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Maintenance Management of Complex Industrial Systems
- a methodology for renewal strategies

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Abstract

For complex technical systems in the electricity and pulp and paper industries, maintenance management addresses how to exploit physical assets in the most profitably way. This is a difficult task that requires taking into consideration parameters of totally different natures – e.g. reliability data, operating costs, condition of technical systems, the environment and rules and regulation.

An incorrect estimate of a residual lifetime can result in a premature renewal with accompanying high capital costs. If, however, renewal is delayed, a breakdown may occur which can cause major damage to technical equipment and a loss of income due to outages. Because of the complexity of many technical systems, it can be hard to select adequate data to use when making decisions about renewal strategies. To cope with this, one approach is to use less detailed models that are operated by skilled analysts.

This work demonstrates the advantage of such an approach by proposing two methods applied in a joint methodology that has its origins in RCM. The methodology consists of Dynamic Lifetime Model (DLA) and the Condition Based Index (CBI). The DLA method copes with the financial risk associated with the point in time for when a renewal is carried out and the CBI method uses critical parameters to estimate the condition of a technical system. The two methods together create a quantitative connection between reliability, maintenance and financial risk. A case study based validation of the methodology was carried out at SCA Ortvikens paper mill on a refiner system and Forsmark nuclear power plant. Lessons learned from the case study showed that the methodology could be used to identify which components could cause costly breakdown. By using the methodology a manager gets a decision support tool for estimating short-term and long-term consequences of decisions regarding maintenance management in order to maximize utility of the system concerned

Outline of the thesis

This thesis is comprised of an introductory essay and four research articles. The essay has been divided into six parts. The Introductory essay provides an extended framework for the four research articles that together presents the research results as a whole.

Under ***Setting the stage*** (Chapter 1) the background, purpose and context of the thesis are introduced.

Part One – Maintenance Management (Chapter 2-5) contributes with a general discussion about maintenance management and the result from a case study carried out at five Swedish energy companies and one pulp and paper industry. The basis for an understanding of the research area is established and other methods that can be used to cope with this issue are presented.

Part Two – Proposed Methodology (Chapter 6-9) describes the DLA method (Dynamic Lifetime Analysis) and CBI (Condition Based Index) and the experiences from a minor case study based evaluation of the DLA are described. Also, the DLA and CBI are put together in a joint methodology. The methodology is also described from in a wider perspective for a reader to gain better understand of the ideas behind the approach.

Part Three – Case Study Based Evaluation of Methodology (Chapter 10-13) consists of a case study based evaluation carried out at Forsmark\s nuclear power station and at SCA Graphic of the methodology. The methodology was first evaluated via a case study on a feed water pump system at Forsmark. Lesson learned from that study was the used to develop the methodology and it was then applied to a refiner at SCA Graphics mill in Sundsvall.

In the ***Concluding Part*** (Chapter 14-16) contains general conclusions from the research work as a whole.

Finally, in the ***Papers*** (Paper I-IV), the four papers describing the major results from the research as a whole, is presented.

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers.

Wärja, M. Björkqvist, O. (2004) "Variety Reduction Model for Maintenance and Renewal Strategies". In *proceedings of NORDAC 2004,* Espoo, Finland, August 2004

Wärja, M. Masman, F. Björkqvist, O. (2004) "A Reliability Based Approach to Maintenance and Renewal Strategies". *In proceedings of PowerCon 2004*, Singapore, November 2004

Wärja, M. Björkqvist, O. (2005) "A Systems Approach to Maintenance and Renewal Strategies". *In proceedings of CIRED'05,* Turin, Italy, June 2005

Wärja, M. Björkqvist, O. (2005) "Evaluation of a Condition Based Index Supporting System Reliability and Maintenance Decisions". Submitted to *Journal of Pulp and Paper Science*

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Writing a thesis is not altogether one person's work. Many people are involved and in some different ways contribute to the work. To mention everyone is impossible, but there are some that I would like to give special thanks to.

First of all I would like to thank Professor Torsten Cegrell, my supervisor, who gave me this opportunity and who has helped me throughout this period. Furthermore, thanks are due Dr Olof Björkqvist who has provided help when I needed it.

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Härnösand, September 2005

Mathias Wärja

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Setting the stage

1. Introduction

1.1. Background

Asset management is emerging as a new approach to how to exploit physical assets in the most profitably way (Östergaard et al., 2001). An important problem for asset management staff is to find out when to carry out a replacement or renewal (Lebow et al., 1998). This is a difficult question, which requires weighting up several parameters of totally different natures – e.g. reliability data, operating costs, condition information from technical systems, the environment and rules and regulation (Anders et al., 2001). In the energy and pulp- and paper industries, technical systems are highly capital intensive. The renewal of a specific technical system can cost tens of millions of euros. The specified lifetime of a system varies greatly and includes sub-systems, each of which has a varying residual lifetime. Some systems operate for only a few years while others can have a lifetime of 50-100 years.

An incorrect estimate of a residual lifetime can result in a premature renewal with accompanying high capital costs. If, however, renewal is delayed, a breakdown may occur which can cause major damage to technical equipment and a loss of income due to outages. For the energy industry a breakdown may also cause problems with the local community, which has to be taken into consideration when managing energy systems. Most of the electricity supply and production systems in Sweden were built between the 1940s and 1980s. Some parts of the energy systems are therefore considered to be approaching the end of their designated lifetime. These energy systems are inherently quite reliable; therefore it seems as if the companies made their renewals too early before deregulation (Campbell, 2001) to ensure that no major breakdowns occurred (Billington, 2000).

Renewals are normally the result of an intensive process, which takes into account all the relevant circumstances. As well as the technical aspects, the internal organisation of the company e.g. the availability of personnel or requirements of the dispatch center may have an influence. The decision whether to renew or not is then taken, based on a balancing of all these facts. As part of a technical system often has to be kept in service, renewal activities are carried out during light load periods, if possible.

The power industry is one of the largest civilian industries and unique in terms of its influence on society. The goal is satisfactory capacity and reliability to meet the demands of society. The conditions for the power industry has changed remarkably due to the deregulation of the Swedish and European electricity market which also affects the maintenance management. The general public’s expectation is that the power industry will deliver reliable supply of electricity at the lowest price. The management on the other hand wants to have the best possible performance and at the same time maximize profit. This is the kernel of the issue, to use the available resources where they are most effective.

1.2. Maintenance management

Maintenance of equipment is a significant fraction of the total operating costs in many industry sectors. (Murthy, 2002). Effective maintenance management requires a multidisciplinary approach where maintenance is viewed strategically from the overall business perspective (Pintelton, 1992). The approach to maintenance has changed dramatically over the last century (Blischke, 2000). Up to about 1940, maintenance was considered an unavoidable cost and the only maintenance was CM (Corrective Maintenance). Whenever an equipment failure occurred, a specialised maintenance workforce was called on to return the system to operation. Maintenance was neither incorporated into the business nor was performance duly recognised. The evolution of operations research from its origin and applications during the Second World War to its subsequent use in industry led to the widespread use of preventive maintenance. Since the 1950s, operation research for maintenance has appeared at an ever-increasing pace. These can be found in many books (Gertsbakh, 1977; Niebel, 1985) and many review paper on the topic (Jardine, 1985; McCall, 1965; Pierkalla, 1976; Thomas, 1986). These models deal with the effect of different maintenance policies and optimal selection of the parameters of the policies.

A competitive environment places increased demands on a company to be aware of its costs and the origins of these costs. (Lefton et al., 1995). Maintenance management determines what planned and programmed maintenance work should be carried out, and it considers what potential problems may require an unplanned, reactive response (Idhammar, 1999). One part of maintenance management is to interpret information in order to manage the equipment in the best possible way. To do so, a lot of information must be gathered and analysed; useful information comes from e.g. SCADA, customers, maintenance- and operating personnel, economy departments, environmental considerations, rules and regulations etc. All this information must be dealt with in a structured manner in order to make the right decisions.

The outcome of the different strategies is a reasoned case for why each of the options of predictive, preventive or corrective maintenance should be carried out on the equipment, and whether a combination of types is appropriate. If required, the needs of the equipment that are of highest priority can be determined using a critical analysis. A prioritized list of equipment is produced and where the consequences are more serious more effort is put into evaluating the maintenance needs. The maintenance strategy will be complemented later by the system's operational cost and revenue are directly related to the availability and cost for maintenance and refurbishment, or replacement, of systems (Lebow et al., 1998).

Today there is no generally accepted method, which can give a concise picture of long and short-term aspects of different maintenance measures, to use as an aid when making decisions about maintenance strategies. There are however some methods that can provide managers with information regarding some aspect of maintenance e.g. economics, spare part optimization, recommended service intervals etc (Alsac et al., 1997).

1.2.1. Maintenance strategies

Several maintenance strategies are mainly used in technical systems. The most common strategies are: corrective, time-based, condition-based and reliability-centered maintenance (Balzer et al., 2001).

In a *corrective maintenance* (CM) strategy replacement or repair is performed only if a failure had occurred. It is used in the case of equipment where investment costs are low and a fault may result in the lowest overall costs. It is often divided into *planned corrective maintenance*, PCM, and *unplanned corrective maintenance*, UPCM. PCM is defined as maintenance that is planned and scheduled not later than the day before it is executed. This approach is only acceptable when the consequences of a failure do not necessitate a more preventive, productive or reactive response. Planning means that the job is thoroughly prepared with tools, drawings, spare parts and materials. UPCM is consequently maintenance work started on the same day as it is requested. Whilst all safety precautions and procedures must be followed, time is taken to gather the correct tools, spare parts and information. During this time the equipment is inactive. As a general rule such failures are two to three times more expensive than a planned job and a breakdown is often ten times more expensive than being in a position to identify the failure early and correct it in a planned manner.

A *time-based maintenance* (TBM) strategy, featuring predefined intervals based on empirical feedback, where components are replaced after a specific period of use, has been practiced as the usual maintenance strategy in electric power systems for many years (Strömberg, 2000). This approach generally produces satisfactory results. It will not however be the most cost-effective option in all cases, since the equipment will not usually remain in operation up to the end of its possible lifetime.

Conditions-based maintenance (CBM) tasks are normally applied to items of systems that do not fail instantaneously but fail over a period of time and give some early indication of an impending failure. The early indication of failure enables the consequences of an unexpected breakdown to be avoided. Early signs can be detected by the use of condition monitoring equipment or by maintenance inspections. The frequency of any inspection schedule depends on the time interval between the early signs and failure and the point at which failure occurs. CBM is driven by the technical condition of the equipment. When following this approach, all major parameters are considered in order to maximize accuracy. For this reason detailed information should be available.

The aim of *reliability-centered maintenance* (RCM) is to include the importance of the equipment in the system and the actual condition of the equipment (Bertling, 2002; Clement et al., 1991; Gustavsen, 2002; Stillman et al., 1995). RCM combines the two aspects of condition and importance to be used when developing an maintenance strategy. Both RCM and CBM strategies require the same data for assessing the condition of the equipment. However, with RCM the importance of the equipment for the network as a whole must be determined e.g. the influence of equipment failure on the reliability of supply. Defining a substations importance and assessing the consequences of a fault basically constitute a practical but also a subjectively influenced value. In this context there are numerous different parameters to be considered, e.g. failure rate, configuration, type of costumer etc.

Many maintenance approaches and models are provided in references (Andersen et al., 1998; G.C. Stone, 2001; Gammelgård, 2003). However, these models and methods give limited decision support regarding the timing of renewal and the financial consequences of neglected maintenance. Today there is no general method to use when deciding about maintenance strategies with a starting point in the actual condition of a technical system. Existing methods have their main focus on separate equipments and are not able give a macro perspective on the actual condition of the system and how different maintenance strategies will affect if over a long period of time.

Maintenance should be carried out in such a way that power is delivered with acceptable cost and high reliability. Because of the long operative lifetime of the equipment it can be difficult to detect slow deterioration of the technical systems. Maintenance and renewal strategies are often focused on availability and reliability; with this approach there is a risk that there will be a conflict between short-term results and long-term conditions (Leite da Silva et al., 2001). If only short-term results are considered and maintenance is cut down there might be a risk that slow deterioration might occur, resulting in high need for resources in the future during a short time span.

The object of condition monitoring is to foresee abnormal states and to detect deterioration. However, the deterioration of large power components with long operative lifetime is difficult to measure due to the fact that the overall condition of a technical system is the result of many variables.

Many attempts have been made to describe the condition of different components in a power system. For generators, partial discharge has been frequently discussed. This method involves measuring small electrical sparks that occurs in a void in an isolation system as it deteriorates. As the magnitude and the number of these pulses increase, the winding isolation is closer to failure. For further details, see e.g. G.C. Stone, (2001) and Hudon et al., (1994).

Another major component of interest in making condition judgments, are transformers. This is due to the important role these have in a power system and the cost and time associated with replacing a wrecked one. Other methods for making judgments on condition are oil analysis surveys, winding movement detection, or isolation tests. Examples of these methods have been described by Lapworth et al., (1998), Schaefer et al., (2000) and Steed, (1995).

Substations are also of importance in this study. The condition of the total substation has to be arrived at by combining the condition of single items of the asset, for example, bays, circuit breakers, instrument transformers and secondary equipment. Methods to cope with this complex issue can be found in Balzer et al., (2001) and Booth, (1996).

Neural networks have been used to calculate the condition. However, this method requires a lot of data to train a neural network. In order to be able to use a neural network it must be "trained" to recognise patterns. Since the electrical systems are built with different technique and are exposed to various environmental and operational differences, the training of a neural network is an immense work. For further reading about neural networks see e.g. Bode, (1998); Gurney, (1999); Molina et al., (2000) and Raghavan et al., (1993).

1.3. Rationale

The purpose of this work is to develop a methodology for supporting decisions regarding renewal of technical systems with long operative lifetime. When working with this issues a lot of different aspects must be taken into consideration. Besides the economic, environmental and personnel aspects, the technical system is subjected to a host of external factors e.g. system events, normal and abnormal loads and human errors. When taking all these factors into consideration and adding the number of technical systems the manager is responsible for, it is clear that this is a task that demands a structured approach.

A structured approach and a methodology to cope with this issue are necessary to help the manager to deal with decisions on maintenance management. The result of this work is three fold: to increase understanding in the area of maintenance management, to present the methods and models used today and finally, to present a methodology that can aid the manager when making decision on the company's assets.

This thesis discusses the most important aspects of maintenance with main focus on renewal decision, what the motives for renewals are and how to use subjective skills in combination with historical records and measured process values. The work resulted in a methodology that addresses the problem in direct economic terms in combination with a variety reduction (Ashby, 1956). The methodology proved to be useful as an aid when deciding about maintenance strategies, renewal priorities and identifying critical components from a financial perspective.

1.4. Research question

The general research question is "how to determine an efficient point in time for when a renewal should be carried out". Technical systems or components of interest are complex, cost millions of Euros to renew, take a long time (months) to replace and the consequences of a breakdown can be substantial in terms of financial, environmental and personnel aspects to a company. Such technical systems can e.g. be components, power or industrial systems or large components in a pulp and paper mill. When answering the general research question a series of sub questions must be dealt with:

- Is there today any generally accepted methods used?
- Is there a need for a support tool regarding renewal decisions?
- What are the demands on such a decision support?
- Is there a need for improvement of commonly used methods?
- Given the answer to these questions, the work must then address another one: Is it possible to develop a quite simple and manageable decision support tool regarding renewal efficiency?
- Can exiting methods be used as a starting point?

The objective for answering these questions is to develop a decision tool regarding renewal strategies. The next step is therefore to validate the methodology by answering:

- Is the developed methodology an efficient decision tool?

Although the research questions above describe the research problem dealt with here, they also must be supplemented with the boundaries of the study in order to define the research area of concern.

1.5. Literature review

Much of the literature concerns itself with replacements only, both after failures and during maintenance, and disregards the possibility of the kind of maintenance where less improvement is achieved at smaller cost. The oldest replacement schemes are the age replacement and the bulk replacement policies described by Barlow (Barlow, 1975) and Anders (Anders, 1990). In the first a component is replaced at a certain age or when it fails, whichever comes first. In the second, all devices in a given class are replaced at predetermined intervals, or when they fail. Newer replacement schemes are often based on probabilistic methods and can be quite complex. Maintenance methods are divided into categories where maintenance is preferred at fixed intervals and where it is carried out as needed. A further distinction is made between heuristic methods and those based on mathematical models; the models themselves can be deterministic or probabilistic. Probabilistic models have advantages over deterministic ones: they are capable of describing actual processes more realistically, and also facilitate optimisation for maximal reliability or minimal costs. A deterministic method uses mathematical models and generally enumerates and combines the probabilities and frequencies of system states to calculate the reliability indices. Simulation techniques, usually known as Monte Carlo simulation because they involve random numbers; treat the problem as a series of 'real' experiments.

The RCM approach referred to in *Maintenance strategies* relies heavily on regular assessments of equipment condition and, therefore, does not apply rigid maintenance schedules. It should be observed that RCM is somewhat fluid concept, defined in different sources (Moubray, 1992; Smith, 1993). RCM is not always based on condition monitoring, but on other features such as failure modes and effect analysis and an investigation of operating needs and properties. The approach is almost always empirical. As an example, the RCM program used consists of the following main procedures:

- System identification, and the listing of critical components and their failures
- Failure mode and effect analysis for each selected component, the determination of failure history, and the calculation of key performance indicators
- Categorization of failure effects and determination of possible maintenance tasks

- Maintenance task assignment
- Program evaluation and cost analysis

However, for a complete evaluation of the effects of the maintenance policy, one has to know how much its application affects the lifetime of a component. To provide the missing link a quantitative connection between reliability and maintenance is needed.

1.6. Delimitations

The technical systems of interest in this research project are the kinds that directly or indirectly have a substantial economic impact on business. The systems must be very important for the operation of the company's business. The systems are characterized by the fact that they:

- Consists of many components that together provide the functionality needed for the business
- Are capital intensive
- Difficult to improve profit by carrying out renewals
- Have a long operative life time
- Are difficult to replace if business operations are changed

Furthermore, the scope of this thesis will not include the development of a technique that can in some way measure remaining lifetime in technical systems. This is because it is just not possible to apply one general method to any technical system. The methods in use today will therefore serve as input for the qualitative judgment that in most cases will be adequate to estimate residual lifetime. Aspects such as cash flow, tax-planning etc. are not included in this thesis.

1.7. Research contribution

When adopting a RCM methodology for maintenance management two aspects cant be dealt with, as stated in *Literature review*, a link between maintenance and reliability and the financial risk associated with decisions of each critical component. To handle the link between maintenance and reliability, a mathematical model of component deterioration is needed, which then is combined with a model describing the effects of maintenance. Once a mathematical model is constructed, the process can be optimised with regards to changes in one or more of the variables. The link between maintenance and condition is the first research contribution. This link is carried out by the use of the CBI.

Since many companies have many technical systems it can lead to sub-optimization if the maintenance managers don't take all technical systems into consideration when developing a long-term strategic plan. It is, however, important for companies to estimate when in time a renewal has to be carried out. The reason for renewing is of subordinate importance, the focus should be on establishing when a renewal has to been carried out in order to minimize costs without taking too high financial risks. To quantify the financial risk associated with decisions regarding maintenance strategies the DLA method was developed; this is the second research contribution. The method sums up the different aspects affecting the decision and visualises the risk associated with a certain maintenance strategy. The CBI method was evaluated and improved to better suit the determination of which inputs to choose when estimating the condition of a technical system.

1.8. Research approach

This work has emerged from a three-phase study. Part one is called “maintenance management” and consists of a case study carried out at seven different power companies and one pulp industry. The main focus in that study was to chart methods used regarding maintenance management and gain pre understanding of the problem area. The method chosen for this survey was unstructured interviews with respondents responsible for maintenance at the companies and a literature review (Wärja, 2004a).

Part two, “Proposed Methodology”, consists of two methods, the DLA and CBI methods, in a joint methodology. One of the methods, the DLA method, was developed from the lessons learned in a interview series (Strömberg, 2001)[1]. The DLA method uses statistical methods to represent the remaining lifetime of a system in combination with the cost for both planned and unplanned maintenance costs. The method gives a manager a concise picture in monetary terms of the “financial risk” for different components in a system. The results from the DLA method is shown in a case-study (Strömberg, 2003). The CBI method was developed by Forsmark nuclear group and is used to describe the condition of complex technical systems. However, this method needed further evaluation and could not, by it self in the present form, be used as maintenance planner. Further, in this part of the thesis the joint methodology is put in a wider perspective in an attempt to justify the approach from a scientific point of view (Wärja, 2004b; Wärja, 2005a).

In Part Three of this work, ”Case Study Based Validation of the Methodology”, a validation of the joint methodology is performed. The validation was carried out in two steps, at Forsmark nuclear power station where a feed water pump system was used as study object. Lessons learned from this study were used to identify weaknesses in the methodology and with lessons learned the approach was modified. The final case study was carried out at Metso Paper and concerned a refiner system at SCA Graphics paper mill in Sundsvall. The work consisted in identifying maintenance methods and surveillance system for critical components from a financial perspective (Wärja, 2005b).

[1] My former name, Mathias Strömberg, was changed to Mathias Wärja in 2004

1.8.1. General content and work distribution of paper I-IV

Paper I: Wärja, M. Björkqvist, O. (2004) Variety reduction model for maintenance and renewal strategies.
This paper is a state of the art study presenting different maintenance management methods applied today. A survey was carried out at six Swedish utility companies. Wärja carried out the study, evaluated the collected material and wrote the paper. Björkqvist contributed with comments on the results in general and the outline of the paper.

Paper II: Wärja, M. Masman, F. Björkqvist, O. (2004) A reliability based approach to maintenance and renewal strategies.
This paper describes and evaluates the CBI and DLA methods. A case study was conducted at Forsmark Nuclear Station. The results were used to improve the joint methodology. Wärja and Masman chose objects for the study and collected material, evaluated the results and wrote the paper. Björkqvist contributed with comments on the results in general and the outline of the paper.

Paper III: Wärja, M. Björkqvist, O. (2005) A systems approach to maintenance and renewal strategies
This paper evaluates the joint CBI/DLA methodology. Materials from the previous case study carried out at Forsmark were used as input. The paper also addresses maintenance management in a competitive market. The evaluation and case study was carried out by Wärja, Björkqvist contributed with comments on the outline of the paper.

Paper VI: Wärja, M. Björkqvist, O. (2005) Evaluation of a condition-based index supporting system reliability and maintenance decisions.
In this paper the joint methodology is applied to a reject refiner system at SCA Ortvikens paper mill in Sundsvall. The refiner system is subject to a new service agreement between Metso Paper and SCA, the methodology was used to identify which parameters to use when specifying the condition of the system. Wärja carried out the case study in collaboration with personnel from Metso and wrote the paper. Björkqvist contributed with the outline and context of the paper.

1.9. Research quality assurance

This work is an applied research project. When assuring the quality of such a study, the relevance of the problem must be determined as well as the quality of the results. The formulation of the scientific problem was based on the result from the interview series. Thus, it is likely that the study is relevant and applicable outside the academic community.

The model formulation, equations and code of the DLA method are validated through internal control and peer reviewed in scientific publications and seminars (Strömberg, 2003; Wärja, 2004a).

The CBI method was mainly developed at Forsmark nuclear power station. The ideas behind the CBI method have emerged from the need in the nuclear industries to find a normalized scale to estimate the condition of a technical system in order to develop their maintenance strategy. The data from years of running CBI was used to evaluate the method. This was carried out together with personnel at Forsmark nuclear station responsible for CBI.

The final step, an evaluation of the methodology was carried out parallel to a “real” maintenance agreement negotiation between Metso Paper and SCA Graphic in Sundsvall. The methodology was used to identify the components most likely to cause costly breakdowns. The result from the study is presented in a peer-reviewed paper (Wärja, 2005b).The methodology proved to work in a real case scenario and has been evaluated internally, externally and by skilled persons in the business.

Part One –Maintenance Management

2. Introduction

This part of the thesis presents a study of how five energy companies and one paper- and pulp industry in Sweden give priority to maintenance and renewal of technical systems. Also, theories in use in these industries after the deregulation of the Swedish power market are presented. The case study was conducted as interviews and the respondents gave their point of view on the issue. The full report is presented in “Beslutsstrategier vid Förnyelseprojekt” (Strömberg, 2000). The result from this case study is a part of the starting point for the model development presented in Part Two.

2.1. Participating companies

Together, the companies participating in the intended paper produce together 85 % of Sweden’s 150,5 TWh electricity. The respondents represent the following companies:

- HEMAB is a municipal company with their main area of business in electricity and district heating. They have about 16,500 customers and on an annual basis they distribute 300 GWh electricity and 130 GWh district heating. The results achieved through this work and the conclusions reached will be used for future Swedish research collaboration on efficient utilization of capital intense technical systems.

- SwedPower Group provides services worldwide in all areas of the energy & power sector.

- Svenska Kraftnät is a company that owns and operates the national electricity grid, comprising the country's 400 and 220 kV power lines, as well as stations. Their duties include the responsibility for the electricity system being in short-term balance, known as the system responsibility.

- SCA has a broad range of high-grade, customized publication papers. Forest Products' net sales 1999 amounted to MSEK 11,532 and the number of employees was 3,533 (average).

- Birka[2] Energy is Sweden's leading energy company in terms of number of customers, and the third largest in terms of production capacity.

- Sydkraft Hydro power that produces about 35% of Sydkraft's electricity. Sydkraft's hydroelectric power is produced by about 100 facilities in Sweden.

3. Method

The choice of method for the first part of this study was interviews of an open-ended nature (Yin, 1994). This method was chosen because the respondent's role in such interviews is more that of an informant rather than just a respondent answering questions; he can speak more freely around the questions. With this method the interviewer follows a certain set of questions, but allows the respondent's answer in some way to affect the following questions. This is a method that helps the interviewer to get a better perspective of the issue he is about to chart and lets him be influenced by the respondent.

4. Results

4.1. Applied methods in the companies

During the interviews the respondents explained how their company worked with renewals, what different strategies they had and what methods they used. The following chapters briefly describe how the companies work with maintenance management.

4.1.1. HEMAB (Härnösands Energi och miljö)

HEMAB is a municipal company with its main sphere of activities in electricity and district heating. This is the smallest of the companies that participated in the case study. Three respondents were interviewed at HEMAB on separate occasions.

Business area District Heating
The district heating operation at HEMAB has two bio-fuelled steam boilers; one of them is a combined power and heating plant with a maximum electric power capacity of about 10 MW. HEMAB district heating also has a few smaller oil boilers and one electric boiler located at different places around Härnösand. The total installed heat capacity is approximately 60 MW.

[2] Birka is now renamed to Fortum

For day-to-day operations and for a small amount of maintenance HEMAB's District Heating has 19 employees. For bigger refurbishments or renewals they hire contractors. It is mainly operators that make judgments on the status of the technical systems. Every year the manager of the District Heating section proposes to the board the renewals he thinks should be carried out during the next year, along with demands for resources to run the daily activities. For renewals up to 2 million Euros the board can decide whether to carry out a renewal or not. For larger investments the owners must be informed. In this case that is the municipal executive board. This means that it can be quite a long process to carry out larger renewals.

Today HEMAB's District Heating has no general method for estimating the residual lifetime of their technical systems; furthermore they don't have a method of prioritizing between renewals. The staff running and maintaining the technical systems make most of the judgments on status. Sometimes they hire external experts to make judgments but it is not a common procedure. The manager for District Heating makes most of the decisions together with maintenance and operational personnel. If larger renewals have to be carried out the manager must confer with the managing director on how to proceed. In most cases the information that they need to make a decision comes from the personnel.

Business area Electricity

The electricity operation is divided into two different divisions, Sales and Grid. This is because in a deregulated power market companies are not allowed to have sales and grid in same division. In this case study the operations manager for HEMAB's power grid was interviewed.

Business area Grid has eight substations, a 10 kV grid in Härnösand, a 45 kV grid in the countryside, a total of 600 km high voltage lines and 1500 km of low voltage lines and a total of 570 low voltage substations. On an annual basis they sell approximately 300 GWh to 16000 costumers.

Today the Grid Division hardly carries out any new construction in their power grid. It is mostly refurbishments and renewals or upgrading. They have two main strategies for their power grid; firstly they try to find the sections in the grid where the most unplanned outages occur and renew those parts of the grid. Secondly, they buy a number of new low voltage substations every year. The number bought depends on the amount of resources allocated to them by the board every year. Sometimes they also carry out larger renewals such as high voltage substations and/or transformers. Since these kinds of investments are rather expensive the decision must be made in the same manner as for the District Heating division through the municipal executive board.

When selecting which low voltage substations to renew the personnel who carry out maintenance make a judgment of the condition. Their opinion is almost the only information the manager of the Electricity Division can rely on when choosing which substations to renew. Other sources of information are breakdowns and if some substations are causing a lot of outages. The same working method is applied to high voltage stations and to the power grid.

As with the District Heating Division, Electricity also has a limit on how much a renewal can cost without the municipal executive board making the decision. This board consists mainly of politicians and they are in most cases laymen. So when it comes to technical aspect of a renewal they have to rely on the opinions of the persons initiating the renewal. In some cases an external investigator may have made a judgment that the board will take into consideration. However, the normal procedure is that operators or maintenance personnel initiate an investigation into what must be done. Normally it is also someone within their own staff who carries out the investigation, writing the report and presenting a solution for the manager. The manager discusses the matter with the managing director. They then decide, together, what to do.

The managing director’s role in renewals has three main aspects: he takes part in the debate in the municipal executive board and presents the options. Secondly he allocates resources on an annual basis to the different operational areas and thirdly he discusses larger renewals with the managers of the different operational areas.

4.1.2. SwedPower

SwedPower is a consultant company doing risk assessment on technical systems. They do risk assessments in various areas such as financial, technical and environmental fields. They try to describe qualitative problems in a quantitative way. The results of different analyses can for example be some kind of distribution, which describes possible scenarios resulting from different actions or events. This distribution gives the people making the decision a view of what the result might be of an event such as e.g. higher oil prices or changes in interest rates. Other applications of this method are lifetime assessments and assistance when trying to estimate what consequences a breakdown may have in terms of capital, personnel- and environmental dangers.

This method has been applied many times when trying to predict when in time a renewal should be carried out in order to postpone a renewal as far as possible without taking too high a risk that a breakdown may occur. One example of this is a lifetime assessment made of transformers in Grundfors. These are so-called system transformers that are used in the national grid. A breakdown may lead to serious social consequences.

When doing these investigations SwedPower must gather information in order to carry out the calculations. They must also adapt the calculation to suit the framework of the decision makers. This can be in financial, technical, environmental, or social terms. A lot of different ways to gather information are used, such as interviews with people working with the systems, historical data, maintenance reports, experiences from equivalent equipment, costs, technical performance etc. One difficulty when working like this is to know when enough information has been gathered to be able to do a calculation that a decision maker can use as aid when making decisions. There are three different aspects that limit how much information can be gathered. Firstly a financial aspects, there is a limit to how much capital that can be spent on gathering information. Secondly, access to information; there is simply no more information to use. The third aspect is perhaps the most common; how great a standard deviation from the mean value is acceptable for a decision maker in order to make a good decision. How much does more information affect the mean value and standard deviation of the result? This is not always easy to answer and many times it is up to the decision maker to decide when he thinks he has enough information.

An illustration of how they work with lifetime assessment can start with a simple question: “what is the residual lifetime of this generator?” The first answer might be 40 years. But that is not precise enough; the next step can be to divide the generators into three different voltage levels. Normally generators with lower voltages can be used up to 45 years and those with higher voltage can be used for 35 years. Further investigation might reveal differences in quality due to different materials and construction methods. With this type of research one can get a pretty good picture of the expected remaining lifetime.

4.1.3. Svenska Kraftnät

Svenska Kraftnät (SvK) is a company that owns and operates the national electricity grid, comprising the country's 400 and 220 kV power lines, as well as stations. Their duties include the responsibility for the electricity system being in short-term balance, known as the system responsibility. Svenska Kraftnäts technical systems consist of approximately 10,000 km 400 kV and 5,000 km 220 kV power lines and a share in 125 substations. The grid is operated from Råcksta in Stockholm and from Sollefteå. SvK have no maintenance personnel of their own so all work must be purchased from contractors. Every third years SvK invite tenders for a maintenance work, where contractors are invited to participate. The lowest bidder gets a three-year contract for maintenance and condition monitoring. Maintenance for substations and the grid are bought in a separate purchase.

When purchasing maintenance from contractors SvK separates actions into two different categories: basic maintenance and specific renewals. Basis maintenance is what contractors carry out and the work mainly consists of clearing vegetation around power lines, day-to-day maintenance and general surveys of the grid or substations. What they must perform is specified in a handbook or in the contract. Every year power lines and poles are investigated from a helicopter. Every seventh year the contractors have to walk under the power lines in order to estimate the status of poles, lines, foundations and wires holding up poles. Specific renewals are bigger actions when larger components have to be renewed e.g. parts of a grid or circuit breakers.

Normally the contractors hired discover something that indicates that action must be taken in order to maintain reliability or avoid a break down. They report it to SvK who start an investigation. The investigation will result in a report, which is used as support when making a decision. Sometimes an investigation shows that a specific power line is not needed and can be taken out of service, but this is rare. Normally some action has to be taken. One problem that has to be taken into consideration is the time it takes from discovery of something that SvK may have to do something about, until the renewal is carried out. Sometimes it can take years before a renewal is accomplished. This in combination with the importance of the national grid makes it even more important in both social and economical terms to avoid breakdowns or unnecessary capital costs due to early renewals.

Furthermore, a lot of extensive renewals during a short period of time may also contribute to both extended project time and costs due to shortage of personnel and material. SvK have seen the dangers inherent in this scenario. Breakdowns due to lack of maintenance are not accepted at any time. Therefore it is important to estimate the amount of investments during a certain period of time in the future. SvK have made an analysis of their technical systems and have estimated remaining lifetimes. This judgment was made in order to estimate the amount of resources needed during five-year periods in the future. By adopting this approach they hope to avoid peaks in renewal demand and to avoid breakdowns due to lack of resources needed to carry out renewals on time. Examples of what the SvK age structure of transformers looks like are shown in figure 4:1, "Age Structure of Transformers".

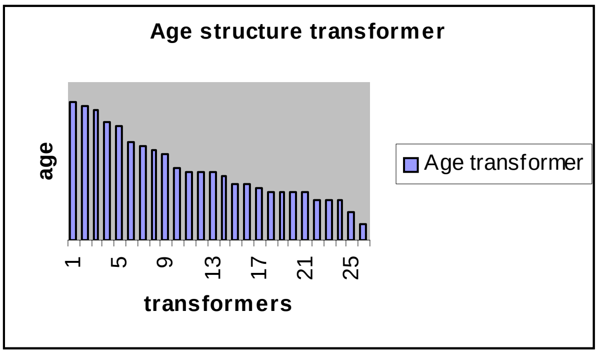

Figure 4:1, Age Structure Transformers

Figure 4:1 shows the age of transformers that SvK manage. Due to company secrecy, the values on the y-axis are not shown. SvK have also calculated similar figures for power lines and different parts of substations. By using this information together with an estimation of residual lifetime in combination with the cost of renewal, SvK can get a picture of investment needs in the future. The results of such an analysis are shown in figure 4:2, "Expected Renewal Cost".

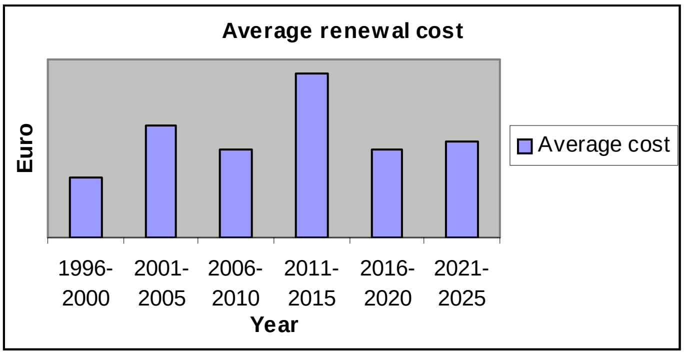

Figure 4:2, Expected Renewal Costs

Here, too, the values on the y-axis have been removed because of company secrecy. From this result SvK can see that renewal needs are quite constant except during the years 2011-2015. With further analysis SvK might carry out renewals before the end of the lifetime for some technical systems during the years 2011-2015. With this approach they can keep the investment needs at a constant level. This will help them to allocate resources in an efficient way.

4.1.4. SCA Ortviken

SCA Ortviken is a paper- and pulp factory whose net sales of forest products, in 1999, amounted to MSEK 11,532 and the number of employees was 3,533. A list of technical components shows that they have approximately 9,775 different objects (e.g. 1,048 fans, 1,007 rollers) together representing a value of 450 million Euros. If one paper machine breaks down SCA loses approximately 6,000-8,000 euros every hour.

When trying to prevent breakdowns and their consequences, SCA works hard with preventive maintenance. Every paper machine is stopped every two or three weeks and an overhaul is carried out. The stops normally last about eight to twelve hours and the machine and rolls are cleaned and thorough inspections are carried out. At the same time, such repairs as are not possible to fix while the paper machine is running, are also carried out. Normally it is the operators or maintenance personnel that notice these faults during production. Minor problems not affecting production are not fixed immediately; instead these problems are dealt with during an overhaul.

To prevent breakdowns and to find possible damage in equipment two methods are applied. The first is preventive maintenance carried out by personnel and the second is condition monitoring. All data collected is stored in a database in order to be able to see trends over time. The whole plant is also described in order to see where different parts are located and to identify what kinds of spare parts are needed to repair any possible breakdown. At the same time SCA has experts whose job it is to work with inspections. When they inspect a machine they follow a checklist and thoroughly work their way through the machine. These inspections are carried out at intervals so it is possible to detect trends over time. Along with these inspections carried out by personnel a lot of other measures are performed. These normally include measuring variables such as vibrations, temperatures, moisture etc. All this collected and measured data is the basis on which decision about what to repair during the overhauls are based.

On average, SCA Ortviken spends 15 million Euros on maintenance every year. On top of that the company spends another 4-5 million Euros on special investments. These are large investments that are planned some time ahead. The allocated resources are spent on renewals where they are most needed. No general method is applied when selecting among renewals. Normally, it is the opinion of personnel working with the technical systems that provides reasons for renewal.

SCA Ortviken works hard with the analysis of unplanned stops. An unplanned stop is when an action is taken that was not planned 24 hours or more before the stop. All these events are logged and reports are written so that SCA Ortviken's personnel can analyse what caused the breakdown. This is carried out so that similar breakdowns can be prevented in the future. SCA Ortviken has developed a systematic approach to work with these issues. From this work they have been able to identify what causes breakdowns. It was shown that 15 % of all maintenance measures are due to poorly performed repairs, 30-40 % are due to incorrect handling of equipment and the rest are problems caused by constructional error.

As mentioned earlier, the personnel working with the technical systems in collaboration with the managers for the different areas make selections among renewals. The work of deciding which renewals to carry out and which to postpone runs all year. The different sections of the factory collect information and decide what they need to renew. The SCA Ortviken board decides every year how much capital they can afford to spend on renewals. When this amount has been set, the work of selecting renewals starts. Normally all the managers of the different areas, together with some personnel, discuss together and try to agree on what to renew. Everyone must state reasons for why they should be granted funds. This method works very well and the personnel are satisfied to be a part of the decision making process.

SCA Ortviken also works hard to find bottlenecks in production. Both maintenance and operators try to find measures that can increase production. One important part in this work is to educate the personnel to understand the different processes specific to the factory. At the same time they work to increase availability and reliability in order to be able to produce more paper without new investments. When working with this complex issue, three different objectives are prioritized; these are production, environmental questions and work environment. For each one of these objectives there are goals set, which they try to reach.

SCA Ortviken has high demands on availability; they run the factory all year around. The whole factory is never stopped except once every third year. With this approach it is utterly important that no breakdown occur in an important section of the factory. A worst-case scenario is a breakdown that stops the whole factory. One of the most important systems is the fresh-water supply. Today a major part of the pipeline is made of wood; a breakdown in this pipeline would lead to a total stop. Therefore most of this pipeline will be renewed during the next major stop. Another crucial system is the production of high-pressure steam. The steam is used to dry the pulp and without it production will stop.

When working with such crucial technical systems SCA Ortviken tries to build redundancy where it is possible. They simply have to calculate the use of a redundant system and compare it with the costs. From this calculation a decision is made.

The normal cause of a renewal is the demands of the market. If the market wants a certain product economical calculations are made in order to see if the investment is profitable.

4.1.5. Birka Energy

Birka Energy is Sweden’s leading energy company in terms of number of customers, and the third largest in terms of production capacity. Birka Energy has developed a model that is used to objectively choose which renewals to carry out and which to postpone. Before the model was developed there were five different factors that decided whether a renewal was carried out or not. These are age, breakdowns, inspections, hired personnel's judgment and the company's own personnel. Incentives from these different areas were the basis for a manager's decision on which renewals to carry out and which to postpone. On many occasions, age was a very strong argument and many times this led to early renewals. This, in combination with a non-regulated market, resulted in renewals just to make sure that no breakdown occurred.

When the power market was deregulated in 1996 the companies faced new conditions. The old method was not working properly so Birka energy decided to develop a new method to use when deciding which renewals to carry out and which to postpone. For this purpose, they started to develop the KUMAR model. The model is built on a type of risk analysis. When working with this model the incentive to start an investigation of some kind of technical system starts with signals from personnel, customers, authorities etc. The different projects that we want to carry out are gathered and analyzed using the model. The biggest advantage of using this model is that when comparing different projects the result is objective. It is possible to compare totally different renewals in different business areas without any subjective judgments.

When starting the analysis of different renewals the first thing they do is to define the project by addressing these issues:

- What kind of technical system?
- What part of the technical system?
- What measures should be taken?
- Describe why the renewal should be carried out.
- Estimate costs for renewal

The next step is to estimate what the consequences of a breakdown may be. This is done in three different areas, they are:

- Work environment (personal injury)
- Environment
- Economical consequences

When grading the consequences a five-step scale is used, for work environment one equals no injury and five a lethal one. With the environment, one equals no impact and five equals large spreading impact with long recovery. Economical consequences describe how much money a breakdown will cost, calculating with loss of sales, repairs, resulting personnel costs etc.

The next thing Birka does is to feed this data into the model, the input into the model are:

- The number of each project
- What technical system
- What part of the system
- What measures should be taken
- Consequences of a breakdown
- Cost of renewal
- Consequences of personal injury
- Consequences of environmental damage
- Economical consequences

After processing this input, the result can be used as an aid when selecting among renewals. E.g. it is possible to only look at projects that improve the working environment; this gives a good general view of which renewals are most important and at the same time be able to estimate resources needed for improving the working environment. When the people responsible for renewals know how much capital is allocated for renewals for a certain year, they can use the result as support when selecting which renewals to carry out and which to postpone. The KUMAR model can be programmed to show which renewals should be carried out depending on the amount of capital allocated. The manager can also program KUMAR to prioritize some specific types of renewals e.g. environmental. With this method he can easily prioritize between renewals, and can even compare economical consequences with environmental consequences.

Because the model is so simple to use, Birka intends to use this model as a tool when doing a first selection within a business area. By doing so Birka thinks they can perhaps avoid too many renewals that have to be more thoroughly investigated. Only the most important ones will be passed on from the business area manager to the people responsible at headquarters. Another big advantage is long-term strategic planning. If the objective is to avoid breakdowns that can cause personal accidents the model can be used to identify which technical systems must be renewed. For Birka it is a huge advantage to have this model to compare different business areas and to identify where the resources will be of most use.

4.1.6. Sydkraft Hydropower

Sydkraft Hydropower produces about 35% of Sydkraft’s electricity. About 120 facilities and 250 generators in Sweden produce Sydkraft’s hydropower. On an annual basis they produce approximately 10 TWh.

When deciding what measures to take, Sydkraft Hydropower started to think about how they would cope with this complex issue 20 years ago. At that time a strategy was developed which resulted in short periodic overhauls in every facility. Every problem that was discovered was fixed and a general estimation was made on the residual lifetime. Sydkraft hydropower applied this method until the power market was deregulated in 1996. When the demands for rationalization and effective economies increased, this method was too expensive.

In general terms, all periodic overhauls are done at twice as long intervals, compared with the time before the deregulation. What they used to do every second year is now done every fourth or fifth year. At the same time Sydkraft Hydropower are more willing to take higher risks when it comes to breakdowns. They are not so concerned about a breakdown; if a power station fails production can be carried out elsewhere in Sydkraft's production facilities. At worst, they calculate on buying electricity on the market if they can't produce the amount they need in order to fulfil contracts.

To do the overhauls and maintenance Sydkraft Hydropower hires internal contractors; a company within the concern carries out most of the work. The only areas where contractors are invited to compete are turbine overhauls. These contractors also make the judgment on what to renew at each facility. They report what they have found to Sydkraft Hydropower, which in their turn decides what to do. Normally, when it is a case of ordinary maintenance, the contractors can decide for themselves what to do. Sydkraft hydropower does not fear being dependent on others when the personnel who know the systems do not work in the company.

Sydkraft Hydropower has divided maintenance into two different areas, projects and normal maintenance. The normal maintenance costs about 9 million Euros and projects cost about 15 million Euros on an annual basis. When deciding what renewals to prioritize, Sydkraft hydropower uses a model they call STEFF (safety, availability and efficiency). Today there are hardly any investments due to efficiency; because of the low price of electricity they simply cannot get an investment to pay off. Many investments to increase availability are very hard to carry out in order to make money. Many investments today are carried out in order to minimize personal- and environmental hazards.

When developing a long-term strategy a group of seven to eight persons representing different areas within Sydkraft Hydropower sit down together a couple of times every year and discuss what should be done. All persons present are responsible for one district, normally a geographical region. They all present the renewals that are prioritized within their area. After all the presentations and with the knowledge of the amount available for renewals, they discuss together which renewals to carry out and which to postpone.

Sydkraft Hydropower maintains that it is very difficult to use historical data from similar equipment. The person responsible for renewals at Sydkraft Hydropower states that one can assume that generator windings made by ASEA 1965 are not good. At the same time they have generators from other companies built the same year that work perfectly. One other example is that generators made by ASEA in 1950 works fine and are in no need of renewal. A lesson learned by the respondent is that this kind of data is only available from people that have been working in this field for a long time. One example of how hard lifetime estimations can be is an investigation two power stations in Mörrumsån conducted in 1952. Conclusions from that investigation were that both stations were in bad shape and needed instant refurbishment. Both those stations are working today with same equipment they had in 1952.

One other experience this respondent has is from generator renewals. He claims that large suppliers of generators and associated equipment have stated that the reasons for renewing windings in generators are just to make sure no that breakdown occurs. Since the Swedish power market historically has had many small companies that were dependent on their power production a lot of them carried out the renewal. Today when companies are much larger and fewer due to deregulation, a breakdown is acceptable; Sydkraft Hydropower has that philosophy. The person responsible is sure that most generator winding renewals were carried out at least 20 years too early.

The policy on long-term maintenance management is that a breakdown is not serious for almost any components except turbines and transformers. On all other production components a higher risk is accepted. Generators are one example of equipment that Sydkraft Hydropower runs closer to an assumed breakdown. Sydkraft hydropower relies on protection equipment to prevent major breakdowns. The fact that it is hard to measure the condition and to stop the process in time to prevent major damages in combination with outage time, makes transformers and turbines more critical.

This policy is shown in the type of renewals carried out during the three last years. They have had more than 20 projects where more than 2 million Euros have been spent. Most of the capital has been spent on electrical equipment, supervision and control systems, in substations and protection equipment in generators, transformers and turbines. The purpose of this is to minimize damage if a breakdown occurs.

5. Conclusions Part One and future work

This case study has shown the complexity of maintenance management. To estimate the residual lifetime is only one part of the renewal process. There are many factors that influence when a renewal should be carried out and the work of developing a model must take into consideration many different aspects. What the respondents all agreed on was the importance of systemic thinking and the need for models that are fairly easy to use and do not demand a great amount of input data.

Every technical system is unique. Awareness of its function, operations and importance to production is essential when deciding about maintenance management. The different aspects of how the companies' works are described below.

5.1. External contractors or the internal organization

During the interviews it was clear that the people who work with the systems, such as operators, maintenance personnel and contractors, provide most of the status information of the technical systems. One question is whether to employ your own personnel or hire contractors? If a company is purchasing all overhauls and maintenance from a contractor there might be a risk that a lot of knowledge of the technical systems will not be retained within the company. One way of partially solving this is to develop some kind of model for how knowledge should be kept within the company. If the company purchases maintenance e.g. every third year there is a possibility that a totally new contractor gets the contract. All personnel previously working with the technical system will leave the company and take all knowledge with them. The company will therefore have persons without experience of this particular technical system, managing it.

In contrast to some of the electricity companies SCA Ortviken uses their internal competence to a great extent when deciding which renewals to carry out and which to postpone. Only a few parts of the maintenance is outsourced. Their experience is that a lot of knowledge exists within their own organization. In a pulp and paper industry almost all technical systems are under the same roof. This means that it is much easier to have personnel close to the technical systems. They can use not only SCADA but also human senses to detect if something is not working properly. In most cases electricity companies do not have this possibility and have to find other ways to work. Maintenance strategies must be adapted to the reality experienced by the company.

5.2. Maintenance strategies

To facilitate decision making for the managers it is important that the company has developed a strategy with clear objectives. This can concern things like: what method to apply for maintenance, what kind of renewals should be prioritized and how this should be carried out. There are many aspects to consider when developing a maintenance strategy.
One issue that must be considered is what the consequences of a breakdown can be; is it absolutely crucial for the business or is a failure acceptable? For the electricity industry there is one more aspect: social consequences. The cost of power failures for the community can be very high and for a company it can be very bad publicity, which in the worst case can result in customers choosing other companies to do business with.

The interviews clearly showed that the importance of a technical system is a very dominant factor when choosing methods for maintenance and supervision. In one way, SCA Ortviken and Sydkraft Hydropower have developed similar methods for long-term strategic work. Both companies rely on protection equipment in combination with the observations made by the personnel working with the technical system.

To sum up long term strategies, there seem to be three different approaches: The first one adopted by Birka, Svenska Kraftnät and HEMAB: these companies work to find the weak points in their technical systems and try to prevent breakdowns by renewing critical components. Sydkraft hydropower relies on protection equipment and the experience and judgment of personnel and is willing to take a higher risk. SCA Ortviken uses both measurement and the experience and judgment of their personnel in order to prevent major breakdowns.

When it comes to prioritizing there are two different approaches: mathematical models or discussion. Perhaps Birka Energy’s model is the most highly developed one in to making objective judgments on which renewals to carry out in order to use allocated resources in the best possible way. The other companies rely more on discussion to try to find the best way to use the resources allocated.

5.3. Risk analysis

When analysing the results from the interviews it was clear that the risk is the sum of probability for an event and the consequence of that event. A risk analysis is therefore carried out to decide firstly, which renewal to prioritize and secondly when to develop a long-term maintenance management for a technical system.

When carrying out a risk analysis the work consists of trying to calculate the consequences of a breakdown and the probability of a breakdown happening, i.e. try to estimate residual lifetime. To do a risk analysis is one of the most common tasks for SwedPower; they collect information on both probability and consequences, describe these values with a distribution and use a computer to calculate the result of different actions taken.

To do a risk analysis is an important part of maintenance management. When trying to identify the consequences and probability of a breakdown, the staffs conducting these analyses gathers a lot of knowledge. With this knowledge awareness is gained of the weak points and what affect a breakdown can have.

5.4. Optimal time for a renewal

When should a renewal be carried out then? In this study imperative renewals are disregarded because when a breakdown has happened the companies in most cases do not have a choice, they simply have to face the facts and deal with the consequences. Normally the best time for a renewal is to carry it out as close to a breakdown as possible. This is the case for many renewals, but not always. One example is Svenska Kraftnäts approach where they try to estimate what resources will be needed during some period of time in the future. The results of such work might show that in order to be able to carry out all renewal some of them must be performed early in order to balance investment needs over time.

When finding the optimum time for a renewal the residual lifetime has to be estimated. All of the companies participating in this case study agreed that it is very hard to accurately estimate residual lifetime. To try to make this estimation two different methods are used, a quantitative and qualitative one.

Quantitative

When making a quantitative judgment, some kind of measurement on the technical system or component is made. Measurements of vibrations, corrosion, temperature, fatigue, performance etc can be used when making an estimation of residual lifetime. Another example is oil samples or isolation measurements of transformers or a partial discharge analysis of a generator. The goal of this kind of investigation is to obtain an objective judgment of residual lifetime.

Qualitative

This is probably the most common way to estimate the residual lifetime of technical systems. When using this method the experience and knowledge of people working with the technical system or hired experts are used. They estimate residual lifetime or take necessary action by using their own experience, history from this or similar technical systems etc. Their opinion forms the basis for what the maintenance manager decides to do.

5.5. Prioritizing

An important part of renewal strategy is how to prioritize among renewals. This is because every company wants to use their resources where it will be most effective. The interviews clearly showed that prioritizing is carried out at least twice during the renewal process. The first time is when prioritizing which renewal to investigate further and the second is after a more thorough investigation has been conducted.

The persons working with the technical system normally do the first prioritizing. They are the ones who notice, for example, a decline in productivity or any change in normal values etc. The person noticing these changes must make a decision on what to do. He will probably report these signals to the area manager. This manager must decide which renewals must be carried out and which to postpone, an initial prioritizing must be done.

When it comes to bigger renewals, the manager cannot decide for himself; a more thorough investigation is needed. Someone else other than the manager normally carries out further investigations. Normally a senior manager or board of directors must make the final decision. It is often necessary for them to prioritize among renewals.

The study showed how important it is to have a structured approach to prioritization. There are many different methods of working with this issue and the organizations surrounding the renewal process are dependent on the size of the company.

All companies participating in this study clearly stated the importance of everyone involved in a renewal being involved in the decision-making process. A dialogue is very important so that all factors will be taken into consideration when a decision must be made. For the decision makers to be able to have access to good information many co-workers must give their point of view. At the same time it can be very time consuming if too much time is spent on investigation. Thus, it is up to the manager to know when he has enough information to be able to make the right decision.

5.6. Surroundings

The world around the company influences how it works on all levels. A big difference between the power industry and the paper- and pulp industry is that competition is relatively new to the power industry. The pulp and paper industry has always been subject to competition. The power companies new role as part of a deregulated market leads to lower income and increased competition, which has resulted in decreased earning capacity. An electricity company cannot afford not to manage its technical systems in an effective way.

To increase revenue, an electricity company can either increase income or reduce expenses. To increase income is very hard in a deregulated power market. At the same time, since the companies cannot increase income by making investments, one way of increasing revenue is to cut costs. One easy way of doing this might be by cutting down maintenance. This will probably not lead to any negative consequences during the first years but can be very costly in future. Another way of staying competitive on a deregulated market for a long time can be by managing fixed capital in the best possible way. The results might not come at once but companies that cut costs too much can have difficulty in surviving on a deregulated power market if renewal costs increases dramatically due to poor maintenance.

5.7. Renewals not carried out

How to handle the renewals that are postponed is an important issue. Some of the participating companies have developed their own methods and some let all postponed renewals be part of the personnel's judgment the following year. This approach can be dangerous if a worker retires or leaves for a new company. He takes all his knowledge with him and the technical systems he might have wanted to renew will continue to be unattended. It seems that the best way of dealing with this issue is to have some kind of project bank so that no renewals are forgotten. It is also important to compare new suggestions for renewals with older ones, in order to ensure that the most important renewals are carried out.

5.8. Future work

The interview series shows clearly that today there is no generally accepted method to estimate residual lifetime. It is also shown that it is very difficulty to estimate residual lifetime and the results depend on many factors. At the same time the consequences of a breakdown have a great influence on how important lifetime estimation is. It seems that a possible approach might be some kind of simulation where different variables are described as stochastic variables. The distributions, which describe these variables, can be developed from either quantitative or qualitative investigations.

It seems that one other important part of this work is how to prioritize between renewals. A developed methodology musts be able to deal with the risk and consequences of a breakdown as well as the need for prioritizing renewal projects.

Part Two – Proposed Methodology

6. Introduction

Part One of this thesis showed the need for a tool to use when working with maintenance management. The interviews and the literature review also showed what output the managers wanted from a methodology. To cope with such a multitask question a new method is proposed, the DLA (Dynamic Lifetime Assessment) method (Wärja, 2004b). This method uses available data on residual lifetime and combines this with a comparison between the costs for a planned maintenance action with an unplanned breakdown. This gives a manager a concise picture of possible outcomes of different renewal strategies.

However, even though the DLA method can deal with the risk of breakdowns and associated costs, the model cannot describe the state of a system. There are several approaches for estimating the status and value of a system (Baron et al., 1999). In this work the CBI (Condition Based Index) was combined with the DLA. CBI was first developed at Forsmark nuclear station and the offshore industry. The intention was to use it to calculate a normalized condition value of a technical system. The idea behind combining these two methods into a joint methodology was to use the DLA to carry out a variety reduction according to Ashby and using the result as influence when choosing input for CBI. With this approach a condition value of a technical system can be calculated using only input that is most likely to cause failures with costly consequences in combination with unacceptable probability.

7. DLA

The interviews showed that to present a concise picture for a manager, in his deciding about maintenance and renewal, a model must live up to three demands:

- It is preferable if results from the model are presented in monetary terms.
- The interviews showed that it not is possible to determine the point in time for a breakdown; a model must therefore be able to deal with the stochastic nature of the probability for a breakdown to occur even if little information describing residual lifetime is available.
- A model must not be demanding on resources but must be easy to use.

The breakdown cannot be determined in advance but the risk can be estimated. The costs can be described using normal financial methods. This leads to a stochastic approach in combination with normal financial calculations.
To estimate the cost for a planned maintenance action/renewal, normal financial methods are used. To estimate the residual lifetime available information is gathered and a distribution describing the probability of breakdown is created using standard statistic methods (Allan, 1992). Also, information from different condition monitoring methods can be used or subjective judgments from persons with knowledge about the

technical system (Billinton, 1995). Thus the DLA method is combination of a preset value analysis and Monte Carlo simulation.

7.1. The DLA Method

To work with the DLA only five inputs are used:

- Length of time period
- Technical lifetime
- Cost of renewal
- Cost of breakdown
- Interest

The outputs from using the model are:

- Cumulative distribution of probability of breakdown.
- Capital value of expected cost
- Capital value of cost of breakdown
- Capital value of cost of planned renewal

7.1.1. Input

All inputs in the model are described below. It is important to know that adding more inputs is very simple. In this version the main focus is on validating the results when using the model. Inputs are therefore held at a minimum.

Length of time period

The length of time period describes how far into the future the technical system is analyzed. The furthest point in time where the time period ends is used for two things:

- To calculate the present value
- To identify a point in time in the future when the technical systems analysis no longer is of interest.

Depending on the type of technical system, the length of the time of the period will vary, from a few years for electrical components, up to 50-100 years for large mechanical components.

Technical lifetime
The technical lifetime describes how long the expected residual lifetime is. When the model calculates the technical lifetime, it randomly takes a number from some kind of distribution. What type, mean value and standard diversion depends on the amount of information available. To get information in order to describe the distribution there are three different ways to collect it:

- Empirical
- Logical systems
- Subjective judgment

Empirical data is collected from similar systems and values can be calculated. This approach demands that a lot of stabile data is available. Logical systems are when data on different subsystems in the system to be analyzed are available. The information from the subsystems is used to calculate e.g. the expected residual lifetime of a technical system. Subjective judgment is when little or no data is available. The manager has to rely on subjective judgments on e.g. residual lifetime.

When the information is gathered and analyzed the distribution is made to describe the residual lifetime. The model for calculating residual lifetime in the iterations then uses this distribution. This stochastic value is then compared with the point in time when a renewal is planned. If residual lifetime is closer in time than the point at which a renewal should be carried out, a breakdown will occur and the cost of a breakdown will be added to the result. If the renewal is carried out before the end of the lifetime for the technical system a cost for planned renewal will be calculated. All these costs are summed up and shown at the end of each simulation.

Cost of renewal
This is the total cost of carrying out a renewal. All cost should be included, from the first indications that something has to be done until the renewal is carried out.

Cost of breakdown
This describes what economical consequences a breakdown leads to. A breakdown, which happens during a period of time, is calculated using the formula below. The cost of a breakdown is capitalized to be able to compare costs regardless of time.

$$c_b = (k + p) * t + s + a$$

c_b = cost of breakdown
k = cost per time unit due to non-payment
p = personal cost per time unit
t = duration of breakdown
s = cost for spare parts
a = fines, extra costs etc.

Interest
The interest shows what demand the company has on yield from the invested capital spent on investments. The interest is also used to make income and expenditure comparable over time. There is no simple way to determine the size of the interest; the company has to consider the following factors when doing so:

- At which interest a company can obtain a loan.
- The yield the company demands on invested capital
- The risk the company takes by making an investment. For nominal economical calculations the interest depends on inflation, real interest and the risk

7.1.2. Output

The different outputs are described under separate headings. What the result of a simulation is and how the model is built are described in chapter 9, results gained by using the DLA model.

Capitalized cost for breakdown
This cost describes the economical consequences of a breakdown in the future. It is calculated by capitalizing the cost of breakdown c_b (described in cost of breakdown) in:

$$C_b = c_b * (1 + r)^{-i_b}$$

C_b = capitalized cost of breakdown
r = interest
i_b = point in time for breakdown

Capitalized cost for planned renewal
The capitalized cost for an investment shows how much a renewal costs to carry out at a point of time in the future. The more a renewal can be postponed, the more capital is saved due to the capital costs of an investment. This cost is calculated by:

$$C_p = c_p * (1 + r)^{-i_r}$$

C_p = capitalized cost of planned renewal
c_p = cost for planned renewal
r = interest
i_r = point in time for renewal

Expected cost for a renewal strategy
To calculate the expected cost for a renewal strategy a Monte Carlo simulation is used. Input for the simulation is:

- density function describing the residual lifetime
- cost for a planned renewal
- cost for a unplanned breakdown

The next step of the simulation is to choose different periods of time. Each period represents the time to a planned renewal, e.g. if a renewal is many years ahead, the length of each period can be five years, first period 0-5 years, second period 0-10 years and so forth. For each period a series of iterations is carried out. For every iteration a lifetime is randomly chosen by the computer from the density function describing the residual lifetime of the component. If the random lifetime exceeds the chosen point in time for a renewal, e.g. the period of 0-10 years, the model calculates the capitalized cost for a planned renewal at year ten. If the random lifetime is shorter than the chosen point in time for a renewal, in our case ten years, an unplanned breakdown occurs with accompanying breakdown costs. This breakdown cost is capitalized, using the interest representing the point in time for when the simulated breakdown occurs.

For every period a series if iterations is carried out, for each iteration the cost is calculated depending on the simulated lifetime of a component. The cost from each iteration is added up and divided with the number of iterations to calculate the average cost. This average cost represents the expected cost for a planned renewal at the end of a certain period of time.

The minimum point of the curve, representing the expected cost, should be chosen as point in time for when a renewal should be carried out. If necessary, more accurate results can be obtained by reducing the difference in time length between the periods.

7.1.3. Results gained by using the DLA model

When carrying out a simulation the first step is to look at a technical system and examine the cost of renewal, breakdown, expected cost and probability of a breakdown. The result of a simulation is shown in figure 7:1, result of simulation.

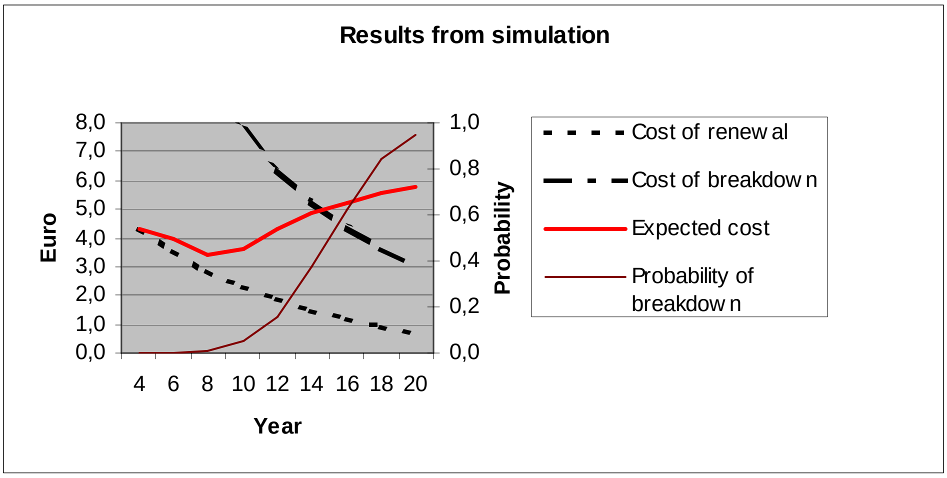

Figure 7:1, Result of simulation

Cost of renewal
This line shows how much it costs to make a renewal at a point in time in the future. The line that describes the cost of renewal decreases exponentially due to capitalization of the cost. In this example, by postponing a renewal from year ten to year fifteen approximately 900 000 Euros in capital costs are saved. However, by doing so the probability of a breakdown increases from 0,05 to 0,4. With that in mind and the knowledge of what consequences a breakdown may have, the manager making the decision must decide if he is willing to take that risk.

Cost of breakdown
The cost of a breakdown also decreases exponentially. In this case a very high breakdown cost is used to show the difference in cost between renewal and breakdown.

Cumulative distribution function
The cumulative distribution function shows the probability of a breakdown at a certain point in time in the future. With this line the manager making the decisions can see how the probability evolves over time. With this in mind it can be an aid when deciding when in time a renewal should be carried out.

Expected cost
This cost describes how much it would cost to renew a technical system in a certain year. When carrying out a simulation the computer calculates what would happen if a renewal were carried out each year, e.g. to decide what the expected cost would be for year fourteen. The model is then programmed so that a renewal is planned to be carried out at that point in time. The model then does a number of iterations where residual lifetime is randomly selected from a distribution. The data for this distribution is collected and analyzed as described previously in this thesis. For each iteration the model compares residual lifetime with the point in time when a renewal should be carried out. If residual lifetime is close in time to when a renewal should be carried out a breakdown will occur and the economic consequences for the actual year is the result. If residual lifetime is further away than when a renewal should be carried out, the cost of a renewal is the result of the iteration.

After performing a simulation for every year, the average cost will describe the expected cost of doing a renewal in a certain year. In the example previously shown the best point in time would be to carry out a renewal around year eight. It would cost a little under 300 000 euros to renew at that point in time. The probability at the same time is also quite low. How great a risk a manager is willing to take is very hard to say, it depends on what kind of decision he makes. However, if *all* consequences are properly described in economical terms the model will tell the manager what to do. In many cases it is very hard to quantify economical consequences. The manager will therefore also rely on his judgment.

The result also shows how much capital postponing a renewal can save. E.g. if a renewal is postponed from year eight to twelve the cost of renewal is reduced by approximately 100 000 Euros. At the same time the probability of a breakdown has increased from near zero to 0,2. A breakdown would cost the company 650 000 Euros. The question if is the manager making the decision willing to take a 0,2 percent risk for a breakdown that would result in costs of 650 000 Euros in order to save 100 000

Euros? Perhaps with these numbers at hand the manager can feel safer when deciding how to act.

7.2. Conclusions DLA

The result of a simulation gives a picture of the economical consequences of different maintenance strategies. When collecting data for input into the model as well as when performing the simulations, there is a lot to be learned. Gathering information on the technical systems, awareness and knowledge of both status and importance are gained. This information can many times be enough to make the right decision. But in some cases the manager might have to analyze further and use the DLA model. With the results from both information and the DLA model the manager can increase his chances of making a good decision. The results can also be of use when forming a long-term maintenance strategy. The manager can get an overview of capital needed for renewals and breakdowns. It is impossible to never have a breakdown; the important thing, if it happens, is that a strategy is developed in order to cope with environmental, technical and economical aspects.

8. The CBI method

The CBI (Condition Based Index) studied in this work was developed by Forsmark and is currently used in their nuclear power station. The idea behind the index was to create a normalized value representing the condition of a component or system by using measured values from a process. The measured values are aggregated higher in the hierarchy by the use of weight factors. By this approach it is theoretically possible to create one value that represents the condition of a whole nuclear power plant. Today Forsmark have implemented the CBI on a number of their technical systems. By calculating the CBI in real time it is possible to detect deterioration of a component even if it is slow. Also, by determining lowest acceptable levels of the index another possibility emerges: the CBI could be used as aid when deciding appropriate maintenance strategy. How CBI works is further described below.

8.1. Input for CBI

The first step when creating the CBI index is to define components and system. A component is defined as the lowest level of data input for the CBI. This means that it is possible to make an approach at any level of a system and define it as a component. Even large systems as e.g. transformers, circuit breakers can be called a component if it suits a manager in a certain decision situation. When the system consisting of several components is defined, the next step is to decide what to measure on the component and consequently represent the condition. Many different values can be used as input e.g. temperatures, vibrations, leakage, MTBF, current, performance etc. It is up to people with good knowledge about the system, and the function it is set up to fulfil, to determine which values to use as input for the CBI.

When the input values are decided, the next step is to create a transform function to normalize the measured value. To do this, any kind of function can be used, both linear and non-linear. By using existing SCADA system measured values are sampled from the process, transformed into a normalized value and stored in a database. This database can then be used to plot the condition of certain components or a group of components over a period of time to detect any deviations.

When creating the CBI to a systems level the condition of each of the components representing the system is aggregated. To perform this aggregating a weight value is used on each component. The sum of the weight values must equal one. This means that the aggregated value also is a normalized value that represents the condition of the system. The idea by Forsmark was then to continue to aggregate higher in the hierarchy so that the condition of very large system can be represented by a single value.

8.2. Output from CBI

When using CBI the output is in the form of a normalized value regardless of where in a system a calculation is carried out. The condition value is normally plotted in a graph displaying how the condition has evolved over a period of time. Software has been developed so that a manager can choose how to display and what to display. The output can show the condition of a single component as well as for a system. If a longer period of time is chosen, slow deteriorations can be detected, it is also possible to trace this down in the hierarchy to detect the cause for this. Also, if acceptable condition limits are added a manager can get a warning before a breakdown occurs. The general idea was to create a normalized condition index where changes should be used to avoid deterioration of a technical system as well as a maintenance-planning tool. A case study based evaluation of CBI is accounted for in 8.3.

8.3. Results gained by using the CBI method

In this chapter the results from a case study based evaluation of the CBI applied to feed water pump system at Forsmark nuclear station are presented. The CBI was implemented in this system in 2000, which means that historic data is available and failures are logged. The time span for the study was chosen to be between January and June 2002; during this period of time a radial bearing in one of the feed water pumps failed resulted in a shorter stop. The choice of object and period of time was chosen in an attempt to evaluate the methodology both from a component and a system point of view. The objective with this approach was to find pros and cons with the methodology and to evaluate if a manager can use the methodology as aid when deciding about maintenance strategies

8.3.1. System definition

The feed water pump system is divided into subsystem, each consisting of one pump. Each of the three feed water pumps is sub system 2. The pump itself was divided into eight components; the result of each level is displayed under separate headings.

8.3.2. Transfer function

The next step in the CBI methodology is to create a transfer function. Determining acceptable levels for the measured values on the components carries this out. The levels are determined from either subjective knowledge or by studying historical records. E.g. axial bearing 1 cooling water temperature was decided to be between 25 and 50 degrees

Celsius. A temperature up to 25 degrees represents a condition of 100 and a temperature over 50 degrees gives 0 in condition. The transfer function that represents the condition if the temperature is between 25 and 50 degrees is displayed in:

$$TTI=200-4*t \quad \text{valid for } 25<t<50$$

For all components such a transfer function was created. These weighted together represent the condition of the system centrifugal pump.

8.3.3. Components

The work on the component level starts with deciding what process values that are acceptable. Such values can be e.g. temperatures, flows vibrations etc. In this case the limits where set using historical data, interviews with skilled people working with either maintenance or operation and by using supplier's recommendation. After highest and lowest value of each component was decided a transformation function was created. The transformation function transfers values into a scale between 100 and 0, where 100 represents perfect condition and 0 a breakdown. In this study all transfer functions were linear.

If the temperature is below 40°c the CBI is 100 and if the temperature is higher then 50°c the CBI is 0. If the temperature increases, it indicates a leakage in the gasket. In this case the temperature started increasing 3 months prior to breakdown, se figure 8:1, "Cooling Water Temperature".

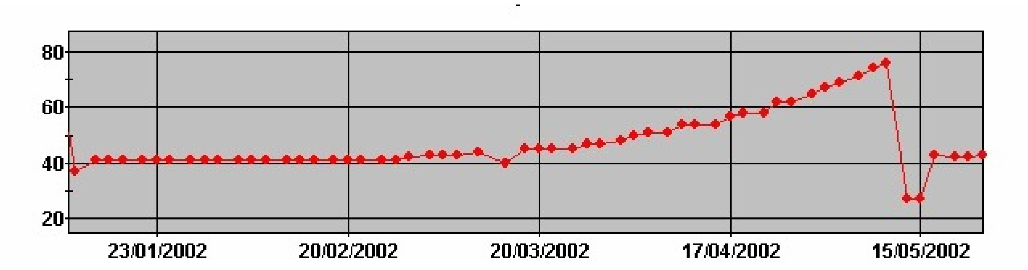

Figure 8:1, Cooling Water Temperature

The result of transferring these values into the CBI is presented in figure 8:2, "CBI Cooling Water".

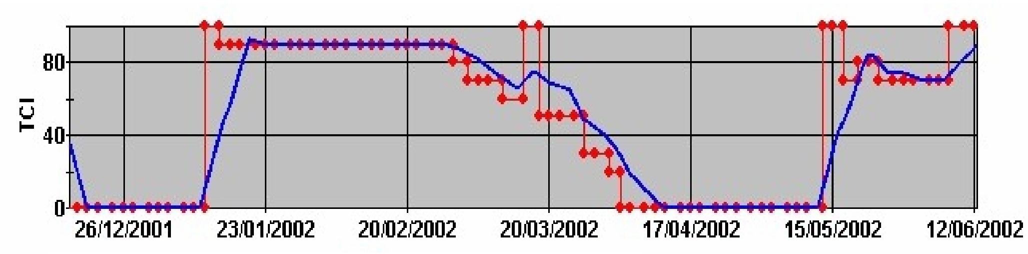

Figure 8:2, CBI Cooling Water

If studying how the CBI has evolved from March its clear that a decrease has occurred, except during a period in March caused by a short planned stop. In April the gasket was replaced and the CBI increased to a normal level.

8.3.4. Condition feed water pump

The CBI for a feed water pump consists of eight different measured values. There values are aggregated to display the condition on the feed water pump. The weight factor used is 1/8 for each one of the components. The CBI for same period as above is displayed in figure 8:3, “CBI Feed Water Pump”.

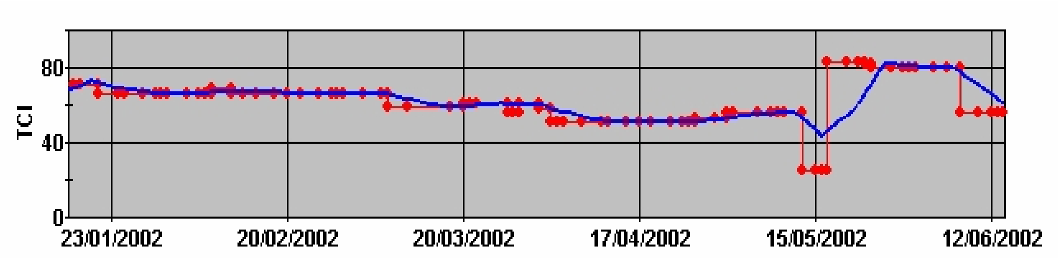

Figure 8:3, CBI Feed Water Pump

8.3.5. Condition feed water pump system

The next level of aggregation includes all three feed water pumps. These are aggregated with a weight factor; in this the weight factor is 1/3. The result from the aggregation is displayed in figure 8:4, “CBI Feed Water Pump System”.

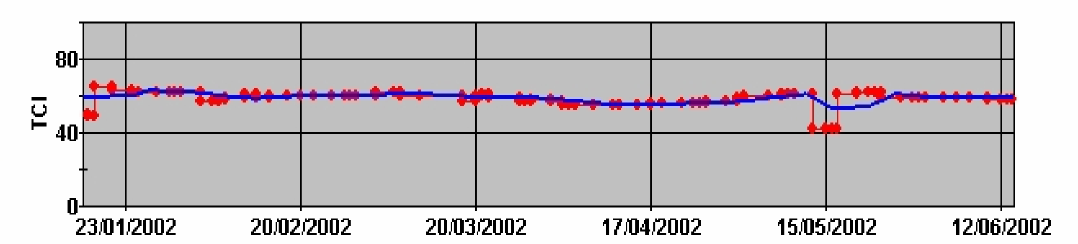

Figure 8:4, CBI Feed Water Pump System

In this study this level represents the top level of approach. It is on this level difficult to detect any deterioration on the axis gasket.

8.4. Conclusions CBI

The CBI as applied at Forsmark gives important insights into the status of the system. However, the methodology has some important shortcomings that make the index difficult to use as an efficient decision tool.

When aggregating index of sub-systems into a summarizing figure, important measurements may be hidden by less important values. Also, CBI gives no hint on which of the measurements that are critical in terms of breakdown and deterioration. The system's complexity, due to many inputs, makes post measurement analysis difficult and expensive. Thus, it is difficult to define acceptable limits for an aggregated index.

A condition-based index, without a method for finding critical measurements, proves unreliable in giving information for the development of maintenance strategies.

The intention of this method was to measure different parameters at a technical system, transform these values in to a uniform scale and aggregate these values into an index that describes the condition of the technical system. However, if studying figures 8,1 to 8,4 in the result part, above, it is obvious that any deviation from a "normal" value is weakened depending on the number of measured and aggregated values. The more measured and aggregated values that are used, the harder it is to detect changes in CBI for a component or system. Because of the detailed approach made by Forsmark, the condition index got too complex and it proved difficult to make any conclusions from a downward trend of the CBI. The case study revealed three difficulties when using CBI, they are:

- Interpretation of CBI
- Acceptable limits for values on components and system
- Complexity due to many inputs

The interpretation of the CBI proved difficult; today the index is looked on as a number. This approach will not help a manager when making decisions. A manager must be able to use the index as information when deciding appropriate maintenance action for a technical system. Our interpretation of how to use the index is twofold: first, as an indicator for when it is time to make a more thorough investigation of the condition of the system and second, as a comparison with historical records to detect deterioration. Unfortunately, to validate these applications a longer time span is needed and the components to use when describing the condition of the system must be chosen more carefully. A suggestion on how to make this selection is described in Methodology. Also, through this selection the numbers of inputs are reduced. This means that the difficulties with CBI, as identified in the case study, can be manageable. Future studies will reveal if this approach is correct.

9. The joint DLA/CBI methodology

The methodology consists of CBI and DLA put together in a joint methodology (Wärja, 2004a; Wärja, 2005a). The intention was to use the DLA as a tool for variety reduction (Ashby, 1956) from a financial perspective. This means that the components that are most likely to cause costly failures are identified and appropriate maintenance strategy is adopted to reduce the ‘financial risk’. However, the DLA by itself cannot handle a systems approach; this is the reason for using DLA with CBI iterative. CBI can be used to make a systems approach if the variety reduction if carried out in an intelligent way without reducing the amount of data to analyze. Also, other variables will be possible to add to the methodology e.g. maintenance resources allocated for a certain system. With this methodology a manager gets a decision tool that can help him analyse the effect of different maintenance plans, both in a long-term and a short-term perspective.

To evaluate the methodology the approach has been applied to a feed water pump system at Forsmark Nuclear station. In this first attempt, data provided by experts at Forsmark was used, together with experts at their production facility in combination with access to their maintenance system a first survey was conducted.

9.1. Result

The result from using the methodology was similar to that for the CBI evaluation described earlier. It proved difficult to apply the methodology to a maintenance system that already was in use and where the variables chosen for input was the result of en effort to use all available data. This resulted in a huge amount of data that needed to be analysed. However, by studying the feed water pump where failures had occurred it is obvious that a lot of variables to use as input could be reduced simply by not using input from components that do not represent a ‘financial risk’. One further study at a different pump at Forsmark nuclear station gave the same result. Consequently, the benefit of an interaction between the DLA and the CBI was clearly shown.

9.2. Conclusions

The level of detail used in this case study was not fully suitable for this methodology. The system was chosen because CBI has been fully implemented in the system and historical records existed. Also, a failure had occurred during chosen period that could be useful when validating the methodology. These factors decided what system to look at and what period of time to chose. The result from this was that we tried to validate a methodology, where CBI is one part, on a system where CBI was not functional. However, many useful lessons where learned, pros and cons of CBI, how to implement the methodology, the importance of detail vs. scope and possible solutions to interpret both the CBI and the result from the methodology. Because of the choice of object for the case study a total cost calculation was not possible to perform.

When joining these methods into a methodology and applying it to the feed water pump system it proved difficult to work with. When using this methodology for evaluation, it proved to be very important to find the right level of detail. In this study, personnel at Forsmark decided the level of approach. It seems as if in order for the methodology to work properly the manager responsible for the system must decide the level of approach. In this study the low level of detail when carrying out a system approach resulted in difficulties with making a long-term analysis on costs and condition. However, both methods proved to work separated from each other in this study. Lessons learned is that a DLA analysis should decide which components to involve in a condition index. By choosing components that can cause expensive failures and/or renewals the long-term perspective and total costs can be dealt with. The result was that a systems approach in this study was not feasible. Lessons learned by this will be used to improve the methodology further, so as to be able to cope with this issue

As mentioned earlier a reduction of inputs for the CBI is crucial to reduce complexity. We suggest that the DLA method can be used to cope with this. By using the DLA method only components that can cause costly failures are included in the CBI. By doing so the benefits of a RCM approach using the DLA method is combined with the CBI of the system. The result can be used when deciding about maintenance strategies and calculate future costs. With this approach only costly maintenance actions are included in the methodology e.g. renewals or major overhauls. And this makes sense, managers today have financial driving factors and this approach supports that.

At Forsmark they are in need of repairing a Voith gear between the electrical motor and the centrifugal pump. The suppliers of the gear recommended a gasket to be replaced every 20^{th} year; this gasket has now been running for 22 years. The consequence of this is a six-week stop resulting in both high repair cost and that no redundant system will exist beside the two remaining feed water pumps. If this had come to our attention earlier the study had included these systems also. When studying this system consisting of three components centrifugal pump, electrical motor and Voith gear it is obvious that these are expensive, take long time to replace and are important for production.

If the methodology had been applied on this system instead of the three centrifugal pumps it might had been possible to make an analysis over a longer period of time and to make a cost analysis.

Part Three – Case Study Based Validation of Methodology

10. Background

This part of the thesis deals with a real industry case. The objective was to validate the methodology on a "fresh" technical system. The methodology was applied on a refiner system at SCA Graphics paper mill in Sundsvall. This type of case was chosen because of four aspects.

Refiner importance to production
At SCA Graphic in Sundsvall wood chips are ground into fiber in refiners. If a failure occurs it can in some cases have a substantial effect on production. The work clearly showed that the MTBF for a package in the refiner was 22 months. If a failure occurs it can, at worst take up to 10 weeks before a restoration can be ready. A package is also rather expensive; this means that preventive maintenance will have a rather high price tag. On the other hand, a failure can in some cases result in reduced production capacity resulting in high costs. This makes the refiner system an interesting object for a unprejudiced validation of the methodology.

SCADA and maintenance
The refiners are well equipped with sensors and all the historical data is stored electrically. There are dozens of measurements on each refiner and values are logged continuously. One example of the enormous amount of values that are stored is when the force on each of the three bearings should be calculated. To calculate the average force applied on each bearing during one-year 51.000 measured values had to be used, and this is only a fraction of the data available. For an example of how values are stored, see appendix 3.

The fact that the refiners are so equipped with sensors shows how important they are for the production. By testing the methodology on such a system with this amount of measuring point and data available for analysis the application of the methodology was tested. I.e. is it possible to use the proposed approach to perform a variety reduction?

On such important equipment preventive and corrective maintenance is essential. However, on these refiners SCA Graphic was not pleased with the availability resulting in too high corrective costs.

Historical records
As stated earlier, a huge amount of data is stored electrically and corrective maintenance actions carried out is also stored. This means that it was possible to apply the methodology, by the use of historical records, prior to a breakdown in order to try to foresee what state the systems was in when a failure occurred. Unfortunately, since the work of identifying multiple causes of failure had not been carried out most of the data stored represented only one sensor value. This means that e.g. particles in the lubricant in combination with high load on the bearings were very difficult to calculate. The main

contribution from the methodology on this point was however the identification of such 'combined' values that in this case could cause the bearings to wear out faster than planned. The result is further described in the article.

Service agreement between Metso Paper and SCA Graphic.
At Metso Paper a new approach on how to supply after guarantee maintenance is under development. The idea with the agreement is that SCA Graphic pays a fixed amount of money to Metso papers and in return Metso Paper will perform all maintenance over a five-year period. However, the new approach also states that a mutual responsibility is taken for the function of the technical system. This means that the cost for repairing a breakdown in a technical system for the owner is a function of age. The idea is that both supplier and owner should benefit; lower costs for the owner and a long contract for the supplier with the possibility to gain knowledge about the system's components. The ambition in this phase for Metso and SCA Graphic is to cooperate and together develop and evaluate the agreement. Lessons learned from this are, however, outside the scope of this study.

With this approach new incitement for Metso Paper to be as cost effective as possible emerge. Metso Paper wishes to maximize profit by minimizing the present value of future maintenance cost without taking too great a risk of a costly breakdown; we call this a "financial risk". To evaluate the financial risk a methodology is proposed that estimates the condition of a technical system by identifying which parts of a technical system that are most likely to cause costly failures.

SCA Graphic on the other hand wishes to evaluate the condition over time in order to avoid a slow deterioration of his technical system. Another reason is to avoid that an external contractor to make money on invested capital by SCA Graphic. One possible conflict lies in that the owner wishes the condition to be perfect the day the contract ends and the supplier wants the condition to be as low as possible. A low condition indicates lack of maintenance, which saves a supplies money. The objective with this case study is to evaluate the methodology and investigate if the methodology can be used as a tool when specifying the service agreement and evaluating condition and financial risk.

11. Method

The evaluation of the methodology was carried out at four refiners situated at SCA Ortvikens paper mill in Sundsvall. The first step in this study was to identify the most common failures to occur and the consequences of these. Through interviews with constructors, operators, planners and maintenance personnel and studying of historical records, information was gathered. The result from this analysis was then used as input for the DLA model in order to identify the financial risk of each failure. The managers of the refiners decided from the DLA result which failures could be considered to have too high financial risk. The possible causes of these failures were then investigated through interviews. The parameters that were most likely to cause these failures were then used as input for the CBI. Acceptable limits were decided by skilled personnel and used when deciding when in time maintenance actions should be taken. From this the total cost for the strategy was calculated

12. Results

A refiner is a mill that grinds wood chips into fibre. Basically a refiner consists of an electrical motor, an axis with bearings and a rotor with a refining disc. The refining disc consists of segments mounted in a ring on the segment holder. A stator plate is supporting the stator segment holder, while the rotor segment holder is mounted to the rotor. The grinding takes place between the rotor and a stator segments, the column between these two discs is called the refining gap and can be as narrow as 0,4 mm. A freestanding oil unit supplies oil to the hydraulic and lubrication system. A refiner is displayed in figure 12:1, “Refiner RGP 200 series”.

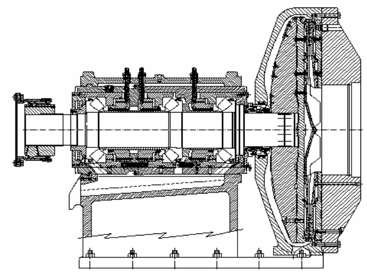

Figure 12:1, Refiner RGP 200 series

12.1.1. Pulp feeding

The material is fed into the refiner though an opening in the centre of the stator plate. Feeding is achieved by means of a screw feeder connected to the inlet of the disc housing.

12.1.2. Refining

The raw material is separated into fibre bindles while passing through the refining gap between the refining discs. The refining surfaces of the discs have a specially designed bar and groove pattern, which beats the raw material on its passage from the centre of the disc to the periphery. The steam pressure generated during the refining contributes to blowing the pulp out of the disc housing.

12.1.3. Sealing

Where the shaft passes through the disc-housing wall there is a mechanical seal. During operation the mechanical seal is supplied with water for sealing and cooling. A broken mechanical sealing can result in either cooling-water mixing with lubricant (unusual) or pulp in the disc housing. If water is mixed with lubricant the oil-film in the bearings is destroyed resulting in major damages.

12.1.4. Bearings

The rotor shaft is carried in a solid bearing assembly, consisting of three spherical roller bearings, two front and one rear bearing in a common bearing housing. The bearing mounted on the shaft with a press fit and spacing sleeves, carry all the axial and radial forces during refining. The bearings are preloaded with a spring assembly to maintain required axial load to all bearings during idling and during operation. This gives the axial bearings sufficient axial preloading irrespective of the operations condition. The bearings are lubricated with circulating lubrication oil from an oil unit, which is shared with the hydraulic system. An electrically driven pump and a belt driven-pump pump lubricating oil from the tank.

The oil flows through an orifice nipple to distribute the required amount of oil to each bearing. Oil flows first through an oil filter and then a cooler, with water acting as a cooling agent. After passing the bearings, the return oil is then drained back to the oil tank in a common pipe. The oil tank is equipped with a separate oil cleaning system consisting of a pump and a CJC filter. The CJC filter separates water and impurities from the oil.

The three bearing seats also serve as single-acting hydraulic pistons. The force and motion of these are transmitted to the shaft by the bearings. This makes it possible to adjust the clearance between the refining discs. To achieve optimum refining, it is essential that the disc clearance can be set with high precision and remains constant. Any variations in axial force caused by the refining process (i.e. uneven feed or pressure) are hydraulically compensated to prevent set disc clearance from changing.

The hydraulic system controlling this consists of two pressure chambers, which operate in opposite directions. Depending on the operating conditions, a certain disc clearance corresponds to a specific pressure ration between the chambers; this is maintained by a guide valve. The guide valve senses any tendency towards deviation from a set rotor position/disc clearance and momentarily corrects it by adjusting the pressure ratio. The guide valve simply directs the oil flow to either chamber for closing or opening the disc clearance.

12.1.5. Historical records

SCA Ortviken store all their measured values electronically. The measured values are logged every second minute and stored in a database. The digitalisation of the measured values started around 96/97, which means that for each one of the refiners there are approximately 50 million measured values stored. This is an immense amount of data that is very difficult to make something from. The study showed that no serious attempt has been made to make any judgement about the condition of the refiner. Examples of how data is stored are shown in table 12:2, “Data for Calculation of Axial Bearing Forces”.

Table 12:2, Data for Calculation of Axial Bearing Forces

		Öppn.tryck	Stäng. Tryck	Malhus try.	FL 1	FL 2	BL 3
2000-01-28	01:30:00	5,52	3,90	0,36	229	248	396
2000-01-28	02:00:00	4,22	5,27	0,37	279	322	337
2000-01-28	02:30:00	2,75	6,38	0,37	320	381	271
2000-01-28	03:00:00	2,97	6,22	0,37	314	373	281
2000-01-28	03:30:00	3,07	6,15	0,37	311	369	285
2000-01-28	04:00:00	3,14	6,20	0,37	313	372	288
2000-01-28	04:30:00	3,19	6,12	0,38	310	367	290
2000-01-28	05:00:00	2,99	6,20	0,38	313	372	282
2000-01-28	05:30:00	2,80	6,42	0,38	321	384	273

12.2. DLA analysis on failures

This study regards four reject refiners at SCA Ortviken that are used to re-refine pulp that not was adequately refined in a first step. Also, pulp to be re-refined can be stored in a silo with approximately 100-ton capacity. When taking into consideration that one refiner processes 130 ton/day (maximum 150 ton/day) it is obvious that using this buffer in combination with an increase in capacity on the three remaining refiners SCA Ortviken will have a maximum of 34 hrs of production (if the buffer is empty). Another advantage for SCA Ortviken is that they have one extra package; to replace a package takes approximately 10 hrs. (Package is the word used for the axis, bearings, rotor, mechanical sealing and segment holders.)

A package restoration is always carried out at Metso Paper; this means that SCA Graphic gets a refiner back in nearly new condition. The drawback is that a restoration can take up to ten weeks; if an industry has no redundant system a stop can be very expensive.

This means that one bearing failure is acceptable if only taking into account production. However, while the extra package is at Metso for repair, SCA Ortviken will not have a redundant system to use for 10 weeks.

The first step of a DLA analysis is to map possible causes of failures. This was carried out via studies of historical record and in collaboration with operators, constructors and maintenance personnel. The result from this showed that the failures that can cause stops are segment replacements due to wear, bearing breakdowns, mechanical seal failure and vibrations in the rotor. Besides these failures a number of minor problems can occur but they don’t cause stop in production and can be repaired when a planned stop is carried out. In collaboration with operators, constructors and maintenance personnel the consequences of the different failures what could possibly cause stops where investigated.

12.2.1. Mechanical seal failure

A failure on a mechanical seal can be detected many months before the leakage increases to such an amount that it might cause a major breakdown. This study showed that up to six month prior to breakdown deterioration is detectable. This means that the bearing can be replaced at the production facility during a planned stop. Consequently, the difference in cost between failure and a planned replacement is insignificant. The maintenance strategy chosen will be condition based and the leakage and temperature should be used as input for a condition index.

12.2.2. Vibrations

If the vibrations exceeds a pre-determined level the package must be replaced and restored. However, the vibration is the symptom of something else in the refiner starting to wear out. A thorough analysis of the vibration might provide some answer to the question if this approach is possible to use for the detection of failures in an early state. This kind of analysis is, however, outside the scope of this study. Example of how SCA Ortviken stores vibration data is shown in figure 12:3, “Vibrations Refiner Foundation”.

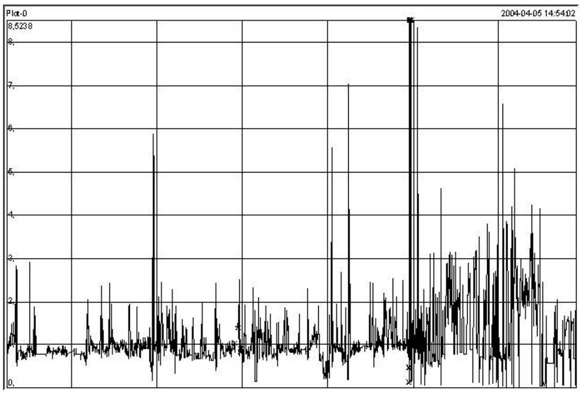

Figure 12:3, Vibrations Refiner Foundation

For additional reading regarding vibration analysis on bearings, see e.g. (Silva et al., 2002; Tandon, 1994).

12.2.3. Segment replacements

Segment replacement takes place when they start to wear out MTBM is approximately 2000 h hours and MTTR is somewhere around 8 hours. However, the lifetime of the segments changes depending on how the refiner is used and what kind of pulp that is processed. Also, if impurities like sand or, in a worst case, fragment of metal pass trough the refiner the segment wears out much faster. It is, however, possible to measure the quality of the pulp processes in the refiner and use this as an indicator of the condition of the segments. This gives an awareness of the remaining life of the segments and a replacement can be carried during a planned stop. The condition of the segment is represented by both operation hours and type of pulp processed in the refiner. Also, a DLA analysis shows that the financial risk is very low. This in combination with the possibility to estimate residual lifetime for the segments makes it possible to use a condition based maintenance strategy.

12.2.4. Bearing failure

By using historical records, a list of which bearing that had broken down and when this had happened, were put together. The result is displayed in table 12:4, “Overview Refiner Statistics”.

Table 12:4, Overview Refiner Statistics

Refiner	Date	Component	MTBM	Extra
R-81	1998-05-18			New package
	2000-02-09	Rear bearing 3	20	
	2001-04-25	Rear bearing 3	15	
	2003-06-19	Rear bearing 3	26	
R-82	1998-05-18			New package
	2000-06-07	Rear bearing 3	24	
	2003-04-08	Front bearing 2	35	
R-83	1998-08-03	Rear bearing 3		
	2001-01-29	Rear bearing 3	29	
	2002-04-04	Rear bearing 3	14	
	2004-04-01	Rear bearing 3	24	
R-84	1998-08-12	Front bearing 1		
	2001-01-24	Rear bearing 3	30	
	2002-08-30	Rear bearing 3	19	

When studying table “Overview Refiner Statistics”, two important lessons are learnt; eight failures out of ten occur in the rear bearing and there are great differences in time between failures. When carrying out a DLA analysis of SCA’s refiners the result is easy to explain and understand, the result is displayed in figure 12:5, “DLA Analysis on Rear Bearing”. Because of SCA Ortvikens unique situation with an extra package available and possibility to store pulp results in that the difference in costs between failure and planned renewal is very small. The conclusion from this is that it is most cost effective to have a corrective based strategy.

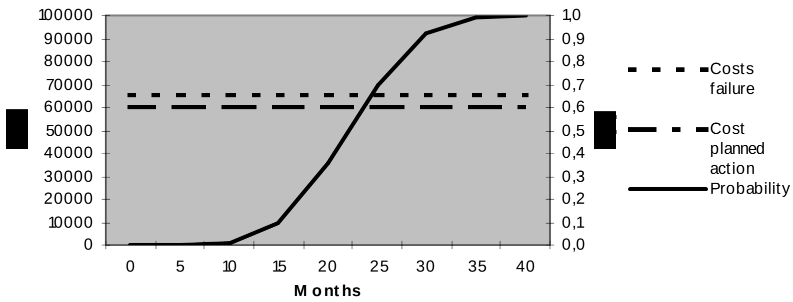

Figure 12:5, DLA analysis on rear bearing

The bearings turned out to be the critical component in the refiners. The historical records showed that since 1998 it is almost only the bearings that have caused costly breakdowns. To repair a package, which is standard procedure when a bearing fails, costs on average 75 000 EUR, depending on the consequences of the breakdown. On top of this the cost for any production loss is added. However, due to the redundancy of the package, a bearing failure does not result in any significant production loss. By studying historical records, a list of which bearings had broken down and when this had happened, could be put together. The record was used to calculate a distribution that represents the lifetime of the rear bearings. It turned out to be a normal distribution with a mean value of 22,3 months and a standard deviation of 5,7 months. Also, the study of bearing failures showed that eight failures out of ten occurred in the rear bearing. SCA Ortviken's unique situation, with an extra package available and the possibility to store pulp, results in a small difference between planned and unplanned maintenance action.

However, during the period when a package is restored at Metso Paper a DLA analysis gives a totally different result because of production loss, if an additional breakdown occurs. If this happens the production loss would be substantial. In situations like this, the DLA method states that the financial risk can be dealt with in two ways, either by reducing the possibility of a breakdown or by reducing the consequences of a breakdown.

If no redundant components were available, the cost of failure would be substantial. In this case study we theoretically assume that no redundant system is available. If this would be true it is very important for SCA Graphics to avoid failure. The next step in the methodology was to carry out a failure mode analysis trying to reveal the causes of rear bearing failures. The intention is to use these findings as input for CBI.

If it is financially justifiable a redundant component can be bought and available (chosen strategy by SCA Ortviken) to reduce the costs in case of a breakdown or measures can be taken to reduce the probability for a breakdown. If adopting a condition-based strategy corrective maintenance can be replaced by preventive maintenance reducing the probability for costly unplanned breakdowns. In this work we suggest that the methodology proposed can cope with this. By using CBI and DLA breakdowns can in some cases be detected in advance and maintenance actions can be carried out during planned stops.

The conclusions from the DLA study is that the condition of the segments, vibrations in the rotor, seal leakage and bearing breakdowns are almost the only things that can cause unplanned breakdowns. However, the rear bearing is the part identified to have the highest financial risk. The next step in the methodology is to carry out a failure analysis trying to reveal the causes of rear bearing failures. The intention is to use these findings as input for CBI.

12.2.5. Failure mode analysis of bearings

To investigate the causes of rear bearing breakdown a study was carried out. By studying damage reports and via collaboration with operators, constructors and service personnel causes and opinions on why the rear bearing failed were listed. The general opinion from the persons participating in the study was that the rear bearing had a remarkable short operative lifetime.

The conclusions from the collaboration regarding the bearings in the refiners were that four different aspect was most probable to affect the lifetime. They are as follows:

- Oil film/quality
- Dumping
- Differences in axial forces between bearings
- Hydraulic oil pressure

These aspects are then further investigated; it is also possible that, in some cases, a combination of these aspects causes abnormal wear of the bearing/bearings.

12.2.6. Oil film/quality

As with all lubricants it is important to have an oil film between the metallic surfaces. If contact is made between the surfaces directly or via some kind of contamination damage might occur. This damage will eventually grow and can eventually cause a bearing failure. A study of the service reports at Metso showed that it is always the inner bearing race that fails, se figure 12:6 “Inner Bearing Race”.

Fig 12:6, Inner Bearing Race

Suppliers of bearings as well as personnel participating in the study claim that as long as the right lubricant is used, the oil film stays intact, and is free from contamination; a bearing should theoretically function for longer periods than is the case at SCA Ortvikens refiners. One conclusion might therefore be that the other aspects affecting the lifetime of the bearing must be regarded in combination with the lubricants condition. However, today there are no historical records to be obtained of the oil quality.

12.2.7. Dumping

Dumping happens if the pressure from the pulp is lost. This can result in impact between stator and rotor and destroy the segments, segment holders and the rotor. Since the disc clearance is around 0,5 mm it is important to have some protection against an impact occurring. This is achieved with the guide valve that will immediately, in case of pressure loss from pulp on rotor, direct the oil flow to chamber resulting in a fast separation of the stator and rotor. However, since the bearing rolls are spherical and aligned with an angle of approximately 45° against the refiner axis any looseness between inner and outer bearing races will result in a small “rise” of the bearing rolls. If this happens the oil film might be ruined for a short period of time leaving a “mark” in the bearing race. If this happens repeatedly it might cause a breakdown. SCA Ortviken or Metso Paper has today no statistic on how often this occurs. The only way to estimate the number of “dumpings” is to manually count how often refiner power rapidly descended from normal operating condition to zero. However, this is rather common and it is difficult to separate a “dumping” from a controlled reduction of refiner power. Dumpings or similar incidents occur on average several hundred times every month. It is therefore very difficult to estimate on how often a dumping occurs and if this has any effect on the bearings residual lifetime.

12.2.8. Differences in axial forces between bearings

The forces on the bearings are a function of the oil pressure in the hydraulic chambers and the pressure in disc housing. The forces in the bearings are calculated with:

Front bearing FFB 1= 3,7·pB +110 - 7·ph [kN]
Front bearing FFB 2= 5,4·pB +37 [kN]
Rear bearing FRB= 4,5·pA+147 [kN]

Hydraulic B-pressure, pB [bar]
Hydraulic A-pressure, pA [bar]
Housing pressure, ph [bar]

To find out if there is a difference in load on the bearings 26000 measured values between 27/1-00 and 21/4-01were used to calculate the average force on each bearing. The result is displayed in table 12:7, “Average Force on Bearing”.

Table 12:7, Average Force on Bearing

	Force (kN)
Front bearing 1	245
Front bearing 2	251
Rear bearing	340

This shows that on average the rear bearing is exposed to higher pressure than the other two bearings, this is probably one explanation why the rear bearing has a shorter operative lifetime. However, this calculation was carried out manually in an Excel sheet, no continuous calculation on the amount of force applied to each bearing is carried out. One possible way to estimate the lifetime might be to integrate the force applied to the bearings over time to find any correlation between accumulated force and residual lifetime. To carry out this calculation using an Excel sheet is an immense work, it is simply not possible to do and the calculation carried out shows with clarity that on average there is a higher load on the rear bearing.

12.2.9. Hydraulic oil pressure

The pump providing oil pressure to the chambers is constructed to produce a pressure of maximum 70 bar. Today the recommendation from Metso Paper is to not exceed 50 bar. However, production and oil pressure have a linear connection so by exceeding 50 bar it is possible to produce more pulp. Because of the high production the differential pressure over the rotor disc creates a force driving the discs together, to avoid the refining disc to collide the rear bearing must be used to “pull” the discs apart. The result of high production is therefore high hydraulic oil pressure that causes high forces on the rear bearing.

12.2.10. Combinations of aspects affecting bearing lifetime

When considering the different aspects that might affect the condition of the bearings one further dimension must be added: the possibility of two or more aspects (e.g. contaminated oil and the number of operating hours) together affecting the condition. Neither SCA Ortviken nor Metso Paper have today any measuring on the different aspects highlighted in this work or combination of these. Because of the time span to implement such measures and get enough data to be able to make a validation will take a long time. It is therefore not possible in this article to present an empirical study to validate these aspects.

12.3. Level of detail

When determining the level of detail for an analysis the idea is to use as few and as large components as possible representing the condition of the technical system. In this case the highest system level is a refiner RGP 262 and the components generating the system have been selected from the result of this study. Constructors, maintenance and service personnel and operators had also been able to give their opinion on the choice of components. The result from the study was that failures that could cause a refiner stop was:

- Segment wear
- Mechanical seal
- Vibrations
- Bearings

These factors will then be used to describe the condition of the refiner. Choosing measuring points together describing each one of the four factors will carry this out. Main focus in this article is not to identify which values that should be measured and the acceptable limits of these. Only examples will be given on which values to use as components when describing the condition of each of the 4 factors.

- Segment wear: operation hours, pulp quality
- Mechanical seal: temperature, leakage seal water, seal water temperature
- Vibrations: vibration measuring and analysis
- Bearings: force on bearings integrated over time, oil quality, dumpings, hydraulic oil pressure, and combinations of these

Below are examples of measuring points in the refiner that can be used as input for a condition index:

- Power on refiner
- Vibrations (foundation)
- Inlet pressure (pulp)
- Outlet pressure (pulp)
- Hydraulic pressure chamber A
- Hydraulic pressure chamber B & C
- Hydraulic pump pressure

- Production
- Segment operating times
- Oil temp rear bearing
- Oil temp front bearings
- Lubricant oil temperature
- Impurities in oil (amount and size)

In some cases new sensors might have to be installed and software have to be upgraded to handle the information in an effective manner. Also, upgrading has to be done to handle those cases when two or more measured values combined might be used. However, to determine which inputs to use and acceptable limits is outside of the scope of this study.

13. Conclusions

When working with complex technical systems important to production and to expensive to have redundancy for the study showed how important it is to have a systematic approach when deciding about maintenance strategies and trying to identify which variables that are most likely to affect the residual lifetime.

The study revealed several interesting facts: First, the methodology was very easy to use and could identify which components by themselves or in combination with other could cause costly breakdowns. In this case study both a redundant system existed and the possibility to store pulp in case of a breakdown, even this the methodology could cope with. It there had been no such “backup systems” the results would have been different, the financial consequences would probably have been higher for more components. However, lessons learned from the case study showed that regardless of redundancy the methodology can be used to identify which components can cause costly breakdown. A manager uses the result from the methodology to motivate investments in term of increased maintenance or by investing in a redundant system to reduce consequences of a breakdown.

Second, when investing in a maintenance system measured values must be handled in an intelligent way. Today it seems like most of the measured values are logged and stored in a database and little or no effort is put into analysing or learning from the huge amount of data that is stored electronically. Some of the measures are used as limits and exceeding these will result in an alarm to an operator or a shut down of the process in order to avoid damages. The case study showed that it was possible, with relatively little work, to identify the variables most likely to affect the residual lifetime. Also, by using combinations of the measured values lessons can be learned, in this case the oil quality in combination with the forces on the bearings. By measuring this lessons might be learned on how much force on bearings in combination with contaminated oil a bearing race can stand.

Third, by using the CBI it is possible to detect a slow degeneration of a technical system. However, the study showed that it is important to choose inputs with care so that not too many variables are used. To interpret the CBI, historical records of similar measures are needed. Because of the combination of variables affecting the condition of the system, it was not possible to evaluate this in this study; the time span is too long. Before such historical records can be used to compare with, the CBI can be used as an indicator of deterioration of the technical aspects. If the index starts to drop it can be used as trigger for maintenance actions to be taken.

Fourth, the methodology can also be used when selecting which variables to measure and store in a maintenance system. The case study showed the difficulty in selecting the parameters to use when measuring and how these should be interpreted. Even if the number of measures will be the same, the methodology is used to highlight some of the variables or combinations of these. However, to make the variety reduction the knowledge of skilled people must be used in combination with the methodology to identify these variables.

Concluding Part

14. Discussion

Today the power companies have problems in knowing what the future will look like. Because of deregulation, the power production company's rules have changed dramatically. Also, with the Network Assessment Model the power transmission and distribution companies will face a market similar to a deregulated one. This means that the market for the production companies will resemble a competitive market like the one the pulp and paper industry have faced for a long time. The reality for the maintenance manager of a power system went from a system where the costs and demand for profit (Tariff = Profit + Costs) determined the tariff to a situation where the manager must adapt his costs to the incomes (Profit = Tariff – Costs). This has lead to a lot of uncertainties regarding fixed capital. It is clear that maintenance management has emerged as a new approach to how to exploit physical assets in the most profitable way. Questions such as: "what maintenance plan will be most effective" and "how will we avoid a slow deterioration of our technical systems" will become more crucial to work with, in a structured manner.

To answer these questions the companies must know how long the lifetime is for each component or system. With that knowledge it would be easy to answer both of the previous questions. Unfortunately there are no easy answers to these questions; there are so many factors and events that predicting them all is impossible. However, the questions remains and the managers must still maintain their systems in an effective manner, both in a long-term and short-term perspective. The methodology proposed has emerged from the study accounted for in Part One of this thesis. This means that the work of developing a easy to use methodology has its roots in the managers' opinions on what knowledge they think is essential to gain when managing technical systems with long operative life time.

The main result from this work is a structured approach to maintenance management and how to cope with different types of systems, regardless of the function they fulfil, and a quantitative link between maintenance and reliability. Also, through the use of Monte Carlo simulation an expected cost can be calculated to determine the point in time when making an optimization. This method can also cope with the financial risk associated with decisions regarding maintenance management. It is also important to state that because of the uniqueness of each system, they demand different maintenance strategies depending on the probability and consequences of a breakdown. Further, because of the long time span and the costs for renewals a lot of money can be saved by simply postponing renewals if a breakdown does not occurs. The methodology proposed is therefore a continuous process with the objective of reducing the financial risk and creating awareness and knowledge about the technical systems. By identifying the many different variables affecting the maintenance needs of the system appropriate maintenance strategy can be chosen.

To sum up the work there are five different areas that need to be taken into consideration when managing technical systems with long operative lifetime. These are explained further under separate heading below. If a manager can get an understanding about these areas, maintenance management decisions will be much easier to make.

14.1. Lifetime prediction

Probabilities can be hard to estimate. From a statistical point of view the ideal case is when there is long series of data over events. If this is the case an ordinary statistical method, called a quantitative approach, can be applied to develop distributions that describe the probability of something happening. When making a quantitative judgment, some kind of measurement of the technical system or component is made. Standard statistical theory precision can perhaps be summarized as saying that accuracy in inferences, and hence parameter estimations, will improve as relevant information continues to accrue (Leech, 1990). Measurement on vibrations, corrosion, temperature, fatigue, performance etc can be used when making estimations of residual lifetime (Villian et al., 1996)]. Another example is oil samples or isolation measurements on transformers or a partial discharge analysis on a generator. The objective of this kind of investigation is to get an objective judgment of residual lifetime. Unfortunately most of the complex technical systems are built with different techniques and operate under unique situations, no one technical system is like another. Breakdown in the form of system collapses are rare and do not provide the data necessary to use ordinary statistical tools.

If it is not possible to use this approach, some other method must be used. To combine knowledge of a logical model of a technical system with data on the components that are part of the technical system, theoretical systems can be built and probabilities can be calculated. The third and last method to estimate residual lifetime, if it is not possible to use empirical data or logical models, is to rely on expert judgments. This is called a qualitative approach. This is probably the most common way to estimate the residual lifetime of technical systems. When using this method the experience and knowledge of people working with the technical system, or of hired experts are used. They estimate residual lifetime or the action necessary by using their own experience, history from this or similar technical systems etc. Their opinion will form the basis for the maintenance manager's decision (Hänninen, 1991).

It may seem as though there is a lot of guessing when using subjective estimations. It is very common that much estimation in technical systems is a combination of subjective judgment and some data. Conclusion from this is that it is better to have a rough estimation of residual lifetime then no one at all relying simply on a gut feeling. The idea is to develop an understanding of the status of the system by studying historical records, talking with people with great knowledge about the system in combination with a surrounding analysis. This means taking into account the special environment and external influence of a system. With these factors in mind a manager can get a concise picture of his knowledge about an estimation of residual lifetime. With such an approach it is also possible to get supplementary details of where an analysis has its weaknesses. We state that an important part of residual lifetime estimation is to get an understanding about the parameters affecting the residual lifetime.

14.2. Consequence of a breakdown

A consequence analysis is made in order to identify what a breakdown might lead to. The consequences are divided into three different areas depending on how they affect the business (Strömberg, 2000).

- Economy
- Environment
- Personal injuries

To be able to compare different consequences a unanimous quantification has to be made. One way of doing this is in economic terms; however some consequences can be hard to quantify e.g. environmental and personal consequences. The economic consequences are easier to quantify in most cases. To estimate e.g. consequential damages and losses due to good will can be difficult. To quantify production losses and mechanical damages is easier.

To economically estimate consequences for the environment is difficult. Knowledge of how the environment may be affected by a breakdown is necessary. Are the effects local, regional or global and what are the long-term consequences? If it is your own business that affects the environment it might lead to high costs due to good will losses.

Personal injuries are also very hard to estimate in financial terms. None of the companies participating in the first case study ever hesitated to make a renewal if it could prevent personal injuries. Many times the big advantage may be just to have analyzed the technical systems and identified where the different dangers are. When developing a long-term maintenance strategy these incitements can be of great importance when prioritizing between renewals.

Why is it of such great importance to perform a consequence analysis? In most companies it is impossible to carry out all renewals so prioritizing must be done. How many of the total number of possible renewals that will be carried out depends on the financial resources available for renewals. To carry out a consequence analysis can be of help when prioritizing.

One further aspect of these events is that it is impossible to calculate the magnitude of the breakdown; can we repair the system or do we have to make a renewal? Since these events are impossible to predict and to calculate the consequences of, in many cases the best thing a manager can do is to try to identify what might happen and what the consequences might be. From this analysis the manager can then decide on suitable solutions for each event if it is economically justifiable. Examples of solutions can be to build in redundancy, keep spare parts and if the systems/components are expensive perhaps buy it together with other companies.

Does this mean that the maintenance manager cannot in any way anticipate future needs? No, since the power market was deregulated it seems that more and more renewals will be carried out due to age or wear and tear. Part one of this study indicated that the maintenance manager will have two main tasks when it comes to renewals, firstly he must have a strategy to deal with events that can cause disturbance in the technical systems: how to solve problems so that events will not have an unnecessary effect on operations. To identify and prioritize between different events RCM can be very effective.

14.3. Maintenance and financial aspects

When working with maintenance management with main focus on renewal strategies maintenance plays for obvious reasons, plays an important roll. However, in this work no clear distinction between renewals and maintenance has been made. One part of maintenance, as we see it, is in fact renewals. With this in mind and the effect day-to-day maintenance has on the operative lifetime it is quite obvious that both must be included when making decisions about maintenance strategies. The objective with the proposed methodology is to be as effective as possible when it comes to renewals. In most cases, and for most of the companies, effective maintenance management equals low costs with acceptable reliability. We mean that when considering technical systems with long operative lifetime this is not enough, both long and short terms must be included in the equation as well as the financial aspects. The proposed methodology is an attempt to quantify subjective judgements and combine them with objective measurements in an attempt to estimate future costs. The future cost is the sum of:

- Maintenance cost
- Cost for breakdowns
- Renewal costs
- Capital costs

By minimizing the sum of these costs a manager as we see it can get an understanding of future costs, condition, and financial risk, provided that the terms for revenues and reliability can be met.

If too much maintenance is carried out the operative lifetime will in most cases be extended. However, maintenance also has a price tag as well as large renewals. This means that in most cases the resources spent on maintenance will have influence on when in time a large renewal should be carried out. If no maintenance is carried out the only cost will be the cost for a renewal. This is perhaps the most expensive scenario in most cases but can in some cases be the only realistic alternative. On the other hand, by postponing renewals capital costs is saved and perhaps resources can be used in a more effective way. What we state is therefore that a manager responsible for large technical systems must minimize the present value of future costs and still live up to demands of revenues and reliability in the long and short perspective.

It was not possible to calculate the total cost during this case study. Again, this probably has to do with the level of approach. A study concerning larger components with longer operative lifetime might give a better result. It was however possible to calculate the cost for the feedwater pumps, but the fact that the cost for both preventive and corrective maintenance was insignificant, in combination with the low probability for a failure, made a total cost calculation unnecessary. However, the methodology supports

Forsmark maintenance strategy on the feedwater pumps, if the system had another reliability the result might have been different. One result of the study is that the financial risk for different components are calculated, this result is then used when deciding about maintenance strategies. However, the total cost calculation needs further investigation.

14.4. Condition

The next step in maintenance management is to estimate the condition that can be used when deciding about the point in time when a renewal should be carried out and finding the point in time, which minimizes the costs.

With the proposed model described in this thesis the manager will be able to estimate the condition and the future trends. By knowing this, the manager can decide when in time a maintenance action should be taken that improve the condition of the system. He can also use the information to allocate resources to avoid future maintenance and renewal peaks. By using DLA in combination with CBI a variety reduction is carried out reducing the amount of data to be analyzed. By doing this iterative and working with this continuously more and more experience feed back will make an analysis more accurate.

Furthermore, the maintenance manager can examine how different parameters such as interest, point in time for renewal and maintenance affects the costs.

14.5. Maintenance, Reliability, and Risk

The purpose of maintenance is to extend equipment lifetime, or at least the mean time to next failure whose repair may be costly. Furthermore, it is expected that effective maintenance policies can reduce the frequency of service interruptions and many undesirable consequences of such interruptions. Maintenance clearly affects components and system reliability; if too little is done, this may result in an excessive number of costly failures and poor system performance and, therefore, reliability is degraded; done too often, reliability may improve but the cost of maintenance will increase. In a cost-effective scheme, the two expenditures must be balanced.

In this work the link between maintenance, reliability and risk is established by the use of RCM and the proposed methodology. Identifying critical components by the use of DLA, and using these as input for the CBI will establish a link between condition and costs. Furthermore, the financial risk can be estimated for each critical component making it possible for a manager to decide appropriate measure to be taken to reduce either the consequence or the probability of a failure.

15. Conclusions

The first part of this thesis describes how the companies work today with maintenance management and how they estimate residual lifetime. Many lessons can be learnt from the first study. The major question was how the different companies work with estimations of residual lifetime. The interviews showed that today there is no generally accepted method for doing this. The complexity of lifetime estimations and the fact that the definition of “residual lifetime” differs from system to system makes it impossible to develop a general tool that answers the question “when to renew”. This is because of an erroneous general definition of residual lifetime, most persons think that the lifetime ends when a system physically breaks and it is considered to expensive to repair. We state that this is one kind of residual lifetime. But a lifetime can also end because of many other different aspects such as: political decisions, environmental affects, financial aspect, changes in capacity needs, danger to persons etc.

Because of this reality the work has resulted in a methodology to use when working with lifetime estimations and trying to identify which parameters that are decisive when deciding about maintenance strategies. Foremost is the methodology used in monetary terms, but the work will also show other aspects of maintenance needs and possible risks. Simply the awareness of potential risks can create new strategies to be adopted.

Next conclusion from the first part of this thesis is the concern of potential conflict between short-term revenues and long-term maintenance management. The major conflict when dealing with technical systems with a long operative lifetime is on the one hand to have an acceptable reliability and on the other hand a reasonable costs. If a company allocates more resources on maintenance, the reliability will increase; on the other hand, if too little is spent, more failures will probably occur. A methodology must be able to show how different maintenance strategies affect both long and short-term costs. With this approach it is possible to avoid a short-term increase in revenues that might in the future result in higher costs due to breakdowns and the consequences of these.

The third conclusion from the first study concerned all the measuring points in a technical system and all the data that are stored in an attempt to determine the condition and in extension the residual lifetime. In general only a few percent of the measured values are used when making decisions and it seems like most of the data not is used for any kind of analysis. It is also an advantage if a methodology could be used to identify which parameters to use when estimating the condition. The methodology must also be able to use both subjective and objective values.

When considering the three major conclusions from the first study our conclusion was that a methodology must be easy to use, general, must be able to cope with subjective and objective values, take into consideration long and short-term aspects of condition and costs and must be able to handle data in an intelligent way.

The second part of this thesis deals with the research area in general in combination with the DLA and CBI methods and how they should be used as a joint methodology. The general study of the research area showed that there are some methods that can be used to answer some of the general conclusions from the first part of this study. However, to use the existing methods demands a huge amount of resources spent on gathering and analysis of data. Sometimes it seems like the costs for doing such an analysis exceeds the earnings of such an approach. The models are also highly specified and can only be used by experts; examples of such methods are neural networks and partial discharge measurements.

The DLA method was developed for identifying the potential financial risks that different decisions might have. The idea is to gather information and provide a concise picture of estimated residual lifetime, consequence of an unplanned failure and the cost for a planned renewal. There are primarily two advantages when working with the DLA model: the result of the analysis and the work of gathering information. A calculation from the DLA model gives the manager the possibility to test how different inputs (strategies) affect the result. If, for example, the economical consequences of a breakdown vary a lot, a simulation will show how different incidents will affect the economic result. Lessons learned from a calculation can be used to identify where resources can be used in order to minimize the consequences of a breakdown if a renewal is postponed.

When making decisions about the future there is always some amount of uncertainty. Therefore the choice of method was stochastic simulation. In combination with economical calculations this describes the manager's dilemma. When combining these two aspects with long term maintenances management the manager gets a good overview over how to act both in short terms and in long terms.

The intention of the CBI method is to find a normalized value that represents the condition of the system. The method proved to be difficult to work with due to too many inputs and an aggregation that may hide possible failures lower in the hierarchy. The ideas proved however to be useful in combination with the DLA method in a joint methodology. In general, the DLA is used to identify potential financial risks and to reduce the amount of data needed to be analysed. The CBI could be used to detect deteriorations of the condition. The first case study is also accounted for in part two: main result from this study was as stated earlier the problem with handling data in an intelligent way. The DLA on the other hand carries this out.

The joint methodology was evaluated in part three of this work. For the first time it was tested in an unprejudiced way on a refiner system. Parallel to the evaluation Metso was carrying out a similar work with the objective to identify which parameters to use as input for an on-line condition monitoring system. The result from their study matches the one from our validation, despite our lack of knowledge about refiners when the validation started. This shows how easy the methodology was to apply and that it is not demanding on resources to implement it.

By identifying the potential financial risks maintenance and on-line measurements can be adopted in order to reduce the financial risk. The study at SCA Graphic showed that it was the rear bearing that had the highest financial risk, and the likely causes for this were identified. One other interesting thing about the methodology proved to be its use when specifying after-guarantee service agreement.

A current trend in the relations between companies and their contractors is to sell function, availability to guarantee production. The suggested DLA/CBI method is a valuable contribution when developing maintenance strategies, defining maintenance contracts and for monitoring ongoing maintenance service contracts.

16. References

Allan, R.N.B., R. 1992. Probabilistic methods applied to electric power systems-are they worth it?, Power Engineering Journal [see also Power Engineer], Vol. 6. pp. 121-129.

Alsac, O., Vempati, N., Stott, B., Monticelli, A. 1997. Generalized state estimation [power systems], Power Industry Computer Applications., 1997. 20th International Conference on. pp. 90-96.

Anders, G.J. 1990. Probability concepts in electric power systems J. Wiley & Sons, New York.

Anders, G.J., Endrenyi, J., Yung, C. 2001. Risk-based planner for asset management [of electric utilities]. Computer Applications in Power, IEEE 14, 20-26.

Andersen, T.M., Thorstensen, T.A., Rasmussen, M. 1998. Decision support in short term and long term maintenance planning using condition monitoring information, Power Station Maintenance - Profitability Through Reliability, 1998. First IEE/IMechE International Conference on (Conf. Publ. No. 452). pp. 45-52.

Ashby, W.R. 1956. An Introduction to Cybernetics Methuen, London.

Balzer, G., Schmitt, O., Halfmann, M., Hössle, A. 2001. Maintenance and Refurbishment Strategies for m.v. Substations, CIRED.

Barlow, R.E.P.F. 1975. Stastistical theory of reliability and life testing Holt, Rinehart and Winston Inc., New York.

Baron, M., Paté-Cornell, E., M. 1999. Designing Risk Management Strategies for Critical Engineering Systems. IEEE Transaction on Engineering Management 46.

Bertling, L. 2002. Reliability Centered Maintenance for Electric Power Distribution Systems. Doctoral, Royal Institute of Technology, Stockholm.

Billington, R.L., D.; Curley, G.M.; Staschus, K. 2000. Reliability information in a competitive market, Power Engineering Society Summer Meeting, 2000. IEEE, Vol. 1. pp. 5-15 vol. 1.

Billinton, R.P.W. 1995. A generalized method for distribution system reliability evaluation, WESCANEX 95. Communications, Power, and Computing. Conference Proceedings. IEEE, Vol. 2. pp. 349-354 vol.2.

Blischke, W.R.M.D.N.P. 2000. Reliability, New York.

Blom, G. 1969. Sannolikhetsteori och statistikteori med tillämpningar Studentlitteratur.

Bode, J. 1998. Decision support with neural networks in the management of research and development: Concepts and application to cost estimation. Information & Management 34, 33-40.

Booth, C.M., J.R.; Bennett, A.; Laycock, W.J. 1996. Substation based data interpretation techniques for improved power system management, Transmission and Distribution Conference, 1996. Proceedings., 1996 IEEE. pp. 65-71.

Campbell, M.K. 2001. Power system deregulation. Potentials, IEEE 20, 8-9.

Clement, M., Marty, A. 1991. Computer aided maintenance for distribution lines: an expert system approach of failure risk evaluation, Probabilistic Methods

Applied to Electric Power Systems, 1991., Third International Conference on. pp. 250-254.
G.C. Stone, B.A.L., M. Krikorian. 2001. Continous Partial Discharge Measurement to Improve Generator Avalability., HYDRO 2001, Riva del Garda. pp. 127-136.
Gammelgård, M. 2003. The Challenge of Regulating Natural Monopolies in Electrical Distribution - Experiences from Sweden, 17th International Conference on Electricity Distrubution, Barcelona.
Gertsbakh, I.B. 1977. Models for Preventive Maintenance, Amsterdam.
Gurney, K. 1999. An Introduction to Neural Networks UCL Press.
Gustavsen, B.R., L.; Andresen, O.; Christensen, H.; Falch, B.; Jankila, K.A.; Myhr, T.; Sandvik, H.; Thomassen, H. 2002. Simulation of wood-pole replacement rate: application to distribution overhead lines. Power Delivery, IEEE Transactions on 17, 1050-1056.
Hudon, E., Reed, C.W., Timperley, J.E. 1994. Use of spectral analysis and phase resolved partial discharge measurements for generator testing, Electrical Insulation and Dielectric Phenomena, 1994. IEEE 1994 Annual Report., Conference on. pp. 103-111.
Hänninen, S. 1991. Analysis of Failure and Maintenance of Large Electrical Motors, the 12th Annual Symposium of the Society of Reliability Engineers.
Idhammar, C.B., G. Wilson, A. 1999. Asset Maintenece Management, Conference communications.
Jardine, A.K.S.B., J.A. 1985. Equipment reliability and maintenance. European Journal of Operations Research 19, 285-96.
Lapworth, J., McGrail, T. 1998. Transformer failure modes and planned replacement, Transformer Life Management (Ref. No. 1998/510), IEE Colloquium on. pp. 9/1-9/7.
Lebow, M.A., Vainberg, M. 1998. Asset management Planner, American Power Conference.
Leech, D.J. 1990. Some factors Afficting Precisions in Estimation of parameters of Lifetime Distributions. Reliability Engineering and System Saftey.
Lefton, S.A., Besuner, P.M., Grimsrud, G.P. 1995. Managing utility power plant assets to economically optimize power plant cycling costs, life, and reliability, Control Applications, 1995., Proceedings of the 4th IEEE Conference on. pp. 195-208.
Leite da Silva, A.M.L., Anders, G.J., Manso, L.A.F. 2001. Generator maintenance scheduling to maximize reliability and revenue, Power Tech Proceedings, 2001 IEEE Porto, Vol. 4. pp. 6 pp. vol.4.
McCall, J.J. 1965. Maintenance policies for stochastically failing equipment: a survey. Maintenance Science 11, 493-524.
Molina, J.M., Isasi, P., Berlanga, A., Sanchis, A. 2000. Hydroelectric power plant management relying on neural networks and expert system integration. Engineering Applications of Artificial Intelligence 13, 357-369.
Moubray, J. 1992. Reliability Centered Maintenance Industrial Press Inc, New York.
Murthy, D.N.P.A., A. Eccleston, J.A. 2002. Strategic maintenance management. Journal of Quality in Maintenance 8, 287-305.
Niebel, B. 1985. Engineering Maintenance Management, New York.

Pierkalla, W.P.V.J.A. 1976. A survey of maintenace models, the control and survaillance of deteriorating systems. Naval Research journal 23, 353-388.
Pintelton, L.M.G., L. 1992. Maintenance management decision making. European Journal of Operations Research 58, 301-17.
Raghavan, R., Simon, B.H. 1993. Advanced plant maintenance and surveillance system for the nuclear power plants of the next century, Proceedings of the 2nd ASME-JSME Nuclear Engineering Joint Conference, Mar 21-24 1993. Publ by ASME, New York, NY, USA, San Francisco, CA, USA. pp. 693-696.
Schaefer, M., Kutzner, R., Feser, K. 2000. Condition monitoring system for power transformers, Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on, Vol. 3. pp. 1701-1705 vol.3.
Silva, A.A., Mucheroni, M.F. 2002. Monitoring conditions of ball bearings by vibration signals with time-frequency analysis. Informacion Tecnologica 13, 95-100.
Smith, A.M. 1993. Reliability Centered Maintenance McGraw-Hill Inc., New York.
Steed, J.C. 1995. Condition monitoring applied to power transformers-an REC view, Reliability of Transmission and Distribution Equipment, 1995., Second International Conference on the. pp. 109-114.
Stillman, R.H., Mackisack, M.S., Sharp, B., Lee, C. 1995. Case studies in survival analysis of overhead line components, Reliability of Transmission and Distribution Equipment, 1995., Second International Conference on the. pp. 210-215.
Strömberg, M. 2000. Bestultsstrategier vid förnyelse projekt (in Swedish). Department of Industrial Information and Control systems, Stockholm.
Strömberg, M. 2001. Lifetime Assesment of Industrial Systems, HYDRO 2001, Vol. Opportunity and Challenges, Rive del Garde, Italy. pp. 691-695.
Strömberg, M. 2003. Lifetime Assessments of Complex Industrial Systems, a Framework for Renewal Strategies. Licentiate, Royal Institute of Technology, Stockholm.
Tandon, N. 1994. A comparison of some vibration parameters for the condition monitoring of rolling element bearings. Measurement 12, 285-9.
Thomas, L.C. 1986. A survey of maintenance and replacement models for maintainability and reliability of multi item systems. Reliability Engineering 16, 297-309.
Villian, B., Pitner, P., Proccacia, H. 1996. Probabalistic Approaches to Life Predictions of Nuclear Plant Structural Components, Plant Systems/Components Aging Management, Vol. 332.
Wärja, M. 2004a. A Reliability Based Approach to Maintenance and Renewal Strategies, PowerCon 2004, Singapore.
Wärja, M. 2004b. Variety Reduction Model for Maintenance and Renewal Strategies, NORDAC 2004, Espoo.
Wärja, M. 2005a. A Systems Approach to Maintenance and Renewal Strategies, CIRED'05. IEE, Turin, Italy.
Wärja, M. 2005b. A case study based evaluation of the Dynamic lifetime model and Condition based index. Nordic Pulp and Paper Journal 12, 52-59.
Yin, R.K. 1994. Case Study Research, Design adn Methods, 2^{nd} ed. Sage Publications.
Östergaard, J., Norsk-Jensen, A. 2001. Can we Delay the Replacement of this Component? An Asset Management Approach to the Question, CIRED.