INTRODUCTION

Facing a competitive environment production utilities are forced to rethink their maintenance strategies[1]. Since the deregulation of the Swedish electrical market in 1996 energy sales have become a competitive market, while distribution and transmission became natural monopolies. For electric production companies the income is a result of the prices for electricity set by supply and demand. The hourly margin cost sets the price for the whole market. Before the change the tariff was essentially the sum of cost of utilities and a reasonable profit: \( \text{Tari}ff = \text{Cost} + \text{Profit} \). Under the new regulation the tariff is determined independently of the cost of utilities. Hence, the profit is what is left when utilities costs are subtracted: \( \text{Profit} = \text{Tari}ff - \text{Costs} \)[2].

A utilities earnings is the difference between incomes and costs, the incomes can be increased by selling more power or by raising prices. To sell more power new investments must be made, either by purchasing other utilities or by building more power production facilities. But even if this approach is adopted the new investments must be maintained as effectively as possible. To increase the price of electricity is beyond the control of a utility. This means that a utility must be as cost effective as possible to survive on a deregulated power market.

Cost effectiveness means minimizing costs and in the same time still live up to the demand of reliability from costumers and regulatory. In this paper we divide costs into cost of failure, cost of preventive maintenance and capital costs.

One important part of preventive maintenance is extensive renewals. Extensive renewals mean buying new components or refurbishing a component into a new condition. This approach has been chosen because it is important to find the point in time when such a renewal must be carried out [3]. By postponing renewal, capital costs are saved. On the other hand, however, the risk for a costly failure increases. One important part, as we see it, about maintenance management is to be as effective as possible when deciding about the point in time for a renewal.

Every manager’s intention is to run the equipment as much as possible without costly breakdowns. The fastest way to increase earning in a short-term perspective is to cut down on maintenance and postpone renewals. Because of the long operative lifetime of many components, often 50 to 100 years, and the inherent reliability, such an approach will in most cases be successful. However, in a long-term perspective this might not be cost effective. It is also difficult to reduce costs by making new investments to reduce capital costs. A manager has to face the fact that he has to manage the assets he is responsible for; he can make new investments just to meet the demands of today. The question is what will happen in a long-term perspective of e.g. 25 years? What will the total costs be and what condition will the technical system be in?

Asset management

Asset management is the ability to model and compare operational, maintenance and capital options with the goal, to find the overall most cost effective solutions that provide the required capability over time. Asset management is how to exploit the asset most profitably[4].

Maintenance in general consists of preventive and corrective maintenance. Preventive maintenance is carried out at planned intervals, while corrective maintenance is carried out at the time of equipment failure. Three approaches to maintenance are well established at present [5]:

- Time Based Maintenance (TBM)
- Condition Based Maintenance (CBM)
- Reliability Centred Maintenance (RCM)

TBM is based on preventive maintenance and is carried out at regular time intervals suggested by the equipment manufacturer. CBM is a method that tries to find the most efficient intervals between preventive maintenance checks and measures. This method requires additional equipment to monitor the condition. RCM focuses directly on the physical assets of the company and the functions they fulfil. It considers how assets could fail to perform their required function and what decisions must be taken when any reduction in performance takes place. The method seeks to establish failure modes and the consequences of failure [6].

However, neither of these maintenance approaches alone can be used as decision-making tools for a manager when making decisions about long-term asset management. Aspects like short-term and long-term consequences, condition and risk can’t be dealt with using these approaches. As stated earlier a manager must minimize the present value of the costs for failures, preventive maintenance and capital costs. When managing assets with long operative lifetime we propose that maintenance management on technical systems are divided this into risk, condition, and total costs.

This interpretation regards only physical assets and does not include issues like organization, operation, personnel etc. What we want to point out with out definition of maintenance
management is that in order to become aware of both long and short term effects of different maintenance strategies it is not enough to cover one or two of the parts, all three must be included in an analysis. Today there is no general methodology that can cope with this complex issue.

In this work a case study based evaluation of a methodology set up to handle this complex issues is carried out. The methodology was applied on a feed water pump system at Forsmark nuclear power plant. The object of this study is to examine pros and cons and use the result to improve the methodology.

Detail vs. scope. When working with the proposed methodology one important issue to discuss is the approach for the study. In order for a study to be possible to carry out, a system can’t be divided into to small components, e.g. nuts and bolts. On the other hand, it is also very difficult to use too large systems and call them components. The idea of this methodology is to make a top to bottom analysis and divide a large system into components. Large systems can be e.g. generators, section of distribution or transmission grids, refiners, transformers etc. These large systems consist of components selected by experts that together represent the condition of the system. This means that in this study we call the lowest level where we collect data a component.

METHOD

In this study the methodology has been applied to feed water pump system at Forsmark nuclear plant. This system was chosen because of three aspects: importance for production, access to data and system construction. These factors are described in greater detail below.

Importance to production

There are three feed water pumps at block 2 in Forsmark nuclear plant, and to run the boiler two of them are needed. If one pump fails there is no effect on production, however, if two pumps fail the capacity of the reactor is reduced with approximately 50 %. This will of course have impact on the power production as well. The power of the generator will also be reduced with 50 %. A breakdown will therefore have very costly consequences.

Access to data

At Forsmark nuclear power plant all processes are measured and the values are stored in SCADA systems. This means that it is fairly easy to find historical data. In this study the history of the feedwater pumps have been used to calculate standard maintenance key figures, e.g. availability, MTBF etc. Also, it is of great interest to study data prior to breakdown to identify if there are any variables that can be used to foresee abnormal states that can lead to a breakdown.

System construction

The feedwater pumps are built with relatively few inputs and it is relatively easy to measure different values. Also, the three pumps together formed the system we applied the methodology on. Since only two pumps are needed in order for the system to function it was also possible to test the methodology on a system with redundancy. Many technical systems, the production, distribution and power industry often have redundant systems, so in order to make this validation of the methodology a fairly simple system analysis will show strengths and weaknesses.

The highest level of system consists of three feedwater pumps. Each one of them is divided into four subsystems, centrifugal pump, motor, oil system and gearbox. These four subsystems are then divided into a number of components. In this study we choose only to use the components representing the centrifugal pump. These are, oil pressure, axial bearing oil pressure, axial bearings 1 and 2 temperature, radial bearings 1 and 2 temperature and axial bearing 1 and 2 cooling water temperature. The maintenance personnel at Forsmark nuclear plant have chosen these components.

RESULT

The results from this study consist of a presentation of each part in the asset management methodology, risk, condition, and costs. These results are then combined and presented in a wider context in an effort to make a systems approach on maintenance and renewals strategies.

Risk calculation

To handle the risk the DLA method is used. This method compares the costs of breakdown, cost of planned maintenance action with the probability of a breakdown.

When calculating the risk, both probability and consequence of a breakdown must be used. In this case a number of different calculations must be carried out. The first step is to do this at a systems level, in this case by doing a calculation on the feedwater pump system. This system has a parallel structure with limited redundancy, which means that two out of the three feedwater pumps must work without any losses of production.

Probability calculation for breakdown. Because of the redundancy in the feedwater pump system minor breakdowns in one pump have little economic impact. However, a second pump failure occurs, the result can be very costly. By being aware of the status, which equals probability of failure via the condition index, a manager can decide the time for when a preventive maintenance action can be carried out.
When calculating the probability of breakdown for the feedwater pump system, the function probability of each component (feed water pump) has been calculated using an exponential function.

When making a systems approach and considering the three feedwater pumps as a system, it can be in different states, all pumps working, one failure and two or more failures. The major difference when talking about financial consequences is if two or more pumps fail. This is because of the reduction in production capacity: if one pump fails the only financial consequence is the repair of the pump and the fact that one more failure will be very costly. When calculating the probability for system function, \( R_{sys}(t) \), [a] is used.

\[
R_{sys} = \sum_{r=0}^{n-m} \binom{n}{r} R^{n-r} F^r \quad [a]
\]

When carrying out a probability calculation of system failure, historical maintenance reports have been studied. The feedwater pumps system is inherently extremely reliable due to redundancy, clean operation environment and constant running conditions.

### Costs

The costs associated with single failures are very low because of relatively cheap spare parts and no production loss. However, every hour two feedwater pumps do not work cost approximately 100 000 SEK. This means that the maintenance strategy choice for the feedwater pumps might be justifiable. If a DLA analysis is carried out on these “cheap” breakdowns it is clearly shown that it would be very expensive not to adopt this maintenance strategy.

To calculate the financial consequences of different breakdowns is fairly easy. In this study, we have three different breakdown scenarios, involving one, two or three broken feed water pumps. First of all, a function to calculate the income loss due to the breakdown is used. Forsmark uses an electricity price at 230 SEK/MWh when doing calculation, from this is 26 SEK/MWh taken which represents the fuel cost and the cost for landfill. The price used in calculation is therefore 204 SEK/MWh. The loss of income is also a function of how long a stop lasts and how many pumps that are broken. Also, the cost for repair and spare parts must be added to the total cost. The cost (TC) for a breakdown is calculated with following function:

\[
TC = (p_i - 1) * (h_p + \sum_{p=1}^{3} \text{rep} \text{cost}_{p_i} + \text{sparep}_{p_i})
\]

\[
\begin{align*}
 p & = \text{pump} \\
 h & = \text{duration of stop} \\
 p_{el} & = \text{price electricity} \\
 \text{rep} \text{cost} & = \text{cost for repair} \\
 \text{sparep} & = \text{cost for spare parts}
\end{align*}
\]

The calculation of cost for breakdowns must be made at different system levels. The first is made on the feedwater pump system, where three different scenarios, involving one, two and three broken pumps have been analysed. Since the duration of a feedwater pump breakdown has great impact on the financial consequences of a breakdown, an analysis of the most common types of breakdowns has been carried out.

Mean Down Time (MDT) have been calculated from the historical maintenance records and are seven hours. When adding up the production loss and material and personnel costs the expected breakdown cost is approximately 800 000 SEK. Because of the redundancy in the feedwater pump system, a planned repair does not result in any production loss. Consequently, the cost for condition based maintenance (CBM) is approximately 50 000 SEK. Making a preventive maintenance measure can save no money; therefore planned corrective maintenance is the most cost-effective alternative.

### Result DLA analysis

A DLA analysis carried out at the feedwater pump system shows that failures must be repaired as soon as possible due to the high probability of another pump failing. The result is displayed in figure [b], DLA analysis on feedwater pump system.

**Figure b, DLA analysis of feedwater pump system**

One important lesson to be learnt from the DLA analysis is that it is very expensive if two or more pumps fail. To avoid failure, CBI can be used in order to avoid any maintenance action that causes a stop during periods where two or more pumps are close to any type of failure. In this study, Forsmark has developed a CBI index for the feedwater pumps, and the DLA analysis carried out supports this strategy.

### Condition

The result from analysing maintenance reports showed that there were three types of failures that caused stops; these are mechanical gasket leakage, automation errors and sensor errors. Automation and sensor errors can’t be detected in advance, so the only way to ensure that no costly stop occurs is to have spare parts available and a strategy to solve the problems if they occur. The study of the historical record
revealed that these types of errors occur a few times every year and take approximately one day to fix.

If a mechanical gasket starts to leak, the temperature of the cooling water raises, a type of error that is described below, in the ‘results’ chapter. Since this kind of failure can be detected in advance a planned repair can be carried out.

**Transfer function.** The next step in the CBI methodology is to create a transfer function and determining acceptable condition levels. The levels are determined from either subjective knowledge or by studying historical records. E.g. axial bearing 1 cooling water temperature was determined 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 [c].

\[ TTI = 200 - 4t \quad \text{valid for} \quad 25 < t < 50 \quad [c] \]

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

**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.

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 to increase 3 months prior to breakdown, see fig [d] temperature cooling water.

![Figure e, CBI cooling water](image)

If studying how the CBI has evolved from March it is 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 increases to a normal level.

**Condition feedwater pump.** The CBI for a feed water pump consists of eight different measured values. These values are aggregated to display the condition on the feedwater 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 [f], CBI feedwater pump.

![Figure f, CBI feed water pump](image)

**Condition feedwater pump system.** The next level of aggregation includes all three feedwater 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 [g] CBI feed water pump system.

![Figure g, CBI feed water pump system](image)

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.

**Total costs.** The final part of the methodology is a cost evaluation. The idea is to sum up preventive maintenance, failure and capital costs. In this study is was obvious that this not was possible due to the level of detail chosen by the personnel at Forsmark. The different costs can’t be used due to the fact that they are too low. Even in the case of a failure, which is extremely rare, the costs are insignificant. Also, because of redundancy the obvious maintenance strategy for the feedwater pumps is corrective maintenance. The reliability calculation earlier showed that the probability for
two breakdowns to occur is so low that the expected cost repair is insignificant. However, if the condition is monitored on wear parts in the feedwater pumps the probability for a second failure will be even lower. The pumps will be operated so that the conditions of the wear parts will not be equal causing two failures at the same time.

A systems approach to maintenance and renewal strategies

When joining these methods into a methodology and applying it to the feedwater pump system it proved difficult to work with. When evaluating with this methodology it proved to be very important to find the right level of detail. In this study the level of approach where decided by personnel at Forsmark. 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 separately 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 to be able to cope with this issue.

CONCLUSIONS

The intention of this evaluation was to use three methods into a joint methodology. The idea with the methodology is to create a wider understanding for managers responsible for maintenance. Many methods today, e.g. RCM, focus on finding appropriate maintenance measures from a FMEA analysis. No attempts are made to make a long-term analysis of condition, cost, and different risks associated with different maintenance strategies. The methodology proposed can handle this complex problem if used systematically.

During the evaluation of the methodology the DLA method proved to be a useful tool when analysing financial risks for technical systems. The DLA method was easy to work with, not demanding on input and can provide comprehensive information for a manager making decisions about maintenance strategies. The financial risk concerns both financial consequences of a breakdown and the probability for a breakdown to occur. The method can also be used when identifying the components in a technical system that can cause expensive failures. By identifying these components strategies to avoid costly consequences can be adopted.

The next step of the evaluation of the methodology concerned the CBI index. The intention of this method was to measure different parameters a technical system, transform these values in to a uniform scale and use this aggregated value as an index on the condition of the technical system. However, if studying the figures in the result part it is obvious that any deviation from a “normal” value is weakened depending on the number of other measured values at the same level and that the higher in the hierarchy one is using CBI, the harder it is to even detect critical low CBI for a component low in the hierarchy. Because of the detailed approach made by Forsmark the condition index simply became too complex and it proved difficult to draw any conclusions from a downward trend of the CBI. Also, it proved very difficult to decide acceptable limits for the CBI. The difficulties when using CBI was:

1. How to interpret the index
2. To decide acceptable limits for values on components and system
3. Complexity due to many inputs

To make the CBI manageable two things must be changed. First, the number of inputs must be reduced and second, the result of the CBI index must be compared to historical CBI records.

If reducing the number of inputs for the CBI index a systematic approach must be adopted. It is important to use components that describe the condition of the system appropriately; we suggest that the DLA method can be used. By using the DLA method only components that can cause costly failures are included in the CBI index. By doing so the benefits of a RCM approach using the DLA method is combined with the condition of the system. 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 methodology supports that.

Because of the transferred values from the components is it very difficult to interpret the index. The study showed that this was the case. However, we think that the index should be used in a longer perspective. We suggest that historical records of CBI should be used to detect e.g. long-term deterioration of large technical system.

In this validation it was not possible to perform a cost analysis of different strategies because of the level of detail chosen by the personnel at Forsmark. Also, the time span for such an analysis was too short; the level of approach seems to determine the time span.

At Forsmark there is a need of making a repair in the Voith gear between the electrical motor and the centrifugal pump. The suppliers of the gear recommended this gasket to be replaced every 20th year; the gasket at Forsmark had now been running for 22 years. The consequence of this is a six-
week stop resulting in both high repair cost and that no redundancy existed for the two remaining feedwater pumps. If this had come to our attention earlier the study had included these systems also. When studying this system consisting of three parts, 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.

Further work

The methods and methodology proved to have both strengths and weaknesses and need further development and tests. The calculation for total cost was not necessary. However, the total cost calculation needs further investigation.

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Methodology improvement. The iterative process between the methods must be improved in order to use them as a joint methodology. Further work will build on a DLA analysis to identify the financial risk and which components affecting this. The components analysis is carried out using skilled personnel e.g. constructors, operators and maintenance personnel. The factors affecting the condition of these components are then used in the CBI. Depending on historical records and information available, the CBI will be compared to historical data if possible. This information is then used to decide appropriate maintenance strategy i.e. preventive or corrective maintenance. With this information an estimation of the total cost should be possible to calculate.

It proved to be very important to have a systematic approach and thoroughly investigate relevant aspects of the technical system. Further, by using the DLA method it is possible to select both system and components that should be used to create a condition index. Components that, in case of failure, result in significant costs should be included.

Further work

The methods and methodology proved to have both strengths and weaknesses and need further development and tests. There are primarily four different things that must be improved or further tested: level of detail, interpretation of the CBI, methodology improvement, and total cost calculation.

Level of detail. The approach made by Forsmark proved to be very ambitious; our contention is that it is not possible to create a useful condition index consisting of so many details. The CBI index is a useful, too, but the amount of input must be reduced. Further work will be concentrated on the work of reducing the amount of input. Next step in this is to reduce the level of detail by using the DLA method. By only including components in the CBI that have proved to have a significant financial risk to the business many components can be excluded. Our ambition will therefore be to choose level of detail using the DLA method and let these components represent the condition of the system. There are some advantages in doing so e.g. the number of components will be significantly reduced and financial factors will decide what components to include.

Interpretation of CBI. The interpretation of the CBI proved difficult. The case study indicated that the CBI could be used in two ways: 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 a deterioration of the technical system. Future studies will reveal if this is a possible application of the CBI.

Total cost calculation. The calculation for total cost was not possible to do 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.