc., and concludes by stating that: "While each of these will certainly contribute to the success of the maintenance organisations, the haphazard way in which they are introduced is a certain formula for sub-optimality (Geraerds, 1990)[3]." (p.276). Also, Moubray (1997) expresses the problematic challenge of choosing the proper technique for a specific company as a success factor for change.

Condition based maintenance, as many other maintenance philosophies and techniques, can truly achieve increased maintenance efficiency. Before cashing in, though, the proper approach must be implemented. This is not always easy. A conclusion that can be drawn from Trodd's (1998) remark is that technology is simply not enough to ensure a successful implementation. McKone and Weiss (2002) share this view, and state that: "Rather than simply adopting the latest technologies, it is important to select the best technology for the particular maintenance situation. No one policy is effective in all situations." (p.123). Other factors obviously need to be taken into consideration.

[3] Original reference Geraerds (1990) could not be found.

4 Research method

This chapter presents the research method that has been used throughout the research. The chapter summarizes the research approach, the research strategy, the research process, and discusses the quality of the research.

4.1 Research on the concept of maintenance

Traditionally, maintenance research has been viewed from an operations research perspective, based in the mathematical theory of reliability, utilizing mostly quantitative methods. Renewal theory, reliability tests, failure rate estimates, fatigue life in materials, etc., have been calculated, researched, and analyzed (see Barlow, 1984; Jonsson, 1999). However, according to Fabrycky (2006), the life cycle for maintenance and logistic support is often neglected until the product and product design is completed. This can serve as an indicator that research in other areas is also important. This research has sought knowledge in areas other than the traditional maintenance research, as described above. Therefore, other methods and approaches have been used; these will be further elaborated on below.

4.1.1 Methodological approach

According to Arbnor and Bjerke (1997), there exist three methodological approaches: the analytical, the systems, and the actors. The analytical approach strives to explain reality as objectively as possible. The researcher seeks explanations of effects by certain causes. The approach strives to find causes that are independent; the classical laws of physics can be regarded as a model (Arbnor and Bjerke, 1997). The systems approach also considers reality to be objective but somewhat differently constructed, as components that are mutually dependent. The systems approach strives for an explanation, or understanding, of a situation by applying it into a comprehensive perspective (Arbnor and Bjerke, 1997). In the systems approach, there may be open and closed systems. An open system interacts with the surrounding environment, and the total solution is not built up mainly by summarizing the sub-solutions, which is a more holistic approach. The actor's approach regarding objectivity is quite different from the other two approaches. The actor's approach suggests that it is difficult not to influence the phenomenon being studied. It also suggests that reality exists as a social construction, not independent from humans, e.g. researchers (Arbnor and Bjerke, 1997).

The research conducted within this research project lies within the art of engineering. The researcher has applied the systems approach when conducting the research (see Figure 12). That is because the systems approach with its reality constructed as components with mutual dependence is how a condition based maintenance system is treated in this research. Also, the research is performed in order to place a certain approach, the condition based maintenance, into a comprehensive perspective, that is, to implement it into an organization.

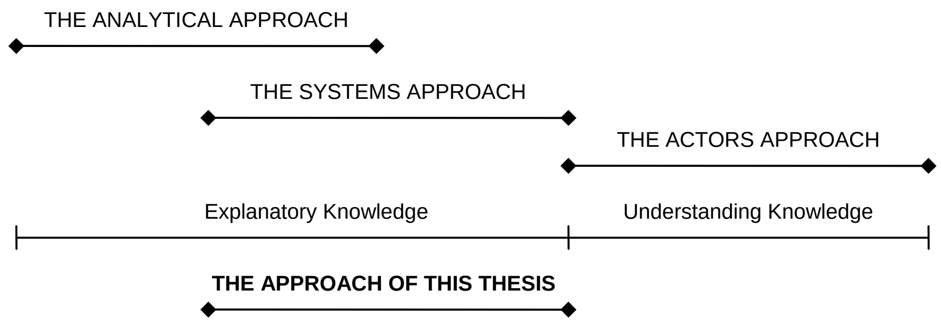

Figure 12. As depicted in the figure, the methodological approach of this research lies within the systems approach, adapted from Arbnor and Bjerke (1997, p.46).

The system in this research is the condition based maintenance system. This should be considered an open system, as it will be under the influence of input from the surrounding environment (see Figure 13). Also, an implementation or change in a company is a complex phenomenon, and will always be influenced by outer forces. Even high-technology based systems will be influenced by how the human will act upon its responses. Also, outer disturbances will influence the results of the measurements and analysis performed by a system.

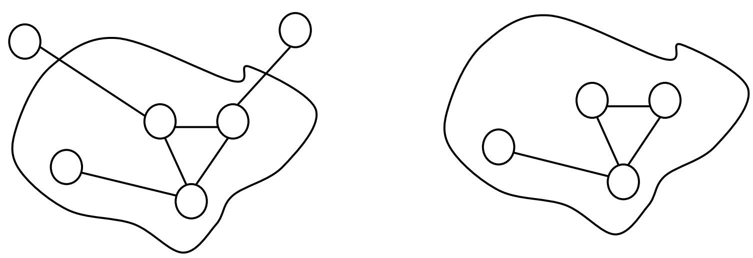

Figure 13. Illustrations of an open system (to the left) and a closed system (to the right), as illustrated by Arbnor and Bjerke (1997, p.113).

4.1.2 A systems perspective on maintenance

In the systems approach, there are some ultimate presumptions that can be seen as prerequisites for a knowledge creator's efforts (Arbnor & Bjerke, 1997, p.351):

- Reality is assumed to be constructed of "units". These units are called "systems".
- The units consist in turn of components that are fairly intimately related to each other.
- Each unit usually has connections to other units, and is then called an "open" system. Open systems have no natural boundaries.
- It makes no difference from the pragmatic methodological viewpoint of the systems approach whether reality is actually constituted in this way or the creator of knowledge studies it as if this were the case.

Banks et al. (1996) have defined a system as: "…a group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose" (p.8). Hubka (1982) states that the purpose of a technical system is to: "…transform certain well-defined input quantities, particularly materials (e.g. auxiliary materials), energy, and information (e.g. commands), into desired effects (output quantities) in space and time (e.g. position, movement, velocity, force)." (p.12).

Not opposing Banks et al. (1996), Fabrycky (2006) states that engineered systems exhibit the following characteristics (p.28):

1. They have a functional purpose in response to an identified need and have the ability to achieve some stated operational objective.
2. They are brought into being and operate over a life cycle, beginning with a need and ending with phase-out and disposal.
3. They are composed of a combination of resources, such as humans, information, software, materials, equipment, facilities, and money.
4. They are composed of subsystems and related components that interact with each other to produce the system response or behavior.
5. They are part of a hierarchy and are influenced by external factors from larger systems of which they are a part.
6. They are embedded into the natural world and interact with it in desirable as well as undesirable ways.

According to Kossiakoff and Sweet (2003), a complex system contains three attributes: (1) it is an engineered product, (2) it contains diverse components, and (3) it uses advanced technologies. A condition based maintenance system can in many cases be considered a complex system. This, because it is engineered, it can contain diverse components (for example, sensors, cables, software, and graphical user interface), it can use advanced technology (for example, signal processing), and it can contain different analyses software (such as neural networks, case-based reasoning, and fuzzy logics) (Bengtsson, 2006a). Bengtsson (2004b) defines a condition based maintenance system as: "a system that uses condition based maintenance to determine and schedule predictive maintenance actions autonomously or in interaction with other systems or humans." (p.19). The purpose of a condition based maintenance system could also be explained through Hubka's (1982) description: to transform input quantities of energy (e.g. vibration, temperature) into desired output quantities (e.g. condition of monitored asset).

4.1.3 Creating new knowledge using a systems approach

The objective of creating new knowledge using the systems approach does not start with formulating a hypothesis, for example. Rather, one moves more cautiously by determining the type of system under study (i.e. categorizing the system). Description, determination of relations, forecasting, and guidance of the system then usually follow the categorization (Arbnor & Bjerke, 1997). In the analytical approach, for example, knowledge creators seek causal relationships (cause-and-effect). Meanwhile, in the systems approach, finality relationships (indicator-effect) are sought. An indicator does not have to be a necessity or cause enough for an effect. It is also accepted that an indicator is one of many possibilities to reach a certain effect, and that an indicator can have alternative effects (Arbnor & Bjerke, 1994). The purpose of using a systems approach is to reproduce reality as objectively as possible. One part of this purpose, though, can be to reproduce individuals' subjective ideas, ambitions, and concepts, and treat these as if they were objective (Arbnor & Bjerke, 1997).

Figure 14 visualizes the research process using a systems approach and in creating new knowledge. As indicated above, the start of the process is extensive, and determining the problem too soon should be avoided. A researcher may capture a problem but be cautious and leave it for revision for a longer period of time. This research started with a wide objective, and it was not until the author defended a licentiate thesis (Bengtsson, 2004b) that the final purposes of this research were formulated. Before formulating the possible finality relations, though, the real system (i.e. the respondents at the companies with the implementation of condition based maintenance) needs to be contacted. Determining the type of system is performed in parallel during the study. However, determining the relations implies that interactive contact with representatives from the reality being studied is necessary. As shall be presented below, this research has been performed through several case studies. This means that iterative contact with the studied object has been performed as well. It is the knowledge creator, sometimes with the help of other persons taking part in the knowledge creation process, who decides when enough knowledge has been obtained in order to meet the goal. This view differs greatly in comparison to other approaches. Before setting the definite finality relations, an applied study with guiding ambition needs to be performed. Even so, the preliminary finality relations should be included in systems theory (Arbnor & Bjerke, 1997).

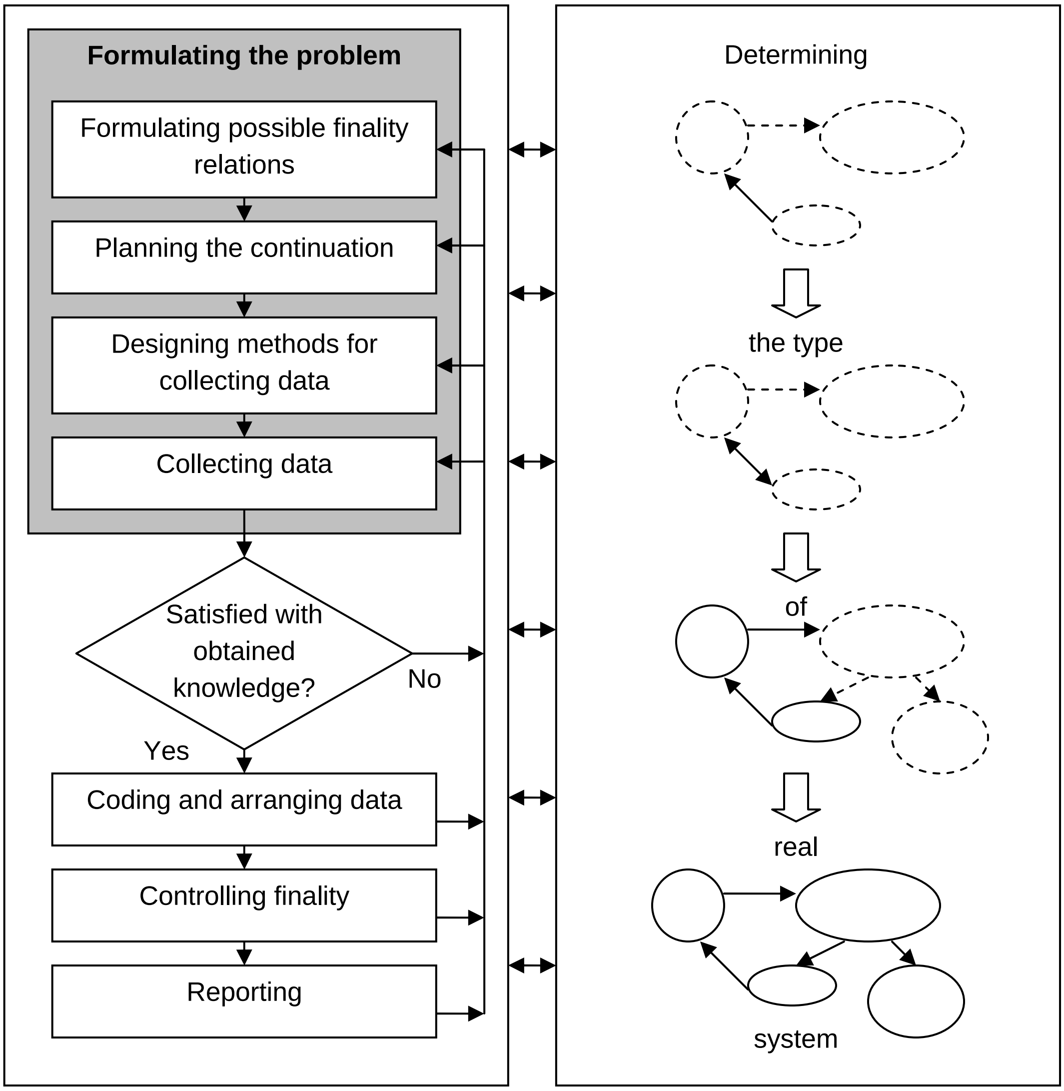

Figure 14. The research process with iterating studies modeling the system, adapted from Arbnor and Bjerke (1997, p.296). The system being modeled can be seen as the implementation method. As the figure depicts, several drafts of the method were developed in the process (compare with Figure 16).

A creator of knowledge within the systems approach may have several interests, although not exclusive. In systems analysis, the real system is depicted in a systems model without changing the real system. Its purpose is to clarify the internal and external factors influencing the system. In other words, systems analysis is both descriptive and explanatory. In systems construction, a potential new real system is depicted in a systems model. This new real system may be a development of another real system that has been clarified in a systems analysis. Systems theory contains system models with indicator-effect relations that are valid in more than one real case. Two things may be referred to when discussing systems theory, general and modern systems theory. In modern systems theory, applied in this research, the models and relations may be applicable to different classes of systems. In developing new systems theory, analysis and construction of real systems are parts of the development. The results, though, are normally less general, if compared to the analytical approach, for example (Arbnor & Bjerke, 1997). The system models depicted in this research are performed at different levels of abstraction. The holistic, or comprehensive, model of the implementation process has a high level of abstraction, whereas the detailed models that can be found therein are depicted on more of a systems analysis level.

4.2 Research strategy

Different research strategies are suited for different research questions (see Table 2). Yin (1994) mentions strategies such as: experiment, survey, archival analysis, history, and case studies, and suggests using case studies as the choice of research strategy when dealing with (p.1):

- Policy, political, and public administrations research
- Community psychology and sociology
- Organizational and management studies
- City and regional planning research, such as studies of plans, neighborhoods, or public agencies
- The conduct of dissertations and theses in the social sciences – the academic disciplines as well as professional fields such as business administration, management science, and social work.

Table 2. Different research strategies (Yin, 1994, p.6).

Strategy	Form of research question	Requires control over behavioral events?	Focuses on contemporary events?
Experiment	how, why	yes	yes
Survey	who, what, where, how many, how much	no	yes
Archival analysis	who, what, where, how many, how much	no	yes/no
History	how, why	no	no
Case study	how, why	no	yes

This research is based upon case studies. A case study may be explained as: "…an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident." (Yin, 1994, p.13). In this research, the condition based maintenance approach can be seen as the phenomenon, while the implementation process in a company can be seen as the context. As has been argued earlier, little research has been reported on the comprehensive implementation process, thus making the boundaries unclear and strengthening the choice of a case study approach. Also, as earlier argued according to Yin (1994), case studies are an appropriate strategy when dealing with organizational and managerial studies, like an implementation of a condition based maintenance approach is a great deal about. Merriam (1994) also states that, with case studies, one can focus on insight, discovery, and interpretation, rather than hypothesis testing. Further, by focusing on one event or situation (i.e. the case), concentration can be directed towards the interplay between important factors that characterize the event or situation being studied.

The fact that the boundaries between the phenomenon and the context are unclear made qualitative data the focus. According to Maxwell (1996), quantitative researchers tend to be interested in whether and to what extent *x* causes variance in *y*. Meanwhile, qualitative researchers tend to be interested in how *x* plays a role in causing *y* and what the process is that connects *x* and *y*. The latter view has been applied in this research, as *x* can be considered factors such as technology, and *y* can be considered the success of implementation. Also, as the studies do not aim at drawing statistical generalizations but at gaining deeper knowledge of the phenomenon and the context, qualitative data has been focused upon.

4.3 Research process

According to Yin (1994), case study research consists of three steps: (1) define and design, (2) prepare, collect, and analyze, and (3) analyze and conclude (see Figure 15). In the define and design stage, theory is studied, cases are selected, and methods on how to conduct the cases are decided. In the prepare, collect, and analyze stages, the cases are conducted and analyzed as well as reported. In the last stage, analyze and conclude, cross-case conclusions can be made and theory may be modified.

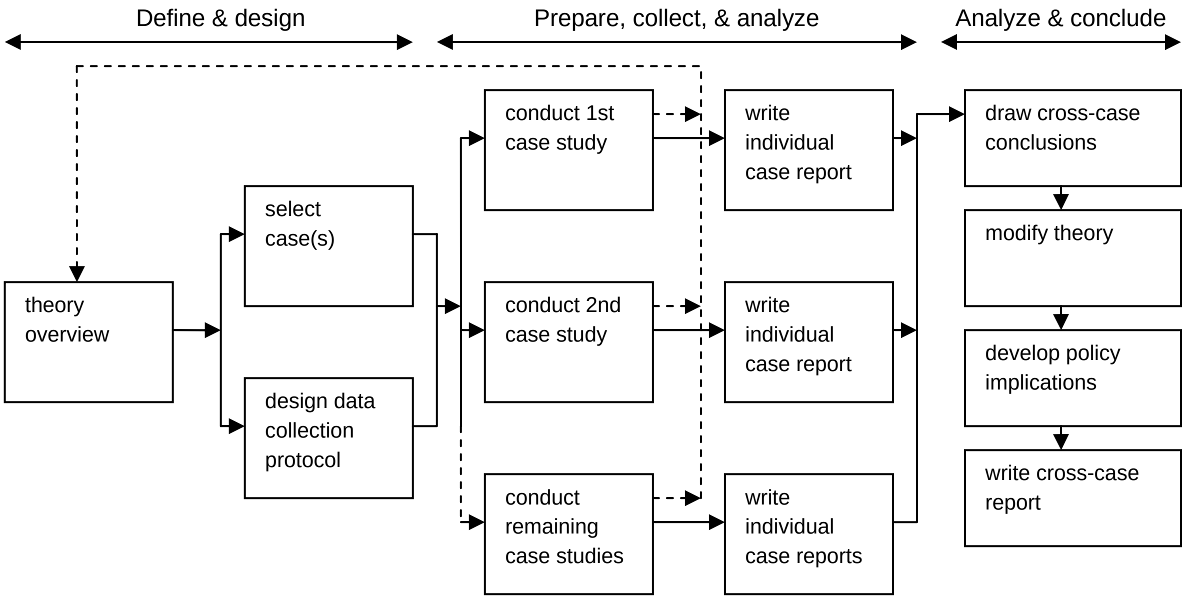

Figure 15. Case study methods, adapted from Yin (1994, p.49).

As indicated in Figure 15, the cases in this research have been performed sequentially and every case performed has given input to the coming case. The dotted feedback arrow depicted in Figure 15 above has been utilized in all cases. Therefore, the selection process has been made on the basis of where new knowledge has been developed (i.e. system analysis and construction).

In dealing with studies concerning qualitative data, Maxwell (1996) divides the process into four main components (p.65). They are the following:

1. The research relationship that you establish with those you study.
2. Sampling: what times, settings, or individuals you select to observe or interview and what other sources of information you decide to use.
3. Data collection: how you gather the information you will use.
4. Data analysis: what you do with this information in order to make sense of it.

4.3.1 Research relationship

In studies with qualitative data, the researcher is the instrument of the research, and the research relationship is the means by which the research gets done (Maxwell, 1996). The relationship with the respondent or the studied object can be a very complex and changing entity. This is because it also functions as a way of gaining entry to the setting or establishing a good relationship with the research participants (Maxwell, 1996).

The relationship in this research has taken the form of giving the respondents information regarding the studies' purposes and their participation as soon as contact has been initiated. The relationship while performing the actual data collection has been objective. In other words, I have tried hard not to inflict any opinions on the respondents during the course of the study. In the test case and the workshop case, I have taken a pragmatic part of the relationship, as these cases have been built on active participation from all involved. In the first study, the investigative case (see further below), I had a pre-understanding of the case company. However, this did not inflict on the relationship, as I had no association to the respondents prior the study.

4.3.2 Sampling

Sampling within studies with qualitative data, i.e. to decide what or whom to study, differs from studies with quantitative data. In studies with qualitative data, purposeful sampling is often used (Patton, 1990). According to Maxwell (1996), purposeful sampling is a strategy in which one deliberately selects settings, persons, or events to study in order to provide important information. Weiss (1994) argues that many qualitative interview studies do not even use sampling, but rather panels, made up of: "…people who are uniquely able to be informative because they are experts in an area or were privileged witnesses to an event." (p.17). One major dilemma with purposeful sampling is key informant bias, particular when the number of respondents is small. Key informants can for instance assume greater uniformity than actually exists. Therefore, a systematic sampling is necessary in order to be able to claim that key informants' statements are representative of the group as a whole (Maxwell, 1996).

In the studies performed, as the basis of this research, I have used the strategy explained above. Information concerning the implementation of condition based maintenance approaches is a rather narrow field in Swedish industry. Even if the maintenance approach has been implemented at a manufacturing or process industry, only a few have information of the entire process. Using other sampling strategies than selecting the appropriate cases and respondents at those cases could possibly have provided less useful data.

4.3.3 Data collection

Yin (1994) mentions six sources of evidence useful in case study research. They are: documentation, archival records, interviews, direct observation, participant-observation, and physical artifacts. All have their strengths and weaknesses, but if combined, at least a few will give greater credibility and also affect the validity positively. This is called triangulation, and is encouraged in both case study research (Merriam, 1994; Yin, 1994) and when dealing with qualitative data (Maxwell, 1996).

Interviews have been the primary data collection method used in the case studies that form the foundation of this research. The interviews have been performed in a semi-structured fashion, an interview form suitable for developing knowledge to create well-developed models including important concepts (Lantz, 1993). The interviews have largely followed Kvale's (1996) seven stages of an interview investigation, containing: thematizing, designing, interviewing, transcribing, analyzing, verifying, and reporting. The interviews have been performed with respondents who have taken part in either an implementation attempt or an initiation of an implementation of condition based maintenance in an industrial setting. Holme and Solvang (1991) find it important to interview respondents with knowledge of the studied object in order for the results to be valuable and even valid. The interviews have predominantly been performed at the respondents' locations, where direct observations have been performed as well. Documents and websites have been studied in order to see organizational schemes and the size of companies and production output. For one study, called the expert case, the respondents were asked to answer two open questions using E-mail; this study can resemble a survey without the statistical inferences.

4.3.4 Data analysis

Analysis in the systems approach is about investigating the relationship of components to both each other and to the real system in general. The ambition of the systems approach is to determine the type of system, to categorize the object under study in terms of complexity, for example (see Figure 14). This includes describing, determining a relation, forecasting, and guiding a system. In the analytical approach, one seeks causal relations (i.e. cause-and-effect), while in the systems approach one seeks finality relations (indicator-effect) (Arbnor & Bjerke, 1997).

Before starting the systems analysis and systems construction, an analysis of the collected data is of course necessary. Maxwell (1996) divides analytical options into three main groups: memos, categorizing strategies, and contextualizing strategies. According to Maxwell (1996), using memos is one appropriate option while performing data analysis, both to capture analytical thinking and to facilitate and stimulate analytical insights. Maxwell (1996) considers coding the most common categorizing strategy. As Maxwell (1996) points out, there is a great difference between coding when dealing with qualitative data, as opposed to quantitative data. In dealing with qualitative data, the idea behind coding is to rearrange it into different categories to aid comparison and in the end to develop theoretical concepts. Examples of contextualizing strategies include case studies, profiles, some types of discourse analysis and narrative analysis, and ethnographic microanalysis (Maxwell, 1996). The similarities of these strategies are that they look for relationships that connect statements and events within a context into a coherent whole. In this research, all three groups have been utilized where suitable (see further Table 3 below).

4.3.5 Cases in short

As indicated in Figure 15, the cases have been performed sequentially, and the output from the previous case has been used in the following one. Five cases are the foundation of this research (see Table 3 and Figure 16). Through the entire research, literature and theory have provided input to the cases. The first case, the investigative case, was reported on in the author's licentiate thesis (Bengtsson, 2004b). That thesis also laid the groundwork for the continuation of the doctoral project. The case led to the conclusion that there was a need for further research within the area of implementing condition based maintenance (see further Chapter 5, Results). The second case, the test case, was performed partly in order for the author to experience the problems an applicability decision (whether to implement condition monitoring tools) can amount to. The case led to the conclusion that a somewhat structured decision-making process was necessary at the least (see further Chapter 5, Results). The third case, the expert case, was performed in order to gather views, ideas, and experiences from a broad perspective of Swedish industry. The case was performed by E-mailing two open questions on the issue of implementing condition based maintenance to 20 respondents. The case led to the results of a first draft of an implementation guideline and a first draft of a decision and development support model (see further Chapter 5, Results). The fourth case, the paper mills case, was performed in order to gather a deeper view of the implementation issue than could be gathered in the expert case. Paper mills were selected to be investigated, as they generally had come a long way in the use of condition monitoring tools. The case led to the result of a second draft of an implementation guideline (see further Chapter 5, Results). The last case, the workshop case, was performed in order for the author to synthesize the data collected; the case consisted of a brainstorming/workshop session with academic participants. The results of the case led to a second draft of a decision-making guideline (see further Results). Finally, cross-case conclusions were drawn, and a suggested implementation method was developed (see further Chapter 6, Contributions).

Table 3. Summary of the case descriptions. All cases have also incorporated theory when analyzing the data.

Case	Design of case	No. of Respondents	Business focus	Unit of analysis	Data collection method	Data analysis	Research question
Investigative case	Single-case/holistic	16	Rail vehicle developement	Implementation process	Interviews/ questionnaire	Memos/ contextualizing (narrative)	RQ3
Test case	Single-case/holistic	2	Swedish Defense Material Administration	Decision-making process	Interviews/ observation	Memos	RQ2
Expert case	Single-case/holistic	20	Variouos industries	Decision-making process, implementation process	E-mail based interviews	Categorizing (coding)	RQ2, RQ3
Paper mills case	Single-case/ embedded	8	Paper manufacturing	View on condition monitoring tools, implementation process	Interviews/ observation	Contextualizing (narrative)	RQ1, RQ3
Workshop case	Single-case/holistic	5 (participants)	Academic participants	Decision-making process	Brainstorming/ review	Memo	RQ2

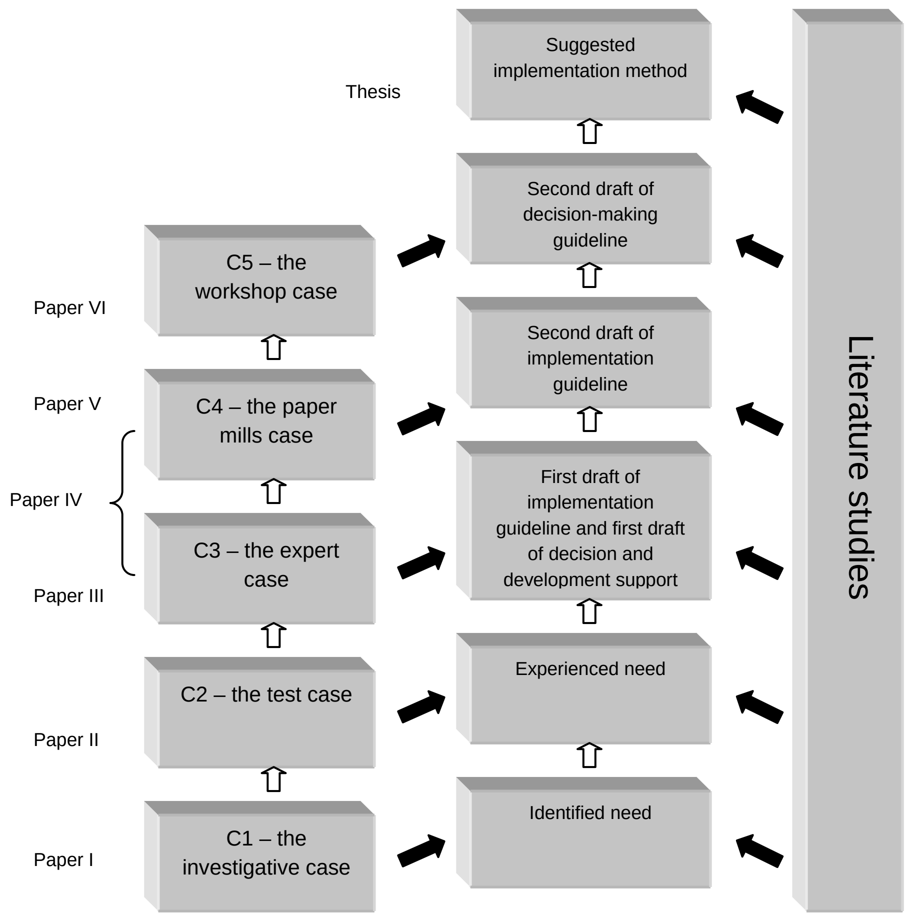

Figure 16. The research process, incorporating the cases as well as continuous literature studies (compare with Figure 14).

4.4 Quality of research

Reflecting on the quality of the conducted research is an important task to undertake, and it is something that should be done continuously throughout the research process. The term quality deserves a short discussion. There exist many different definitions of quality, many of which stem from customer satisfaction. Juran (1989) provides a short and comprehensive label of quality by stating that "Quality is fitness for use." (p.15). Bergman and Klefsjö (2001) define quality as: "The quality of a product is its ability to satisfy, and preferably exceed, the needs and expectations of the customers" (p.24). Deming (1986) gives a similar definition, and adds the dimension of also considering the customers of tomorrow, by stating that: "Quality should be aimed at the needs of the consumer, present and future." (p.5). Who is then the customer of this research? Two parties become visible, practitioners and the academic environment. Below, a theoretical discussion of the concept of quality of research is presented. This section will, for purposes of this research, be resumed in Chapter 7, Conclusions and discussion.

Just as many definitions of quality exist, so, too, exist many different ways of estimating the quality of research. The most common criteria, though, are to discuss and estimate the reliability and validity of the research design. Reliability can be seen as to what extent the result of a study can be repeated at another time or setting (Merriam, 1994; Yin, 1994). Validity can be seen as the extent to which a measurement actually measures what is intended to be measured (see Figure 17).

The view on reliability and validity differs somewhat depending on the chosen methodological approach (the analytic, the systems, or the actors) and the data intended to be collected (qualitative or quantitative). Within the systems approach (not as quantitatively oriented as the analytical), the results of a measurement are not as precise, nor are they regarded as highly desired. As in other contexts, the systems approach takes on a pragmatic attitude. The focus is on what the measurements can be used for, not how the measurements were conducted or how precise they were. Thus, reliability is not as important in the systems approach as it is in the analytical (Arbnor and Bjerke, 1997). Merriam (1994) explains that reliability is a problematic notion within social science, as human behavior is dynamic, not static.

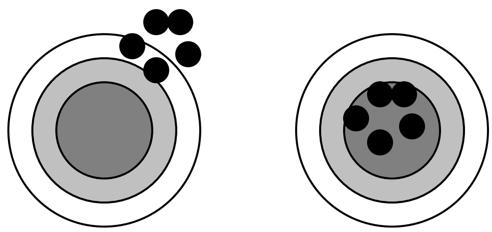

Figure 17. The goal target to the left shows a result with a high reliability but low validity. The goal target to the right shows a result with both a high reliability and validity (Arbnor and Bjerke, 1997, p.233).

The systems approach treats validity somewhat differently. The connections between theory, definitions, and reality are not considered as important as in the analytical approach. The focus is more directed towards the connections being considered essential and real by both the researcher and the participants located in the real system. It is these persons who have the ability to judge if the measurements are reasonable and correct. According to the systems approach, a decisive validity control lies within the effect one can gain by applying the measurements in reality (Arbnor and Bjerke, 1997).

There exists different theories on how to validate measurements and results; again, choosing which theory to use has a great deal to do with the methodological approach and type of data collected. When applying an analytical approach, and thus dealing primarily with quantitative data, Arbnor and Bjerke (1997) suggest estimating *face validity, internal validity,* and *external validity*, preferably in combination, to prove the validity of research. Face validity implies estimating the plausibility of the results; internal validity implies estimating the logical proportions between the study and the existing theories on the topic; and external validity implies the possibilities to generalize the study's results outside the particular study area. These three categories of validation are not that different from validity discussions within case study methodology. In those discussions, Yin (1994) enumerates *construct validity, internal validity,* and *external validity* as categories to use, while Merriam (1994) enumerates only *internal validity* and *external validity*. The difference in the view on validity might also be found in the data, collected within the case studies. Maxwell (1996), dealing with qualitative research design, uses validity to "…refer to the correctness or credibility of a description, conclusion, explanation, interpretation, or other sort of account." (p.87). Nonetheless, Maxwell (1996) still sees validity as something that can never be proven or taken for granted. Maxwell (1996) sees three types of validity in qualitative research: *description, interpretation,* and *theory*. Maxwell (1996) also provides a checklist of validity testing: the Modus Operandi approach, discrepant evidence and negative cases, triangulation, feedback, member checks, "rich" data, quasi-statistics, and comparison. Merriam (1994) refers to some of these (triangulation, member checks, observation during longer periods of time, feedback, respondent participatory approach, and explanation of any bias) as tests of internal validation.

Internal validity thus deals with to what extent the results agree with reality. Meanwhile, external validity deals with to what extent the results can be generalized to other populations and situations beyond that which is studied. Maxwell (1996) distinguishes between internal and external generalizability. Internal refers to the results' generalizability within the setting or group studied, while external refers to the results' generalizability outside the setting or group studied. Maxwell (1996) means that it is particularly difficult to prove external generalizability. However, he also points out that it is often not a crucial issue for qualitative studies. Further, he means that qualitative studies often have something called *face* generalizability, defined as when "…there is no obvious reason not to believe that the results apply more generally." (p.97).

5 Results

This chapter presents the results of the cases performed within the research. The results are presented in summarized form. The chapter starts with a short introduction of how the appended papers, the cases, and the research questions are connected.

5.1 Correlation between papers, cases, and research questions

As explained in Chapter 4, the research has been conducted through case study research. The cases have been developed from each other, and some have been performed, partly, iteratively. Figure 18 below visualizes the correlations between the appended papers, the cases, and the research questions.

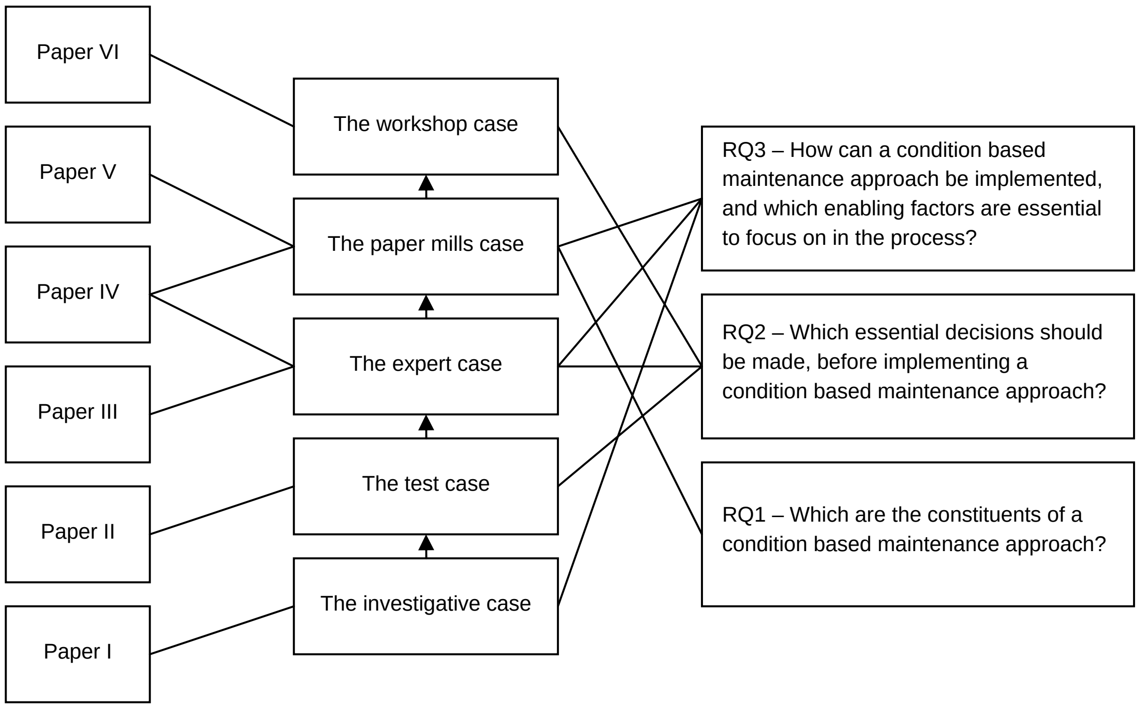

Figure 18. Illustration of the correlation of the appended papers, the cases, and the research questions.

5.2 The investigative case – identified need

The investigative case (Paper I) was performed at the end of 2003 and the start of 2004, and was also reported on in the author's licentiate thesis (Bengtsson, 2004b). The licentiate thesis had three research questions, which covered: standards and standardization proposals within condition based maintenance system technology, the design of condition based maintenance system technology, and aspects to take into consideration when implementing a condition based maintenance system.

Thus, the investigative case was performed to investigate the third research question in the licentiate thesis and the third research question of this thesis.

5.2.1 Background

The case approach combined a literature review with an interview study. The interview study incorporated a questionnaire in which the respondents were also asked to furnish open comments on all statements. The key search index used for the literature review was: condition based maintenance, condition monitoring, predictive maintenance, implementation, implementation strategy, organizational aspects, Total Productive Maintenance, and Reliability-Centered Maintenance. The literature review was the grounds for the questionnaire. A total of 38 statements were given to the respondents for them to answer with a six-level scale (1 equal to strong disagreement and 6 equal to strong agreement). The respondents were also asked to give the main reasons why a condition based maintenance implementation could fail in their company. The interview study was performed at a large international company that develops and manufactures rail vehicles. The focus of the implementation process came thus to be on the companies' products, not on the production equipment. A manager within the case-company recommended the respondents of the study, the total number of respondents amounted to 16, divided in two categories, managers (10) and technicians (6).

5.2.2 Findings

The analysis of the interview and questionnaire followed the first five steps of Nakajima's (1988) twelve-step implementation plan of Total Productive Maintenance. Those steps were considered to be general and accepted. The focus of the steps thus came to be: a managerial issue; an employee, information, and education issue; an organizational issue; a goal-setting issue; and getting started. The results indicate that it is important in the early phases of an implementation to, among other things, have management support, determine incentives (business case), have a communication strategy, and set realistic and clear goals in a phased approach.

The case company had not implemented condition based maintenance on a full scale on their products. Thus, the open question of what the main reason to why condition based maintenance would not be implemented was posed. Twelve of the 16 respondents chose to give a comment on the question. Only two of these mentioned anything remotely close to technology. One comment dealt with the dilemma of maintenance scheduling that would impose a problem with an implementation. The other simply stated that the company's strategy at that time was to work with known solutions and designs, and that there was a big lack of resources to commit to new technology development. The other answers mainly dealt with the problems of investment costs, separated divisions (which would make joint projects difficult), the lack of top management interest and support, and the customers' unawareness of the incentives. Below, three answers to the question are presented. These three statements together reflect all twelve answers:

"There is an unwillingness to work with condition based maintenance from the top management; there is also unwillingness to invest in the initial costs needed. There is also a lack of competence within the area, in particular at decision-making level. There is no industry standard, there is a lack of approaches, and we have a hard time understanding our customers' needs."

"There is a fear of investing, from the company's side, and of committing until there is an order from any customers. The top management does not really understand the importance of condition based maintenance. We might also be overestimating the maturity level of condition based maintenance within our own company, when we really have to lift the level of maturity across the entire company."

"The largest threat is that the wrong people are left to decide, people who are scared of change, people who want to leave things as they have always been. We also need to provide our customers with enough data on what condition based maintenance really is."

The case conclusions, also a part of the licentiate thesis conclusions, were that there is a need for additional research within the issue of implementing condition based maintenance. This was but one study performed, and only one case was investigated. However, the literature studied also suggested there was a lack of research within the area of condition based maintenance implementation. Therefore, the new research questions and purposes were formulated after the licentiate thesis had been presented.

5.3 The test case – experienced need

The test case (Paper II) was performed in 2005. The objective of the test case was to perform a test to find out if a certain system would benefit from a condition based maintenance approach. The system in the study was the Main Battle Tank 122, commonly called Leopard 2, and the delimitation was set to the final drive. The test case was, thus, performed to investigate the second research question of this research.

5.3.1 Background

The study approach of the test case was interviews and observations. The case started with a workshop at the Swedish Defence Material Administration in Stockholm. The workshop included presentations on condition based maintenance and brainstorming on the possible delimitation for a study. Two visits were made to the Swedish Defence Material Administration and its workshop facilities in the city of Skövde, Sweden. The interviews were performed with technicians and test personnel. Observations were made in the workshop where the maintenance and test of the Main Battle Tank were performed.

5.3.2 Findings

It was decided the criteria to work with in concluding whether condition monitoring was applicable were availability, financial, and safety. The availability criteria was concluded using the equation commonly used for the calculation of operational availability in manufacturing industries, A_o (see [1]):

$$A_O = \frac{MTBM}{MTBM + MLDT + MTW(A) + \bar{M}} \quad [1]$$

where MTBM is an abbreviation of Mean Time Between Maintenance, MLDT is Mean Logistics Down Time, MTW(A) is Mean Time Waiting Administrative, and M is Mean Maintenance Time, where both corrective and preventive maintenance time is included. Also, the financial and safety criteria came to be concluded with the equation in mind.

The interviews and observations revealed that the final drive was submitted to corrective maintenance mostly, but with a lubrication program and some sporadic subjective controls. The subjective controls consisted of finding oil leakage, below the final drive, as it had been in parked mode in the workshop, which could indicate impending failure. Also, there was a possibility in controlling a gap when the tracks were dismantled. It proved not to be too easy to find incipient failures. Further, the final drive was usually only changed when a breakdown had happened, after which the tank was equipped with an exchange unit and the faulty one was shipped for corrective maintenance at the visited location in Skövde. The technicians and test personnel estimated that the repair times to change a final drive amounted to five hours in the workshop and ten in fieldwork. It was also made clear that all military units utilizing the Main Battle Tank 122 were in possession of exchange units. This implies that the logistics (MLDT) and administrative waiting times (MTW(A)) were quite low and difficult to reduce further. Using exchange units also implied that the mean maintenance time was rather fixed and difficult to decrease by introducing condition monitoring. Thus, the availability of the final drive was ruled difficult to increase by the introduction of condition monitoring. The financial criteria were also found difficult to improve. Exchange units would probably cost the same whether a part had broken down or was close to breaking down. The financial criteria that could possibly be improved would be the repair cost of the unit in the workshop, where a monitoring system would possibly lead to less trouble-shooting time. Although, as the technicians had good knowledge of what usually breaks down in the final drive, this criterion might be negligible as well. The safety criteria were more difficult to estimate. A well functioning monitoring system would of course imply that better knowledge of the tanks' condition would be gained and the missions might be planned thereafter. However, the failure processes were estimated to be quite rapid. Thus, developing a monitoring system that can give a long enough warning time would be difficult.

Therefore, the final recommendations for the Main Battle Tank 122 were not to implement condition monitoring on the final drive, but to look at other sub-systems and components to see if incentives were present. The conclusion from the case was that it was difficult to know how to go about estimating the applicability of condition monitoring without any guideline or checklist.

5.4 The expert case – first draft

The expert case was performed in 2005 (see Paper III; Paper IV; also, see Bengtsson, 2006b and 2006c). The purpose of the expert case was to present ideas, views, and experiences from an implementation effort of a condition based maintenance approach and to structure these into a guideline and a decision and development support to aid companies in an implementation process. Thus, the expert case was performed to investigate the second and third research questions.

5.4.1 Background

The study approach of the expert case was E-mail based interviews with 20 experts within Swedish industry. The respondents were known to have knowledge of and an interest in the subject. Two open questions were E-mailed to the respondents:

1. How is condition based maintenance best implemented, considering both the technology and the organization where the technology will be used?
2. Do any models exist that one could use, and are there any specific factors one should focus upon when implementing condition based maintenance?

The respondents were asked to answer in writing in a replied E-mail, and also to categorize themselves in one of following categories:

A. They who have practical experiences from a live implementation of Condition Monitoring Equipment (CM)/Condition Based Maintenance (CBM) on their production equipment.
B. They who have practical experiences from a live implementation of CM/CBM in their products (that are sold to customers).
C. They who might not have practical experiences from a live implementation of CM/CBM, but who teach or perform research within the area of CM/CBM.
D. They who might not have practical experiences from a live implementation of CM/CBM, but develop CM/CBM tools.

5.4.2 Findings

The findings of the case are presented in two parts. Part one (Paper IV) includes factors that were found in the respondents' answers, as well as an attempt at developing a guideline for implementation (the very first attempt, though, is presented in Bengtsson, 2006b and 2006c). Part two (Paper III) includes a first attempt at developing a decision and development support.

Part 1: First draft of a implementation guideline

The analysis of the respondents' answers suggested 13 factors essential to take into consideration as condition based maintenance is implemented (Paper IV). The factors were as follows: use a decision support method, management support, cooperation between departments, quantify possible gains and losses, implement gradually, visualize goals and incentives, educational effort, motivation of co-workers, involve champions, communication, organizational maturity, pilot projects, and assign responsibilities (see Figure 19).

The factors presented were not controversial in comparison to literature and theory presented in general change management or implementation of various maintenance approaches. The difference may be found in the global approach of the study, incorporating several different types of respondents and industries to give their ideas, views, and experiences on the topic that might have provided an added collective grip on the issue. One interesting aspect of the factors found lies in the fact that all categories of respondents gave quite similar answers; no category distinguishes itself particularly more than the other. The support for the different factors is in many cases spread over several groups, and in only two cases does one single group support a factor. This might indicate that the implementation of condition monitoring tools and a condition based maintenance approach is composed of general issues and problems and that it might be possible to develop a generalized implementation method. Actually, four respondents did raise concerns regarding the implications of developing a standardized and generalized implementation method, and three respondents could not give ideas to any models or methods to be used. Their thoughts proved them wrong in that they shared common ground in many aspects, specifically on the non-technological topics. Figure 19 shows the support for the different factors.

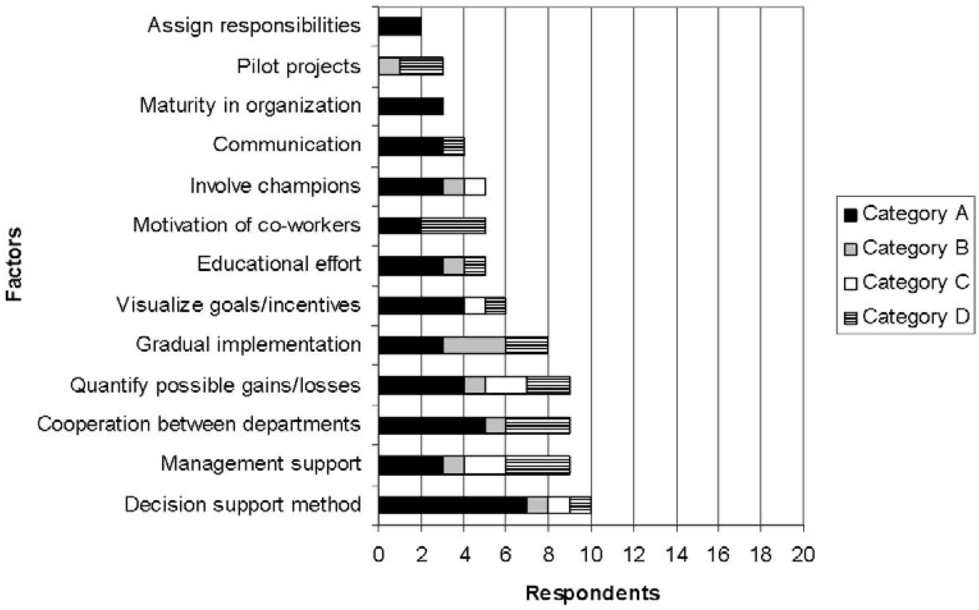

Figure 19. The 13 factors, essential to focus upon in an implementation attempt, found in the expert case (Paper IV).

The factors were rephrased into activities. A first attempt was also made to arrange them in the order of sequence of an implementation process (see Figure 20). The guideline was divided in three phases: a preparation phase, a design phase, and an implementation phase. In the preparation phase, the analysis of the current situation and the applicability of condition based maintenance would take place. In the design phase, decisions should be made. Also, other additional activities should proceed and be planned. In the implementation phase, the condition based maintenance approach should of course be introduced and implemented. In it, it is essential that many activities, such as education, communication, and motivation, are performed. This, the first draft of the implementation guideline, is further developed in the paper mills case.

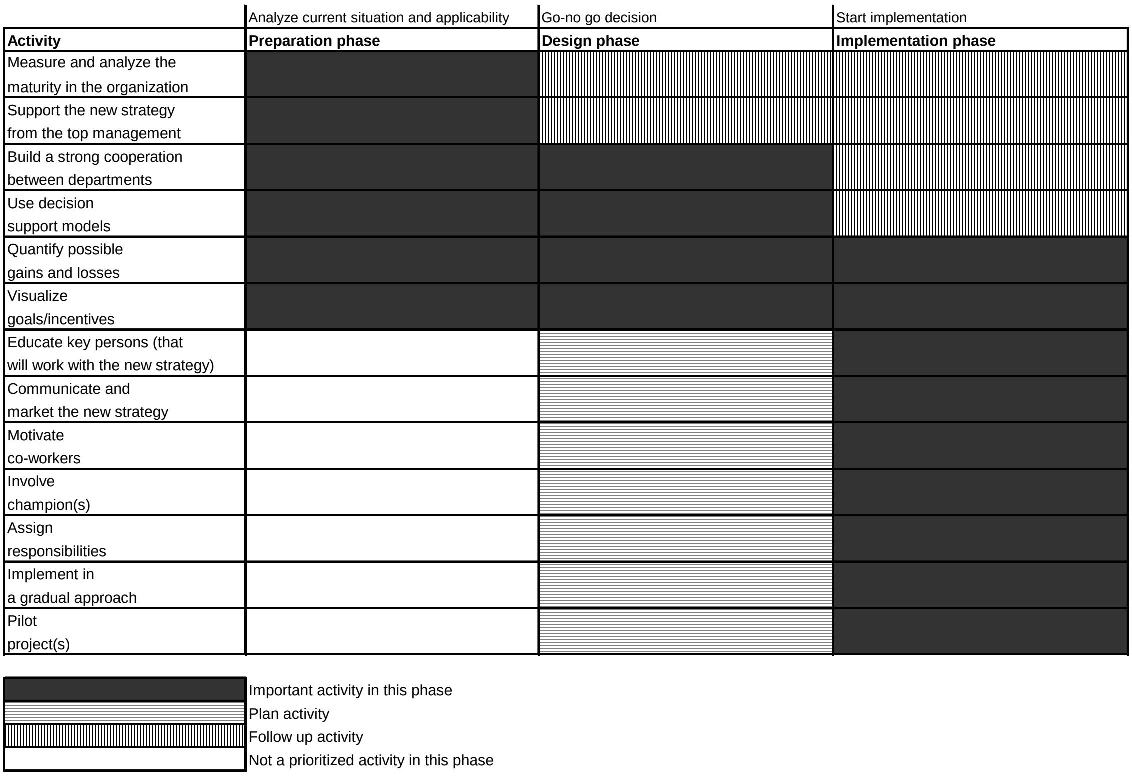

Figure 20. First draft of an implementation guideline for condition based maintenance, presented in Bengtsson (2006b and 2006c).

Part 2: First draft of a decision and development support

It was clear following the analysis of the factors that using some sort of decision support in the implementation process was valued very highly among the respondents (see Papers III and IV). Half of the 20 respondents mentioned the importance of using some sort of a structured process in making decisions when implementing condition based maintenance. The respondents did not provide clear suggestions as to any method to be used, other than maybe using Reliability-Centered Maintenance or a Six Sigma DMAIC approach. However, they did suggest tools and measurements possible to use in the decision-making process. They are the following:

- DuPont calculation,
- Return on investment calculation,
- Cost benefit calculation,
- Life Cycle Cost (LCC) calculations,
- Organizational maturity estimations,
- Criticality analysis,
- Overall Equipment Effectiveness (OEE),
- Reliability-Centered Maintenance (RCM), and
- RAMS calculations (Reliability, Availability, Maintainability, and Safety)

In an attempt to systematize the tools and measurements the respondents suggested, they were incorporated into the Six Sigma methodology DMAIC: define, measure, analyze, improve, and control (Paper III). One respondent suggested DMAIC as a rather straightforward process improvement method. It was suggested that the rather extensive improvement phase in DMAIC be performed through the use of the Systems Engineering philosophy V-diagram, again in order to systematize the decisions and development and as a help in order to verify and validate the decisions taken. Integrating the philosophies of V-diagram, with its verification and validation processes in particular, with the DMAIC methodology, into a decision and development support model of condition monitoring tools would provide a suggested model in which decisions of which condition monitoring tools to invest in can be made on a more structured level. The DMAIC methodology would be utilized in order to first find out if condition based maintenance and condition monitoring is, at least, one of the most effective ways to improve a process. Consequently, applying verification and validation processes into the technical implementation phase of condition monitoring tools would imply that the proper kind of tools are being invested in and implemented. These, or similar, processes can and should of course be utilized when designing new condition monitoring tools. However, they could probably also be utilized when implementing an off-the-shelf condition monitoring tool into an operating production process.

The underlying issue of the model lies in the need for some kind of process improvement on the maintenance function of a company. The DMAIC methodology defines and measures the underlying problem, analyzes the root-causes of the problem, and suggests solutions of improvements (see Figure 21). If condition based maintenance and the use of condition monitoring tools is applicable and considered an effective and financially justifiable solution, the model then uses the V-diagram. The strengths of the V-diagram lie in its verification and validation processes between the different phases in the development/purchasing process (see Figure 22). Using verification and validation in the development or purchasing process can ensure that the proper condition monitoring tool is being invested in and implemented. This is the first draft of the decision and development support, and it is further developed in the workshop case.

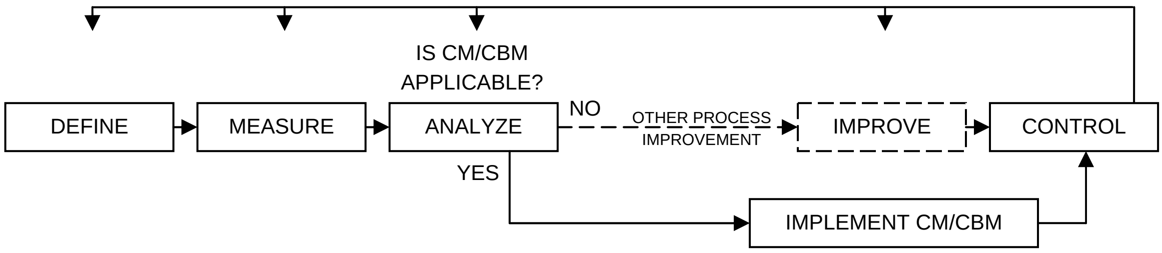

Figure 21. First draft of decision and development support when implementing a condition based maintenance approach (Paper III) (see further Figure 22).

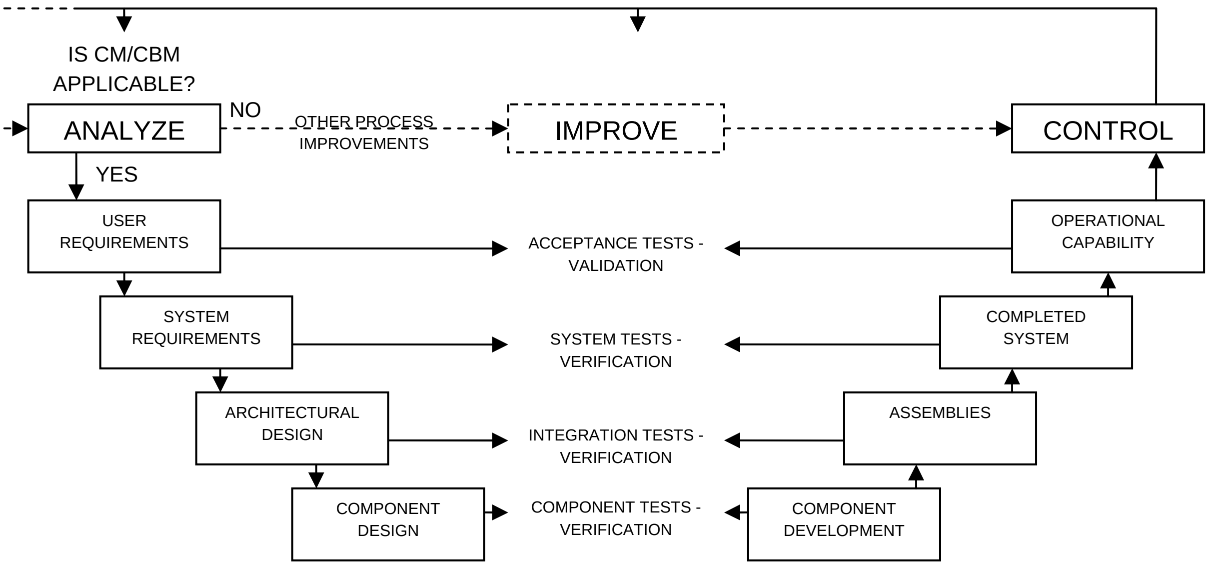

Figure 22. A specific part of the first draft of decision and development support, visualizing the improvement phase in DMAIC utilizing the V-diagram (Paper III).

5.5 The paper mills case – second draft

The paper mills case was performed in 2005 (see Papers IV and V). Four paper mills were visited, and two types of respondents per mill were interviewed, the managers of the mills' condition monitoring programs and the preventive maintenance technicians that performed the measurements and analysis. The purpose of the paper mills case was to gain deeper knowledge as to how companies have implemented a condition based maintenance approach. The paper mills case was performed to investigate the first and third research questions.

5.5.1 Background

The study approach of the paper mills case was interviews and observations. Contact with the maintenance managers of four paper mills was initiated through a vendor of condition monitoring equipment. The maintenance managers, in turn, suggested preventive maintenance technicians to interview. The managers were interviewed to gain comprehensive knowledge of the implementation process of condition monitoring. The preventive maintenance technicians were interviewed to gain knowledge as to how the measurements were carried out and what type of information was collected and used in the analysis.

5.5.2 Findings

The findings of the case are presented in two parts. Part one (Paper IV) includes further development of the implementation guideline, as well as a model development of a condition based maintenance approach. Part two (Paper V) includes a model development of communication and information in a condition monitoring context. Both models are developed in order to visualize the entire approach of condition based maintenance. This is to highlight that implementing condition based maintenance is not as easy as purchasing a tool; rather, it involves additional factors.

Part 1: Implementing condition based maintenance

Several success factors were identified in the analysis of the interviews held with the managers (Paper IV). The respondents were quite unanimous in sharing success factors in an implementation effort. All the respondents stated the importance of management involvement and support, education and training, and effective communication. Additional factors included: involved champions, creativity, setting clear goals and giving adequate resources for the goals, visualizing incentives, treating condition monitoring as core competence, placing the human in the center, and building trust in the technology by empowering the preventive maintenance technicians.

The respondents also shared that the implementation, and specifically gaining full acceptance of the condition monitoring programs, took a long time. The implementation was gradual, and all mills started with a subjective monitoring program before incorporating technology. The mills had also long before implemented the technology performed maintenance preventively. In other words, the maturity in the maintenance organization was high.

According to the respondents, some of the experienced difficulties during the implementation phase involved visualizing and proving that the initial increase in workload that can arise when first being successful in a monitoring program will eventually decrease. According to the respondents, the experienced increase in workload could cause attitudes like: *"All you people [preventive maintenance technicians] do is to find faults that did not exist prior your measurements"*. Another difficulty connected to the above problem was creating a sense of trust towards both the technology and the employees using the technologies and proving that the measurements actually gave results. One manager expressed it as: *"It takes fewer burdens of proof to hire a mechanic to repair a pump than a preventive maintenance technician to perform measurements on the same pump"*.

In answering the question as to what the main mistake an organization can make during an implementation effort, the respondents focused on lack of information strategies, lack of management support, investing in the wrong technology, and having too large a focus on the technology (and forgetting the humans and the organization that are supposed to work with it). The respondents focused a great deal on the importance of visualizing and proving that the workload will decrease in the long run. The respondents also acknowledged that an implementation can take several years, and that management must support the implementation from start to finish (if an implementation can ever be considered finished).

The data from the paper mills case regarding factors to focus upon in an implementation effort were incorporated with the expert case data and theory on the topic. The implementation guideline developed in the expert case was then expanded further into a checklist. The implementation process was divided into four phases (compared to the earlier three), an analyze phase, a manage phase, an introduction phase, and a verify phase (see Figure 23).

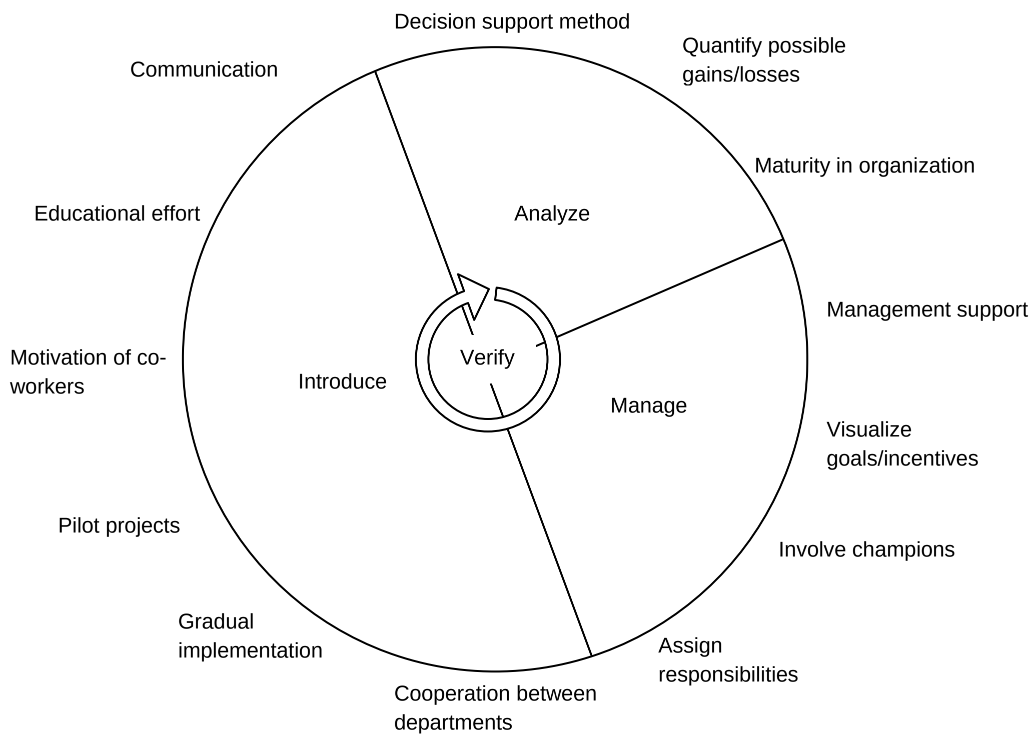

Figure 23. Checklist with essential factors to take into consideration when implementing a condition based maintenance approach. The process is divided in four phases: analyze, manage, introduce, and verify (Paper IV).

As the respondents in the paper mills case pointed out, it is not solely the technology issue that should be considered when introducing a condition based maintenance approach. Rather, the interplay between the technology, humans, and organization is important in order to achieve success. Adapting Hubka and Eder's (1988) model of a transformation system so that it fits a condition based maintenance approach may assist in visualizing what actually needs to be focused upon during an implementation (see Figure 24).

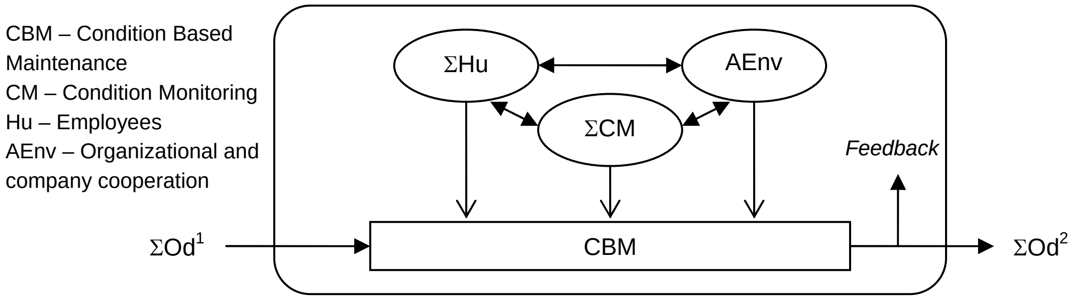

Figure 24. Model of a condition based maintenance approach, where Od^1 is the input quantities in energy (e.g. an increased vibration or temperature) and Od^2 is the output quantity, condition assessment that can be the ground for a maintenance activity (adapted from Hubka and Eder, 1988, p.23). As visualized in the figure, both technology (i.e. condition monitoring) and the interplay between technology, humans, and organization are vital for a successful result. Thus, it is the interplay that needs to be implemented, not simply the condition monitoring equipment (Paper IV).

Part 2: Information design in condition monitoring

In analyzing the data from the interviews (including both the management and the preventive maintenance technicians), taking a holistic perspective when implementing and operating a condition monitoring program was identified as essential (Paper V). Also, different kinds of information forms exist, all of which should be taken into consideration as a condition assessment is performed. In Figure 25 below, the different information forms are visualized as a communication and information process model. The model is divided in the three levels of contexts (inner, close, and external), as well as information provider, information system, and information user. The inner context is the condition monitoring tool (i.e. information set), and it contains *embedded* information. The information set contains *recorded* data that can be analyzed. The data is recorded in the close context from the information provider, which contains *embodied* information in the forms of machine characteristics (such as vibrations, sounds, and temperatures) and machine space, which in many cases can be disturbances that need to be filtered out. The information provider also contains *expressed* information in the forms of verbal communication and information from the operations department and maintenance department, for example. It is the information user that transforms and analyzes the collected information with amongst other *experienced* information in the forms of human senses. The transformed and analyzed data is, in the external context, shared with, for instance, a machine or maintenance manager that writes a work order for the maintenance department to execute. In the external context, *enacted* information is shared between the different actors in the communication system.

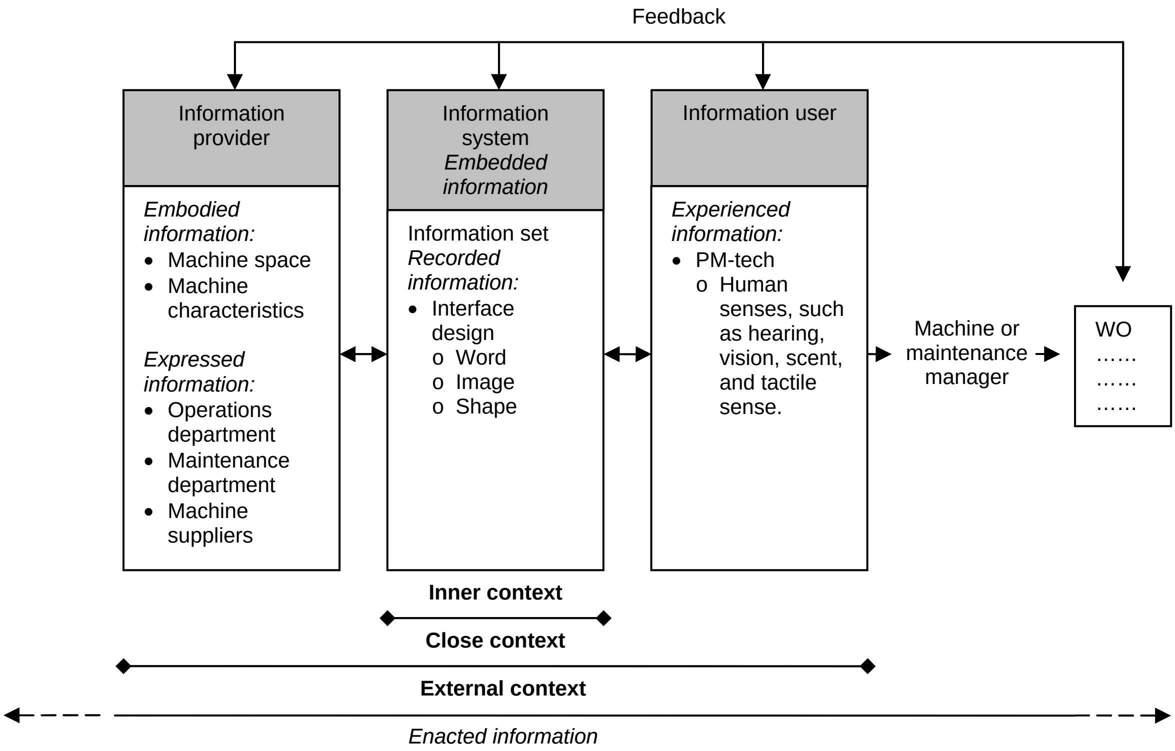

Figure 25. The communication and information in a condition monitoring context, as seen from a paper mill perspective (Paper V). Notice that there exist different forms of information in different contexts.

One of the respondents in the management category, even though generally positive to on-line monitoring, expressed uncertainty about a development towards more on-line and automated condition monitoring systems. The respondent was concerned that the preventive maintenance technicians would then spend less time in close contact to the machine space. Thus, only analyzing the *embodied* and *recorded* information, they would miss much of the *experienced* and *expressed* information.

5.6 The workshop case – decision-making guideline

The workshop case was performed as a brainstorming/workshop session in the fall of 2006 (Paper VI). The session was attended by three PhD-students and two senior researchers with industrial experience, all associated with maintenance and/or production related research. The purpose of the session was to examine and discuss necessary decision-making to undertake prior to the implementation of condition based maintenance. The workshop case was thus performed to investigate the second research question.

5.6.1 Background

As visualized in the expert case above, one of the most important factors to take into consideration when implementing a condition based maintenance approach was the use of some sort of decision support. A first draft of such decision support was also developed in the expert case. However, a workshop was performed in order to further enhance the decision support.

The study was built on a combination of theory and a brainstorming/workshop session. As an introduction to the brainstorming session, the participants read three papers as inspiration, without knowing the topic of the session. The papers, respectively, covered: (1) tools and decision-making in condition based maintenance and condition monitoring (Tsang, 1995), (2) aspects (including organizational) regarding condition based maintenance implementation (Mitchell and Murry, 1995), and (3) advanced techniques and technologies in condition based maintenance, condition assessment, and decision support systems (Yam et al., 2001). The author chose the papers, after a theory overview, with the intention that all the participants could read and reflect upon the impact an implementation of condition based maintenance can have in an industrial setting. The session started with the theory of Tsang (1995), in which he mentions three decisions in condition based maintenance: (1) selecting the parameters to be monitored, (2) determining the inspection frequency, and (3) establishing the warning limit (the trigger). It then grew from there, with open discussions regarding additional decisions that possibly need to be addressed in an implementation effort. Following the workshop session, the author reviewed additional theory on a deeper level, before synthesizing the general thoughts ventilated during the session. A draft of the decision guideline was iterated between the participants in the brainstorming session. This was done in order for them to give feedback on the material and to make sure no one was misunderstood during the session.

5.6.2 Findings

The result of the workshop was presented as a decision-making guideline, consisting of five steps: feasibility test, assignments of responsibilities, selection of assets to monitor, selection of parameters to monitor with associated technique, and selection of technology (see Figure 26). The steps are basically structured to answer the following questions:

- Should condition based maintenance be implemented?
- Who will implement it, and who will perform the monitoring?
- Where will monitoring take place?
- What will be monitored?
- How will monitoring be performed?

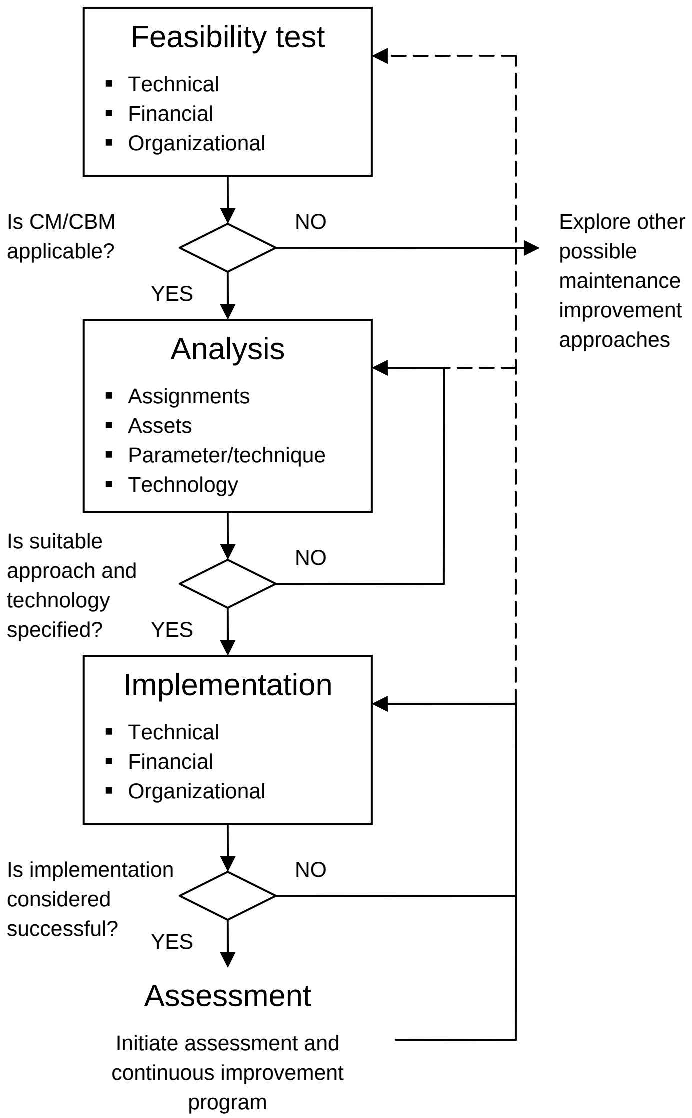

Figure 26. The decision-making guideline, with its four phases: feasibility test, analysis and technical development, implementation, and assessment, CM is an abbreviation for condition monitoring, and CBM is an abbreviation for condition based maintenance (Paper VI).

The decision-making process thus starts with an open and quite general decision as to whether a condition based maintenance approach is even feasible for a specific company and their process. It was concluded that this feasibility test should be based on a technical, financial, and organizational judgment. Theory on the topic, as explained in Chapter 3, suggests taking a technical and financial perspective in the decision-making process. Thus, the findings of this case add an extra dimension in the process, the organization, and, particularly, the maturity therein. The second step in the guideline, assigning responsibilities, was included to achieve a drive in the process. Considering the opposite, not assigning any responsibilities, the time to finish the process would likely take longer and the quality of the decision would possibly be lower. Assigning responsibilities was also one of the factors found in the expert case, as well as in theory. The remaining steps in the guideline imply working with some of the same tools also presented in the expert case. In order to select the proper assets to be a part of a monitoring program it is necessary to perform a criticality analysis. This can be performed, possible, using Failure Mode and Effect Analysis, FMEA, or Fault Tree Analysis, FTA. Selecting the parameters to monitor with the associated technique can be performed through potential failure to failure, P-F, interval analysis, for example. If more than one possible parameter is found, decision matrices can be used as a help in the evaluation. In selecting technology, many decisions must be made (see Figure 10). Using subjective or objective monitoring might be the first decision. Several other decisions follow. They include: off-line or on-line systems, periodic or continuous monitoring (and if periodic, what intervals), static or dynamic warning limits, and manual or automatic analysis of the collected data. This is especially true if deciding for an objective approach. Again, using P-F interval analysis, for instance, with decision matrices, ranking the cost for the technology versus the effectiveness of it, was suggested as an approach.

The conclusion of the case was that the guideline was rather extensive and might be difficult to work with in a sequential order. However, this is not necessary. Iteration between the steps should be seen as a good thing as it can be seen as verification. The governing idea behind the developed guideline was to not overlook necessary decisions and to be systematic in the process.

5.7 Summary of cases

The cases have revealed the need for a systematic procedure when implementing condition based maintenance. Several cases in different industries and companies, using different research methods, have visualized a general view of how the implementation of the condition based maintenance approach should be performed. As a summary, it seems that the implementation is not all that different from other change management or implementation projects. Factors such as management support, communication, education and training, and goal setting are essential in the process. The problem with condition based maintenance seems to be that too much focus is directed on the technology, when an equal amount of focus should be directed on the employees using the technology and the organization they work in.

6 A condition based maintenance implementation method

This chapter presents the development of a suggested implementation method. The chapter starts by introducing a taxonomy of some key terms used within the method development.

6.1 Preconditions for the implementation method

The implementation method presented in this chapter has been developed iteratively through the cases presented in the previous chapter and the theory presented in Chapters 2 and 3. Throughout the research and in the appended papers in particular, the terminology has not been stringent. Terms such as model, method, and guideline have been mixed. Therefore, a taxonomy of some key terms has been developed in an attempt to clarify the development of the implementation method. The descriptions of the key terms presented in Table 4 are not supposed to be seen as general definitions, but, rather, as a description of how the terms have been treated in the method development in this research.

Table 4. Descriptions of the different components in the developed implementation method. Descriptions are inspired and adapted from www.ne.se.

Term	Description
Method	a systematic procedure in order to achieve a specific result
Guideline	an instruction of the main features of a certain activity and how it will be carried out
Process	a course of events that implies something is changed or developed
Model	a representation of a phenomenon
Checklist	a list of activities and/or factors to take into consideration
Factor	a circumstance that influences a certain result
Activity	a continuously performed purposeful work

6.2 The implementation method

The method itself should be seen as the overall methodology and a guide to the implementation process. The method contains a comprehensive implementation guideline, with suggested tools and measurements, models, and a checklist with factors and activities.

6.2.1 Overview

The implementation method is divided in four phases, as visualized in Figure 27 and Figure 33. The process starts with a feasibility test. The test should investigate whether a condition based maintenance approach is applicable or not. If so, the process continues with an analysis phase, which is supposed to answer questions such as: who is responsible for the process, where is it applicable to monitor, what is applicable to monitor, how should monitoring be executed, and when should monitoring be executed. Following the answers to these questions, the process continues with an implementation of the technical solutions in an organizational setting. Thus, management and introduction proceed. The process in this context is preferably continuous. Also, one should perform an assessment of the analysis and implementation phase before feeling too complacent. If considered applicable, a continuous improvement program can be initiated at this phase.

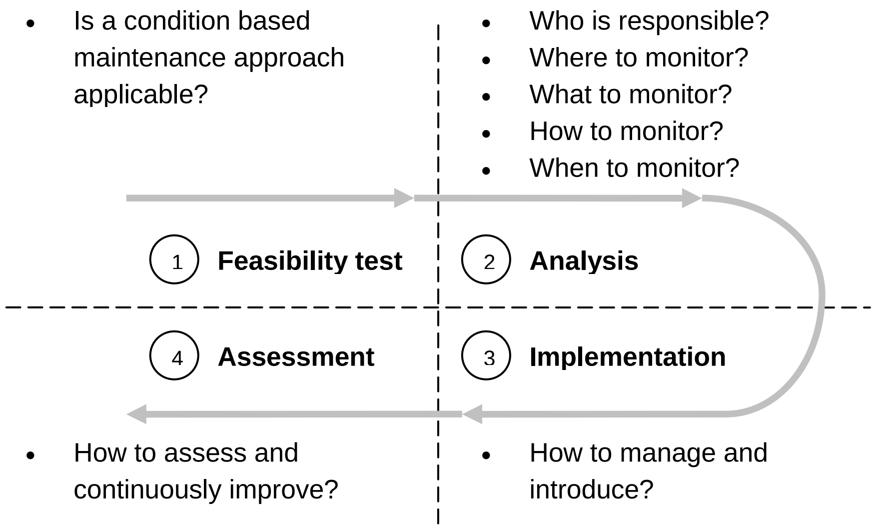

Figure 27. The implementation method is divided in four phases: feasibility test, analysis, implementation, and assessment, where the basic questions phrased in the figure need to be answered.

The comprehensive component in the implementation method is the guideline (see Figure 28). It takes an implementation attempt through the phases indicated above. The guideline also contains feedback loops that might be necessary within the attempt. The process is further described below.

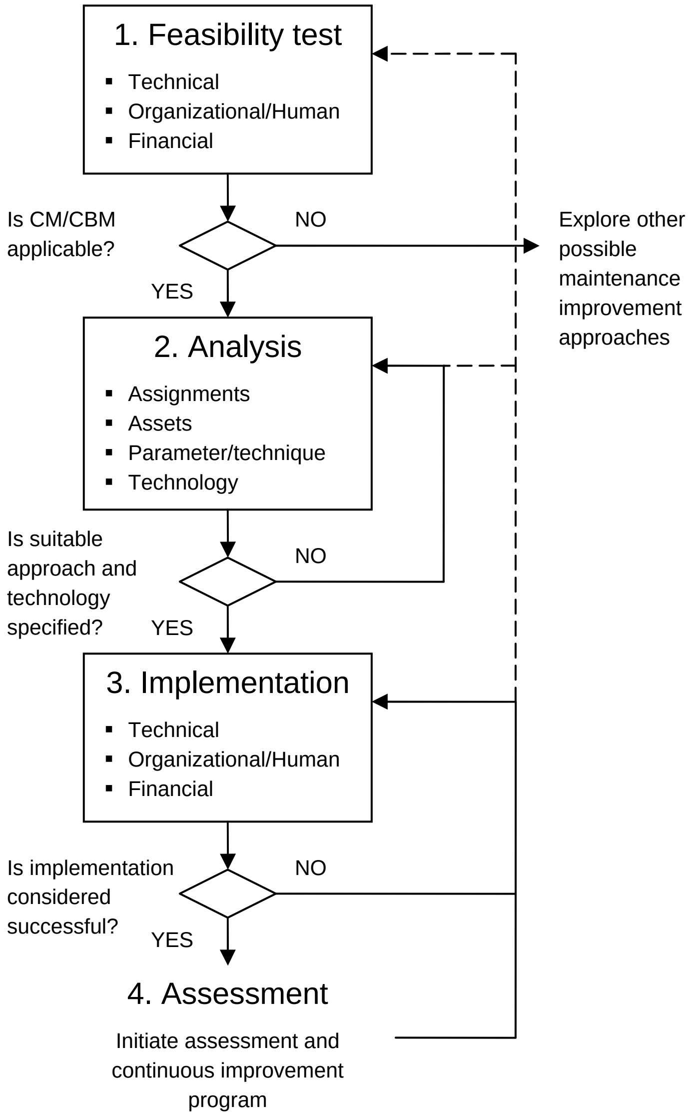

Figure 28. The comprehensive component of the method is an implementation guideline (Paper VI).

6.2.2 Feasibility test

The feasibility test should answers the question of whether a condition based maintenance approach is applicable. As pointed out in Chapter 3, condition based maintenance can be very effective where appropriate and a deep disappointment where not. Condition based maintenance, with the use of condition monitoring technologies or other on-condition tasks, should thus not be decided on and implemented by a happening. Rather, meticulous evaluation should take place before the first investments are even considered. As discussed in Chapter 3, the decision of whether to implement condition based maintenance must be made on both a technical and a financial level. An additional factor to take into consideration when investigating the applicability of condition based maintenance is the organization and its maturity. Both theory and the cases presented support this additional factor (see Papers III and VI). The respondents state that it is necessary to make sure that the proper technology should be implemented at the proper location, that gains and losses should be investigated, and that maturity in the organization should be assessed all prior to and in the process of deciding condition based maintenance technologies (see Figure 29).

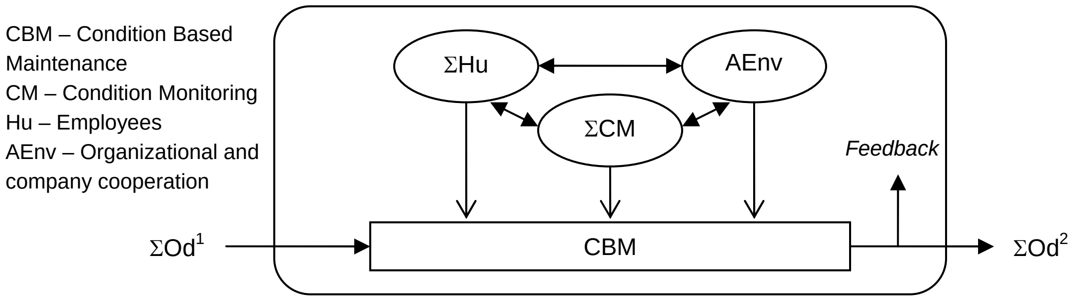

Figure 29. Model of a condition based maintenance approach visualizing that not only technology (i.e. condition monitoring technologies) needs to be implemented; rather, it is the interplay between technology, humans, and the organization that needs to be in focus (Paper IV).

At this stage, it is suggested to not try to conclude the applicability on too deep a level. By using tools and measurements, possibly in light-approaches, the applicability should be rather easy to determine. It is suggested in this phase that companies utilize tools and measurements well-known to the organization. Examples include a smaller version of FMEA, some of the seven quality tools, and decision trees. For the technical issue, questions to be answered in order to assess the applicability can include the following (Paper VI):

- Are the mechanism and the criticality of component failure known, and if so are they measurable?
- Are there any suitable indicators of the status of failure and degradation, and if so are there any suitable diagnostic tools to measure the indicators?
- Is the defect or degradation reversible?
- Is the difference between the maximum and minimal damage high?
- Is it possible to reduce the probability of major damage?

It is difficult to assess the financial issue with high accuracy at such an early stage. Further, it might not be greatly important that it is. However, assessing the financial issue, even in the simplest form, is a necessity in order to visualize a business case. Discussions and brainstorming on the possible gains, in comparison to what a possible investment cost might be, cost for lost production, lost customers, and so on, can serve as input in assessing a business case.

The assessment of the organizational maturity is an important issue. Doing this helps to see if condition based maintenance will be accepted in a company. Even though condition based maintenance technology can be found on various levels, from high-tech to low-tech, and even no-tech, it should be considered a state-of-mind. Thus, going from a corrective fire-fighting mentality to a predictive one, possibly with high-tech tools, might be a step too large to take on. It might be better to start with an implementation of some predetermined actions beforehand and grow in maturity before implementing condition based maintenance. Several indices, maintenance audits, and benchmarking, among other things, can be used to assess the maturity of a maintenance organization. Performing a maintenance audit can be seen as an appropriate method to choose. The audit can be used to see whether the organization is mature enough for an implementation. It also gives a good reference data set that can be used in the later phases of an implementation when assessing the entire implementation process. Different scholars have also developed different maintenance maturity grids that can be used for this phase (see Table 5).

Table 5. Example of a maintenance organizational maturity grid that can be used as a simple tool when companies assess their maturity (Cholasuke et al., 2004) (see also Fernandez et al., 2003).

	Level 3. Excellence	Level 2. Understanding	Level 1. Innocence
1. Maintenance effectiveness (output)	Over 80% OEE. Maintenance department was rated as having a very satisfied performance	20-80% OEE. Maintenance department was rated as having satisfactory maintenance performance	Lower than 20% OEE. Maintenance department was rated as having unsatisfactory maintenance performance
2. Policy deployment and organization	Have a written maintenance policy that is driven from business or production strategy. Directors involved in policy setting and the policy is regularly reviewed	Written maintenance policy in place. Have middle or junior manager responsible for maintenance. Maintenance under production. The policy is occasionally reviewed but without director involvement	No formal maintenance policy. Embodied maintenance department with production
3. Maintenance approach	Employ proactive maintenance strategy for sustainable improvement. All problems are analyzed and permanently solved. Autonomous maintenance is applied	Have preventive maintenance as a main approach. Some operational involvement in maintenance	Rely heaviliy on reactive maintenance strategy (>50% of effort). No operation involvement in maintenance
4. Task planning and scheduling	More than 90% work planned accomplished. Low overtime (<15%)	More than 50% work planned accomplished. Relatively high overtime (>15%)	Less than 50% work planned accomplished. High overtime (>30%)
5. Information management and CMMS	Integrated CMMS used. Best utilization of CMMS features and the benefit of CMMS are realized	CMMS or at least PC used. Have performance measurements. CMMS are not very well utilized and the benefits are not fully realized	No CMMS used. Manual work. Batch information flow on paper. No performance measurement system used
6. Contracting out maintenance	Get high benefits from contracting out maintenance	Get some benefits from contracting out maintenance	Get low or no benefits from contracting out maintenance
7. Continuous improvements	Proactive maintenance. TPM or RCM applied, performance measurements are in place and effectively used	Have PM in place, with management involvement in policy setting and reviews	Have no PM or TPM or RCM. Low involvement of management. Reactive maintenance is very common
8. Financial aspects	Low maintenance spends with an effective performance. Excellent budget control. Loss of production are measured and investigated	Relatively high maintenance spends due to the lack of efficient cost control. Loss of production are measured but not investigated	No maintenance spends record. No maintenance budget. Poor understanding of production losses and its associated costs
9. Human resource management	Emphasis on management training geared to future needs. Job description is well understood. Maintenance people are well motivated	Based on technical training but have some team working and problem solving training. Job description is well understood. Good performance but human resource management is not efficient	No training. Lack of maintenance skill. Lack of motivation. Relatively high number of maintenance employees but low performance
10. Spare part management	Low stock value/plant replacement value. Pareto is effectively used to control stock requirement	The stock value/plant replacement value is relatively high compared with the best in class. No Pareto use	No spare part stock record. No stock controlling system used

6.2.3 Analysis

The analysis phase should answer where to, what to, how to, when to, and who should monitor (Paper VI). A decision-making guideline was developed employing theory and data collected in the cases. The guideline is composed of five major decisions where the feasibility test, explained above, is the first. Additional steps are assignments of responsibilities and authorities, selection of assets to monitor, selection of parameters to monitor with associated technique, and selection of technology.

Assignments of responsibilities and authorities

If responsibilities and authorities have not yet been assigned, it is time to do so in this phase. With no one feeling responsible for a certain task, it might be difficult to actually get the task done. At the same time, assigning authorities can give the motivation to get the tasks done. Mitchell and Murry (1995) define three levels of responsibilities in their implementation plan and schedule: development of program requirement, implementing program, and assessing the program. Thus, the responsibilities and authorities should be decided for the entire process.

Selection of assets to monitor

Selecting appropriate components, sub-systems, and/or systems to be included in a condition based maintenance approach is an activity that makes the process manageable. As pointed out above, condition based maintenance is not to be implemented as an overall policy; rather, it should be utilized systematically where effective. Performing a criticality analysis is an appropriate way to proceed, according to both theory and the cases presented above (Papers III and VI). Again, the tools, measurements, or methods to be used in performing the criticality analysis, whether it is an FMEA, an FTA, a complete RCM approach, RAM-calculations or other, ought to reflect what a specific company is used to working with.

Selection of parameter to monitor with associated technique

When knowing where to monitor, the question that arises is of course what to monitor (i.e. what parameter and with what technique). As discussed in Chapter 2, an incipient failure in most cases does show different symptoms at different stages, and this information can be used in making the decision (see Figure 4, for example). Using the potential failure to failure, P-F, interval analysis, several options most often will be revealed. Performing this analysis will give decision-makers options to choose from, both the choice of parameters and the time interval in which that particular parameter will reveal its presence.

Using a structured approach in evaluating the different options, of what to monitor and what technique to employ, is recommended. Using a decision matrix, as visualized in Table 6, can be one alternative. For more facts on decision matrix, see Tague (1995).

Table 6. Example of a decision matrix, where different criteria have been weighted and different potential techniques have been evaluated. In this particular example, a low evaluation is considered better than a high one.

Potential technique	Criteria				Summary
	Ease of implementation (5)	Potential impact (5)	Cost (5)	Most recommended by suppliers (3)	
Vibration	4x5=20	1x5=5	3x5=15	1x3=3	43
Oil analysis	4x5=20	3x5=15	4x5=20	2x3=6	61
Audible noise	2x5=10	4x5=20	2x5=10	3x3=9	49
Heat (by touch)	2x5=10	5x5=25	1x5=5	3x3=9	49

Selection of technology

Knowing where to and what to monitor, the next questions should answer how and when to monitor. As presented in Chapter 3, condition monitoring can be performed in different levels of technology (see Figure 10). If subjective monitoring is selected, decisions regarding who should perform the monitoring, how often, how to report the results and to whom, how to set up a trend and so on need to be made. For some assets, operators working in close perimeter of the source might easily detect the incipient failures. Using an expensive objective monitoring system might, thus, in some cases be excessive. If objective monitoring is selected, decisions regarding off-line or on-line monitoring, periodic or continuous monitoring, static or dynamic warning limits, and manual or autonomous analysis, etc., need to be taken.

Although many monitoring programs of today are on-line, still many are off-line, based with, for example, handheld monitoring equipment. Either way, deciding a proper monitoring interval can be a troublesome task. As discussed in Chapter 2, it is usually sufficient to select a monitoring frequency equal to half of the P-F interval. Nonetheless, a good thing can be to also consider the nett P-F interval. As was also discussed in Chapter 2, determining the P-F interval can be performed in a number of different ways. The rational approach, asking the right questions to the right people and concentrating on one failure mode at a time, is a surprisingly accurate approach.

Deciding upon static or dynamic warning limits and manual or autonomous analysis of the measured data depends heavily on, for example, the type of equipment being monitored, the parameter measured, and the P-F interval. Even if an autonomous analysis is decided, it will most likely still be necessary for humans to be engaged in the process.

The different technologies will have differences in cost, and they will demand different knowledge and training by the technicians performing the monitoring.

Setting up a decision matrix to evaluate the different options is suggested in order to make the decision on an informed basis. Hess et al. (2001) categorize different technologies into a graph of cost vs. effectiveness with four regions (see Figure 30). The cost factor in this categorization should include organizational cost, such as cost for training and practicing, in addition to the cost of condition monitoring tools. Suggested is to categorize the selected parameters, techniques, and technologies in an orderly fashion for systematic decisions on all levels. P-F interval analyses, benchmarking, decision matrices, and so on can conclude the effectiveness of the parameters, techniques, and technologies. Region I would imply high cost with low effectiveness and, consequently, a recommendation not to implement the parameters, techniques, and technologies. For regions II and III, it is recommended to implement on mission critical assets only and where no other parameters, techniques, and technologies exist or are a possibility. In region IV, it is recommended to implement wherever practical.

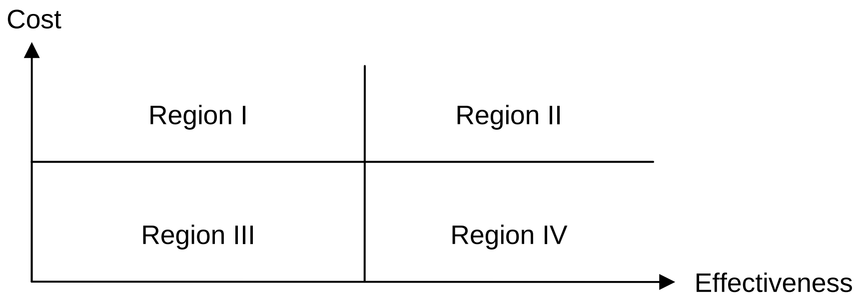

Figure 30. Categorization of selected parameter, technique, and technology with respect to cost and effectiveness (Hess et al., 2001). Region I implies high cost-low effectiveness and, consequently, a recommendation not to implement. For regions II and III, it is recommended to implement on mission critical assets only. Region IV implies low cost-high effectiveness and, consequently, a recommendation to implement wherever practical.

No matter what sort of technique, parameter, or technology that is being decided upon, monitoring is performed not only through technology but also through human senses. More than recorded and embedded information from, for example, a sensor reading of vibrations (i.e. embodied information) should be used in a condition assessment. Additional information can and should be collected and taken into consideration for a holistic condition assessment (see Figure 31). Employee experience and additional expressed information, from operators, for example, is also vital information that should not be forgotten. It is essential not to forget this, even if high-technological on-line systems are chosen.

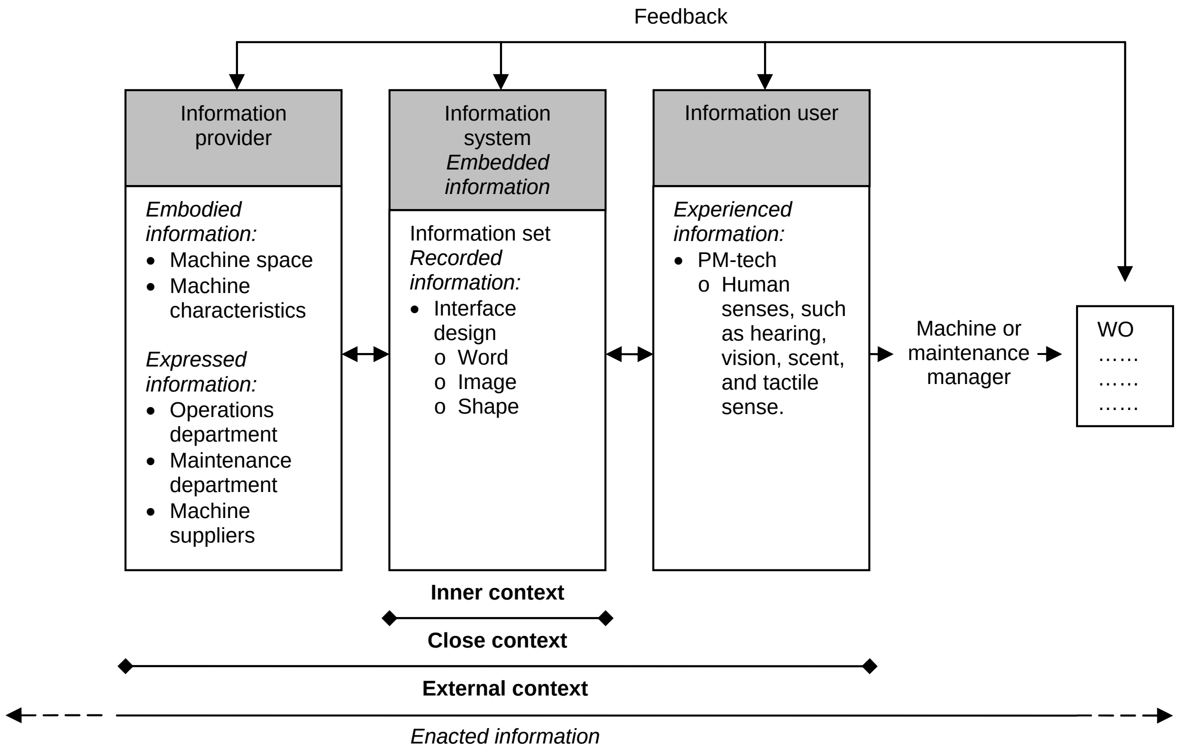

Figure 31. Model of the information and communication in a condition monitoring context, visualizing that additional information other than that which the condition monitoring technologies can provide is important to take into consideration (Paper V).

6.2.4 Implementation

Having decided on the proper approach to monitoring, whether it is high-technological condition monitoring technologies or a subjective approach, an implementation phase must follow. As has been stated earlier, implementing condition based maintenance is not simply a matter of implementing a technology, but rather implementing a new culture. There are as many human and organizational factors to take into consideration as technological. Stated another way, the interplay between the three types of factors need to be focused upon in order to achieve success.

The implementation phase has been divided in two phases; management and introduction (see Figure 32). In the management phase, it is important that management gives support for an implementation and communicates this support. It is necessary that implementation goals are set at an early stage. The goals should be set in a phased approach with several short-term and a few long-term goals. It is essential to let the organization, at least the maintenance department, be involved in the goal setting, as they are supposed to fulfill the goals at a later stage. It is of course also essential for management to provide the necessary funding for a program implementation to be successful. Also, in the management phase, it can be wise to involve champions. Employees who strongly support the new technologies and methods and who can be communicators between different departments and between top management, middle management, and employees. Responsibilities and authorities should have been assigned in an earlier phase. Nonetheless, it might be necessary to revise or enforce the assignments. Also, responsibilities and authorities for the entire implementation process (and even beyond) are essential in order to not experience the implementation coming to a standstill, not knowing who to decide the coming activities.

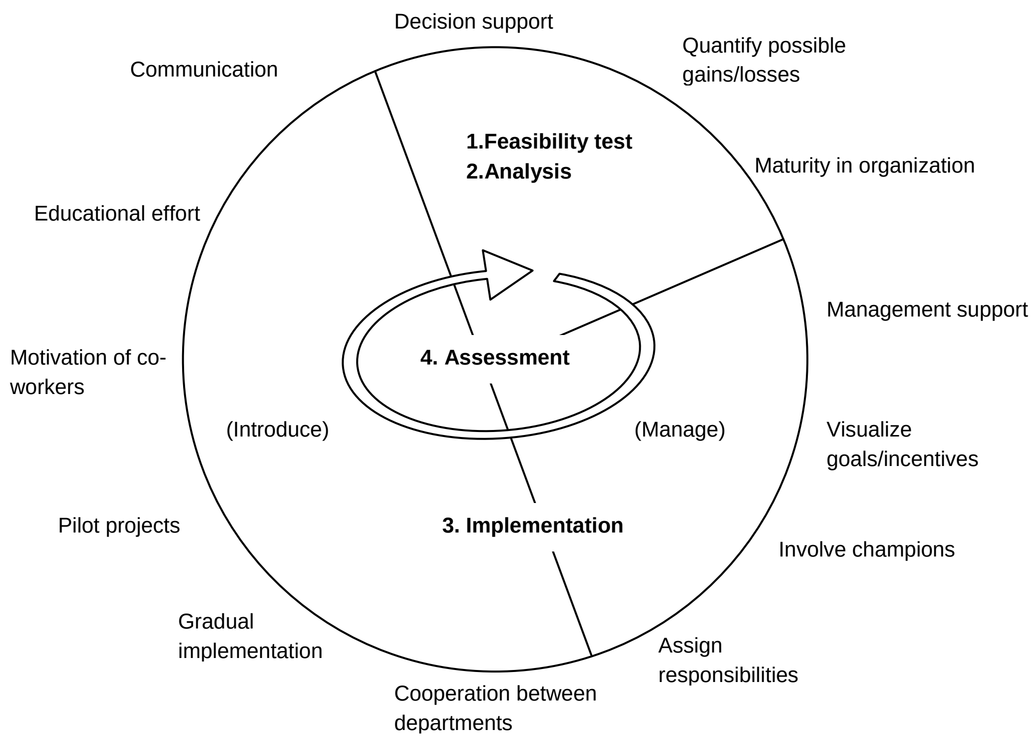

Figure 32. A checklist with enabling factors to take into consideration when implementing condition based maintenance, starting with a feasibility test, followed by analysis, implementation, and ending with assessment.

In the introduction phase, all the decisions should have been made and all the effort should be focused on the actual change (i.e., the implementation). Many activities must take place in order to not to lose momentum. The condition based maintenance approach needs to be integrated into other departments besides maintenance. The operation department must be introduced to the new method so that an understanding of the new technologies is absorbed into the company. Operators are most often the employees closest to the machines or processes, thus having the deepest knowledge of how well the equipment functions. Enforcing strong cooperation between maintenance and operation will therefore increase the quality of a condition based maintenance approach. The implementation can very well start with pilot projects; this is a good approach to verify the correctness of earlier decisions. The approach of pilot projects also visualizes the strengths of the technologies and methods. As it is important to set the goals in a phased approach, so is the case as well with the implementation. It can be dangerous to run into the unknown too fast risking the entire implementation. Other activities in the introduction phase are of course to motivate all employees affected by the implementation. Communicating good results and training and practicing can perform this.

6.2.5 Assessment

During the implementation of a condition based maintenance approach, it is necessary to assess the process; hence the arrow in Figure 32. The results of the implementation need to be compared to the early decisions and calculations as well as employee perception. Maybe parts of the process need to be iterated a few times, additional training and education might be necessary, additional tools might need purchasing, etc. The important thing is to never feel too satisfied. Thus, the assessment of the technological decisions, the financial estimations (i.e. the cost effectiveness), and the organizational analysis are necessary.

6.3 Summary

The method thus contains four phases. The first aims at determining if it is even of value to go further with an implementation of condition based maintenance. This phase analyzes the feasibility of condition based maintenance for specific applications and takes the starting point in technical, financial, and organizational feasibility. If considered feasible, an analysis phase is the second step. The analysis phase should determine what type of condition based maintenance is applicable and for what specific assets. It is also recommended that responsibilities and authorities are assigned in this phase. In knowing what to implement, the actual change process lies at hand. This phase involves several enabling factors being taken into consideration (see Figure 33). The final phase involves an assessment of the implementation being performed, as well as a possible initiation of a continuous improvement program.

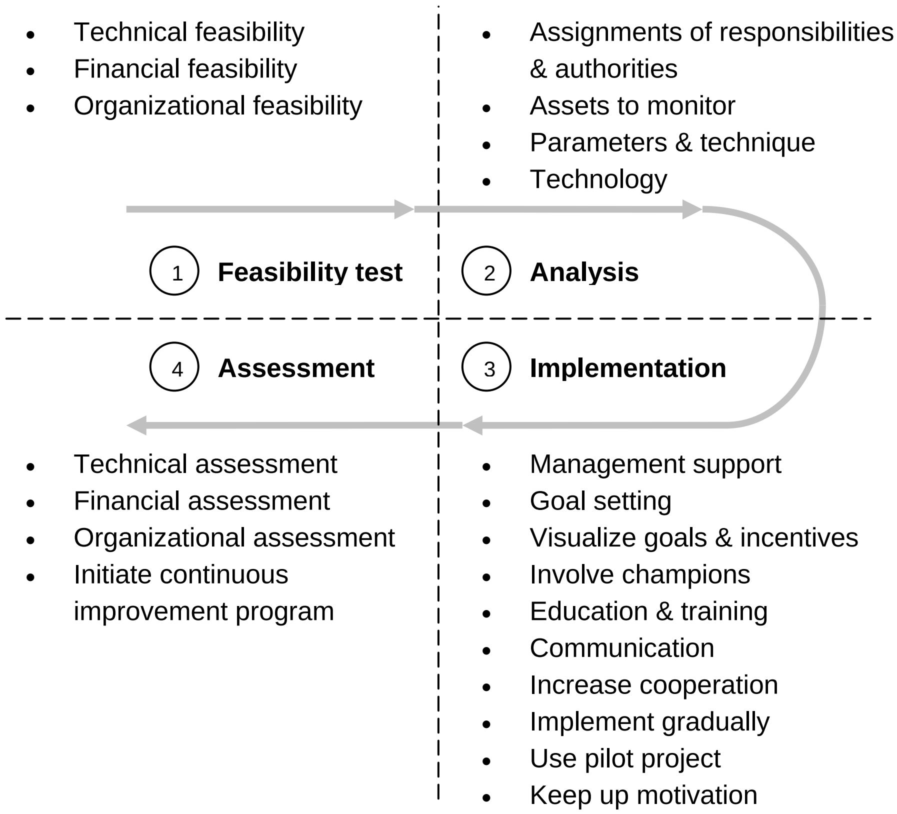

Figure 33. The implementation method with its four phases: feasibility test, analysis, implementation, and assessment, with enabling factors to focus upon in an implementation process.

7 Discussion and conclusions

This chapter presents the conclusions of the research. The chapter starts with a discussion of the research purposes and research questions, and continues with a discussion of novelty of research, quality of research, and relevance of the research. The chapter ends in reflections and suggestions for future research.

7.1 Discussion on the research purpose and the research questions

The research is based on the problem discussion presented in Chapter 1. Three purposes were formulated: personal, industrial, and research-related. The research-related purpose will be discussed below. The industrial and personal purposes will be further elaborated on below, in Chapter 7.5. The research purpose was formulated as follows:

The research purpose of this research project is to investigate how a condition based maintenance approach can be implemented in an industrial setting, and to develop a method that can assist companies in their implementation efforts.

The second part of the research purpose – to develop a method that can assist companies in their implementation efforts - is presented in Chapter 6. A method has, within this research, been treated as "a systematic procedure in order to achieve a specific result". The implementation method has been developed using a mixture of theory and data collected through different cases. It has evolved over time as the system development has progressed with additional data. The implementation method is developed to assist the entire implementation process, from the first phases in finding a business case and investigating the applicability, to the introduction and implementation, and ending in an assessment of the process.

The research purpose is, as explained by Maxwell (1996), supposed to be focused on understanding something, to gain insights into what is going on and why. As the research purpose has been formulated, it has focused on the investigation of the implementation process of condition based maintenance. The condition based maintenance should here be seen as the phenomenon, while the implementation process is the context. The investigation has been performed continuously throughout the entire research, and it has also been tightly connected to the research questions.

7.1.1 Revisiting the research questions

The three research questions formulated in Chapter 1 can be concluded as follows:

RQ1. Which are the constituents of a condition based maintenance approach?

The research question was formulated in order to investigate what a condition based maintenance approach needs to comprise in order to achieve a successful implementation result. Or, rather, what constituents should be taken into consideration in an implementation effort. Throughout the research, it has become increasingly clear that a condition based maintenance approach is far more than technology. The expert case and the paper mills case in particular visualized that it is the interplay between technology, humans, and organization that is important when both implementing and operating a condition based maintenance approach (see Figure 24).

RQ2. Which essential decisions should be made, before implementing a condition based maintenance approach?

The research question was formulated in order to investigate the decision-making process necessary to reflect upon before implementation of condition based maintenance can start. As stated above, condition based maintenance is not to be used as an overall policy but only where appropriate. A rigorous decision-making process is thus necessary. This view was also reinforced in the expert case where half of the respondents, in response to an open question regarding the implementation of condition based maintenance, mentioned the use of some sort of decision support. Also, literature on the topic visualized that there is an interest in the issue. The expert case and theory led to the workshop case, where five basic steps were structured: feasibility test, assignments of responsibilities and authorities, selection of assets to monitor, selection of parameters to monitor with associated technique, and selection of technology. The steps were formulated to answer questions such as: is there a business case for condition based maintenance, who will implement it, who will perform the monitoring, for what assets is monitoring appropriate, what parameters are appropriate to monitor, and how should the monitoring be performed.

Although there are many complex ways and calculations regarding how to decide what sort of condition monitoring to invest in, many of the respondents in the expert case suggested quite common tools and measurements when deciding where and what to implement. Tools and measurements included DuPont calculations, LCC calculations, OEE measurements, and criticality analysis, such as FMEA, FTA, and a complete RCM-approach. The conclusions drawn from the workshop case were to utilize the tools and measurements a company is used to working with, at least in the beginning of an implementation. One factor to take into consideration in the decision-making process, which stood out from the others in the expert case, was to also examine the maturity level a company operated on. This was to better reflect what type of condition monitoring equipment and what level of technology the company was ready for at that point in time.

RQ3. How can a condition based maintenance approach be implemented, and which enabling factors are essential to focus on in the process?

The research question was formulated in order to investigate how companies successfully can implement a condition based maintenance approach and to visualize enabling factors that can help in an implementation attempt. The 13 factors found are presented in Table 7. The factors seem general enough to fit any change or implementation initiative, and this might be. The important finding might be just that: that an implementation of condition based maintenance consists of quite general factors found in change and implementation management and that these might be forgotten, only focusing on the technology and how it can be used more effectively.

Table 7. The 13 enabling factors found essential to consider when implementing condition based maintenance, presented in the same sequential order as they appear in the checklist, presented in Figure 32. The 14th factor, that is assessment, is in this table added to better reflect Figure 32.

Enabling factors	Phases
Decision support Quantify possible gains/losses Maturity in organization	Feasibility test/Analysis
Management support Visualize goals/incentives Involve champions Assign responsibilities and authorities	Implementation (Manage)
Cooperation between departments Gradual implementation Pilot projects Motivation of co-workers Educational effort Communication	Implementation (Introduce)
Assessment	Assessment

The factors depicted above, in Table 7, should be seen as context dependent. Different companies attempting to implement condition based maintenance will possess different experience and maturity. It is therefore difficult, if not impossible, to rank the factors in order of importance. The level of abstraction of the factors is on a rather high level. Some of them have been aggregated in order to fit the entire implementation process.

Also, the respondents in the paper mills case revealed a common ground on how they had implemented condition based maintenance. The consensus could be found in many areas. The time it had taken was but one of many. All mills explained that the implementation had taken several years, and that it had been implemented gradually, starting with subjective rounds to grow in maturity with the implementation of on-line systems. Also, the maturity in the maintenance departments and the mills in general were on a rather high level before attempting the implementation; all had worked with predetermined maintenance long before implementing condition based maintenance.

Interesting, though, is also to look at what to avoid in an implementation effort. In the paper mills case, the respondents shared some of their experience. They stated that among some of the main mistakes a company can make during an implementation were the following: a lack of information and communication strategies, a lack of management support, investing in the wrong technology, and having too large a focus on the technology.

7.2 Novelty of the results

Much research has been devoted to change and implementation management. However, not a lot of this research has been performed within the area of maintenance and within condition based maintenance in particular. Pengxiang et al. (2005) state that most research within condition based maintenance in the power industry gives little attention to how the power utilities should carry out condition based maintenance and what strategies they should apply. Several similar statements[4] give proof that there is a need for additional research within the area.

However, if not in abundance, some research has been performed within the area. The question then is this: how does this research differ from earlier research? A discussion of this topic can be performed on different levels. At a higher, more comprehensive level, this research has taken a holistic approach to the problem discussion: it has involved several different industries and respondents, capturing ideas, views, and experiences in particular. A comprehensive implementation

[4] See Section on Background in Chapter 1.

method has been developed, consisting of a guideline, models, a checklist, suggested tools and measurements, and enabling factors. By contrast, earlier publication has been either single case study research or on rather conceptual levels.

One major critique of the developed method, though, can be the relatively brief discussion regarding the assessment phase. However, this was known beforehand. As presented in Chapter 1.6 Delimitation, the approach for such a study implies that a company and its implementation effort are followed for many years and this was not a possibility in the relatively short span of the research. Thus, the focus of the method is on the first steps of an implementation effort, assisting companies to a good start.

At a deeper, more delimited level, this research has visualized new views on condition based maintenance. It has been visualized that the interplay between technology, humans, and organization is highly important in both an implementation process and in operating a program. Also, a third factor has been added to the issue on decision-making, and maybe in particular the early phases of decision-making. As Hess et al. (2001, p.240) state, "Selection of which technologies should be used in a particular application has predominantly been based on the capabilities of the technology to provide early detection of degraded performance with little or no regard for whether its use is warranted based on a business perspective.", visualize that decisions within condition based maintenance must be decided with both a technological and financial perspective. In this research, the maturity in the organization has surfaced as an important factor as well.

7.3 Estimating the quality of the research

This research, as discussed in Chapter 4, has been performed using a systems approach and a case study method, with the collection and analysis of primarily qualitative data. Even so, focus has, through the research, been to conclude the results with creditability. Internal and external validity and reliability have been considered in both research design and execution.

As pointed out in Chapter 4, the sampling of respondents has been committed purposefully. Stated another way, the respondents have been chosen on the basis of their expertise or on the basis that they have witnessed certain events. One can argue that purposeful sampling is in conflict with internal validity: it only chooses "good" examples to study, and not the real world. I chose instead to view the purposeful sampling as a strategy for finding input for the research purpose and questions. Thus, I sought either good or bad examples of how to perform a change. Using, for example, random sampling purely in order to increase internal validity would not enhance the applicability of the research, as respondents with no pre-understanding of the issue might be included in such sampling. Thus, the collected data comes from a somewhat constructed reality in which everybody has a pre-understanding of the research issue. One might argue that this will lack validity. However, I maintain that the benefits from working with sought-after data exceed the validity discussion.

Even so, I have used some of the ideas presented in Maxwell (1996) and Merriam (1994) continuously through the case studies to check that the results reflect the somewhat constructed reality. Triangulation has been used where possible. Although interviews have been the primary data collection method, other methods have been used as secondary in order to receive a deeper understanding of the studied issue. Observations and guided tours of the companies visited, as well as the examining of certain documents, followed the interviews. Transcriptions of interviews have always been sent back to the respondents for review. The analysis and conclusions have also been presented at site where possible in order to receive comments on nearly completed work. Professors and PhD-student colleagues have continuously reviewed drafts and completed works.

The external validity, as theory suggests, is often difficult to prove in practice. In this research it is also something very hard to claim. Different companies of partly different sizes and, in particular, from different industries have been included in the separated case studies. This, to some extent, can help in ensuring that the results can be applied in several settings. In other words, it would have been more difficult to prove generalizability in the results if merely a few companies in perhaps only one industry had been part of the studies. Maxwell's (1996) discussion of face generalizability can also be claimed. There is no reason to believe that the results can not be applied generally. It is at least not easy to prove so.

To a large extent, the purpose within the systems approach is to map the reality objectively. A part of this can also be to map respondents' subjective ideas, ambitions, and perceptions, and to treat them as objective (Arbnor and Bjerke, 1997). In this research, the mapping has been utilized to a large extent, as ideas, views, and experiences regarding the studied subject have been sought-after. This can complicate the reliability issue, since these constantly change as humans gain new insights and experience. Replication of the case studies, either by me or other researchers, would possibly produce similar results, but most likely not exactly the same; this is to a large extent not even coveted. Industry of today is fast moving and constantly changing, particularly in the technological setting. Replicating these studies and concluding the same results would imply that industry has not gained new insights or experiences. Such a conclusion is quite unlikely. Further, such a conclusion, were it to happen, would be rather sad.

7.4 Relevance of research

The academic and industrial relevance of the research can be summarized as follows:

7.4.1 Academic

The academic relevance of the research stems from the fact that previous research on change and implementation management has been re-worked with new data to fit a new area, the implementation of condition based maintenance. Several enabling factors from previous research have been verified to also fit this new area.

7.4.2 Industrial

The developed implementation method that companies can use when implementing condition based maintenance constitutes the industrial relevance. Such a general implementation method has thus far been lacking for the condition based maintenance approach.

7.5 Reflections

The practical purpose, as stated in Chapter 1, was supposed to be focusing on accomplishing something (i.e., meeting a need, changing a situation, or achieving a goal). As argued for, the practical purpose of this research was formulated as the industrial purpose to facilitate for companies to implement condition based maintenance where applicable. Does, then, this research assist companies in implementing condition based maintenance? This is, of course, very difficult to answer and hard to claim. As stated above, it is highly context-dependent on what experiences and maturity a company attempting an implementation has. The studies performed within the research have not focused on a single company or even a single industry. Therefore, the results are holistic and rather general. Even if a company cannot utilize all the results of the research, parts of it can be utilized to facilitate an implementation. Again, it is context-dependent.

According to Maxwell (1996), the personal purposes of a study are the ones that motivate a researcher to perform a study, and those purposes can come from a number of different aspects. As a researcher, I have had two personal purposes with this research: to qualify for a doctoral degree through the acquisition of deeper knowledge within the academic subject of Innovation & Design (and, in particular, maintenance technology), and to acquire practical research experience in change management in industry and, in particular, the implementation of condition based maintenance.

A little more than five years ago, as I was at the end of my educational program of Mechanical Engineering, I applied for a PhD-student position. The research was at first rather vaguely formulated, somewhere in between reliability engineering and condition based maintenance with the main focus on technology development. As is probably the case most often, the research started with comprehensive literature studies, PhD courses, and a few smaller studies. After a short time, I found that operating a condition based maintenance approach in industry required a great deal. At the same time, I also found out, both from literature and from studies of my own, that condition based maintenance was not utilized to the extent I would have thought. At the time of the research (2002-2007), scholars, organizations, and individuals strongly advocated condition based maintenance, both nationally and internationally. It was mentioned as one appropriate way of achieving a more effective maintenance execution. Why, then, was condition based maintenance not utilized more? This came to be the focal point of the research.

Five years on, with some knowledge added, I feel content with the process leading up to this thesis. I also do feel I have achieved the second personal purpose formulated – to acquire practical research experience in change management and, in particular, in the implementation of condition based maintenance. I have spent substantial amounts of time visiting companies, with the dual objectives to performing studies and sharing the results of those studies. In reflection, I also feel that I have been successful, by qualifying for the doctoral degree, through the acquisition of deeper knowledge within the academic subject Innovation & Design and, in particular, maintenance technology. Courses, studies, and interdisciplinary projects with PhD-student colleagues, among other things, have broadened my views in the research subject Innovation & Design, which consists of the research areas of Innovation Science and Management, Information Design, and Product and Process Development.

7.6 Future research

There are several future research areas that come to mind when reaching the end of my own. First, I would certainly like to take this research one step further at the minimum, testing the suggested implementation method on a "live" case. That test would preferably be performed as an action research case following a real implementation process. This has unfortunately not been a possibility in this research. Rather, all effort has been on the development of the method. In performing such a study, it would also be possible to investigate the assessment phase in greater detail.

There are other possible future studies that come to mind. As brought up earlier in this thesis, Jonsson (1997) presents a study on the use of condition based maintenance and condition monitoring in Swedish industry. In it, he concludes that large companies utilize condition monitoring to a greater extent than small- and medium-sized companies. It would be interesting to, first, find out why, and, second, try to develop tools to help the smaller-sized companies to implement condition monitoring. Also, as reported in Elfving (2007), for example, there is a low level of integration of the maintenance and logistics functions in product development projects. This ties up costs in an unnecessary way. Utilizing Design for Maintenance/Maintainability and perhaps Design for Condition Monitoring in early phases of development projects might help remove some of the wasted resources brought up in Chapters 1 and 2.

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9 Appended papers

Paper I Important Aspects To Take Into Consideration When Deciding to Implement Condition Based Maintenance.

Paper II The Possibilities of Condition Based Maintenance on the Main Battle Tank 122.

Paper III Decision and Development Support When Implementing a Condition Based Maintenance Strategy – A Proposed Process Improvement Model.

Paper IV Supporting Implementation of Condition Based Maintenance: Highlighting the Interplay Between Technical Constituents and Human & Organizational Factors.

Paper V Essential Information Forms in a Condition Monitoring Context.

Paper VI Decision-Making During Condition Based Maintenance Implementation.