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On Maintenance Management of Wind and Nuclear Power Plants

Julia Nilsson

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Abstract

Electrical production in Sweden today is mainly from nuclear and hydro power. However, there is large increase in renewable energy like wind power and the installed new capacity goals are large. Several electrical production sources are important for the sustainability of the energy system. Maintenance is an approach for keeping a system sustainable. The importance of structured maintenance for reliable electrical production systems triggers the development of qualitative and quantitative maintenance management methods. Examples of these methods are Reliability-Centered Maintenance (RCM) which is a structured qualitative approach that focuses on reliability when planning maintenance, and Reliability Centered Asset Management (RCAM) which is a development of RCM into a quantitative approach with the aim to relate preventive maintenance to total maintenance cost and system reliability.

This thesis presents models, as applications of RCAM, based on the methods of Life Cycle Cost (LCC) and mathematical optimization, applied to wind and nuclear power plants. Both deterministic and stochastic approaches have been used and the proposed models are based on the *Total Cost* model, which summarizes costs for maintenance and production loss, and the *Aircraft* model, which is an opportunistic maintenance optimization model. Opportunistic maintenance is preventive maintenance performed at opportunities. The wind power applications in this study show on different ways to cover costs of condition monitoring systems (CMS) and further on economic benefits of these when uncertainties of times to failure are included in the model. The nuclear power applications show on that the optimization model is dependent on the discount rate and that a high discount rate gives more motivation for opportunistic replacements. When put into a stochastic framework and compared to other maintenance strategies it is shown that an extended opportunistic maintenance optimization model has a good overall performance, and that it, for high values of the constant cost of performing maintenance, is preferable to perform opportunistic maintenance. The proposed models, applied to wind and nuclear power plants, could be extended and adapted to fit other components and systems.

Key words: Electrical Production Systems, Wind Power, Nuclear Power, Maintenance Management, Reliability Centered Maintenance (RCM), Reliability Centered Asset Management (RCAM), Life Cycle Cost (LCC), Mathematical Optimization, Opportunistic Maintenance.

Preface

This thesis is part of the PhD project "Reliability and Cost Centered Maintenance Methods" at the Royal Institute of Technology (KTH), the School of Electrical Engineering, Division of Electromagnetic Engineering. The project is financed by the Swedish Center of Exellence in Electric Power Engineering (EKC2).

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Stockholm, October 2009

List of Publications

Appended Papers

Paper I Nilsson J. and Bertling L., "Maintenance Management of Wind Power Systems Using Condition Monitoring Systems – Life Cycle Cost Analysis for Two Case Studies", IEEE Transactions on Energy Conversion, vol.22, No. 1, March 2007.

Paper II Besnard F., Nilsson J. and Bertling L., "On the Economic Benefits of Using Condition Monitoring Systems for Maintenance Management of Wind Power Systems", submitted to the 11th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS 2010), 14-17 June 2010, October 2009.

Paper III Nilsson J., Wojciechowski A., Strömberg A-B. Patriksson M. and Bertling L., "An Opportunistic Maintenance Optimization Model for Shaft Seals in Feed-Water Pump Systems in Nuclear Power Plants", published in the proceedings of 2009 IEEE Bucharest Power Tech Conference, June 28th – July 2nd, Bucharest, Romania.

Paper IV Nilsson J., Wojciechowski A., Strömberg A-B. Patriksson M. and Bertling L., "An Evaluation Approach for Opportunistic Maintenance Optimization Models for Nuclear Power Plants", submitted to IEEE Transactions on Power Systems, September 2009.

Author's contributions in appended papers

The author of this thesis is main author of, and has written and contributed to, the major parts of Paper I, Paper III and Paper IV and has also contributed to the writing of Paper II.

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We're the trees still green in November.
Laleh

Chapter 1

Introduction

1.1 Background

A sustainable energy system must involve several electrical production sources. Local conditions are decisive for determining the electrical production system that should be dominating. Electrical production in Sweden today is mainly from nuclear and hydro power [1]. There are however large increase in renewable energy production from e.g. wind power.

Wind power is one type of energy generated from natural resources that are naturally replenished. Large investments are today done in wind power both globally and nationally. The in Sweden installed capacity today (corresponding to about 1% of the total electricity production) of 2 TWh will be 10 TWh in year 2015 and 30 TWh in year 2020 according to the Swedish Energy Agency [1]. The electricity certificate system makes the process of building new wind power plants and parks profitable in more cases [2].

Nuclear power is almost free from climate-affecting pollution in operation. It has however a large disadvantage with waste and its final storage. The total amount of nuclear power in Sweden is today 65-70 TWh a year, corresponding to about 45% of the total electricity production. The ten reactors that are in operation today were all taken into operation between 1975 and 1985.

The operation and maintenance management of wind power plants and especially nuclear power plants must always be reliable and structured. Cost effectiveness is however growing in importance. Lower investments, due to the deregulation of the electric power system and the introduction of the electricity market, have led to the development of new methods for maintenance management. A structured qualitative approach for maintenance management is Reliability Centered Maintenance (RCM) [3]. It has its origin in the civil aircraft industry and the Boeing 747 and the first

description came in 1978 [4]. It was introduced in nuclear power in 1980. RCM is a systematic qualitative approach to balance between preventive and corrective maintenance. It chooses the right preventive maintenance activities for the right component at the right time to reach the most cost efficient solution. A development of RCM into a quantitative method is Reliability Centered Asset Management (RCAM) [5], [6]. The aim of RCAM is to more closely relate preventive maintenance's impact on total maintenance cost and system reliability. The issues of the RCM and RCAM methods are how the maintenance should be performed in an optimal way, qualitatively and quantitatively respectively.

1.2 Related work in the RCAM research group

At the Royal Institute of Technology (KTH), the School of Electrical Engineering, the work and development within the principles of the RCAM method started about ten years ago with the PhD thesis by Prof. Lina Bertling [5]. Two more PhD theses have been produced so far in the RCAM group [7], [8], and four PhD projects are under progress with several theses and publications e.g. [9]-[12]. The *Total Cost* model developed in [5], and further developed for power distribution systems and used in an optimization method in [7], is within this work developed for different applications in power production systems using methods of Life Cycle Cost (LCC) and mathematical optimization. At the Department of Mathematical Sciences at Chalmers University of Technology, the *Aircraft* model [13] was further developed from [14] for opportunistic replacement of components in aircraft engines and cooperation in this project has been carried out concerning mathematical optimization methods.

1.3 Objective

The objective of this project is to further develop the RCAM method, especially for electrical production systems and to use mathematical maintenance optimization methods. As applications of RCAM different wind power systems and a subsystem in a nuclear power plant, the feed-water pump system, are studied.

1.4 Scientific contribution

The main scientific contribution of this thesis is the application of the *Total Cost* model and the *Aircraft* model on electrical production systems using methods of LCC and mathematical optimization.

Paper I presents a study where LCC is used in six strategies to show on that condition monitoring systems (CMS) could be profitable. This is investigated further and in a more sophisticated way with an extended cost model and stochastic LCC cost models with and without CMS in *Paper II*.

Paper III presents a model for opportunistic maintenance of shaft seals in feed-water pump systems where mathematical optimization is used to minimize the different costs of maintenance and spare parts. This proposed model and an extended model are evaluated in *Paper IV* in a stochastic framework together with some simple policies of maintenance to compare their value.

1.5 Thesis outline

This thesis is organized as an introduction and summary with the main concepts of *Paper I* - *Paper IV*. Chapter 2 presents definitions of maintenance management important for this work, including concepts mainly of reliability, maintenance and cost. Chapter 3 presents two methods for maintenance decisions, LCC and mathematical optimization and continues with two models for system costs; the *Total Cost* model and the *Aircraft* model. In Chapter 4 the different case studies are presented. Case studies are of wind power and a subsystem in the nuclear power plant, the feed-water pump system. Chapter 5 concludes the thesis.

Chapter 2

Definitions for Maintenance Management

To be able to comply with system function, maintenance is required. To perform correct maintenance is also important for cost effectiveness and reliability. Maintenance management is a concept including features of how the effect of maintenance on components and systems could influence on system function and tools and methods for how to perform maintenance. In this context, definitions that are most relevant for this work are reliability concepts (section 2.1), maintenance (section 2.2) and cost terms (section 2.3).

2.1 Reliability

Reliability includes measures like e.g. availability, failure rate and repair time. An item is defined as either a component or a system.

Reliability is the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time [15].

Availability (*A*) is a fundamental measure of reliability. It combines both the outage time when an interruption has occurred and the frequency of interruptions. Availability is the ability of an item – under combined aspects of reliability, maintainability, and maintenance support – to perform its required function at a stated instant of time or over a stated period of time [15]. Inherent availability (A_i) is the instantaneous probability that an item will be up or down. It considers only downtime for repair to failures. No preventive maintenance is included.

$$A_i = \frac{MTBF}{MTBF + MTTR} \qquad \textbf{(2.1)}$$

where Mean Time Between Failures (*MTBF*) indicates the mean exposure time between failures [16]. Failure rate (λ) indicates number of failures per time unit. When failures are exponentially distributed λ is constant over the time and this gives that $\lambda = \frac{1}{MTBF}$.

Repair time (*r*) is the mean time to replace or repair a failed component [16], also called MTTR, Mean Time To Repair.

Availability can be calculated as 1 - Unavailability (*U*), which in its turn can be approximated as $U = \lambda \cdot r$.

2.1.1 Modeling Failures

The state of an item can be modeled with a variable *X(t).* Different states could be: function, failure or maintenance. It is often assumed that an item can be in two states according to [15]:

$$X(t)=\begin{cases}1 & \text{if the item is in function at time t,}\\ 0 & \text{else.}\end{cases}$$

Time to failure (i.e. transition time from state 0 to state 1) can be characterized by a distribution function, noted *F(t)*. It denotes the probability that a component fails within the time interval (0, t].

Reliability function, or survival function, is the probability that the item does not fail in the time interval (0, *t*], or, in other words, the probability that the item survives the time interval (0, *t*] and is still functioning at time *t* [15].

$$R(t)=1-F(t) \qquad \textbf{(2.2)}$$

The Weibull Distribution

The Weibull distribution function is commonly used to model the life length of components. If *T* represents the random variable of the time to failure of an item, times to failure could be modeled with the Weibull distribution, according to [15]:

$$F(t)=P(T\le t)=\begin{cases}1-e^{-(t/\alpha)^{\beta}}, & \text{for t}>0,\\ 0, & \text{otherwise,}\end{cases}$$

where α is the scale parameter and β is the shape parameter. $F(t)$ denotes the distribution function. The probability density, $f(t)$, and failure rate, $z(t)$, functions of the Weibull distribution are:

$$f(t)=\frac{\beta}{\alpha}\cdot\left(\frac{t}{\alpha}\right)^{\beta-1}e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad \textbf{(2.3)}$$

and

$$z(t)=\frac{f(t)}{1-F(t)}=\beta\cdot\frac{t^{\beta-1}}{\alpha^{\beta}}. \qquad \textbf{(2.4)}$$

When α is small the distribution is close to have only one value of for example life lengths and the model is close to a deterministic model. When β = 1, the failure rate is constant and the Weibull distribution is equal to the exponential distribution. When β >1, the failure rate increases with time which can represent the behaviour of an ageing component.

Failures can be generated randomly according to a Weibull distribution with e.g. Monte Carlo simulation [15].

2.2 Maintenance

Maintainability is the ability of an item, under stated conditions of use, to retain it in o restore it to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources [15]. Maintenance is a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in or restore it to a state in which it can perform the required function [17].

2.2.1 Preventive Maintenance

Preventive maintenance (PM) is maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item [17].

Scheduled maintenance

Preventive maintenance carried out in accordance with an established time schedule or established number of units of use [17]. The maintenance is planned in advance.

Condition based maintenance

Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions [17]. An example of condition based maintenance is when condition monitoring systems (CMS) are used to control the condition of the component or system, and thereby preventive maintenance is possible to perform.

Opportunistic maintenance

Opportunistic maintenance refers to the situation in which preventive maintenance is carried out at opportunities [13]. A typical example is when one component is out for maintenance and it is decided to take out another component for maintenance before

failure. Such a decision would be based on a rational decision, e.g. by saving cost by performing several maintenance activities at the same time.

2.2.2 Corrective Maintenance

Corrective maintenance (CM) is maintenance carried out after failure recognition and intended to put an item into a state in which it can perform its required function [17].

2.2.3 Maintenance Balance

A general goal for performing maintenance in an optimal way is to minimize total cost for operation and maintenance. An aim is to reach a level of availability at lowest cost. Maintenance should be performed so that the availability is high and system function and reliability is withheld at a total cost as low as possible. Long life of the component or system is also of importance. The balance between PM and CM and the optimal relationship between them could be difficult to find.

Reliability Centered Maintenance, RCM

Reliability Centred Maintenance (RCM), gives a systematic method to balance between PM and CM, and to choose right PM-activities for the right component at the right time to reach the most cost efficient solution. To analyze the maintenance aspects of a system and its components, the first step is to identify the system items, and which of these that ought to be analyzed.

According to Moubray [3] seven questions should be answered when the items of the systems and which of those that should be analysed have been identified:

1. What are the functions and performances required?
2. In what ways can each function fail?
3. What causes each functional failure?
4. What are the effects of each failure?
5. What are the consequences of each failure?
6. How can each failure be prevented?
7. How does one proceed if no preventive activity is possible?

In the first point it is stressed that when the function is specified it is important to indicate a certain level that the unit should meet. Functions are what an asset is expected to perform but can also be anything an asset has to comply with, such as

colour or shape. Functions are divided into primary and secondary functions. The primary functions describe the main purpose of the asset. Secondary functions describe additional features the asset should meet such as colour or safety aspects.

Then there is indicated in which ways the unit cannot cope with the demands. The cause of the failure is then described and it is important that this is done on the right level. Too much detail can make the process long and expensive; while too low detail level could make the process worthless.

In point four the course of events at a failure should be described. Among other things physical or environmental damage and how to restore the equipment should be in the description.

The consequences of a failure are divided into three categories:

1. Safety- and environmental consequences
2. Operational consequences
3. Non-operational consequences

If a person could be injured or if the failure could cause an environmental law to be broken the consequence is classed as a safety- and environmental consequence. Operational consequences affect costs regarding production and operation. The non operational consequences only gives cost in the form of operations.

Then a decision tree is used to determine which maintenance should be carried out. Depending on the consequence classifying of the failure and what kind of maintenance is applied the best maintenance strategy is determined.

Failure Mode and Effect Analysis, FMEA

FMEA, Failure Mode and Effect Analysis, can be used in reliability analysis and with this method the connection between possible failure modes for a construction and the failure effects that these give rise to can be determined. Failure mode is the effect by which a failure is observed to occur [16]. The purpose of FMEA is to find all the ways that the item can fail, that is to identify critical components for the reliability of the system observed. Three questions are answered, these are [18]:

1. What failures/events could appear?
2. What are the effects of the failures/events?
3. What are the causes of the failures/events?

Then the failures probability, seriousness and possibility of discovery should be estimated. To perform this estimation the system is being divided into several sub systems. When the three questions have been answered the frequency of which the failure can occur is indicated with a number between 1 and 10. Then a number indicates the seriousness of the consequence. Finally a number indicates the probability for discovery. These numbers are multiplied into a combined index number, for which a higher value indicates a worse failure. This number is called risk priority number. This gives a ranking list for the failures, from which using the size of the risk priority number one can make an estimation of the seriousness of the failures.

Reliability Centered Asset Management, RCAM

The aim of RCAM is to relate preventive maintenance to the total maintenance cost and system reliability [5]. The method is developed from RCM principles attempting to relate more closely the impact of maintenance to the cost and reliability of the system [6]. The aim is to see with quantitative methods the effect on a component level of preventive maintenance on system reliability results.

As a first step in the method, the critical components for the system reliability are identified. The critical components are studied further, focusing on the impact of maintenance measures. The relationship between reliability and maintenance has been established by relating the effect of preventive maintenance to the causes of failures for the component being assessed.

The information deduced in the critical component analysis is used when comparing different preventive maintenance strategies with respect to reliability and cost.

The main stages of the RCAM approach are as follows [6]:

1. System reliability analysis: defines the system and evaluates critical components affecting system reliability.
2. Component reliability modeling: analyzes the components in detail and, with the support of appropriate input data, defines the quantitative relationship between reliability and preventive maintenance measures.
3. System reliability and cost/benefit analysis: puts the results of stage 2 into a system perspective, and evaluates the effect of component maintenance on system reliability and the impact on cost of different preventive maintenance strategies.

These three stages emphasize a central feature of the method: that the analysis moves from the system level to the component level and then back to the system level.

2.3 Cost

2.3.1 Discounting

The *Present Value Method* compares all future payments over a certain time to the present time. The present value (PV) means the amount of money that should be deposited into the bank now at a certain interest rate (r) to pay for an outlay (C) after n years. This means that all future payments are re-calculated to the equivalent value at the present time. The present value of one outlay (C) to be paid after n years is gained by multiplying C by the *present value factor* ($PV_f(n,d)$) as follows [5]:

$$PV = C \cdot PV_f\left(n, r\right) = C \cdot \left(1 + r\right)^{-n}. \qquad \textbf{(2.5)}$$

2.3.2 Interest

When discounting with the present value method, real or nominal interest rates could be used. The nominal interest rate takes inflation into account. The discount rate r depends on the real interest r_1, and the inflation r_2, according to [19]:

$$1 + r = (1 + r_1)(1 + r_2)\,. \qquad \textbf{(2.6)}$$

The interest is decided by the company management and indicates the return that is required for making an investment. The choice of interest rate is not obvious or trivial. The choice of interest value depends on, for example, the length of the investment. A long investment can include larger risks as the future is unknown. Investments where a higher risk is taken require a higher interest. Commonly used real interests, are 7% for wind power and 4% for nuclear power [27], [30].

2.3.3 Cost for production loss

In production of electricity the cost for interruption is the cost for production loss. C_{PL} can be calculated as:

$$C_{PB} = c_{PB} \cdot ENS \qquad \textbf{(2.7)}$$

where c_{PL} is cost for production loss per energy in [EUR/Wh] och ENS (Energy Not Supplied) is not delivered energy a year in [Wh].

Not delivered energy can be modeled as planned production multiplied by the unavailability according to:

$$ENS = x \cdot 8760 \cdot U \qquad \textbf{(2.8)}$$

where x is number of MWh/h, 8760 is the number of hours per year and U is the unavailability.

Chapter 3

Maintenance Decision Methods and Models

In this work two different methods to solve problems of deciding maintenance plans are used. First the total cost for a system during its life length is calculated, that is the Life Cycle Cost (LCC) is formulated. Then this total cost is minimized according to constraints, that is mathematical optimization is used. Modeling of how failure events occur could be performed deterministic or probabilistic. Deterministic models do not take into account the randomness of failures, however, probabilistic models do. When modeling failure events a probabilistic approach makes the solution to the problem more realistic. The methods of LCC and mathematical optimization are first used deterministic and then a probabilistic LCC is performed and a stochastic framework for the optimization models is used. *Paper I* presents a LCC analysis with different strategies and *Paper II* presents a method for probabilistic LCC. *Paper III* presents an optimization model which in *Paper IV* is evaluated in a stochastic framework.

Models for calculating and optimizing the total system cost used in this work are the *Total Cost* model and the *Aircraft* model. The *Total Cost* model is for the production system based on costs for maintenance and production loss. The *Aircraft* model is an opportunistic maintenance optimization model and minimizes costs for maintenance according to constraints. *Paper I* and *Paper II* are based on the *Total Cost* model, while *Paper III* and *Paper IV* are based on the *Aircraft* model.

3.1 Life Cycle Cost, LCC

The Life Cycle Cost (LCC) for a technical system constitutes its total cost during its lifetime. It is the sum of the total cost divided over the total life length. The goal is to minimize the total lifetime cost. The total cost typically includes costs associated with planning, purchasing, operation and maintenance, and liquidation of the system. Power plant financial concerns could typically be investment, maintenance, production loss and rest value. The LCC for a system can be defined as [19]:

$$LCC = C_{Inv} + C_{CM} + C_{PM} + C_{PL} + C_{\mathrm{Re}}, \qquad \textbf{(3.1)}$$

where C_{Inv} is the cost of the investment, C_{CM} is the cost for corrective maintenance, C_{PM} is the cost for preventive maintenance, C_{PL} is the cost for production loss and C_{Re} is the rest value.

The choice of life length that should be used for a special system depends on several things. The economic life length, which is the life length used when discounting the total cost, for nuclear power plant used is typically 40-60 years and the economic life time for wind power plants is typically 20-30 years. The LCC could be discounted with real or nominal interest, where nominal interest also includes inflation. The model used to calculate the sum of costs, for maintenance and production loss, in this work is the *Total Cost* model.

3.2 Mathematical Optimization

Optimization is a wide concept and maintenance optimization could be to perform maintenance "*as good as possible*". The question is in what sentence the maintenance should be "*as good as possible*". Two optimization criteria important for maintenance are reliability and cost. When minimizing costs for maintenance, e.g. a spare part must be replaced within a special life length according to constraints; both reliability and cost could be considered. Mathematical optimization used in this work is Mixed Integer Linear Programming (MILP). The optimization problem is described with a mathematical model with linear cost function and constraint functions with continuous and integer binary variables. Problems with decision variables restricted to two values, 0 and 1, binary variables could be used to solve for example problems with maintenance decisions. MILP models can e.g. be solved with linear programming (e.g. using the Simplex Method [20]) by relaxing the integer constraints and divide the model into sub-models if the solution does not respect the integer properties (Branch and Bound method). The modeling softwares GAMS and AMPL, and solver Cplex have been used to implement the different optimization models and

the results have been presented graphically in MATLAB [21], [22]. The optimization model used in this work is based on the *Aircraft* model [13].

3.3 Total Cost Model

A total cost model for electrical distribution systems has been constructed in [5]. The costs that have been included are costs of failure, or cost of CM, cost for PM and cost of interruption. For production systems, the interruption cost is the cost for production loss (PL). The resulting proposed model is as follows:

$$TC = C_{PL} + C_{CM} + C_{PM} . \qquad \textbf{(3.2)}$$

In this work this model has been developed for production systems. For a production system a main cost is due to production loss. The cost for PL has here been modeled as a cost per energy unit times energy not supplied (ENS). The cost for CM can be modeled as a cost per failure times the failure rate. The cost for PM is planned and modeled as plain input data.

3.4 Aircraft Model

In this work a model called the *Aircraft* model has been used. This general optimization model was applied to the replacement of components in aircraft engines in [13]. The model is a MIP with components $i = 1,..., N$ and time units $t = 1, \ldots, T$, and it uses two binary variables, one for replacement called x_{it}, and one for maintenance called z_t. The binary variables could be formulated:

$$x_{it} = \begin{cases} 1 & \text{if part } i \text{ is to be replaced at time t,} \\ 0 & \text{else.} \end{cases}$$

$$z_t = \begin{cases} 1 & \text{if some of the parts is to be replaced at time t,} \\ 0 & \text{else.} \end{cases}$$

The constant cost for performing maintenance d multiplied by the binary variable for maintenance z_t, and the cost for replacement, that is the spare part cost, c multiplied

by the binary variable for replacement x_{it} makes the sum of costs, the goal function, that should be minimized.

$$\min \sum_{t=1}^{T} \left(dz_t + c \sum_{i=1}^{N} x_{it} \right) \qquad \textbf{(3.3)}$$

The first constraint says that every time the replacement of some part is trigged a fixed cost must be paid. This means that if a replacement is carried out then maintenance is performed. The constraint pushes the binary variable z_t to be one if x_{it} is one.

$$x_{it} \leq z_t \text{ , } i \in N, \ t \in T. \qquad \textbf{(3.4)}$$

Each component *i* has a fixed life length T_i, and each component must be replaced within its life length. The fact that the part must be replaced at least once every T_i time step yields the constraint:

$$\sum_{t=l}^{l+T_i-1} x_{it} \geq 1, \ i \in N, \ l = 1,..,T - T_i + 1. \qquad \textbf{(3.5)}$$

This yields the total model:

$$\min \sum_{t=1}^{T} \left(dz_t + c \sum_{i=1}^{N} x_{it} \right) \qquad \textbf{(3.6)}$$

subject to

$$x_{it} \leq z_t \ , i \in N, \ t \in T, \qquad \textbf{(3.7)}$$

$$\sum_{t=l}^{l+T_i-1} x_{it} \geq 1, \ i \in N, \ l = 1,..,T - T_i + 1, \qquad \textbf{(3.8)}$$

$$x_{it}, z_t \in \{0,1\}, \ i \in N, \ t \in T. \qquad \textbf{(3.9)}$$

Chapter 4

Case Studies

Experience data for the analyses in *Paper I* - *Paper IV* are based on mainly three cases; two of wind power systems and one of a nuclear power system. *Paper I* and *Paper II* are based on experience data from a wind turbine at *Näsudden* based on interviews and a study visit, and data from the wind turbine park *Kentish Flats* based on interviews. Analyses in *Paper II* also include data from two technical reports [23], [24]. *Paper III* and *Paper IV* are based on data from *Forsmark* nuclear power plant based on interviews and study visits.

4.1 Wind Power Application Study

4.1.1 System description

A wind turbine is a machine that transforms kinetic power in the wind into electricity. The main parts are rotor and hub, several bearings, gearbox, generator, brakes, control system and a part that balance the electricity. Design of the wind turbine when it comes to rotor and hub can vary, but the most common is that the axis is horizontal. That is the axis of rotation rotate parallel with the ground with two or three blades. The gearbox task is to speed up the rotation from a low speed to a speed that can operate the generator. Some turbines use special generators that work at a low speed and then do not need a gearbox.

Nearly all wind turbines use induction or synchronous generators that demand a constant or close to constant speed. There are two brakes in a wind turbine; one slows down the rotor and the other is placed between the gearbox and generator and is used as an emergency brake or when the wind turbine is being repaired to avoid that the rotor starts spinning. The task of the control system is to put an upper limit on the torque and to maximize the energy production. There is also a small motor that runs a gearwheel so that the nacelle can be turned so that it always is in the wind direction. The nacelle also contains a controller that controls the different parts of the wind turbine [25].

4.1.2 Experience Data

At *Näsudden*, Gotland, Sweden, more than 100 wind turbines are installed, owned by different companies [27]. Vattenfall owns about 30 of those wind turbines from different manufacturers. Some of the turbines at *Näsudden* are part of research projects and are prototypes. Here the turbine *Olsvenne2*, a Vestas V90 on 3 MW, has a CMS developed by Vestas called VCMS. This is a prototype and data from this system cannot be accessed by the personnel of Vattenfall, only by Vestas.

The operation of *Kentish Flats*, an offshore farm with 30x3 MW turbines placed in the North Sea, UK, was first taken over by Elsam, which also operated several turbines and farms in Denmark [28]. *Kentish Flats* was completed in September 2005. The majority of Elsam's wind turbines in Denmark are now taken over by Vattenfall, and now also Kentish Flats has been taken over by Vattenfall. The CMS system VCMS, that is Vestas own CMS, was installed at *Kentish Flats* in the summer of 2006. Vattenfall has contracts for maintenance with several companies, e.g. Vestas, Siemens and Enercon. Maintenance contracts are valid one year at a time.

For all new farms under Elsam a five-year contract with full maintenance is signed with the manufacturer. This is in line with the five-year warranty period on the wind turbines. For *Kentish Flats* a five-year contract was signed with Vestas. Today's wind power maintenance is mainly scheduled maintenance. At Vattenfall scheduled maintenance is carried out approximately twice a year in general. The maintenance is categorized as either minor or major. Minor maintenance takes about 4 hours for two people and major maintenance takes about 7 hours for two people.

At Elsam scheduled maintenance is carried out in three to six month intervals, for older smaller turbines. Newer, larger turbines have intervals of six months to a year. Older turbines are maintained by Elsam's own maintenance division, Elsam Vind Service, which has 10 to 15 workers. For larger tasks, Elsam rents external independent services. At *Kentish Flats* scheduled maintenance requires two people working two days per turbine per year.

Vattenfall use a maintenance manual by Vestas. The manual includes e.g. general rules, safety procedures, changing oil filters and controlling leakages. At Elsam there is a manual for scheduled maintenance that is followed when maintenance is carried out. Manuals are often of varying quality and as a result interest groups want to establish standards for maintenance manuals. The main problem is that the manufacturers are writing these manuals and not the operators.

4.2 Nuclear Power Application Study

4.2.1 System description: Boling Water Reactor (BWR)

The system observed is the feed-water system at Forsmark1. Forsmark1 is a Boiling Water Reactor (BWR), and its function is explained here to provide an understanding of the importance of the feed-water system and its function. In the reactor tank there is fuel from Uranium that, when nuclear atoms are split, generates large amounts of heating energy [26]. Nuclear fission is started by pulled out control rods from the core. Heat that is generated at nuclear fission is transferred to the water, which is boiled into steam. The steam produced in the reactor is led in large steam pipes to a turbine facility. The difference in pressure between the reactor and the condenser gives the steam force on its way to the turbine, where the steam's heat energy is transformed into kinetic energy. A generator is connected to the shaft of the turbines. The generator's rotor is rotating at the same speed as the turbines. In the generator, kinetic energy is transformed into electrical energy. The electrical energy leaves the plant from a switchyard that divide the electrical power into different lines that connect to the Swedish national grid.

The steam still has a large energy when it leaves the low- pressure turbines. This energy is cooled off by large amounts of cooling water. The water is brought into the cooling water channel and is pumped into a condenser, which is a large heat exchanger placed under the low pressure turbines. The cooling water is led into water chambers and passes through the condenser through a large number of pipes, where it gathers the heat of the steam. From the outlet chambers, the cooling water is led in a tunnel. The steam that has turned into water again is collected at the bottom of the condenser. The water collected at the bottom of the condenser is called condensate. It is to be returned to the reactor and is therefore passed through a heat- and pressure-increasing process. After a condensate cleaning process, there are feed-water pumps that can give the water the pressure necessary for it to pass into the reactor. The condensate is at this moment changing name to feed water, which will be heated even more in high pressure pre-heaters. These gain steam from the high pressure turbine to warm up the feed water.

The feed water is pumped into the reactor again and the primary circle is closed. The feed water will replace the amount of water that has boiled to steam and left the reactor. The flow is adjusted continuously in relation to the steam output so that the water level in the reactor is preserved. In all situations there must be total control of the neutron flux in the core and the pressure and the water level in the reactor tank.

These parameters affect each other mutually, and the feed-water pump system is important for keeping the process stationary.

Feed-Water Pump System

The feed-water pump system works with a special type of redundancy so that two out of three pumps always must be in operation and one is redundant [29], [30] . Reactor 1 and 2 at Forsmark nuclear power plant are constructed so that they have two turbines with three feed-water pumps on each turbine. If two pumps out of three on one turbine where to go down for some reason, there would be a loss in power of 25% on the actual reactor. If three pumps where to go down the loss in power would be 50%. As a first step, production loss is not considered, since one pump at a time is observed. To gain a model that can consider production loss, the entire system with three pumps must be observed.

The mechanical failures that dominate in feed-water pumps are failures on shaft seals in the pump. They are today replaced when they fail as they are expensive components, i.e. no PM is carried out. Indications of failures are that hot water is leaking from the shaft [29]. When this phenomenon appears, or when temperature sensors show that the temperature is over a certain limit, inspections are made. Then a decision on whether the shaft seal should be replaced or not is made. Each pump has two shaft seals.

4.2.2 Experience Data

Working orders from Forsmark1 have been studied and an average time for exchanging one or two shaft seals has been calculated. An average time for the life length of the shaft seals has also been calculated, with data extracted from working orders. The time for exchanging shaft seals times the working cost, is not the only cost included in the constant cost. Other costs should be included to get a more realistic model. These are however difficult to estimate for a single isolated component [29].

The cost associated with performing maintenance is a constant cost d. The cost associated with the replacement, a cost per shaft seal called c, is the spare part cost. An estimation of data that depends on whether both shaft seals are replaced at the same time, or if only one is replaced, has been made. The average times for exchanging one or two shaft seals are different. This together with the spare part cost for k shaft seals (k = 1,2) gives the total cost for replacing k shaft seals:

$$n_P \cdot t_{RWT}(k) \cdot c_{WT} + k \cdot c_{SP}, \qquad \textbf{(4.1)}$$

- where k is the number of shaft seals being replaced, (one or two),
- n_P is the number of people required to perform the maintenance,
- $t_{RWT}(k)$ is the total working time for the maintenance in hours for k shaft seals,
- c_{WT} is the labour cost in EUR for the working time per hour and
- c_{SP} is the cost per spare shaft seal in EUR.

This equation gives the input data necessary for the Aircraft Model, which are the constant cost d and the spare part cost c.

Chapter 5

Closure

5.1 Conclusions

This thesis has presented models for maintenance management applied to wind and nuclear power plants. Total costs of maintenance are first analyzed and then mathematically optimized and the first deterministic models are later developed to be stochastic.

For the wind power case a LCC analysis was at first performed for a wind turbine onshore and a wind park offshore to compare different maintenance strategies. To further analyze economic benefits of different maintenance strategies a more sophisticated LCC analysis has been made where two different cost models, with uncertainties in time to failure included, were compared. For the nuclear power case at first an opportunistic maintenance optimization model for replacement of shaft seals in feed-water pump systems was developed based on the *Aircraft* model. Sensitivity analysis was performed and especially the discount rate was studied. To validate the opportunistic maintenance optimization model it was extended and put into a stochastic framework together with other strategies for maintenance and simulations were made to compare the different strategies.

Results for the wind case studies show on that there are many ways to cover the cost for condition monitoring systems (CMS), especially for the wind farm offshore where the planning of maintenance could be planned more efficiently. When failure rate is included in the analyses it is shown that high costs of components justify the use of CMS. Results for the nuclear power case studies show on that the optimization model is dependent on the discount rate and that a high discount rate gives more motivation for opportunistic replacements. When put into a stochastic framework and compared to other maintenance strategies it is shown that an extended model has a good overall performance and that it for high values of the constant cost of performing maintenance is good to perform opportunistic maintenance.

5.2 Future Work

The optimization models applied to subsystems in nuclear power plants could be used for other sub systems in nuclear power and also in wind power. The optimization models could be further developed to also include costs for production loss. The stochastic framework, so far used to evaluate different deterministic models and strategies, could even evaluate models that are stochastic. The optimization models could also be extended to be valid for a larger amount of components and systems.

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