Cost Effective Maintenance for Competitive Advantages
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Abstract


This thesis describes the role of cost effective maintenance in achieving competitive advantages. It explores by means of a survey which maintenance practices are used, and how maintenance policies are selected in Swedish industries. Also, it suggests a model for selecting the most cost effective maintenance policy, and how to improve the effectiveness of condition based maintenance decision-making. Finally it discusses how to assess the impact of maintenance practices on business strategic objectives.

The main results achieved in the thesis are 1) A better understanding of maintenance organisation, management, systems and maintenance status in Swedish industry. For example, it was found that about 70% of Swedish companies still consider maintenance as a cost centre. Preventive and predictive maintenance approaches are also emphasised. 2) Most Swedish firms, i.e. about 81%, use the accumulated knowledge and experience within the company as a method for maintenance selection. Besides, about 31% use a method based on modelling the time to failure and optimisation. About 10% use failure mode effect and criticality analysis (FMECA) and decision trees and only 2% use multiple criterion decision-making (MCDM). However, the most used maintenance selection method is not the one most satisfactory to its users. Furthermore, about 30% use a combination of at least two methods. 3) A practical model for selecting and improving the most cost effective maintenance policy was developed. It is characterised by incorporating all the strengths of the four methods used in industry. 4) A mechanistic model for predicting the value of vibration level was verified both at the lab and in a case study. 5) A model for identifying, assessing, monitoring and improving the economic impact of maintenance was developed and tested in a case study. Thus it was proved that maintenance is no longer a cost centre, but could be a profit-generating function.

To achieve competitive advantages, companies should do the right thing, e.g. use the most cost effective maintenance policy, and they should do it right, e.g. ensure that they have the right competence. Furthermore, they should apply the never-ending improvement cycle, i.e. Plan-Do-Check-Act, which requires identifying problem areas by assessing the savings and profits generated by maintenance and monitoring the economic impact of the applied maintenance.
policy. Thus, they would know where investments should be allocated to eliminate the basic reasons for losses and increase savings.

The major conclusion is that proper maintenance would improve the quality, efficiency and effectiveness of production systems, and hence enhance company competitiveness, i.e. productivity and value advantages, and long-term profitability.

Key words: Maintenance approaches, Maintenance Costs, Savings and Profit, Operations, Quality, Effectiveness, Efficiency, Competitiveness, Productivity, Value Advantages, Profitability, Performance, Balanced Scorecard BSC, Maintenance Selection Method, Fuzzy MCDM, TTT-plot, Cost Effective Maintenance, Mechanistic Model, Vibration Level Prediction, Condition-Based Maintenance, survey, case study.
Acknowledgements

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Moreover, I would like to express my appreciation and thanks to those who have contributed to my research work in one way or another, Prof. David Sherwin, Dr. Dhananjay Kumar, the anonymous reviewers of my published papers, the researchers from whom I have learned a lot by reading and analysing their published research work. Also, I thank the maintenance department staff at Stora Enso Hylte AB and Magnus Magnusson at the Swedish Post Terminal in Alvesta. As well, I acknowledge the inputs from the maintenance managers of the Swedish companies who participated by answering the questionnaire. I express my appreciation of my colleagues and friends at the school of industrial engineering at Växjö University who participated in one way or another. I like to thank Dr. Staffan Klintborg for proofreading the thesis, and Kerstin Brodén for her efforts in editing the thesis.

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Imad Alsyouf
Växjö, April 2004
List of appended papers

This dissertation for the degree of Doctor of Philosophy (Terotechnology) is based on a collection of eight research papers. The papers are attached in Appendix C and referred to in the text of the thesis by their respective number, e.g. Paper I, noting that they are ranked with respect to their relevance to the research questions and not according to their chronological order:


Paper IV  Al-Najjar and Alsyouf (2004), Mechanistic Model for Predicting the vibration Level: A Case Study, proceeding of the international conference on Modelling Industrial Maintenance and Reliability (MIMAR), 5-7 April 2004, University of Salford, the UK.


Explanation of some terms

Definitions adopted by researchers are often not uniform, so some key and controversial terms are explained to establish positions taken in the PhD research.

**Agile Manufacturing**
A comprehensive response to the business challenges of profiting from rabidly changing, continually fragmenting, global markets for high quality, high performance, and customer configured goods and services. Goldman (1995)

**Bartlett’s test of sphericity**
A statistical test for the overall significance of all correlations within a correlation matrix. Hair et al. (1998)

**Communality**
Total amount of variance an original variable shares with all other variables included in the analysis. Hair et al. (1998)

**Condition Monitoring (CM)**
The continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance. (BS 3811:1993)

**Condition based maintenance (CBM)**
Maintenance carried out according to need as indicated by condition monitoring (BS 3811:1993)

**Effectiveness**
The accomplishment of the ‘right’ thing on time, and within the quality requirements specified. Sink and Tuttle (1989)

**Efficiency**
It is a measure of how economically the firm’s resources are utilised when providing a given level of requirements. Sink and Tuttle (1989)

**Eigenvalue**
The amount of variance accounted for by a factor. It is calculated as the column sum of squared loadings for a factor. Hair et al. (1998)
Factor Analysis
It is a statistical approach that can be used to analyse interrelationships among a large number of variables and to explain these variables in terms of their common underlying dimensions (factors). It is considered as an objective basis for creating summated scales. Hair et al. (1998)

KMO Measure
A statistical test, named Kaiser-Meyer-Olkin Measure, of Sampling Adequacy used with factor analysis. Hair et al. (1998)

Lean Production
The term ‘Lean’ comes from using less of everything compared to ‘Mass Production’. It focuses on improving productivity by reducing costs. Goldman (1995)

Maintenance
It is defined as the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. BS 3811:1993

Maintenance concept
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)

Maintenance function
It is defined by the Maintenance Engineering Society of Australia (MESA) as: “The engineering decisions and associated actions necessary and sufficient for optimisation of specified capability”. Where “capability” in this definition is the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality and responsiveness. Tsang et al. (1999)

Maintenance management
All activities of the management that determine the maintenance strategy, objectives, and responsibilities and implement them by means such as maintenance planning, maintenance control, and supervision, improvement of methods in the organisation including economic aspects. BS 3811:1993

Measure of Sampling Adequacy (MSA)
A measure calculated both for the entire correlation matrix and each individual variable evaluating the appropriateness of applying factor analysis. Values above one-half, i.e. 0.5, for either the entire matrix or an individual variable indicate appropriateness. Hair et al. (1998)
Operations
It concerns the transformation process that involves taking inputs and converting them into output together with the various support functions closely associated with this task. Hill (2000)

Ordinal scale
It is the next higher level of non-metric measurement scales’ precision after the nominal scale. Variables can be ordered or ranked with ordinal scales in relation to the amount of the attribute possessed. Every subscale can be compared with another in terms of a “greater than” or “less than” relationships. Hair et al. (1998)

Performance
The level to which a goal is attained. Dwight (1999)

Performance measurement
The process of quantifying the efficiency and effectiveness of an action. Neely et al. (1995)

Performance measurement systems
The means of gathering data to support and co-ordinate the process of making decisions and taking action throughout the organisation. Schalkwyh (1998)

Preventive maintenance
Any task designed to prevent failures or mitigate their effects. Sherwin (2000)

Productivity
It is the relationship between what comes out of an organisational system (assuming that the output meets the attributes established for them) divided by what comes into an organisational system (i.e., labour, capital, materials, etc.) during a given period of time. Sumanth (1998)

Profitability
It is the best overall indicator of company performance; it measures the outcome of all management decisions about sales and purchase prices, levels of investment and production, and innovation, as well as reflecting the underlying efficiency with which inputs are converted into outputs. Rantanen (1995)

Ratio scale
It is one of the two metric scales, i.e. interval scales and ratio scales, it provides the highest level of measurement precision, permitting nearly all mathematical operations to be performed. However, unlike the interval scales that have an arbitrary zero point such as Fahrenheit and Celsius temperature scales, Ratio scales have an absolute zero point that indicates a zero amount. Hair et al. (1998)
Response rate
The percentage of respondents in the initial sample from which complete responses are obtained. It is the chief index of data quality in a survey because it defines the extent of possible bias from non-response. Judd et al.(1991)

Significant component
A component is considered significant only if its probability of causing a costly or dangerous failure is non-negligible. Al-Najjar(1997)

Terotechnology
It used to be defined as a combination of management, financial, engineering, building and other practices applied to physical assets in pursuit of economical life cycle costs. But later on the following was added “Its practice is concerned with the specification and design for reliability and maintainability of plant, machinery, equipment, buildings and structures, with their installation and replacement, and with the feedback of information on design, performance and costs”. “Life-cycle costs” could now, with advantage, be replaced by “Life-cycle profits” in the above. Sherwin (2000)

Total Productive Maintenance (TPM)
It consists of a range of methods, which are known from maintenance management experience to be effective in improving reliability, quality, and production. It requires the operators to take over some of the maintenance staff tasks, e.g. cleaning, lubricating, tightening bolts, adjusting and reporting their observations about changes in the machine condition. Nakajima (1988)

Total Quality Maintenance (TQMain.)
It is a concept which enables the user to continuously maintain and improve the technical and economical effectiveness of manufacturing process elements. Its role may be defined as “a means for monitoring and controlling deviations in a process condition and product quality, and for detecting failure causes and potential failures in order to interfere when possible to arrest or reduce deterioration rate before the product characteristics are intolerably affected and to perform the required actions to restore the machine process or a particular part of it to as good as new. All these should be performed at a continuously reducing cost per unit of good quality product”. Al-Najjar(1997)

Overall process effectiveness (OPE)
It is a reconstructed version of overall equipment effectiveness (OEE). It is defined as: a measure of process effectiveness which reveals the contribution of the basic process elements to the process total effectiveness, e.g. the effect of environmental conditions on machinery availability, performance of manufacturing procedures or product quality. Al-Najjar(1997)
Total overall process Effectiveness (TOPE)
It is an extended OEE/OPE. It is calculated as the product of OEE/OPE with a new index called the planned operative index. The planned operative index is calculated as \{the theoretical production time, e.g. 1 year minus (the planned vacation and major planned stoppage time)\} divided by the theoretical production time. Altyouf (2001)

Unplanned but before failure replacement (UPBFR)
Replacements performed at unplanned but before failure stoppages, to prevent the occurrence of failure. This situation arises because of a sudden increment in the measured variable(s), e.g. the vibration level, due to undetected defect causes at an early stage. Al-Najjar(1997)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BSC</td>
<td>Balanced scorecard</td>
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<td>CBM</td>
<td>Condition based maintenance</td>
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<tr>
<td>CM</td>
<td>Condition monitoring</td>
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<td>CBR</td>
<td>Condition based replacement</td>
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<td>CIC</td>
<td>Centre for industrial competitiveness</td>
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<td>FBM</td>
<td>Failure based maintenance</td>
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<tr>
<td>FMECA</td>
<td>Failure mode effect and criticality analysis</td>
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<td>FMS</td>
<td>Flexible manufacturing systems</td>
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<tr>
<td>FTA</td>
<td>Fault tree analysis</td>
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<tr>
<td>GTTT</td>
<td>Generalised total time on test</td>
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<td>JIT</td>
<td>Just in time</td>
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<td>KPI</td>
<td>Key performance indicators</td>
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<td>LCC</td>
<td>Life cycle cost</td>
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<td>LCP</td>
<td>Life cycle profit.</td>
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<tr>
<td>MCDM</td>
<td>Multiple criteria decision making</td>
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<tr>
<td>MSEK</td>
<td>Million Swedish kronor</td>
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<tr>
<td>OEE</td>
<td>Overall equipment effectiveness</td>
</tr>
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<td>OEM</td>
<td>Original equipment manufacturer</td>
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<td>OPE</td>
<td>Overall process effectiveness</td>
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<tr>
<td>PM</td>
<td>Preventive maintenance</td>
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<tr>
<td>ROI</td>
<td>Return on investment</td>
</tr>
<tr>
<td>SAW</td>
<td>Simple additive weighting</td>
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<tr>
<td>TOEE</td>
<td>Total overall Equipment effectiveness</td>
</tr>
<tr>
<td>TOPE</td>
<td>Total overall process effectiveness</td>
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<tr>
<td>TQMMain.</td>
<td>Total quality maintenance</td>
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<td>TQM</td>
<td>Total quality management</td>
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<tr>
<td>VBM</td>
<td>Vibration based maintenance</td>
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<td>UPBFR</td>
<td>Unplanned but before failure replacement</td>
</tr>
<tr>
<td>WIP</td>
<td>Work-in-progress</td>
</tr>
</tbody>
</table>
Contents

Abstract....................................................................................................................v
Acknowledgements ...............................................................................................vii
List of appended papers.......................................................................................... viii
Explanation of some terms...................................................................................... ix
Abbreviations.........................................................................................................xiv
Contents...............................................................................................................xv

1. Introduction .....................................................................................................1
   1.1 Background .................................................................................................... 1
   1.2 Research problem .......................................................................................... 4
   1.3 Purpose and research questions ...................................................................... 6
   1.4 Relevance ....................................................................................................... 7
   1.5 Delimitations .................................................................................................. 8
   1.6 Thesis disposition ......................................................................................... 8

2. Methodology..................................................................................................10
   2.1 Methodology concept .................................................................................. 10
   2.2 Research methods ....................................................................................... 13
   2.3 Research design ........................................................................................... 16
   2.4 Thesis research design ............................................................................... 18
      2.4.1 Survey method ..................................................................................... 18
      2.4.2 Theoretical research method ................................................................ 21
      2.4.3 Experiment method ............................................................................. 21
      2.4.4 Case study method ............................................................................. 21

3. Literature Survey...........................................................................................24
   3.1 Overall management strategy ....................................................................... 25
   3.2 Maintenance .................................................................................................. 25
      3.2.1 Maintenance practices .......................................................................... 25
      3.2.2 Maintenance approaches ...................................................................... 26
      3.2.3 Maintenance selection methods ............................................................ 27
      3.2.4 Plant monitoring and decision making accuracy .................................... 28
   3.3 Maintenance impact on business processes ............................................... 28
      3.3.1 Maintenance costs, savings, and profits ................................................ 29
      3.3.2 Business performance measurement .................................................... 30

4. Cost Effective Maintenance for Competitive Advantages ..............................32
   4.1 Maintenance practices in Swedish industry .................................................. 32
      4.1.1 Maintenance organisation, management systems and status ................ 32
      4.1.2 Identification of maintenance practices using factor analysis ................ 35
   4.2 Maintenance selection in Swedish industry .................................................. 37
      4.2.1 Features of an ideal maintenance selection method ............................... 38
      4.2.2 Characteristics of maintenance selection methods used ........................ 39
      4.2.3 Empirical evaluation of maintenance selection methods ....................... 40
   4.3 A technique for selecting the most cost effective maintenance policy ... 42
1. Introduction

1.1 Background

The increasing competition in the market creates an urgent need to search for new ways in which manufacturing companies can differentiate themselves and gain better competitive position. By examining the debate on markets and resources one could realise the existence of two opposing perspectives, i.e. the inside-out perspective and the outside-in perspective, De Wet and Mayer (1998). Proponents of the ‘inside-out perspective’ pinpoint the two fundamental assumptions on which the resource-based view rests: the firms have different resources and these resources cannot be easily transferred to, or copied by, other firms, Barney (1991). It is argued that these resources can be the basis of a competitive advantage if they meet four criteria: being valuable, rare and difficult to imitate and to substitute. Recently much research in the resource school, i.e. the inside-out perspective, of strategic thinking has shifted from focusing on tangible assets as a source of advantages to intangible assets, which include knowledge, core competence, learning, and ‘invisible assets’ such as brand image or corporate culture, Pehrsson (2000). On the other hand, supporters of the ‘outside-in perspective’ argue that two central questions underlie the choice of competitive strategy. First, the strategists must select a competitive domain with attractive characteristics and then they must position the firm with regard to the five competitive forces encountered. These five forces are the entry of new competitors, the threat of substitutes, the bargaining power of buyers, the bargaining power of suppliers, and the rivalry among the existing competitors, Porter (1985). Regardless of which perspective is adopted by the manufacturing company’s management the firm should in both cases utilise its valuable and rare resources efficiently and effectively to achieve the above-average performance in the long term.

Success in any competitive context depends on offering superior customer value (i.e. value advantage) or operating with lower relative costs (i.e. cost advantage) or, ideally, both, see for example, Porter (1985), Christopher (1998) and De Wet and Mayer (1998). The survival of any business depends on its ability to compete effectively, Madu (2000). The competitive advantages occur when a firm uses its resources and capabilities to develop organisational competences that, in turn, create value for customers, Sago (2003). As a response to the challenges posed by a business environment, e.g. increased global competition, many manufacturing companies are seeking ways to gain competitive advantages with respect to cost, service, quality and on-time
delivery. Furthermore, the focus has moved from ‘Lean Production’, which focuses on the reduction of total costs towards ‘Agile Manufacturing’ that focuses on increasing total revenue, Goldman et al. (1995). Consequently, the manufacturing company structure has changed from a labour-intensive industry to a technology-intensive, i.e. capital intensive, industry. The production pattern has changed from mass production to the production of many variations to meet diversified needs, i.e. Job-shop, and finally, to a separate model for every customer or mass customisation.

Many changes in the internal environment of the companies are taking place: the increased use of mechanisation and automation of operations, such as flexible manufacturing systems (FMS), robots, automatic warehousing, automatic guided vehicles (AGVs); the increasing trends of using Just-In-Time (JIT), and TQM philosophy, Yamashina (1995), Luxhoj et al. (1997) and Suito (1998). These entire changes tie up much invested capital, for example, companies within process and chemical industries, such as paper mills and refineries, use extremely expensive and fully automated production lines, Swanson (2003). Furthermore, there is increasing pressure to protect the ecological environment from the danger of harmful industrial waste and pollution. This means that the manufacturing plant should be used effectively, efficiently, and provides high quality products at a competitive price in addition to showing concern for the environment and safety.

In the move towards world-class manufacturing many firms are realising a critical need for the use of a proper, i.e. efficient and effective, maintenance of production facilities and systems, Luxhoj et al. (1997) and Stephen (2000). Industrial plants, machinery and equipment are becoming technologically more advanced and at the same time more complex and difficult to control. JIT management systems, lean and agile manufacturing and the use of automated and integrated systems have made production systems increasingly vulnerable to risks and susceptible to diverse consequential effects due to breakdowns, Luce (1999), Vineyard et al. (2000), and Holmberg (2001). For example, Implementing JIT requires an effective and efficient maintenance which can ensure a smooth flow of production and, ideally, a 100-percent quality cost effectively, Charlene (1989) and Al-Najjar (1996). Maintenance is a business function that serves and supports the primary process in an organisation. The maintenance process adds to customer value in terms of profit, quality, time and service, Zhu et al. (2002). Therefore, the maintenance function became more essential for a manufacturing organisation’s ability to maintain its competitiveness. Without well-maintained equipment, a plant will be at a disadvantage in a market that requires low-cost products of a high quality to be delivered quickly, Stephen (2000), Swanson (2001 and 2003).

Therefore, the importance of the maintenance function has been greater than before, due to its role in maintaining and improving availability, performance efficiency, quality products, on-time deliveries, the environment, safety requirements and overall plant productivity at high levels, Al-Najjar (1997), Riis
et al. (1997), Mckone and Weiss (1998) and Bevilacqua and Braglia (2000). Furthermore, an increasing awareness of maintenance and its influence for both industrial enterprises and society as a whole can be recognised. Many researchers and practitioners have highlighted the total losses due to maintenance omission or ineffectiveness, Ahlmann (1984 and 1998), Jardine et al. (1996), Al-Najjar (1997), Davies (1998), Ljungberg (1998), Luce (1999), Vineyard et al. (2000) and Holmberg (2001). Nevertheless, maintenance is still considered as a cost centre and little research has been done to highlight the impact of the maintenance function on the overall plant performance, i.e. productivity and profitability, Ahlmann (1984 and 1998), Al-Najjar (2000a), Al-Najjar et al. (2001), Carter (2001) and Kutucuoglu et al. (2001).

We can see that the maintenance task is becoming increasingly more complex due to the changes in the production and the environment of companies. These changes can be described by factors such as the level of automation and capital intensity associated with automated production lines, globalisation, restructuring and downsizing strategies, organisation structures, personnel competence development and the difficulty of assessing the impact of maintenance on the companies’ competitiveness. It has been realised that a typical manufacturing system consists not only of mechanical components, but also of other elements such as electronic, hydraulic, electromechanical elements, software and human beings. This means that disturbances and deviations in the production process may occur due to different factors such as the failure of significant components of equipment, the quality of purchased material and spare parts, design, manufacturing process control, management systems and human errors, AL-Najjar (1997) and Holmberg (2001).

Maintenance decision problems could be classified with respect to the time scale involved. It starts early in the design phase of systems; the type of equipment, the level of redundancy, and the accessibility that strongly affects the maintainability, Dekker and Scarf (1998). Furthermore, a very critical decision should be made regarding which event (e.g. failure, the passing of time, etc) triggers what type of maintenance, i.e. inspection, repair or replacement. Usually, the maintenance objective is to reduce failures of industrial plant, machinery and equipment/component, thus improving the overall productivity of the plant. This objective can be achieved using various approaches: corrective maintenance; the changing of a component at a pre-specified time using statistical models based on collected historical failure data; condition-based maintenance through monitoring the condition of the component using one (or more) of the condition monitoring (CM) techniques. In every case, the decision maker tries to select from all the possible maintenance approaches one approach for each piece of equipment or component. However, the current practices in plant and equipment maintenance and replacement decisions are frequently based on informed opinions such as following the original equipment manufacturer’s (OEM) recommendations, or subjective responses to common situations such as reacting to a critical component failure by introducing a
company-wide programme of preventive replacement or condition based replacement of such components.

However, while such procedures for establishing a maintenance programme may improve plant reliability, it is by no means guaranteed to provide the most cost effective solution, Jardine et al. (1996). The identification and implementation of the proper maintenance approach will enable managers to avoid premature replacement costs, maintain stable production capabilities and control the deterioration of the system and its component parts, Vineyard et al. (2000). This means that industry could improve its performance if it implements the proper maintenance approach for eliminating the causes of production disturbances, Swanson (2001 and 2003).

1.2 Research problem

This research treats theoretically and empirically the extent to which proper maintenance practices are deployed and the links between applied maintenance practices and overall business performance. Based on the results of the research presented in the licentiate phase, it was proved in a case study that cost effective maintenance would improve the quality, efficiency and effectiveness of a company’s operations. Hence, this would enhance its competitiveness, i.e. productivity advantages, value advantages and long-term profitability. Consequently, the shareholders, customers, and society would be affected positively, as illustrated schematically in Figure 1.1.

Furthermore, it was shown that the use of one of the maintenance approaches, i.e. vibration-based maintenance (VBM) for planning maintenance activities could result in great savings, especially when the down time cost is high, e.g. in the process industry. To generalise these results, there is a need to investigate which maintenance practices are used within various types of industries and how these practices influence industrial competitiveness, Adebiyi et al. (2003) and Tse (2002). Maintenance practices in this study include activities such as planned maintenance, condition monitoring (CM), autonomous maintenance, technical analysis, personnel education and training, systems for planning and controlling work, expert systems, multitasking and team work. The extent of usage of such activities influences the business performance outcomes. Normally, various maintenance actions are used to reduce failures of industrial plant, machinery and equipment and their consequences as much as possible. These actions can take several forms such as failure based maintenance (FBM), preventive maintenance (PM), i.e. replacing components at a pre-specified time using statistical models based on collected historical failure data, or condition-based maintenance (CBM). In all cases, the decision maker, however, needs to select from all the applicable maintenance policies the most cost effective for each component, module or equipment.
The identification and implementation of the appropriate maintenance policy will enable managers to avoid premature replacement costs, maintain stable production capabilities and prevent the deterioration of the system and its components, Vineyard et al. (2000). Thus, in this study the main research problem addressed is:

**How to select and improve the most cost-effective maintenance policy and how to assess its financial impact**

The research problem is investigated theoretically and empirically within Swedish industries, using both quantitative and qualitative research methodologies with different research questions, as will be illustrated in Chapter Two in details.
1.3 Purpose and research questions

The purpose of this research work is to study the impact of maintenance practices on companies’ performance outcome. The objective is achieved via investigating the following research questions:

\textit{RQ1: Which maintenance practices are used in Swedish industry?}

\textit{RQ2: How are maintenance policies selected in Swedish industry?}

\textit{RQ3: How to select the most cost effective maintenance policy?}

\textit{RQ4: How to improve the effectiveness of condition-based maintenance (CBM) decision-making?}

\textit{RQ5: How to assess the impact of maintenance practices on the business strategic objectives?}

In my licentiate thesis the third, forth and fifth research questions, see Figure 1.2, have been primarily investigated, where Paper V and a first version of Paper I, Paper VI and paper VIII were produced. In this study, i.e. the PhD thesis, the same three research questions were further investigated in addition to the first and second research questions, i.e. RQ1 and RQ2. In Figure 1.2, the connection between the research questions and the research papers is illustrated.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Link between the research questions and the research papers}
\end{figure}
The dependency and link between the research questions can be described as follows. The first research question examines empirically the maintenance practices in Swedish Industry. From this we obtain a better understanding of important issues such as maintenance status, maintenance organisation, maintenance management systems and implemented maintenance policies. The second research question investigates empirically (within Swedish industry) which methods are used for selecting the applied maintenance policy. From this we identify maintenance selection methods used and their ability to satisfy the firm’s needs. The third research question helps the decision maker in selecting the most cost-effective maintenance policy based on the theoretical results obtained in Paper I and Paper II and the empirical results obtained in Paper III.

Once we have selected the right, i.e. the most cost effective, maintenance policy, then we should enhance its effectiveness. Therefore, the fourth research question assists the maintenance manager in improving the effectiveness of decision-making when implementing condition-based maintenance (CBM). Finally, the fifth research question is about how to assess theoretically and empirically the financial impact of maintenance practices on strategic business objectives, i.e. companies’ competitiveness.

1.4 Relevance

In the following we discuss the relevance of the research problem and the research questions, showing why it is important to do research in this area. We also show how the research problem addressed in this study is very important on both theoretical and practical grounds as could be justified through:

- The need to identify which maintenance practices are being used and to investigate the links between these practices and performance outcome, Liptrot and Palarchio (2000), Mitchell et al. (2002), Tse (2002) and Adebiyi et al. (2003).
- The lack of a systematic, adequate and user-friendly model for selecting the most cost effective maintenance policy. Furthermore, the need to investigate how the industry selects maintenance policies.
- The increasing recognition of the maintenance role in keeping and improving availability, performance efficiency, quality products, on-time deliveries, the environment, safety requirements and overall plant productivity at high levels, Al-Najjar (1997), Riis et al. (1997), Mckone and Weiss (1998) and Bevilacqua and Braglia (2000).
- The need to develop and improve the effectiveness of the implemented maintenance programs, Al-Najjar (1997, 1998 and 2000b). For example, when using CBM it is important to assess the seriousness of the equipment (significant component) damage and predict the remaining life that will help in improving the effectiveness of maintenance scheduling.
- The false thinking that maintenance, as it has been traditionally considered, is a necessary evil, while in fact it can be a profitable business, rather than...

- The need to get rigorous and statistically generalised results using systematic and quantitative methods, i.e. a survey across a large sample, to enhance the research results that were achieved using the case study research method during the licentiate phase.

- The usefulness of the potential applications of the research findings.

### 1.5 Delimitations

In this thesis, the first three research questions are restricted to Swedish industry. The population studied consists of a set of Swedish manufacturing companies that have at least 100 employees\(^1\). However, in the fourth research question, we deal with condition-based maintenance (CBM) in general and vibration-based maintenance (VBM) in particular. That is because vibration monitoring is generally considered as one of the key tools of most condition monitoring programs for rotating and reciprocating machines, Collacott (1977), Bloch and Geitner (1994) and Al-Najjar (1997). In the fifth research question, the case study company is selected from an industry which is characterised by having high-invested capital with a high downtime cost, i.e. the paper industry, where the use of VBM policy is usually justified. Finally, although we are studying the maintenance function in general, there are some research areas in the maintenance field that will not be dealt with, such as maintenance and design, repair methods, maintenance scheduling, maintenance optimisation, detailed failure analysis, troubleshooting and other soft issues needed when implementing a maintenance policy such as maintenance organisation or competence.

### 1.6 Thesis disposition

Chapter One starts with the background, which outlines the broad field of the study and then leads into the focus of the research problem. Next, the broad research problem area is discussed. Afterwards, the purpose and research questions of the study are presented. Then, the relevance and justification of the research is presented. Next, the delimitation of the scope of the study is discussed, and finally the thesis outline is stated.

Chapter Two describes the major methodological issues: the methodology concept, research methods, research design and thesis research design.

Chapter Three reviews and summarises the relevant literature to establish a frame of reference for the research questions, which are worth researching

\(^1\) More details about the population characteristics will appear in the methodology chapter.
because they are either controversial or have not been answered adequately by previous researchers. The purpose of this chapter is to guide the reader into the existing literature that is considered to be important to the research problem.

Chapter Four presents the empirical results of the research that is conducted to solve the research problem and its stated research questions. It shows the data collected and the treatment and analysis of them according to their relevance to the research questions and research papers.

Chapter Five then discusses the research findings, i.e. results and conclusions, for each research question and the research problem. Furthermore, it discusses implications for theory and practice, suggestions for future research and finally my own criticism of the study.
2. Methodology

It is very important to have a clear and obvious stance regarding the methodology of a research study. The selected methodology affects the validity, the reliability and research results. Therefore we illustrate how one can select and design the research methodology.

2.1 Methodology concept

The methodological problem can be worked out by creating harmony and fit between three concepts, i.e. basic assumptions, methodological approaches, and researched problem, see Jonsson (1999). Figure 2.1 illustrates the relation between these three elements as suggested by Arbnor and Bjerke (1997).

![Figure 2.1. The methodology concept (constructed from Arbnor and Bjerke, 1997)]
Ultimate presumptions

The ultimate presumptions define the researcher’s view of the social world and the way in which it may be investigated. It shows how the researcher looks at reality, ideals, science, ethics, etc. These assumptions, as suggested by Burrel and Morgan (1979), could be grouped using the subjective-objective dimension as “objectivist” approach or “subjectivist” approach. The researcher may view reality as objective “out there” independent of the researcher, something that can be measured objectively by using a questionnaire or an instrument. On the other hand, one can view reality as only constructed by the individuals involved in the research situation, thus multiple realities exist in any given situation. However, Arbnor and Bjerke (1997) added that many analytical scientists refer to intersubjectivity rather than objectivity. They illustrated that intersubjectivity means there is conformity among the research results reached by different individuals in their studies, given the same circumstances and competence and applying the same methods.

When considering assumptions about grounds of knowledge, the researcher should determine his position on the issue of whether knowledge is something that can be acquired on the one hand, or something that has to be personally experienced on the other hand. Regarding the relationship of the researcher to what is being researched, the “objectivist” approach implies that the researcher should remain distant and independent of what is being researched. Thus in surveys and experiments, researchers attempt to control for bias, selecting a systematic sample and being objective in assessing a situation. While in the “subjectivist” stance, researchers interact with those they study, by living with or observing informants over a prolonged period of time, or by actual collaboration.

In this thesis, the author considers himself as a researcher closer to the “Objectivist” approach, because of his scientific background in engineering. This means that the author views the reality as objectively accessible, independent and measurable objectively. Knowledge can be acquired, and the researcher should remain distant and independent of what is researched. However, since what is considered as objective by a certain social setting could be considered subjective by other community’s point of view, therefore I emphasise that this thesis focuses on a community of researchers within maintenance science and people within a factory or a business setting.

Methodological approaches

Arbnor and Bjerke (1997) illustrated that knowledge can be developed using one of the following three methodological approaches: analytical approach, systems approach, or actors’ approach. The analytical approach assumes that reality is objective and has a summative character: “the whole is the sum of its parts”. The systems approach assumes that reality is objectively accessible. Reality is arranged in such a way that the whole differs from the sum of its parts. The relation among the parts themselves and between the parts and the environment are very important. Knowledge depends on systems. The parts are explained (understood) in terms of the whole system. The actors’ approach assumes that the whole exists only as meaning structures, which are socially constructed.
Knowledge depends on individuals. The whole is understood via the actors’ finite provinces of meaning. It assumes that reality is socially constructed. Qualitative studies are used with this approach.

Maintenance as a support function is part of the manufacturing system of the company, which means that it affects and is affected by the other parts of the system, e.g. the manufacturing strategy. Therefore, the author believes that the closest methodological approach is the systems approach, because by this approach one can study the mutual effects of any part of the system with respect to the other parts and the environment, and still maintaining the “objectivist” assumptions.

**Operative paradigm**

The operative paradigm describes the relation between the methodological approach and the area under study. It is determined in terms of the methodological procedures used to capture data, analyse, and draw conclusions. Jonsson (1999) stated that the research and solving techniques are either of an empirical or conceptual (theoretical) nature. Burrel and Morgan (1979), Larsson (1993), and Bengtsson et al. (1997), among others, used the terms Nomothetic (general laws and procedures for exact science) and Idiographic (the understanding of particular cases) to represent the quantitative and qualitative research methodologies, respectively. The characteristics of the Nomothetic and Idiographic approaches in addition to the case survey methodology are illustrated in Figure 2.2.

![Figure 2.2](image-url)  
**Figure 2.2**  
*Quantitative, qualitative and case survey methodologies*

The Idiographic approach is based on a process oriented case study approach that emphasises qualitative (interpretative and explanatory study) multi-aspects.
and few in-depth studies, often covering a long period of time with the objective of explaining and understanding. It aims to provide rich descriptions and to make theoretical generalisations. This is in contrast with the Nomothetic approach, which deals with quantitative analyses of a few aspects across large samples (cases) in order to test hypotheses and make statistical generalisations using systematic and quantitative methods to describe and explain causality.

Nomothetic (quantitative) studies have the advantage of providing rigorous and statistically generalisable cross-sectional analyses of patterns across large samples, but the context of the studied object is usually limited, i.e. context free. Idiographic (qualitative) studies have the advantage of providing practically relevant, in-depth analyses of complex organisational processes, both in time and in context, i.e. they are content-specific. They contribute by providing new unexpected insights and by building new theories and concepts, Larsson (1993) and Bengtsson et al. (1997). Case-survey methodology bridges the Nomothetic-Idiographic research gap. It enhances the relevant findings of prior empirical studies through a systematic analysis of pattern across cases. It overcomes the problem of generalisation from a single case study and at the same time provides more in-depth analysis of complex organisational phenomena than questionnaire surveys. But it requires a long time and great efforts in addition to the availability of an efficient number of prior empirical studies, Larsson (1993).

In this thesis both the Idiographic (qualitative) and Nomothetic (quantitative) approaches were used with different research questions and in different periods of research study. For example Paper VI, Paper VII and Paper VIII were based on an idiographic approach, while Paper III was based on a nomothetic approach. However, the rest of the papers could be considered theoretical.

2.2 Research methods

There are different research methods that could be used with each operative paradigm. In the following we discuss the three main methods.

Case studies

Yin (2002) defined case study 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. Sekaran (2000) clarified that case studies involve in-depth, contextual analyses of similar situations in other organisations. It can be based on any mix of quantitative and qualitative evidence. It does not always need to include direct, detailed observations as a source of evidence. Case studies are considered as a less desirable form of inquiry than experiments or surveys because of the lack of rigor, the little basis for scientific generalisation, and because they take too long time, Gomm et al. (2000). However, Yin (2002) clarifies that the lack of rigor also exists in the other research strategies, but in case study research it has been more frequently encountered and less frequently overcome. He criticised the
hierarchical view by which the various research methods are arrayed. He questioned the common conception that case studies are only appropriate for the exploratory phase of an investigation that surveys are appropriate for the descriptive phase, and that experiments are the only way of making explanatory or causal inquiries. He emphasised that what distinguishes the methods is not this hierarchy but the following three conditions: the type of research question posed, the extent of control an investigator has, and the degree of focus on contemporary events. “How” and “Why” questions are likely to favour the use of case studies if there is no need to have control of behaviour event, and when focusing on contemporary events. Regarding the generalisation problem, he showed that case studies, like experiments, could be generalised to theoretical propositions and not to populations or universally. He illustrated that a fatal flaw in conducting case studies is to conceive of statistical generalisation as the method of generalising the results of the case study. This is because the cases are not “sampling units” and should not be chosen for this reason. Therefore, the mode of generalisation when using case studies is “analytic generalisation”, in which a previously developed theory is used as a template with which to compare the empirical results of the case study.

Experiments
Experiments are performed by investigators in virtually all fields of inquiry, usually to discover something about a particular process or system. Montgomery (2001) defined experiment as a test or a series of tests in which purposeful changes are made to the input variables of a process or a system so that one can observe and identify the reasons for changes that may be observed in the output response. Gomm et al. (2000) contrasted experimental research with case studies. They showed that experimental research usually involves the investigation of a small number of cases compared to survey work, and what distinguishes it from case study is not so much the amount of data collected as the fact that it involves direct control of variables. In experiments, the researchers create the cases(s) studied, whereas case study researchers construct cases out of naturally occurring social situations. Yin (2002) emphasised that “How” and “Why” questions are likely to favour the use of experiments if there is a need to have control of the behaviour event, and when focusing on contemporary events.

Survey
Graziano and Raulin (2000) showed that survey research utilises several basic research procedures to obtain information from people in their natural environments. The basic instrument used is the survey, which is a set of one or more questions that ask people about several issues. The survey could be performed by choosing from two types of survey instruments: (1) questionnaire surveys, in which participants read the questions and then write down their responses, and (2) interview surveys, in which participants hear the questions and speak their responses, Mitchell and Jolley (2001).
Unlike the experiment research the survey researcher does not manipulate variables but does impose some constraints on participants by using the survey instruments. It could be used to test relationship between variables. Yin (2002) highlighted that “what” and “who” and “where” questions (or their derivatives “how many” and “how much”) are likely to favour survey methods. A survey study is an appropriate method to use, for example, when the study concerns finding distinct features in a population (ibid). It can be a relatively inexpensive way to get information about people’s attitudes, beliefs and behaviours by collecting a lot of information on a large-scale sample in a short period of time, Mitchell and Jolley (2001). A comparison among three research methods, i.e. case studies, experiments and survey is illustrated in Table 2.1.

Table 2.1  
Comparison among the three research methods (developed from Gomm et al., 2000, Yin (2002) among others)

<table>
<thead>
<tr>
<th></th>
<th>Case study</th>
<th>Experiment</th>
<th>Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form of research question</td>
<td>How, why?</td>
<td>How, why?</td>
<td>Who, what, where, how many, how much?</td>
</tr>
<tr>
<td>The aim</td>
<td>It aims at understanding the case studied itself, with no interest in theoretical inference or empirical generalisation.</td>
<td>It aims at either, theoretical inference, the development and testing of theory, or the practical evaluation of intervention.</td>
<td>It aims at empirical generalisation, from a sample to a finite population, though this is sometimes seen as a platform for theoretical inference</td>
</tr>
<tr>
<td>Number of cases studied</td>
<td>Small (Sometimes just one)</td>
<td>Relatively small</td>
<td>Relatively large</td>
</tr>
<tr>
<td>Number of features (questions)</td>
<td>Large</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Type of cases and level of control</td>
<td>Study of naturally occurring cases, where the primary concern is not controlling variables.</td>
<td>Study of cases created in such a way as to control the important variables.</td>
<td>Study of a sample of naturally occurring cases; selected in such a way as to ensure that the sample is representative of the larger population, where the primary concern is not controlling variables.</td>
</tr>
<tr>
<td>Type of data</td>
<td>Quantification of data is not a priority. Qualitative data may be treated as superior</td>
<td>Quantification of data is a priority.</td>
<td>Quantification of data is a priority.</td>
</tr>
</tbody>
</table>
2.3 Research design

Research design is the logical sequence that connects the empirical data to a study's initial research questions and, ultimately, to its conclusions, Yin (2002). He described research design as an action plan for getting from here to there, where here may be defined as the initial set of questions to be answered, and there is some set of conclusions about (answers to) these questions. Defining the research question is the most important condition among other conditions such as the need of control over behavioural event, and degree of focus on contemporary events. Another way of thinking about research design is as a “blueprint” of research, dealing with at least four issues: what questions to study, what data are relevant, what data to collect, and how to analyse the results, as stated by Yin (2002). The main purpose of the design is to help avoiding the situation in which the evidence does not address the initial research questions. Yin (2002) identified five components that are considered important for a research design: a study’s questions; its proposition, if any; its unit(s) of analysis; the logic linking of the data to the propositions; and the criteria for interpreting the findings. Although the substance of the research questions will vary, the form of question - in terms of “who,” “what,” “where,” “how,” and “why” provides an important clue regarding the most relevant research method to be used. As for the study proposition, if any, it helps to direct attention to something that should be examined within the scope of the study. The third component, i.e. the unit of analysis, is related to defining what the research is about. It could be about an individual, an event, an entity such as a machine, a department, a function, a company, an industry, etc (ibid).

Controlling research design quality

The quality of any research design can be judged according to certain logical tests. Various validity and reliability tests have been commonly used to establish the quality of any empirical research, see for example, Arbnor and Bjerke (1997), Mitchell and Jolley (2001), Patton (2002) and Yin (2002).

Validity is considered a very important factor in assessing the quality of measurements. It is defined as the extent to which the results are true or correct and represent reality. In the analytical approach the validity of measurement can be divided into the following types (ibid):

- **Construct validity**: it is concerned with establishing correct operational measures for the concepts being studied, for example, the names given to the measures are accurate, i.e. to be sure that the instrument measures what it is supposed to measure. This requires that the instrument must then be administrated in an appropriate, standardised manner according to prescribed procedures.
- **Internal validity**: for explanatory or causal studies, it aims at ensuring that a certain observable event (input variable) was responsible for or influenced a change in behaviour (output). Arbnor and Bjerke (1997) added that it could
be concerned with the logical relationship (relevance) between a study and the existing theory in the area.

- **External validity**: the possibility of generalising the results beyond the actual area being studied.
- **Face validity**: it is an assessment of the degree of acceptance of the results.

The **reliability** test, on the other hand, aims to minimise the errors and biases in the study. It demonstrates that the operations of the study such as the data collection procedures can be repeated with the same findings and conclusions, Yin (2002). The systems approach views the validity problem somewhat differently. The connections among theory, definitions, and reliability are not as strong as they are in the analytical case. A common systems approach for guaranteeing that measurements are correct is to reflect the real system from as many angles as possible. The researchers try to study the system as long and as often as possible, to talk to as many people as possible, and to study as much relevant material as they can. In the actors’ approach they talk about the quality and credibility of qualitative analysis. The credibility issues for qualitative research depend on three elements, Patton (2002):

- Rigorous techniques and methods for gathering high-quality data, which are carefully analysed, with attention to issues of validity, reliability, and triangulation.
- The credibility of the researcher, which is dependent on training, experience, methodological skill, competence, sensitivity, and the rigorousness of the person doing the fieldwork, Arbnor and Bjerke (1997).
- Philosophical appreciation of qualitative methods, inductive analysis, and holistic thinking.

Yin (2002) added that in addition to the trustworthiness, credibility, conformability and data dependability tests that are used for judging the quality of research design, tests such as construct validity, internal validity, external validity and reliability tests are also relevant to case studies.
2.4 Thesis research design

This thesis consists of five research questions that are related to eight papers. The methodology used in these papers is illustrated in Table 2.2.

Table 2.2 Illustration of thesis research design

<table>
<thead>
<tr>
<th>Paper No.</th>
<th>Operative Paradigm</th>
<th>Unit of analysis</th>
<th>Research Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper I</td>
<td>Conceptual</td>
<td>Related literature</td>
<td>Review</td>
</tr>
<tr>
<td>Paper II</td>
<td>Conceptual</td>
<td>Related literature</td>
<td>Review</td>
</tr>
<tr>
<td>Paper III</td>
<td>Nomothetic</td>
<td>Swedish firms with at least 100 employees</td>
<td>Survey</td>
</tr>
<tr>
<td>Paper IV</td>
<td>Idiographic</td>
<td>Test rig and rolling bearing in a paper mill</td>
<td>Experiment and Case study</td>
</tr>
<tr>
<td>Paper V</td>
<td>Conceptual</td>
<td>Related literature</td>
<td>Review</td>
</tr>
<tr>
<td>Paper VI</td>
<td>Idiographic</td>
<td>One paper-mill machine</td>
<td>Theoretical and empirical (Case study)</td>
</tr>
<tr>
<td>Paper VII</td>
<td>Idiographic</td>
<td>One paper-mill machine</td>
<td>Theoretical and empirical (Case study)</td>
</tr>
<tr>
<td>Paper VIII</td>
<td>Idiographic</td>
<td>One paper-mill machine</td>
<td>Theoretical and empirical (Case study)</td>
</tr>
</tbody>
</table>

2.4.1 Survey method

A survey method was used with Paper III. This paper is related to the first, second and third research questions. It is an empirical verification of the model developed in Paper II. According to the classification of the operative paradigms, this paper is classified as “Nomothetic” using the survey research method. In the following we discuss the research method that is used in this paper, i.e. the participant, the data collection tool and the procedures.

**Participant**

The empirical study was performed by conducting a cross sectional survey to obtain information from the maintenance managers of the Swedish firms (production plants) that have at least 100 employees. Large plants will probably invest significantly in technology and are likely to require an internal maintenance group to care for equipment. We wanted to make comparisons across a wide range of groups of Swedish industries, aiming to make rigorous and statistical generalisation from the studied sample to a larger population, i.e. Swedish industry. We got the addresses of 1440 Swedish firms from Statistics Sweden “Statistiska Centralbyrån” (SCB). The population was selected from the Swedish Standard Industrial Classification (SE-SIC) 2002.
At first, it was decided that we survey every member of the selected population, i.e. 1440 firms. However Mitchell and Jolley (2001) warned that even if one starts with an unbiased sample, by the end of the study the sample may become biased because people often fail or refuse to respond to a questionnaire. However, they showed that a typical mail survey response rate might reach only 10 percent. A mail survey with a return of 30 percent or so is often considered satisfactory, Emory and Cooper (1991). However, Jonsson (2000) mentioned that response rates from similar studies in the USA, Australia, New Zealand and Singapore vary from about 10 to 40 percent, with a median response rate around 20 percent.

Out of the 1440 questionnaires that we sent by surface mail, 38 questionnaires were removed from the population for various reasons. However, the total number of respondents was 185. This means that the response rate is 13.2%. Furthermore, it was found that there is bias to certain types of industries. Therefore, in order to improve the possibility to generalise the results we decided to restrict the studied population to the industries that have a high response rate, they were also characterised by having expensive down time due to high-invested capital, which also mean that the maintenance could have big role. This means that we can generalise to only the studied population and not to the Swedish industry in general. The size of the restricted population becomes 539 and the total number of respondents is 118, hence, the overall response rate increased to about 22%, as shown in Table 2.3.

Table 2.3 Distribution of the response rate with respect to type of industry.

<table>
<thead>
<tr>
<th>Type of Industry</th>
<th>Number of Questionnaires sent</th>
<th>Number of Answered Questionnaires Received</th>
<th>% Received</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrochemical</td>
<td>5</td>
<td>4</td>
<td>80.0%</td>
</tr>
<tr>
<td>Pulp and Paper</td>
<td>82</td>
<td>11</td>
<td>13.4%</td>
</tr>
<tr>
<td>Wood and Timber</td>
<td>60</td>
<td>16</td>
<td>26.7%</td>
</tr>
<tr>
<td>Steel and Metal work</td>
<td>58</td>
<td>12</td>
<td>20.7%</td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>247</td>
<td>55</td>
<td>21.4%</td>
</tr>
<tr>
<td>Pharmaceutical, Chemical</td>
<td>68</td>
<td>13</td>
<td>19.1%</td>
</tr>
<tr>
<td>Media, Printing</td>
<td>19</td>
<td>7</td>
<td>36.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>539</td>
<td>118</td>
<td><strong>21.9%</strong></td>
</tr>
</tbody>
</table>

Data collection tool
The questionnaire used in this study consists of five main parts and 43 main questions comprising a total of 12 pages. Previous studies showed that questionnaires of up to about 12 pages produced response rates that did not depend on length, as stated by Judd et al. (1991). Therefore, we designed the questionnaire taking this criterion into account. To encourage response and
promote rapport the questionnaire started with general questions that are considered more interesting and also easier to answer.

To guarantee that the questionnaire fulfils the construct validity requirements, i.e. being adequate and measuring what it is supposed to measure, a special table was created to test if the questionnaire covered all the aspects of the research objectives considered necessary, such as technical, financial, organisational, environmental and educational aspects. As can be seen in Paper III, every aspect as well as every objective was covered by at least one question. Furthermore, one of the most important criteria of questionnaire design is that the questions should be short, relevant and easy to understand. At the same time it is very important to make sure that the respondents have interpreted the questions as intended. Therefore, the questionnaire was designed with structured questions where the respondent could choose an answer from a set of listed possibilities. This is recommended for mail surveys, and when necessary an open-ended option is used to guarantee that the respondent has interpreted the question as intended. This will improve the validity and reliability of the instrument. To guarantee a high degree of content and construct validity, e.g. a concept being studied such as the names given to the measures, the questionnaire was based on the related theory and literature and pre-tested by academics and practitioners. At the same time all the procedures for data collection were written down in detail to ensure the repeatability of the process to enable good reliability.

Procedure
The designed questionnaire passed through the procedures of drafting the questionnaire, pre-testing, questionnaire finalising and production, first mailing, first reminder using mail, and second reminder using telephone. Based on the study objective and the main research problem, questions were drafted to cover all relevant aspects. Both the question content and the wording were selected carefully. Then the questionnaire (written in English) underwent a series of tests. The first test was performed by the designers as part of the research project activities, and then it was presented in a seminar as part of the yearly meeting with the centre of industrial competitiveness (CIC). After that other colleagues and PhD students at the department tested a draft of the questionnaire translated into Swedish. All their comments were considered and incorporated in a revised version. The quality of translation was controlled and tested in a way that guarantees interactive and back translation during all the stages.

Then the Swedish version of the questionnaire was tested on the field by sending the questionnaire with a covering letter to one of the companies participating in financing the research project. The maintenance manager of the Swedish terminal post in the town of Alvesta was asked to write down his reflections on how clear the questions were and how easy they were to answer. After that, the questionnaire was revised and retested again with the same manager. When we were satisfied with the questionnaire it was reproduced and mailed.

A mail survey was used to collect the empirical data. In a mail survey the respondent can take more time to collect facts and talk with others. Another
advantage of a written questionnaire is the avoidance of potential interviewer bias. However, the major weakness of the mail survey is the non-response, Emory and Cooper (1991).

2.4.2 Theoretical research method
A conceptual research method was used in Paper I, Paper II and Paper V. Paper I is related to the third research question. It is a theoretical study. Its objective is to assess the various maintenance approaches so that one can select the most informative one. Based on analysing the literature of decision-making theory, a fuzzy multiple criteria decision-making (MCDM) evaluation methodology was suggested for assessing the maintenance approaches. It was tested empirically by two illustrative examples using typical data, showing the ability of the suggested methodology to select the most informative maintenance approach according to the contextual conditions. Paper II is related to the third research question, too. It continued and extended the work done in Paper I. It is a theoretical study based on performing a critical analysis of the literature related to maintenance selection methods. As a result of contrasting and logically assessing the existing maintenance selection methods a conceptual model for maintenance selection was developed and discussed. The model is verified in Paper III.

Paper V is related to the fourth research question. It is a conceptual study. Its objective is to investigate how to improve the effectiveness of plant monitoring and enhance the reliability of decision-making systems. The study was based on performing a critical analysis of the related literature.

2.4.3 Experiment method
Experiment was used in Paper IV, which is related to the fourth research question. The purpose of the paper is to verify a model that predicts the value of vibration level. An experiment was conducted at the CM laboratory at the Department of Terotechnology at Växjö University. The purpose of the experiment is to generate a set of vibration measurements similar to what could be found in real life applications. A test rig was used in the experiment. It consists of an electric motor (994 RPM and 0.075 KW), four-teeth coupling, one shaft mounted on four rolling-element bearings and a pulley mounted at the other end of the shaft. The experiment was designed to simulate a simple case of unbalance. A set of vibration measurements were collected by means of SKF CMVA55 Microlog Data Collector/Analyser using a standard velocity measurement via a standard 100-mV/g accelerometer (SKF’s CMSS787A). The collected vibration data were analysed using Data Management and Analysis Software (SKF PRISM4 for Windows).

2.4.4 Case study method
Paper VI, Paper VI and Paper VIII are related to the fifth research question. They aim to describe how to assess the contribution of maintenance function to business strategic objectives. According to the classification of the operative
paradigms, these papers are classified as “Idiographic”, i.e. qualitative methodology, using case study research. However, quantitative data and analysis were implemented according to the scientific approach which is common among natural scientists and engineers. A case study was conducted in the natural environment of the studied organisation, where researchers did not interfere with the normal flow of work, i.e. the researchers remained distant and independent of what is being researched. The unit of the analysis of the study was one of the Swedish paper companies, where technical and economic data were collected from one of the company’s four machines, i.e. PM2. In-depth and practically relevant analyses of the complex organisational and manufacturing processes took place for a long period of time, i.e. about 16 months.

We used previously collected data, i.e. secondary data covering the period from 1997 to 2000, about the machine and its environment. We designed our own tables for collecting data, because the required data were not possible to find in one database in the required format. To avoid any confusion during data collection, and ensure that the instrument, i.e. data collection table, measures what it is supposed to measure, all the terms used in the tables of data collection were discussed, explained, and agreed on by the company personnel involved in the case study. In addition, to guarantee that the measurements were correct, we tried to study the system as long and as often as possible, to talk to as many people as possible, and to study as much relevant material as we could. Furthermore, the research team was characterised by being well-trained, experienced in methodological skills, competence, and rigorous supervision, which ensured the credibility of the researchers. Finally, we can ensure the validity of the measurement, i.e. the extent to which the results are true and represent reality by showing how the results compare to the following criteria suggested by, among others, Arbnor and Bjerke (1997), Mitchell and Jolley (2001), Patton (2002) and Yin (2002):

**Face validity**
The degree of acceptance of the results, i.e. their credibility, was examined in several ways. At first by discussing the findings with the company of the case study, and then by presenting and discussing the results with the project’s steering committee, which consists of representatives of the organisations that supported the research project financially, i.e. SKF, Volvo, Alstrom Power, and StoraEnso. Next, the project results were printed as a report and distributed to the project supporting organisations and universities. After that, the findings were presented and discussed as scientific papers at international scientific conferences both in Sweden and the UK. Also, the result in the form of a scientific paper, i.e. Paper VI, was published in a scientific journal of a high reputation, i.e. ranked with an “A” rating2. Furthermore, two other papers, i.e. Paper VII and Paper VIII have also been sent for publication in an “A” rated journal.

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2 The European Journal of Operational Research, for the ranking see http://hal.boku.ac.at/fao/journal_ranking
**Internal validity**

We can say that the study also has a high internal validity, because the findings of the study are relevant to and a logical output of the theory developed at the beginning of the project. This study was able to prove quantitatively for the first time that the maintenance function should no longer be considered as a cost centre, but that it is a profit generating function.

**External validity**

Yin (2002) showed that normally the findings of a case study could be generalised to theoretical propositions. He argues that the findings of case studies could not be generalised to populations or universally because of the lack of rigorousness, statistical and quantitative evidence. However, Lukka-Kari and Kasanen-Eero (1995) believe that statistical and case studies are not as far from one another with regard to generalising as is commonly considered. They argue that generalisation from statistical studies is only one of the possible modes of generalisation. They claimed that “in case studies an attempt is usually made to counterbalance the impossibility of applying statistical inference by, for example, the large theoretical or practical relevance of the research subject, the thoroughness of analysis and interpretation, and the triangulation of research methods”.

Therefore, properly conducted case studies of a high quality can produce generalisable results, where inferences are not drawn to some larger population based on sample evidence, but generalisation are rather made back to theory. However, Yin (2002) believes that generalisation is not automatic, because a theory must be tested through replications of the findings in a second or even a third neighbourhood. Lukka-Kari and Kasanen-Eero (1995) stated that the significance of replication is emphasised by the idea that the generalisability of research results could be substituted by their transferability. Therefore they argue that generalisation is possible from a properly conducted case study. One way of realising this is by building an argument that the substantial results of a case study also hold true for other cases.

Based on the previous discussion, we argue that the findings of this study can be generalised both as theoretical propositions and to other similar populations or universally. This is because the case study was characterised by being an in-depth study for about sixteen months. We believe that the findings can be transferred, to other paper machines within the same company and among other paper mills. Furthermore, the theory can be applied to similar types of industries such as chemical, process industries, and fully automated manufacturing industries, which have high downtime costs.
This chapter aims to build a theoretical foundation upon which the research is based by reviewing the literature relevant to identifying research issues, which are worth researching. Based on this chapter the research problem and research questions that were presented in Sections 1.2 and 1.3 are discussed with respect to other researchers’ work and publication. Figure 3.1 shows the study’s theoretical foundation, illustrating the relationship to the theory of knowledge related to the research problem. However, more a specific and comprehensive related theory is presented in the respective research papers.

The chapter starts by discussing the overall management strategy in Section (3.1) showing the lack of evidence of linkage between maintenance practices and overall corporate strategy. Then Section (3.2) discusses maintenance practices, reviews maintenance approaches, considers maintenance selection methods, illustrates maintenance efficiency and discusses the need to improve plant monitoring decision-making accuracy. Next, Section (3.3) discusses the impact
of maintenance practices on competitive advantages through its impact on business processes. It discusses maintenance costs, savings and profits. And finally it deals with business performance measurement.

3.1 Overall management strategy

By examining the debate on markets and resources one could realise the existence of the two opposing perspectives, i.e. the inside-out perspective and the outside-in perspective, Porter (1985), Barney (1991), De Wet and Mayer (1998) and Pehrsson (2000). Regardless of which perspective is adopted by the manufacturing company’s management the firm should in both cases utilise its valuable and rare resources efficiently and effectively to achieve long-term above-average performance.

Each business or firm needs to develop a clearly established overall management strategy to satisfy its customers’ needs at minimum costs and keeping up the best image. Then each function, e.g. the maintenance function, will have its own strategy within the overall management strategy context. This is despite the fact that many authors and practitioners have acknowledged that maintenance is a major contributor to the performance and profitability of manufacturing companies, see among others Maggard and Rhyne (1992), Foelkel (1998), Ralph (2000), Swanson (2001) and Mitchell et al. (2002). There is evidence of the lack of linkage between maintenance practices and overall corporate strategy, see Ahlmann (1998), Tsang (1998), Coetzee (1999), Tsang et al. (1999), Kutucuoglu et al. (2001) and Mitchell et al. (2002). The maintenance manager must be able to convince top management that maintenance strategies or policies and overall management strategy are interdependent, and that maintenance could produce economic benefits. He must therefore learn to communicate in the language of money, Ahlmann (1984 and 1998).

3.2 Maintenance

Different authors have defined maintenance variously, see among others Moubray (1991), Pintelon and Gelders (1992), (BS 3811:1993), Al-Najjar (1997), Mike et al. (1997). The definitions differ in their scope, i.e. the target of maintenance varies from concentrating on an item only to including the whole process. Tsang et al. (1999) stated that the scope of maintenance management should cover every stage in the life cycle of technical systems (plant, machinery, equipment and facilities): specification, acquisition, planning, operation, performance evaluation, improvement, replacement and disposal.

3.2.1 Maintenance practices

The premise that good maintenance practices are fundamental to success in manufacturing is beyond question. Maintenance practices such as planned maintenance, condition monitoring (CM), autonomous maintenance, preventive
engineering and technical analysis, personnel education and training, systems for planning and controlling work, expert systems, multitasking and team work are considered very essential to achieving world-class performance, Liptrot and Palarchio (2000), Mitchell (2002), and Mitchell et al. (2002). Although good maintenance practice could be “common sense” there is a need to know if it is adopted as “common practice”, and to what extent good maintenance practices are deployed. Furthermore, one must know how to assess the impact of maintenance practices on performance outcomes, Mitchell et al. (2002).

3.2.2 Maintenance approaches
The maintenance concept (as shown in Figure 3.2) has passed through several major developments. Consequently, several maintenance approaches, i.e. various maintenance strategies, policies, methodologies or philosophies, have been implemented by practitioners or suggested by intellectuals, see among others Moubray (1991), Dekker (1996), Al-Najjar (1997), Mckone and Weiss (1998), Sherwin (2000), Swanson (2001) and Mitchell (2002).

![Figure 3.2: Maintenance concept developments](image-url)

Kelly (1997) showed that maintenance strategy involves the identification, researching and execution of many repairs, replacement and inspection decisions. It is concerned with formulating the best life plan for each unit of the plant, and formulating the optimal maintenance schedule for the plant, in co-ordination with production and other functions concerned. Maintenance strategy describes what events (e.g. failure, passing of time, condition) trigger what type of maintenance (inspection, repair or replacement). Maintenance strategy consists of a mix of policies/techniques, which varies from facility to facility, Dekker (1996), Al-Najjar (1997) and Zeng (1997). It depends on several factors such as the goals of maintenance, the nature of the facility or the equipment to be maintained, work flow patterns (process focus, product focus), and the work environment, see among others Gallimore and Penlesky (1988), Pintelon and Gelders (1992) and Al-Najjar (1997).

Usually, maintenance actions are used to control failures of industrial plant, machinery and equipment. These actions can take several forms and make use of various approaches: corrective (breakdown) maintenance, preventive maintenance (PM), i.e. replacing components at a pre-specified time using
statistical models based on collected historical failure data, or condition-based maintenance using data from monitoring the condition of the component/equipment through utilising one (or more) of the condition monitoring (CM) techniques. In all cases, the decision maker needs to select from all the applicable maintenance policies the most cost effective one for each component, module or equipment that suits the operating context. The identification and implementation of the appropriate maintenance policy will enable managers to avoid premature replacement costs, maintain stable production capabilities and prevent the deterioration of the system and its component parts, Vineyard et al. (2000). Knowing what is the right maintenance program for an asset is no easy task. It has nothing to do with the number of years the company has been doing maintenance. For the most part, companies are doing either too much maintenance too early, or too little too late, all of which has cost consequences to the organisation, Liptrot and Palarchio (2000).

3.2.3 Maintenance selection methods

Maintenance decision problems could be classified with respect to the time scale involved. It starts early in the design phase of systems; the type of equipment, the level of redundancy and the accessibility strongly affect the maintainability, Dekker and Scarf (1998). Furthermore, in the operations phase a very critical decision should be made regarding which event (e.g. failure, passing of time, etc) triggers what type of maintenance action, i.e. inspection, repair or replacement. Another classification is with respect to the level at which maintenance decisions need to be taken, i.e. national or company-wide, plant, system, unit or component level.

Making a cost-effective maintenance decision is not an easy task, especially when the production system consists of several different components with different maintenance characteristics and the maintenance program must combine technical requirements with the firm’s managerial and business strategies.

In the literature, it is possible to find methods that can help in selecting the most cost effective maintenance policy or action such as the models used for maintenance optimisation, e.g. age, block and GTTT-plots, see for example Sherwin (2000), Campbell and Jardine (2001) and Al-Najjar (2003). Furthermore, there are sets of rules, such as the systematic approach of maintenance planning applied by reliability centred maintenance (RCM) for selecting the suitable maintenance action, O’Connor (2002). Additionally, there is the method of multiple criteria decision-making (MCDM), which is implemented in some cases. All these methods have different strengths and weaknesses, for example block and age models only deal with PM and require historical failure data, GTTT-plots demand condition-based replacement or failure data, the RCM-procedure does not consider the organisational aspects and MCDM-method does not consider technical analysis before data gathering. Thus, there is a need to develop a method for maintenance selection that is characterised by incorporating the strengths of the above-mentioned methods and avoiding their weaknesses.
3.2.4 Plant monitoring and decision making accuracy

Mechanical and electrical systems in power stations, paper mill machines, hydraulic systems, etc. consist of many sub-systems, components and modules such as rolling element bearings, pumps, motors and gearboxes. Replacing the mechanical parts at the right time, which could be achieved by using condition-based maintenance (CBM) or age replacement at cost-optimised interval, reduces the contribution of each part to the system rate of occurrence of failures (ROCOF) and therefore reduces the ROCOF itself, Sherwin (2000).

If we can assess the condition of the machine’s significant components accurately, we can prolong the mean effective life length of the component, Al-Najjar (2000b). Thus, the machine will not fail so often, and we will not perform maintenance far too frequently. This would improve the overall equipment effectiveness (OEE) and consequently result in higher company savings and enhanced competitiveness.

However, in many cases, in spite of using cost effective maintenance approaches which may be based on sophisticated and advanced techniques, e.g. vibration based maintenance (VBM), machines still experience failure and unplanned but before failure replacement (UPBFR), which result in high economic losses, Al-Najjar (1997). UPBFR replacements are performed at unplanned but before failure stoppages to prevent the occurrence of failures. This situation arises because of a sudden increment in the measured variable(s), e.g. the vibration level, due to the inability to detect the cause(s) of the defect at an early stage. Davies (1998) reported that at present there is insufficient knowledge to understand and predict the behaviour of rotating machinery, which may lead to unpredictable systems failure and an expensive shutdown. However, Sheppard and Scicon (1993) believe that the vital data required for accurate condition monitoring are now available. However, extracting the important information from the mass of data is the problem. Therefore, further research and development are needed in the area of evaluation and analysis techniques of condition monitoring and diagnostics, to provide more effective, accurate and precise knowledge of plant or system conditions, see among others Davies (1998), Al-Najjar (1997), and Williams et al. (1994).

3.3 Maintenance impact on business processes

Most of the operational and maintenance costs of physical assets are linked to decisions taken at an early stage of the machine design. Therefore, it is easier to reduce future maintenance costs at the design stage than at the operational stage, see Blanchard (1986), Husband (1986), Al-Najjar (1997) and Ahlmann (1998).

Maintenance affects production cost effectiveness. It has an effect on the consumption of the various resources used in the company’s processes, Al-Najjar (2000a), and Ralph (2000). Moreover, workplace safety is affected by failure related accidents due to ineffective maintenance, Keller and Huwaishel (1993). Capital investments in the plant are influenced by factors such as
equipment/component useful life, equipment redundancy, extra spare parts inventory, buffer inventory, damage to equipment due to breakdown, extra energy consumption, etc. On the other hand, the capability of the machine to produce quality products, e.g. products that satisfy customer requirements, is highly affected by maintenance effectiveness, Henning (1989), Taguchi et al. (1989), Oakland (1995), Al-Najjar (1997), Ahlmann (1998), and Edwards et al. (1998). Maintenance affects the technical performance and cost effectiveness of the production department, according to Ollila and Malmipuro (1999). The technical performance of the production function can be assessed by so-called overall equipment effectiveness (OEE) in TPM, see Nakajima (1988), or a modified version of OEE, i.e. the Overall Process Effectiveness (OPE), see Sherwin (2000). Efficient maintenance contributes by adding value through better resource utilisation (higher output), enhanced product quality, and reduced rework and scrap (lower input production costs). In addition, it avoids the need for additional investment in capital and people due to expanding the capacity of existing resources, Git (1992 and 1994), Ben-Daya and Duffuaa (1995), Al-Najjar (1997), Ahlmann (1998), Dunn (1998), Ralph (2000), and Swanson (2001).

Maintenance can have an impact on customers, society, and shareholders. Dearden et al. (1999) showed that firms try to capture new customers, satisfy them and retain existing customers by giving them assurance of supply on time, which in turn depends on adequate production capacity with a minimum of disturbances and with high quality products. The impact of maintenance on society can be traced through its effects on safety, on the environment and on ecology, see Keller and Huwaishel (1993) and Rao (1993). Finally, the impact of maintenance on shareholders can be traced by analysing the effect of maintenance on the generated profit, which is usually measured by indexes such as Return on Investment (ROI) percentage, Ahlmann (1984 and 1998). From this we can see that there is a need to know how to assess the impact of maintenance practices on performance outcomes, Mitchell et al. (2002).

3.3.1 Maintenance costs, savings, and profits

Traditionally, maintenance has been considered as a non-productive support function and not as a core function, i.e. as a necessary evil, Bamber et al. (1999), Ralph (2000), Sherwin (2000), Al-Najjar (2000a) and Al-Najjar et al. (2001). Maintenance cost usually consists of direct and indirect costs. Direct (visible) costs comprise factors such as direct labour, e.g. manpower, direct material, e.g. spare parts, and overheads, e.g. tools, transportation, training and methods. Indirect (invisible) costs are all the costs that may arise due to planned and unplanned maintenance actions, e.g., lost production costs, accidents, etc., see among others Blanchard (1986 and 1997), Ahlmann (1984 and 1998), Shonder and Hughes (1997), Wilson (1999), Al-Najjar (1997), Al-Najjar et al. (2001), and Mirghani (2001).

Recently more emphasis has been put on maintenance as a profit generating function. There is talk now of life cycle profit rather than life cycle cost, see among others Ahlmann (1994 and 1998), Jonsson (1999), Wilson (1999), and
Many researchers have been talking about the savings, gains or profits that could be made when implementing more effective maintenance approaches, see among others Ahlmann (1984 and 1998), Maggard and Rhyne (1992), Foelkel (1998), Coetzee (1999), Walsh (1999), Miller (2000), Ralph (2000), Carter (2001), Kutucuoglu et al. (2001), and Swanson (2001). Nothing, however, has been mentioned about how to calculate/estimate the relevant life cycle cost factors, or where to find the required information parameters from the available accountancy system. This is because the impact of the maintenance function can be found in many areas in the company such as production, quality, logistics, etc., Al-Najjar (2000a) and Al-Najjar et al. (2001). Dunn (1998) illustrated that when a breakdown happens, it is often easy to show that a lack of maintenance was responsible. But when breakdowns do not happen, it is not easy to demonstrate that maintenance had prevented them. It is easy to say that maintenance costs so much per year but not what is the gain of that maintenance, and how it can be measured.

### 3.3.2 Business performance measurement

Kutucuoglu et al. (2001) reported there is now a much clearer and more evident acknowledgement of maintenance as a potential profit-generating function than ever, due to factors such as the potential impact of equipment maintenance on flexibility, quality, costs, environmental and employee safety. Equipment maintenance and system reliability are important factors that affect the organisation’s ability to provide quality and timely services to customers and be ahead of competition, see Cooke (2000), and Madu (1999 and 2000). Coetzee (1999) showed that the increased use of various methodologies, techniques, or philosophies to improve the effectiveness and efficiency of the maintenance function in the organisation is a very important step to enable it to cope with the increased importance of the function. But since maintenance is a service function for production, neither the merits nor the shortcomings of the service rendered are immediately apparent, Pintelon and Van Puyvelde (1997). Dwight (1995) showed that it has not been made scientifically credible that there exists a link between the inputs to the maintenance process and the outcomes for the organisation, due to the difficulties of establishing a causal link between actions and outcomes and the determination of organisational goals. He argues that much of the activity related to maintenance is directed towards the future performance of the organisation to the detriment of current performance.

The importance of maintenance to a business strategy can be paradoxical, see Dunn (1998) and McGrath (1999). On one hand, the more maintenance contributes positively to the overall strategic goals of an organisation the less noticeable as a value adding activity it becomes to top management. Instead it might be noticed as just more costs. On the other hand, poor maintenance programs can obstruct the addition of value, retard the advantage of a capital resource, and destroy a business strategy. Appropriate performance measurement systems are crucial to ensure the successful implementation and execution of strategies, since measurement provides the link between strategy and action, see Neely et al. (1995) and Schalkwyk (1998). Therefore, integrating maintenance
into the overall company strategy is essential especially in capital-intensive industries. Actually, there is a need for a holistic performance measurement system that can assess the contribution of the maintenance function to the business strategic objectives, see among others Ahlmann (1998), Tsang (1998), Tsang et al. (1999), and Muthu et al. (2000).
4. Cost Effective Maintenance for Competitive Advantages

This chapter presents the results of the research that are achieved through solving the research questions. It introduces the collected empirical data and their analyses according to the sequence of the research questions discussed in Chapter Two. The relevant literatures, problem formulation and data collecting procedures are presented in the respective research papers.

Notice! The connection between the research questions and research papers was illustrated in Section 1.3. Chapter Five will discuss the findings of Chapter Four and draw general conclusions and implications.

4.1 Maintenance practices in Swedish industry

In the following we present the results obtained for the first research question connected to Paper III in Appendix C.

*Which maintenance practices are used in Swedish industry?*

4.1.1 Maintenance organisation, management systems and status

Data were collected from 118 Swedish manufacturing firms in a survey conducted in the way discussed in the methodology chapter. It was found that about 28% of the firms have no maintenance strategy or policy at all, about 48% have a written maintenance strategy or policy and 24% have an oral one. Also, it was found that about 39% of the firms have a maintenance department that is organisationally independent of the production department, while about 56% are organised as part of the production, whereas about 5% have other organisational relations with production such as an independent company within the mother company that sells service to the production plants. On the other hand, it was found that about 41% have a centralised organisation, 15% have a decentralised organisation, 41% have a combination of centralisation and decentralisation, and about 3% have other types of organisation.
It was found that about 50% of the time is spent on planned tasks, about 37% spent on unplanned tasks and 13% allocated for planning. However, the causes of planned maintenance actions were distributed on average so that 34% were the recommendation of the original equipment manufacturer (OEM), 33% the use of condition monitoring (CM) techniques, 9% the use of statistical modelling of failure data, 7% the use of Key performance measures and 17% other factors such as those based on the company’s own experience, see Figure 4.1.

![Distribution of causes of planned maintenance](image1)

**Figure 4.1** Distribution of causes of planned maintenance

The respondents were asked if they use a computerised maintenance management system at their plants. About 22% answered that they use a manual maintenance management system, about 36% use a computerised maintenance management system (CMMS), about 35% use a combination of a manual system and CMMS and about 7% answered that this question is not applicable in their plant, see Figure 4.2.

![Maintenance management systems types](image2)

**Figure 4.2** Maintenance management systems types
The respondents were asked if they use a CMMS, and if they do that to rate, using a 5-point Likert scale, the level of integration of the CMMS with other company information systems. The Likert scale measures the extent to which a person agrees or disagrees with the question. The scale used was “1=Not integrated” and “5= completely integrated”. It was found that about 29% so not use a CMMS, an answer that confirms results illustrated in Figure 4.2 where the percent of the respondents who use CMMS was 71%. However, among the users of CMMS about 20% are using a CMMS that is not integrated with other company information systems, about 14% of these systems are somewhat integrated, 17% are moderately integrated, 10% are highly integrated and 10% are totally integrated computerised maintenance management systems, see Figure 4.3.

![Figure 4.3 Level of Integration of CMMS](image)

Regarding the attitude to maintenance, it was found that about 70% consider maintenance as a cost centre, 26% consider it as a profit centre and 4% think that it is both a cost and a profit centre. On the other hand, the respondents were asked to estimate the maintenance budget in the year 2002 as a percentage of the production cost. Only 49 valid answers were received, in which the average estimate was about 11% with a range from one to fifty percent. Also, when estimating the budget as a percentage of the turnover, it was found to be on average about 4% with a range from 0.3 to sixty percent. However, the distribution of the maintenance budget among the different tasks and resources is illustrated in Figure 4.4
4.1.2 Identification of maintenance practices using factor analysis

Here we tried to empirically find a construct that can describe the maintenance practices in Swedish industry using exploratory factor analysis. Factor analysis is a statistical approach that can be used to analyse interrelationships among a large number of variables and to explain these variables in terms of their common underlying dimensions (factors), Hair et al. (1998). Therefore, we analysed the 26 variables, i.e. maintenance activities, mentioned in question M1, see Appendix (A), using principal component factor analysis with varimax rotation.

At first we tried to ensure that the data are suitable for factor analysis. Therefore we tested all the variables using both the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett’s test of sphericity. Thus we got a KMO value of 0.789 and a Chi-Square value of 1225 with significance 0.000, see Table b1 in Appendix B. This indicates that the data could be used with factor analysis. The communality values, also confirm that the data are suitable for factor analysis, since they range between 0.450 to 0.835, i.e. there are no values close to zero or one. In addition, the measure of sampling adequacy (MSA) is in the range of 0.480 to 0.905. This means that it is suitable for use in factor analysis since all the MSA values are greater than one-half, and furthermore, the majority are greater than 0.70. Thus, we can derive new factors from the 26 variables, Hair et al. (1998).

Figure 4.4 Maintenance budget distributions
We determine the number of factors using an eigenvalue over one as an extraction criterion. Consequently, we got seven factors that account for about 64% of the variation, see Table b1 in Appendix B. Analysing the factor loading, i.e. the correlation of each variable and the factor, can help deriving the new construct. The loading indicates the degree of correspondence between the variable and the factor. It is the means of interpreting the role each variable plays in defining each factor. It ranges between {minus one: plus one}; the higher loading absolute value makes the variable more representative of the factor. A loading was considered significant if it has an absolute value higher than 0.30, Hair et al. (1998). Knowing that the communalities are defined as the amount of variance accounted for by the factor solution for each variable, the researcher may as a guideline specify that at least one-half of the variance of each variable must be taken into account (ibid). Thus, we can say that more or less all the variables have a communality value greater than or equal to one-half, e.g. only two variables had a value less than 0.5. Since we have got a factor solution in which all the variables have at least one significant loading on a factor, we identified the following seven factors:

1) **The first factor (process oriented “holistic” approach)** includes the following variables that have a significant loading factor, ordered according to the value of their loading:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helping in improving the production process</td>
<td>0.79</td>
</tr>
<tr>
<td>Helping the purchasing department in OEM selection</td>
<td>0.74</td>
</tr>
<tr>
<td>Using cross functional groups</td>
<td>0.64</td>
</tr>
<tr>
<td>Helping designing the production process</td>
<td>0.62</td>
</tr>
<tr>
<td>Using company wide information for diagnosis</td>
<td>0.56</td>
</tr>
<tr>
<td>Performing periodic planned replacements</td>
<td>0.42</td>
</tr>
</tbody>
</table>

2) **The second factor (autonomous approach)** includes the following variables:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording the periods and frequencies of failures</td>
<td>0.84</td>
</tr>
<tr>
<td>Recording the periods and frequencies of short stoppages</td>
<td>0.82</td>
</tr>
<tr>
<td>Recording poor quality rates</td>
<td>0.73</td>
</tr>
</tbody>
</table>

3) **The third factor (predictive approach)** includes:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using CMMS</td>
<td>0.67</td>
</tr>
<tr>
<td>Investing in training and competence</td>
<td>0.61</td>
</tr>
<tr>
<td>Off-line monitoring</td>
<td>0.58</td>
</tr>
<tr>
<td>On-line monitoring</td>
<td>0.52</td>
</tr>
<tr>
<td>Performing maintenance tasks based on CM</td>
<td>0.51</td>
</tr>
<tr>
<td>Performing maintenance tasks based on Statistical modelling</td>
<td>0.51</td>
</tr>
<tr>
<td>Analysing equipment failure causes and effects</td>
<td>0.41</td>
</tr>
</tbody>
</table>
4) The fourth factor (diagnostic “expert system” approach) includes:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote diagnostic</td>
<td>0.82</td>
</tr>
<tr>
<td>Automatic diagnostic</td>
<td>0.75</td>
</tr>
</tbody>
</table>

5) The fifth factor (Traditional Preventive approach) includes:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performing maintenance tasks based on OEM recommendations</td>
<td>0.80</td>
</tr>
<tr>
<td>Using failure data</td>
<td>0.62</td>
</tr>
</tbody>
</table>

6) The sixth factor (reactive approach) includes:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installing new equipment</td>
<td>0.73</td>
</tr>
<tr>
<td>Fire fighting (acute maintenance)</td>
<td>0.64</td>
</tr>
<tr>
<td>Having WIP between the machines</td>
<td>0.49</td>
</tr>
<tr>
<td>Performing annual overhauls</td>
<td>0.48</td>
</tr>
</tbody>
</table>

7) The seventh factor (strategic approach) includes:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keeping low level of spare parts inventory</td>
<td>0.74</td>
</tr>
<tr>
<td>Decreasing repair time</td>
<td>0.68</td>
</tr>
</tbody>
</table>

4.2 Maintenance selection in Swedish industry

In the following we present the results obtained from the second research question that is connected to Paper III in Appendix C.

How maintenance policies are selected in Swedish industry

As can be seen in Paper III, by means of factor analysis, we could identify three main groups from the respondents’ answers of how much emphasis is placed on a set of aspects when deciding on or selecting a maintenance policy. The first group is called the business oriented group because there they try to achieve competitive advantages through concentrating on aspects such as machine availability, reducing lost production costs, machine reliability, smooth production, product quality, on-time delivery, replacement costs, cost effectiveness and investment costs. The second group is labelled the greens because they focus mainly on aspects related to health, safety and the environment. The third group was labelled the followers because they only work according to the original equipment manufacturers’ recommendation and company policy.

It was found that most of the firms, i.e. 81%, do not use a specific method when selecting their maintenance policy, but use the knowledge and experience accumulated within the company. Besides, about 31% of the respondents use a method based on modelling the time to failure and optimisation when selecting a
maintenance policy. While about 10% use \textit{FMECA and decision trees} in their selection and only 2% use \textit{MCDM}. On the other hand, about 6% have mentioned using other maintenance selection methods such as monthly lists, documentation and experience, major overhauls twice a year, maintenance cost, manufacturer recommendations, risk analysis and their own databases, see Figure 4.5.

![Figure 4.5](image)

\textit{Figure 4.5 Maintenance selection methods used in Swedish Industry}

It should be noticed that about 30 percent of the respondents use combination of at least two methods at the same time, for example, experience and FMECA or experience and modelling and optimisation. This explains why the total percent illustrated in Figure 4.5 exceeds 100%.

\subsection{4.2.1 Features of an ideal maintenance selection method}

A set of features was suggested and discussed in Paper II as ideal features for a maintenance selection method. These features are:

<table>
<thead>
<tr>
<th>Feature No.</th>
<th>Maintenance Selection Method Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Ability to be used across all maintenance approaches</td>
</tr>
<tr>
<td>F2</td>
<td>Dependability on failure-data</td>
</tr>
<tr>
<td>F3</td>
<td>User friendliness</td>
</tr>
<tr>
<td>F4</td>
<td>Utilizing personnel knowledge and experience</td>
</tr>
<tr>
<td>F5</td>
<td>Considering financial aspects adequately and consistently</td>
</tr>
<tr>
<td>F6</td>
<td>Considering technical analysis before data gathering</td>
</tr>
<tr>
<td>F7</td>
<td>Ability to consider organisational aspects</td>
</tr>
<tr>
<td>F8</td>
<td>Ability to measure cost effectiveness</td>
</tr>
<tr>
<td>F9</td>
<td>Flexibility (allowing feedback and continuous improvements)</td>
</tr>
<tr>
<td>F10</td>
<td>Ability to consider the plant holistically</td>
</tr>
</tbody>
</table>
The respondents were asked to rate the importance of these features using a 5-point Likert scale. The Likert scale measures the extent to which a person agrees or disagrees with the question. The scale used was 1=Not Important and 5=Very Important. As can be seen in Figure 4.6, all the features got a mode value greater than three, which confirms that these features should be available and employed in an ideal maintenance selection method. The mode measure was used since we are dealing with an ordinal scale, which means that the answers have an inherent order or sequence, and therefore the mode or median could be used. However the mode is probably the most suitable alternative for easy interpretation.

![Figure 4.6 The rank order of importance of maintenance selection method features as assessed by the respondents](image)

4.2.2 Characteristics of maintenance selection methods used

The respondents were asked to evaluate the maintenance selection method(s) that they use the most at their plants with respect to the ideal features. They were asked to rate the capability of the method using the 5-point Likert scale, where 1=Bad and 5=Good. An example of the assessment of the method depending on accumulated knowledge and experience is illustrated in Figure 4.7. As we can see, utilizing personnel knowledge and experience, i.e. F4, obtained a mode value of five, which means that this method is rated as completely good in 10% of the features. Also, we can see that this method is deemed rather good in 30% of the features, i.e. its ability to be used across all maintenance approaches (F1), its user friendliness (F3) and its ability to consider organisational aspects (F7). On the other hand, it is considered completely bad in 10% of the features, i.e. its ability to measure cost effectiveness (F8). The assessment results of the other methods are presented in Paper III.
4.2.3 Empirical evaluation of maintenance selection methods

The maintenance selection methods used by Swedish industry were evaluated using MCDM methodology. They were assessed with respect to their capability to fulfil the features of an ideal maintenance selection method. A rank ordering was performed based on the mode value of the respondents’ assessment of both the importance of the features of maintenance selection methods and the capability of each maintenance selection method to fulfil these features. It was assumed that the value of the mode corresponds to a metric measure with a ratio scale ranging between zero and five. By means of the MCDM methodology suggested in Paper I a score representing the capability of each selection method to satisfy the ideal features was obtained using the simple additive weighting (SAW) method for decision-making. Then, a normalised rank order, with a range between zero and one, was obtained by dividing the SAW score of each selection method by the summation of the total SAW scores.

It was found that FMECA, which is related to the RCM procedures, obtained the first rank according to the evaluation methodology. The Modelling and Optimisation method came next, third came the knowledge and experience method and finally the multiple criteria decision making (MCDM) maintenance selection method with a small marginal difference, see Figure 4.8. Note that the
sample size used to evaluate the *MCDM maintenance selection method* is very small.

![Figure 4.8](image)

**Figure 4.8** Rank order of maintenance selection method using MCDM methodology
4.3 A technique for selecting the most cost effective maintenance policy

In the following we present the results obtained from the third research question connected to Paper I, Paper II and Paper III in Appendix C. In this section we introduce a practical model that enables the maintenance manager to select and improve the most cost effective maintenance policy. This section describes the results achieved by answering the third research question:

*How to select the most cost effective maintenance policy?*

### 4.3.1 Fuzzy MCDM for maintenance selection

In Paper I a fuzzy MCDM evaluation methodology was developed for selecting the most informative maintenance approach. The most informative maintenance approach is considered the most cost effective one if it utilises the available information cost effectively. The objective is to rank the maintenance approaches by evaluating their ability to provide information about the changes in the behaviour of failure causes that are used as criteria, as illustrated in Table 4.2.

<table>
<thead>
<tr>
<th>Failure cause (Criterion)</th>
<th>( C_1 )</th>
<th>( C_j )</th>
<th>( C_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance Approach (Alternative)</td>
<td>( \tilde{W}_i )</td>
<td>( \tilde{W}_{i2} )</td>
<td>( \tilde{W}_{in} )</td>
</tr>
<tr>
<td>( A_1 )</td>
<td>( \tilde{R}_{i1} )</td>
<td>( \tilde{R}_{ij} )</td>
<td>( \tilde{R}_{in} )</td>
</tr>
<tr>
<td>( A_i )</td>
<td>( \tilde{R}_{i1} )</td>
<td>( \tilde{R}_{ij} )</td>
<td>( \tilde{R}_{in} )</td>
</tr>
<tr>
<td>( A_m )</td>
<td>( \tilde{R}_{mi} )</td>
<td>( \tilde{R}_{mj} )</td>
<td>( \tilde{R}_{mn} )</td>
</tr>
</tbody>
</table>

The decision problem is composed of a matrix of m maintenance approaches rated on a set of n failure causes (criteria) that are applicable to the case in question. \( W = \{ w_j, \text{ for } j = 1, 2, \ldots, n \} \) is a set of fuzzy numbers (weights) on the unit interval [0 1] denoting the importance of considering the jth failure cause (criterion) \( C_j \). Let \( R = \{ R_{ij}, \text{ for } i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \} \) be a set of fuzzy number, also, on the unit interval {0 1}, denoting the rating (capability) of the ith maintenance approach on detecting changes in the jth criterion using a suitable measure. The suggested methodology consists of five main phases as illustrated in Figure 4.9:
Assessment of the importance of considering the failure causes (criteria) using a fuzzy linguistic variable.

Assessment of the capability of the maintenance approaches, using a Fuzzy Inference System (FIS) that results in an assessment of the fuzzy linguistic variable.

Defuzzifying of the fuzzy linguistic variables.

Rank ordering the approaches using simple additive weighting (SAW).

Selecting the most informative (efficient) maintenance approach.

For more details, see Paper I, where two examples illustrate how the suggested evaluation methodology could identify the most informative approach.
4.3.2 A practical model for maintenance selection

In Paper II, a review of the relevant literature identified the main methods that are suggested or being used for selecting maintenance policies. These methods are: *Maintenance Optimisation* (both graphical and non-graphical); *Reliability Centred Maintenance (RCM)* and *Multiple Criteria Decision-Making (MCDM)*. In the following we present a model that was suggested as a result of analysing the matrix diagram illustrated in Table 1 in Paper II. It was possible to identify the strength and weakness of the available maintenance selection methods, which enabled us to highlight the gaps in these methods. Consequently, we developed a practical model for selecting and improving the most cost effective maintenance policy.

**Model development**

The model proposed in Paper II and shown in Figure 4.10, is based on the continuous improvement concept (i.e. Plan, Do, Check, Act) known as the PDCA-cycle. It is recommended that an improvement group that includes representatives from all the relevant working areas and is authorised by the top management perform this work. The planning phase consists of four main stages:
Figure 4.10 Conceptual model for selecting and improving the most cost effective maintenance policies
Stage 1
The initiation of the selection process could take place periodically or whenever there is a need. The first stage depends on gathering relevant data and performing technical analyses to assess the current state of the component, equipment or plant. In this stage it is necessary to identify the production characteristics, the most critical production machine or line, damage causes, failure modes and consequences, the maintenance concept used, and the current estimate of the overall equipment effectiveness (OEE), which includes availability, performance efficiency and quality rate. In addition, all the technically applicable maintenance policies should be identified.

Stage 2
In the second stage, when considering significant components or equipment (e.g. rolling element bearings in a machine or sub-system), the GTTT-plot method can be used, if historical failure data or on condition replacement data or both are available for all the applicable maintenance policies. Thus the decision-maker can get a list of the applicable maintenance policies ranked according to the long-term cost per unit time. When considering a new plant, machine, component and maintenance policy or when there are no historical (failure or condition) data, the selection can be made using the fuzzy MCDM method. That could end up with a list of the maintenance policies ranked according to their ability to provide and utilise more information.

Stage 3
The selection of the most cost effective maintenance policy should be based on a method that enables the user to build a holistic view of the production process through considering all relevant aspects. Therefore, the ranking of the applicable maintenance policies is based on the following:

1. The assessed value of OEE,
2. The ability of each applicable maintenance policy to improve current OEE,
3. The required investment needed to apply each maintenance policy.

Then the benefit/cost ratio of each maintenance policy should be calculated. After that, the applicable maintenance policies could be ranked with respect to the value of the benefit/cost ratio. Consequently, the decision maker can select which maintenance policy is the most cost-effective based on the highest benefit cost ratio and the available budget.

Stage 4
The previous procedures illustrated in stage 3 should be repeated for all machines or equipment in order to select the most cost-effective maintenance policy for the whole machine, production line or plant. When we are ready with the plan phase in the PDCA-cycle, we continue with the remaining phases, i.e. Do-Check-Act, which are represented by the following three stages:
Stage 5 (Do)
Based on the results obtained by the planning phase, the working group is given the task of implementing the most cost effective maintenance policy(ies). It is of great importance to make everyone involved fully aware of the requirements of the implementation process such as the technical and organisational aspects.

Stage 6 (Check)
When appropriate steps have been taken, the results of the implementation process should be investigated to control its cost effectiveness. This could be achieved by measuring and evaluating the results with respect to the expected performance.

Stage 7 (Act)
If the results obtained in stage 6 were not satisfactory, we have to go through the cycle once more. However, if the results were successful, the implemented maintenance policy(ies) should be adopted for longer application. It is very important to repeat the whole process periodically, i.e. every three to five years or when there is a need, due to the fact that market and technical changes occur.

4.4 Effective condition based maintenance decision making

In the following we present the results obtained by solving the fourth research question, which is connected to Paper IV and Paper V in Appendix C. The fourth research question was stated as:

How to improve the effectiveness of condition based maintenance (CBM) decision-making?

Complex manufacturing systems are becoming more sensitive to disturbances, and cannot tolerate expensive and unpredictable behaviour. Therefore the availability and reliability of manufacturing systems are vital, and the importance of using effective decision-making systems is increasing. In order to ensure the optimum performance of automated manufacturing systems, various condition-monitoring techniques are used.

When dealing with vibration-based maintenance (VBM), the condition of significant parts (e.g. rolling element bearings) cannot be assessed effectively, i.e. with high certainty, without considering both probabilistic and deterministic aspects of the deterioration process. Modelling the time for maintenance action and predicting the value of the vibration level when damage of a significant component is detected are examples of the probabilistic part, which is discussed in Paper IV. However, issues related to machine function, failure analysis and diagnostics are examples of the deterministic part that is discussed in Paper V.
4.4.1 Mechanistic model for predicting the vibration level

When a potential failure (damage under development) of a significant component is detected, predicting the value of the CM parameter, e.g. vibration level, during the interval until the next measurement or planned stoppage, accurately, would enhance the effectiveness of decision-making process. A model for predicting the CM parameter, e.g. vibration level, during the next period and until the next measuring moment was developed by Al-Najjar (2001). In Paper IV we reformulated the model as illustrated by equation 4.1. Let \( Y \) be the dependent variable representing the predicted value of the vibration level. It is the function of three independent variables \((X, Z & T)\) and three parameters \((a, b \text{ and } c)\). For \( i=1, 2...n \), and \( i \) the number of measuring opportunities after damage initiation.

\[
Y_{i+1} = X_i + a \exp(b_i T_{i+1} Z_i^c) + E_i
\]  

(4.1)

Where

\( Y_{i+1} \) : The predicted value of the vibration level at the next planned measuring time.

\( T_{i+1} \) : The elapsed time since the damage is initiated and its development is detected.

\( X_i \) : The current vibration level value.

\( Z_i \) : The deterioration factor, i.e. the function of the current and anticipated future load and previous deterioration rate.

\( a \) : The gradient (slope) by which the value of the vibration level varied since it started to deviate from its normal state \((x_o)\) due to initiation of damage until detecting it at \( x_p \).

\( b_i \& c_i \) : Non-linear model’s constants.

\( E_i \) : The model error, which is assumed to be identical, independent and normally distributed with zero mean and constant variance, \( N(0, \sigma) \).

To test and verify the model two tests were performed. The first test was based on conducting an experiment at the department’s CM laboratory and the second test was based on real data collected from a Swedish paper mill. In both cases the model was able to predict the value of the vibration level accurately.

Figure 4.11 shows the results achieved when testing the model using laboratorial experiment data. As we can see, the model can predict the value of the vibration level with an absolute error that ranges from –1.14 to 0.77 mm/sec with an error mean value of 0.15 and a standard deviation of 0.51. The model is capable of adapting to the changes that are taking place within the machine’s operating condition. It can be seen that the model learns from the experience encountered in the recent performance, i.e. the predicted value follows the trend and latest development in the recent vibration level actual value. For example, in measuring opportunity number eight the actual value was smaller than the
predicted value (which could happen in real life applications), and therefore, for the next point (measuring opportunity number nine) the model was adapted and predicted a value that goes with the actual changes experienced recently, i.e. with a decreased rate. Then, again since the actual reading at measuring opportunity number nine was higher than the predicted value, the model adapted again and predicted a value with an increasing rate at point 10, and so forth. Furthermore, by eyeballing the trend for the actual and predicted points we can see that both sets of points can be fitted by more or less the same curve. We can see that the error, i.e. the dispersion between the predicted value of the vibration level and its actual value, is decreasing with time.

![CM Parameter Value Graph](image)

Fig. 4.11. The actual CM value, the predicted CM value and the error obtained when predicting the CM parameter value

To verify the model in a real life application, real vibration data collected about a spherical roller bearing installed at the lead roller of a paper mill machine were used. It was found that the model could predict the value of the CM parameter with an absolute error that ranges from –0.47 to 0.04 mm/sec with an error mean value of –0.18 and a standard deviation of 0.26. For more details see Paper IV

### 4.4.2 Improving the effectiveness of decision-making systems

To improve the accuracy of decision making, more attention, in the literature, is paid to integrating and interpreting richer information from the fusion of multiple sensor data, reducing noise and obtaining the most reliable extracted features. But less attention was devoted to the integrated CM system, which enables the user to evaluate a multi-variant system based on the data collected from different
sources such as CM transducers, maintenance, quality, production, accountancy, machine tools and process monitoring. On the other hand, although expert systems help analysts dealing with information and decision-making by accepting data from multiple sources, and then using a model and rule-based programming to diagnose a problem, we believe that there exist additional elements, which should be considered to increase the expert system’s effectiveness.

The manufacturing system that consists of the machines, tools, materials, product, quality control system, manufacturing methods and management, can be monitored and controlled by implementing the most cost effective maintenance policy. In Paper V, a new approach to an expert system concept is suggested. It benefits from the advantages of a common database, artificial neural network and fuzzy logic, and applies an expert system method in a more effective and reliable way. Using a common database ensures that the required data for particular purposes are available and continuously updated. The user interface is added to the expert system to provide a user-machine-expert system link, which in addition to the common database enables the expert system to be more flexible and continuously improved based on the new experience gained by the user or others. At the same time, artificial neural network, fuzzy logic and fuzzy neural network algorithms can be utilised in the inference engine part to enhance the certainty of data and remove any ambiguity or noise from the signal. Also, using fuzzy neural networks enables the controller to take proper action at the suitable time, due to their ability to reduce the time needed for learning. Finally, the beneficial integrated information available in the common database, which provides more accurate and comprehensive perception of the condition of the manufacturing system, production, product quality and costs results in more accurate diagnosis/prognosis and decisions. For more details see Paper V.
4.5 Maintenance contribution to business strategic objectives

In the following we present and discuss the results of solving the fifth research question.

*How to assess the contribution of maintenance function to the business strategic objectives?*

We demonstrate some of the results of a case study that was conducted at StoraEnso Hylte AB (a paper company in Hyltebruk in southern Sweden). The complete results can be found in Paper VI, Paper VII and Paper VIII in Appendix (C).

4.5.1 Assessment of maintenance cost, savings and profit.

To fill the need of having a model for assessing maintenance costs, potential savings and profits a new model was developed in Paper VI, see Figure 4.12. At first, the model’s cost factors are identified, from which the relevant technical and economical input-data are determined. The next step is to know where to find these input-data in the accountancy system available. Moreover, suitable formulas are used for assessing the model’s output discussed in Paper VI.
Identification of the model's cost factors

Determining the technical and economic input data

Where to find the input data in the Plant Databases?

Equations to calculate or estimate the model’s factors

A) Potential saving (economic losses)
B) Direct Maintenance Cost
C) Investments in maintenance

D) Savings that could be achieved due to more effective maintenance policy
E) Maintenance profits

F) Maintenance measures

Analyzing tools, e.g. Pareto diagram

Problem identification

Decision-making

Recoverable expenses

Changes

Maintenance investment

Figure 4.12 Maintenance cost, savings and profits model
Case study results
The case study was conducted at a Swedish paper mill company. The data collected were delimited to only stoppages of mechanical components that were monitored by vibration signals. The study was conducted at PM2, one of the company’s four machines. It was selected due to its valuable database, especially during the period studied (1997-2000). A special data sheet was designed for collecting manually the relevant technical and economic information parameters from the company databases. We think that one of the reasons behind the unavailability of certain data is that these data had not been needed before for analysis. The other is that these data were either hidden or confused with other data.

Model validation
The conceptual model shown in Figure 4.12 was validated using the data collected from the case company. As the economic data were confidential, the data used in the analysis were transformed by several suitable factors, which still allowed accurate analysis. The total maintenance investment in PM2 both in general and training, on average, was about 0.455 MSEK (about 45.5 thousand USD) per year. The total economic losses (potential savings) consist of the summation of profit losses and the costs of unutilised resources, e.g. the fixed cost of an idle machine, during the time in which the machine is not producing due to failures, UPBFR, planned stoppages, and short stoppages. The economic losses due to bad quality products caused by maintenance deficiency and tied up capital due to extra spare parts inventory are considered as part of the potential savings, too. On average the total potential saving was about 30 MSEK (about three million USD).

The maintenance department has been implementing VBM for several years. Therefore, their long experience and competence in VBM enabled them to achieve high technical efficiency and precision. For example, the average number of failures was only one failure per year with an average time of about 1.6 hours. Furthermore, the average number of UPBFR was about 3.25 per year, with an average time of about 4.07 hours per stop. Moreover, they managed to integrate the VBM with the production schedule. According to the production schedule, the paper-mill machine is stopped every other week on average for about eight hours on the basis of technical production reasons. Therefore, the maintenance department planned and performed based on VBM recommendations, throughout the time window initiated by the production department, on average about 12 replacements of rolling element bearings per year. Consequently, the minimum saving achieved due to performing these maintenance tasks was estimated to be on average about four MSEK (about 0.4 million USD), see Figure 4.13.
4.5.2 Maintenance impact on productivity and profitability

In the following we illustrate using empirical data how maintenance practices could increase manufacturing company productivity, and hence its competitiveness and profitability. This work is related to Paper VII in Appendix C.

In general, improvements in maintenance aim to reduce operating costs and improve product quality; therefore, the cost effectiveness of each improvement action could be examined by assessing the relevant cost parameters before and after improvements. Figure 4.14 illustrates the relationship of quantity of good quality items produced with both total cost per unit (TC/unit) curve and product price. Here we assume that the product has a constant price and unchanged input costs. Furthermore, the market is in a boom condition, i.e. there is high demand in the market. Knowing that the total cost consists of variable cost and fixed cost, the variable cost per unit quality item is assumed to be constant in the short run, while the fixed cost per unit quality item decreases with the quantity produced.

We assume that Q1 is the quantity of quality product produced when using a certain maintenance policy, which resulted in total manufacturing cost TC1, see position 1 in Figure 4.14. If the company improves the implemented maintenance policy, or uses a better maintenance policy that requires a new investment of (I), this could result in increasing the quantity produced to Q2. Assuming that no other actions were performed, then, the new total manufacturing cost (following the same curve) has a value of TC2. Consequently the impact on the company profitability can be estimated using the equations 4.2 to 4.4 as:

\[
\begin{align*}
\text{Profit after improvement } & \text{ } F_2 = Q_2 \text{ (Price-TC2)} \quad (4.2) \\
\text{Profit before improvement } & \text{ } F_1 = Q_1 \text{ (Price-TC1)} \quad (4.3) \\
\text{Net Profit} & \text{ } = F_2 - F_1 \quad (4.4)
\end{align*}
\]

Figure 4.13. Estimated yearly average total investment, potential savings, and maintenance savings for one paper mill machine
If the net profit achieved is greater than the cost of improvement, i.e. \( I \), required for achieving the increase in output, then the investment is cost effective. The relation between the costs of investment needed to improve maintenance effectiveness, e.g. reduced breakdowns, and the expected savings is not easy to predict. As far as the absolute level of maintenance improvement is concerned, there is a finite limit to the impact that maintenance improvements can have upon the generated savings. In other words, after some point diminishing returns will start. Beyond this point we are in a region where additional investment on improving maintenance does not give payback.

**Case study results**

In this part of the case study that was conducted also at StoraEnso Hylte AB, both technical and financial data were collected, although the technical data were not restricted to stoppages of mechanical components, but also covered other types of stoppages such as electrical, hydraulic and instrument stoppages. Technical data included parameters such as planned operating time; planned production rate; planned stoppage time; unplanned stoppage time, i.e. failures and unplanned-but-before-failure replacements (UPBFR); short stoppage time; bad quality products. Further, financial data were collected, including parameters such as fixed and variable operating costs, profit margin, net profit, working capital, maintenance costs, investments in maintenance and spare parts inventory. As the economic data were confidential, the data used in the analysis were transformed using several suitable factors, which still allowed accurate analysis.
It was found that 5.8% of the planned working time, the machine was stopped for several reasons such as failures and UPBFR, planned stoppages and short stoppages. The total stoppage time was distributed as short stoppages, 48%, unplanned stoppages, 34%, and regular planned stoppages, 18%, see Figure 4.15.

Figure 4.15 Causes of total stoppage time at one paper-mill machine

The short stoppage constitutes the largest portion of the stoppage time; on average it amounted to about 1624 short stoppages. Regular planned stoppages (about eight hours each) were planned, in general, every other week to perform certain tasks ordered by the production department. This planned stoppage time creates a great opportunity that could be utilised to perform pre-planned maintenance tasks if the right maintenance policy is implemented. The causes of the unplanned stoppages and the percentage of each with respect to the total unplanned stoppages are illustrated in Figure 4.16.

Figure 4.16 Causes of unplanned stoppage time at one paper-mill machine
In this study, it was found that the actual annual quantity produced during the case study period, i.e. the years 1997-2000, was \( Q_1 = 176,963 \) tons. The average selling price was about 3000 SEK per ton. The average total production cost, i.e. \( TC_1 \), at \( Q_1 \) was about 1949 SEK per ton, and the fixed cost per ton was about 724 SEK. The average quantity of production lost because of unavailability due to all types of unplanned stoppages such as mechanical, electrical and hydraulic, was 3775 tons. The average quantity of bad quality production lost due to causes related to maintenance problems was about 432 tons. This figure was estimated according to the company personnel’s experience at about 7.5% of the total bad quality production. This means that if, ideally, an effective maintenance policy is used which can get rid of all the unplanned stoppages and all the bad quality production related to maintenance problems, the new output quantity, i.e. \( Q_2 \), could amount to 181,170 tons. Thus, the new fixed cost per ton would be about 707. Thus total production costs, i.e. \( TC_2 \), would be about 1932 SEK per ton.

Based on the above-mentioned data, the productivity index calculated at point \( Q_1 \) is about 1.539. Also, the value of productivity index could be improved to about 1.553 at \( Q_2 \). This means that the productivity index of one paper machine, i.e. PM2, could be improved by an increment of about 0.014 if a better maintenance policy is used. Thus, the ideal net impact on the company profit without the cost of investment can be calculated using equations 4.2 to 4.4 as:

\[
\begin{align*}
F_2 &= 181,170 \times (3050-1932) = 202.6 \text{ million SEK} \\
F_1 &= 176,963 \times (3050-1949) = 194.8 \text{ million SEK} \\
F_2 - F_1 &= 7.8 \text{ million SEK}
\end{align*}
\]

This means that in this case, ideally, at least 7.8 million SEK (approximately US$ 0.975 million) per year could be gained as a result of the productivity improvement of one paper machine, if a better maintenance policy had been used. This value will increase according to how the maintenance actions are linked to the causes of other elements of the overall equipment effectiveness, i.e. short stoppages and planned stoppages. Practically, we cannot avoid all unplanned stoppages. To assess the cost effectiveness of a new investment in maintenance, the savings increment due to the output achieved by improving maintenance could be compared to the investment needed.

This represents the economic effect of maintenance due to its impact on the profit margin value only. In addition, there are other factors such as the lost expenses due to not utilising the fixed cost elements such as idle labour or idle machine. On the other hand, there is a possibility in the long run to decrease the total manufacturing costs (when using a more efficient maintenance policy) due to the maintenance effect of elements such as less tied capital in raw materials, work in progress (WIP), and finished goods. Furthermore, the price could be improved by providing value advantages to the end customer such as on time and consistent delivery.
4.5.3 A strategic approach to measure maintenance performance

A strategic approach to maintenance management has become essential, especially in capital-intensive industries. The impact of maintenance actions cannot be viewed only from their effect on the maintenance department, since the consequences of maintenance actions may seriously affect other units of the organisation. Actually, there is a need for a holistic performance measurement system that can, among other things, assess the contribution of the maintenance function to the business strategic objectives and provide feedback information about all relevant areas of business operations for the success of continuous improvement efforts (Plan-Do-Check-Act). Hence, the traditional performance measurement system that is based only on financial measures became inadequate. Therefore, a modified balanced scorecard (BSC) model adapted to measure maintenance performance is suggested in Paper VIII.

When the BSC model was tested, i.e. the case study discussed in the previous section, it was found that the calculated Overall Equipment Effectiveness for one paper machine is about 91%. However, when considering the major planned stoppages and yearly vacations, a new measure called Total Overall Equipment Effectiveness (TOEE) was suggested and calculated to be about 85%. Figure 4.17 illustrates the causes of unproductive time that resulted in the TOEE value. They are distributed among 44% planned inoperative time that consists of major planned stoppages and yearly vacations; 19% bad quality representing all unaccepted production; 19% unavailability consisting of the time lost due to unplanned stoppages and 18% performance inefficiency representing short stoppages.

![Figure 4.17 Causes of unproductive time at one paper machine](image)

The economic consequence, i.e. profit losses, of the measured TOEE has the potential to increase the Return On Investment (ROI) by an absolute value of about 1.47, i.e. about a 9% increase in the ROI value. The potential increment in ROI is equivalent to about 67 million SEK.
Finally, the cause-effect relationship for the suggested BSC model when used to measure maintenance performance at one paper machine is illustrated in Figure 4.18.

**Figure 4.18** Impact of maintenance on company performance as measured by the balance scorecard
5. Results, Conclusions and Implications

This chapter shows the main research results, the conclusions and how this research makes a distinct contribution to the body of knowledge. As was illustrated in Chapter One, the main research problem is how to select and improve the most cost-effective maintenance policy and how to assess its financial impact. The overall objective of the thesis is to study the impact of maintenance practices on companies’ performance outcome. The objective was investigated based on five research questions related to eight research papers.

5.1 Research results and conclusions

In the following we discuss the findings, i.e. research results and conclusions, obtained for each research question.

5.1.1 Maintenance practices

Based on the data collected from a survey conducted in Swedish industry related to the first research question (i.e. which maintenance practices are used in Swedish industry?) and the empirical results and analyses illustrated in Paper III, the following findings were achieved:

- A better understanding of maintenance organisation, management systems and maintenance status in Swedish industry.
- Knowledge about which maintenance approaches (strategy, policy or technique) are used in Swedish industry.

The main conclusion is that although preventive and predictive maintenance approaches are emphasised in Swedish industry, there is much room for improvements to be made. For example, about one third of the planned tasks is initiated based on the OEM recommendations only and this may not be the best policy to use because the context (e.g. the working environment, speed, load, etc) may be not considered. Furthermore, another third of the planned tasks is based on the use of various CM techniques, in which visual inspection is the most emphasised but may not be the most cost effective one. On the other hand, the majority, i.e. about 70% of the respondents, still consider maintenance as a cost centre.
5.1.2 Maintenance selection

Based on the data collected from a survey conducted in Swedish industry related to the second research question (i.e. How are maintenance policies selected in Swedish industry?) and the empirical results and analyses illustrated in Paper III, the following findings were arrived at:

- **Classification of the factors considered important when selecting maintenance policy.** Thus, the following three factor sets were identified, where both the factor and group using that factor were labelled, respectively, as follows: (competitive advantage: business oriented), (safety and environment: the greens) and (instructions: the followers).

- **Identification of which maintenance selection methods are used in Swedish industry.** As a result, it was found that the maintenance selection methods reviewed and discussed in Paper II are implemented in industry at different levels of use. The most common maintenance selection method, i.e. company experience and knowledge, is not the most satisfactory one to its users. Besides, about 30% of the firms use more than one maintenance selection method for different circumstances or situations.

- **Assessment of the importance of a set of ideal features of a maintenance selection method.** As a consequence, it was found that all the features suggested and discussed in Paper II as ideal features for maintenance selection methods were considered important by the respondents. However, none of the applied maintenance selection methods fulfils the requirements of ideal maintenance selection method features to a great extent, e.g. only 10% of the features got a mode value of five in only two methods. In addition, they are different with respect to which features receive the more emphasis in each method.

- **Using an MCDM method to rank order the implemented maintenance selection methods.** Hence, it was found that FMECA is the most satisfactory method, followed by modelling the time to failure and optimisation method, after which comes the companies’ own knowledge and experience method and finally the MCDM maintenance selection method.

From the above results we conclude that none of the implemented maintenance selection methods is adequate and capable to satisfy all the firm’s needs, i.e. the ideal maintenance selection method features. This means that there is a need in industry for a maintenance selection method that integrates the strengths of the available maintenance selection methods and avoids their weaknesses.
5.1.3 Selecting the most cost effective maintenance policy

The main results achieved from the third research question (i.e. How to select the most cost effective maintenance policy?), which is related to Paper I, Paper II and Paper III, can be summarised as follows:

- In Paper I a fuzzy MCDM methodology for selecting the most informative maintenance approach was developed and illustrated using two examples based on typical data.
- In Paper II a model for selecting and improving the most cost effective maintenance policy was developed. It is based on the continuous improvement method, i.e. Plan, Do, Check and Act. It is characterised among other things by being general, since it can be used for selecting from all types of applicable maintenance policies and also for selecting a maintenance policy for both new and existing plants or machines regardless of the availability of historical failure data.
- In Paper III it was found that there is a need in industry for a maintenance selection method that integrates the strengths of the available maintenance selection methods and avoids their weaknesses.

This means that the model suggested in Paper II for selecting and improving the most cost effective maintenance policy will, with a high probability, satisfy the requirements of ideal maintenance selection method features, since it is based on the integration of the four methods used by industry. This is because it integrates the strength of the maintenance selection methods used in industry and avoids their weaknesses. Therefore, it could be considered very strong in fulfilling all the ideal maintenance selection feature requirements as discussed in Paper II.

We can conclude that using the practical model developed and suggested in Paper II, it would be possible to select the most cost effective maintenance policy(ies) and improve it (them) continually. This will enhance the overall equipment effectiveness (OEE) of the machine and process, which could be achieved, for instance, through the maintenance impact on stoppages and on poor quality caused by maintenance ineffectiveness. Improving the OEE cost effectively will improve the productivity and profitability of the company, i.e. its competitive advantage.

5.1.4 Effectiveness of CBM decision making

The main results achieved from the fourth research question (i.e. How to improve the effectiveness of condition based maintenance (CBM) decision-making?) can be summarised as follows:

- In Paper IV a mechanistic model for predicting the vibration level in the near future, e.g. at the next planned measuring time, was verified at a laboratory experiment in addition to using data collected in a case study.
In Paper V, a new approach to an expert system was suggested. It is based on the use of a common database, an artificial neural network (ANN) and fuzzy logic in the inference engine and user interface.

The following conclusions can be drawn from the results achieved in Paper IV and Paper V:

1) The effectiveness of CBM decision-making could be improved by accurately predicting the CM parameter level at the next planned measuring time. This could reduce the risk of unexpected deviation in the condition of the significant components.

2) In complex systems, signals from only one condition monitoring parameter are insufficient and cannot provide accurate prediction of failure and accurate diagnostics. Thus, the integration and management of data obtained from maintenance, operations, production, quality control, surroundings and accountancy are important to achieve an efficient and effective plant-monitoring, diagnosis/prognosis and decision-making system.

3) The main conclusion is that better data coverage and quality will reduce the uncertainty and improve the effectiveness of CBM decision-making. This would reduce the number and duration of planned and unplanned stoppages, which has a direct impact on the company’s productivity, and hence, on its competitiveness.

5.1.5 Assessment of maintenance contribution

The main results achieved from the fifth research question (i.e. How to assess the impact of maintenance practices on business strategic objectives?) can be summarised as follows:

- In Paper VI a model to assess the economic impact of maintenance was developed and validated in a case study. Using the model one can identify, reclassify and assess maintenance-related costs, so that the user can reveal maintenance benefits, highlight profits, analyse the situation, identify the problem area, and help the decision-maker to perform the continuous improvement process, i.e. KAIZEN. When the model was validated in a case study, it was found that implementing VBM in a paper machine achieved yearly maintenance savings and profit, on average, of at least about 4.0 and 3.6 million Swedish Kronor (SEK), respectively. Moreover, investments to improve maintenance, on average, amounted to 1.4% of the 30 million SEK which represents the estimated potential savings (production losses).

- In Paper VII, a conceptual model that illustrates the impact of maintenance on a firm’s profitability was developed and tested in a case study. It was found that, ideally, at least 7.8 million SEK per year could be gained as a result of the productivity improvement of one paper machine, if an effective maintenance policy is used which can get rid of all the unplanned stoppages.
and the bad quality products related to maintenance problems. This figure could be increased in accordance with how maintenance actions affect other factors such as short and planned stoppages.

- In Paper VIII, a modified balanced scorecard suitable for measuring the performance of production support functions such as maintenance, quality and logistics was developed. The model widens the perspectives of BSC to cover the extended enterprise such as the suppliers and machine designers. The model was validated in a case study.

The main conclusion can be stated like this: effective maintenance affects the production systems’ ability to provide quality products and timely services to customers through its direct impact on factors such as number and duration of stoppages, quality, environmental and employee safety. The better the data coverage and quality, the greater the ability to detect deviations in maintenance performance and the higher the possibility of identifying problem areas at an early stage. Thus, assessing maintenance costs, savings and investments needed to eliminate the causes of deviations, enables the decision-maker to make the right decision maximising the contribution to the performance and profitability of manufacturing companies.

### 5.2 Thesis contribution

In the following we summarise the main contributions of this thesis:

- Studying which maintenance practices are deployed in Swedish industries, and showing, empirically, that there is a need for improving the implemented maintenance practices. In particular it was shown that the most used maintenance selection method is not satisfactory to its users. In addition it was found that none of the applied maintenance selection methods fulfils the requirements of the ideal maintenance selection method features.

- Developing an evaluation methodology based on fuzzy MCDM to select the most informative maintenance approach.

- Developing a practical model for selecting and improving the most cost effective maintenance policy. The model is based on a literature review and analyses of the available maintenance selection methods and is supported by the results of a survey conducted about Swedish industry.

- Verifying a mechanistic model for predicting the vibration level at the next planned measuring time.
Suggesting a new approach to an expert system for improving the effectiveness of plant monitoring and its diagnostic/prognostic decision-making systems.

Formulating a new classification of maintenance costs, which presents the maintenance function in a new perspective and provides evidence of the linkage between maintenance and overall corporate strategy, i.e. that maintenance is a major contributor to the performance and profitability of manufacturing companies. Assessing the economic impact of maintenance according to the new classification provides, among other things, a tool for measuring the cost effectiveness of the investment required to improve maintenance performance.

Suggesting and testing a model that illustrates the impact of maintenance on the profitability of firms.

Modifying the balanced scorecard (BSC) to suit the measuring of the performance of a production support function, i.e. the maintenance function, showing its effect on the strategic objectives of the manufacturing company.

Proving that maintenance could improve the quality, efficiency and effectiveness of production systems and consequently enhance the competitiveness and profitability of manufacturing companies. Thus, it was proved that maintenance is no longer a cost centre; but a profit generating function.

Finally, we can say that just like every other function in production systems, maintenance has a role in gaining and maintaining competitive advantages. However, the weight of this role varies according to the type of production system. Nevertheless, this role is not easily seen due to the lack of linkage between maintenance practices and performance, e.g. the profitability, of manufacturing companies. In summary, the contribution of the thesis can be developing tools that improve the efficiency and effectiveness of maintenance practices, e.g. selecting and improving the most cost effective maintenance policy, and assessing the financial impact of maintenance practices on business strategic objectives.

5.3 Implication for theory

This section shows that this research has not only contributed to the maintenance field, but the research findings can also be used in other disciplines as seen by the following:

- The models developed and suggested to assess the impact of maintenance practices on business strategic objectives (discussed in Paper VI, Paper VII
and Paper VIII) can be used to assess the impact of other support functions employed in production systems such as quality, logistics.

- Proving that maintenance is not a cost centre could affect the view of the maintenance staff whose function is usually given a low status in manufacturing companies. This may have positive psychological effects.

### 5.4 Implication for practice

The results achieved in this thesis are important for the industry as can be seen in the following:

- Giving maintenance managers an idea of the different maintenance practices in Swedish industry.
- Providing maintenance managers with a practical model (tool) that helps them in selecting and improving the most cost effective maintenance policy.
- Providing the decision-maker with a tool that helps in performing the never-ending improvement tasks and assessing their cost effectiveness.
- Helping the decision-maker to assess a number of alternatives based on several criteria or objectives by using an MCDM evaluation methodology.
- Helping the decision-maker to improve the effectiveness of maintenance schedules by accurately predicting the vibration level until the next measuring opportunity.
- Helping the maintenance staff to improve the accuracy of diagnostic/prognostic decision-making when using CBM.
- Helping the decision-maker a holistic picture of the cause-effect relationships of the effect of production support functions such as maintenance, quality and logistics, on the performance of the company using the BSC.

### 5.5 Implications for further research

Based on the research findings and the issues that were not covered in this research, the following points are suggested for future research:

- The survey conducted in Swedish industry could be repeated in different countries, for example, within Scandinavian countries, other European countries, or developed and developing countries.
- Studying the relationship between the seven maintenance practices discussed in Section 4.1.2 and the companies’ performance.
- Studying how the maintenance practices discussed in the survey results change with different types of industry.
- The practical model for maintenance selection and improvement could be validated in a case study to obtain a deeper understanding of implementation requirements.
• The conceptual model for an expert system suggested in Paper V could be developed further through a prototype test in lab and validated in a case study.
• Investigating the phenomenon of diminishing returns of new investments needed for maintenance improvement suggestions. This is because the impact that investment could have on maintenance savings, and consequently on maintenance profits, is limited.

5.6 Criticism of the thesis

I believe that there is no perfect work. There is always room for improvement. Therefore, in the following I discuss some of the points that could have been done in a better way:
• The low response rate achieved in the survey is considered the main serious problem affecting the ability to generalise the results to a larger population. However, since this survey is part of a current project, efforts are being made now to call the surveyed firms and encourage them to respond to the questionnaire.
• Because the research work was performed during a long period and involved two main research projects and other conceptual research work performed at different times, it was not possible to present the research papers and research questions in a chronological order. Therefore, the research papers were numbered according to their relevance to the research questions.
References


British standard glossary of terms used in terotechnology, BS 3811:1993.


Sumanth, David (1998). Total productivity management- a systematic and quantitative approach to compete in quality, price, and time. CRC Press LLC, USA.


Appendix (A): Example of a question used in the survey

M1 How much emphasize is placed on each of the following activities where 1=Not Important and 5=Very Important.

- Restoring equipment to operation (acute)
- Installing new equipment
- Keeping the level low in spare parts inventory
- Having inventory between machines, Work in Process/Progress (WIP)
- Decreasing the repair time
- Investing in improving the skills and competence of maintenance staff
- Use of computerized maintenance management systems (CMMS)
- Analysing equipment failure causes and effects
- Using failure historical data
- Off-line Monitoring of critical machinery purchasing (production is stopped during test)
- On-line Monitoring of critical machinery (test is done during production)
- Performing the maintenance tasks according to the original equipment manufacturer (OEM) recommendations
- Performing the maintenance tasks based on Condition Monitoring
- Performing the maintenance tasks based on statistical modelling of failure data
- Helping the purchasing department in OEM selection
- Performing periodic planned replacement
- Automatic diagnosis (expert system)
- Remote diagnosis (measurements are sent to another places for analyse)
- Use of company wide information for diagnosis
<table>
<thead>
<tr>
<th>Cross functional groups (for instance improvement groups)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helping improve the production process</td>
</tr>
<tr>
<td>Helping design the production process</td>
</tr>
<tr>
<td>Recording the period and frequency of failures</td>
</tr>
<tr>
<td>Recording the period and frequency of short stoppages</td>
</tr>
<tr>
<td>Recording the poor quality rate.</td>
</tr>
<tr>
<td>Annual overhaul</td>
</tr>
</tbody>
</table>
Appendix (B): Factor analysis results for maintenance activities

<table>
<thead>
<tr>
<th>KMO and Bartlett's Test</th>
</tr>
</thead>
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<tr>
<td>Kaiser-Meyer-Olkin Measure of Sampling Adequacy.</td>
</tr>
<tr>
<td>Bartlett's Test of Sphericity</td>
</tr>
<tr>
<td>Approx. Chi-Square</td>
</tr>
<tr>
<td>df</td>
</tr>
<tr>
<td>Sig.</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

| Kaiser-Meyer-Olkin Measure of Sampling Adequacy. | 0.789 |
| Bartlett's Test of Sphericity                    |     |
| Approx. Chi-Square                               | 1225.173 |
| df                                              | 325  |
| Sig.                                            | 0.000 |

Table b1 *KMO and Bartlett’s Test for maintenance activities*
Figure b1 Scree plot used for determining the number of factors extracted from the maintenance activities
<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Communalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restoring equipment to operation (acute)</td>
<td>-0.01</td>
<td>0.00</td>
<td>-0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.64</td>
<td>0.15</td>
<td>0.45</td>
</tr>
<tr>
<td>Installing new equipment</td>
<td>0.12</td>
<td>-0.11</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.16</td>
<td>0.73</td>
<td>0.12</td>
<td>0.61</td>
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<tr>
<td>Keeping the level low in spare parts inventory</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.30</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.74</td>
<td>0.65</td>
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<td>Having inventory between machines (WIP)</td>
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<td>0.01</td>
<td>0.15</td>
<td>0.26</td>
<td>0.49</td>
<td>-0.25</td>
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<td>Decreasing the repair time</td>
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<td>0.11</td>
<td>0.16</td>
<td>0.00</td>
<td>0.34</td>
<td>0.23</td>
<td>0.68</td>
<td>0.68</td>
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<tr>
<td>Investing in improving the skills and competence of maintenance staff</td>
<td>0.01</td>
<td>0.33</td>
<td>0.61</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.44</td>
<td>0.68</td>
</tr>
<tr>
<td>Use of (CMMS)</td>
<td>-0.01</td>
<td>0.12</td>
<td>0.67</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.13</td>
<td>0.26</td>
<td>0.55</td>
</tr>
<tr>
<td>Analysing equipment failure causes and effects</td>
<td>0.38</td>
<td>0.29</td>
<td>0.41</td>
<td>-0.20</td>
<td>0.32</td>
<td>0.11</td>
<td>0.01</td>
<td>0.55</td>
</tr>
<tr>
<td>Using failure data</td>
<td>0.26</td>
<td>0.32</td>
<td>0.28</td>
<td>0.00</td>
<td>0.62</td>
<td>0.00</td>
<td>0.18</td>
<td>0.66</td>
</tr>
<tr>
<td>Off-line Monitoring</td>
<td>0.19</td>
<td>0.00</td>
<td>0.58</td>
<td>0.41</td>
<td>0.00</td>
<td>0.00</td>
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<td>0.54</td>
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<td>On-line Monitoring</td>
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<td>0.18</td>
<td>0.52</td>
<td>0.23</td>
<td>0.28</td>
<td>0.00</td>
<td>-0.23</td>
<td>0.51</td>
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<tr>
<td>Following (OEM) recommendations</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>0.80</td>
<td>0.24</td>
<td>0.00</td>
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<td>0.51</td>
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<td>0.23</td>
<td>-0.01</td>
<td>-0.12</td>
<td>0.53</td>
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<td>Performing the maintenance tasks based on statistical modelling of failure data</td>
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<td>0.37</td>
<td>0.51</td>
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<td>0.16</td>
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<td>0.25</td>
<td>0.01</td>
<td>0.01</td>
<td>0.16</td>
<td>-0.10</td>
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<td>Performing periodic planned replacement</td>
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<td>0.01</td>
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<td>0.01</td>
<td>0.12</td>
<td>0.72</td>
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<tr>
<td>Remote diagnosis</td>
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<td>0.11</td>
<td>0.82</td>
<td>0.00</td>
<td>0.00</td>
<td>0.14</td>
<td>0.75</td>
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<tr>
<td>Use of company wide information for diagnosis</td>
<td>0.56</td>
<td>0.13</td>
<td>0.30</td>
<td>0.31</td>
<td>0.11</td>
<td>0.00</td>
<td>0.19</td>
<td>0.56</td>
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<tr>
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<tr>
<td>Cross functional groups (for instance improvement groups)</td>
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<td>0.33</td>
<td>0.12</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.26</td>
<td>0.01</td>
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<td>Helping improve the production process</td>
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<td>0.62</td>
<td>0.46</td>
<td>-0.01</td>
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<td>0.17</td>
<td>0.11</td>
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<td>Recording the period and frequency of failures</td>
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<td>0.84</td>
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<td>0.18</td>
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<td>0.26</td>
<td>0.00</td>
<td>0.12</td>
<td>0.00</td>
<td>0.68</td>
</tr>
<tr>
<td>Annual overhaul</td>
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<td>0.22</td>
<td>0.20</td>
<td>-0.37</td>
<td>0.48</td>
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**Eigenvalues**

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<thead>
<tr>
<th></th>
<th>Before rotation</th>
<th>After rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of variance before rotation</td>
<td>7.2 1.9 1.8 1.7 1.5 1.4 1.1</td>
<td>3.3 3.1 2.7 2.0 1.9 1.8 1.7</td>
</tr>
<tr>
<td>% of variance after rotation</td>
<td>27.7 7.2 7.1 6.3 5.7 5.3 4.1</td>
<td>12.6 11.9 10.4 7.8 7.1 6.9 6.6</td>
</tr>
</tbody>
</table>

# Appendix (C): Research papers

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<th>Paper</th>
<th>Pages</th>
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</thead>
<tbody>
<tr>
<td>Paper I</td>
<td>[85-100]</td>
</tr>
<tr>
<td>Paper II</td>
<td>[1-16]</td>
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<td>Paper III</td>
<td>[1-18]</td>
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<tr>
<td>Paper IV</td>
<td>[1-15]</td>
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<tr>
<td>Paper V</td>
<td>[267-276]</td>
</tr>
<tr>
<td>Paper VI</td>
<td>[1-15]</td>
</tr>
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<td>Paper VII</td>
<td>[1-13]</td>
</tr>
<tr>
<td>Paper VIII</td>
<td>[1-12]</td>
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