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MASTER'S THESIS

Maintenance optimization in nuclear power plants—modelling, analysis, and experimentation

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Abstract

This thesis presents a variety of optimization models for opportunistic maintenance planning for a system of feed-water pumps in nuclear power plants. The feed-water pumps form an essential part of a nuclear reactor and failures can be very costly due to the consequence of production losses. Maintaining them optimally is therefore important in order to maximize the availability of the nuclear reactor. Different variations of the model are presented and also studied with respect to solution times, stability, and total cost of maintenance. A comparison between the opportunistic models and common maintenance policies is made in order to examine the respective resulting availability of production. Our calculations show that the opportunistic optimization model is stable with respect to changes in the cost of maintenance, and that it is the preferred maintenance planning policy.

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Chapter 1

Introduction

1.1 Background

This masters thesis is focused on maintenance planning optimization and one of its applications. Maintenance planning in industry is important to maintain a high availability of production and optimizing maintenance schedules can substantially improve the availability as well as decreasing the total cost for performing maintenance.

1.2 Maintenance in industry

A large part of the operating cost in industry comes from maintenance of equipment and machines. The cost of maintenance in the United States was estimated to rise from $600 billion in 1981 to $1.2 trillion in 2000 [1]. It is estimated that one third of these costs are due to inefficient management of maintenance. Therefore large savings can be made by increasing the efficiency of maintenance operations in industry. Maintenance can also be seen as an investment in availability and reliability of the equipment. This will further increase the profit.

When optimizing a maintenance schedule over a time period the aim is to minimize the number of maintenance occasions and spare parts needed as well as the time the machine has to be taken out of use and thereby minimizing the cost of maintenance and loss of production. An optimal maintenance schedule can reduce the cost of keeping the machine running as well as increasing its reliability and availability.

There are different principles for when and why maintenance is carried out. Corrective maintenance is when a component is replaced or repaired when a failure takes place. This simple method of maintenance is however the most expensive method to use. Preventive maintenance is when a component is replaced before it fails using a predicted life. To make this principle cost-effective, however, requires a sufficient amount of historical and/or measured data concerning the wear of a component to calculate an expected life of the component. An advantage of preventive maintenance is that the reliability and availability of the machine is improved. Opportunistic maintenance is a combination of preventive and corrective maintenance. When a component fails, a decision is taken on whether or not to perform maintenance on other components while the machine is opened for maintenance. This may increase the time until another component fails or needs maintenance which can save the cost of extra maintenance occasions.

1.3 Feed water pumps in nuclear reactor cooling systems

In 2008 nuclear power plants represented 42% of the electricity production in Sweden [2]. Nuclear power is considered to be a renewable energy source and does not contribute much to the carbon dioxide emissions. There are, however, disadvantages with nuclear power, mainly concerning the final storage of the waste. There are currently three nuclear power plants running in Sweden with a total of ten reactors. The safety and reliability of a nuclear reactor is very important since a failure can have major consequences in terms of radioactive contamination.

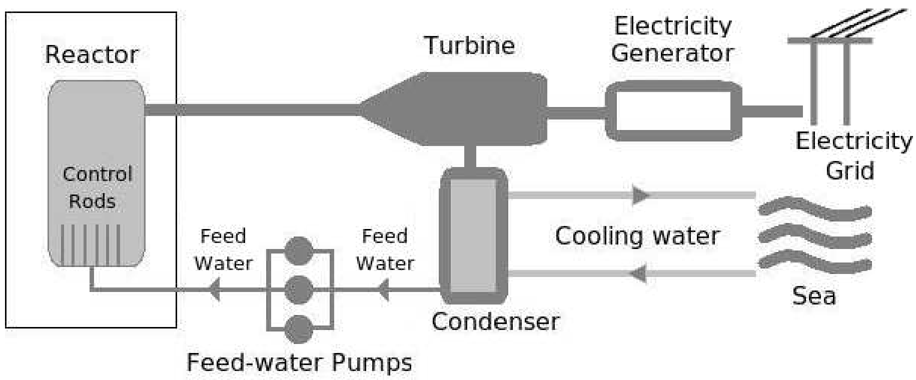

Figure 1.1: A schematic picture of the cooling system of a Boiling Water Reactor

The nuclear reactor at Forsmark 1 is a Boiling Water Reactor (BWR) with two turbines; this type of reactor uses steam to produce electricity. A schematic picture of the reactor is shown in Figure 1.1. Heat is generated from the nuclear fission taking place in the uranium fuel and controlled by the control rods that are pulled out of the core to start the fission. The thermal energy in the core is then transferred to water which is boiled into steam. A difference in pressure pushes the steam through the steam turbines. A generator connected to the turbine by a shaft transfers the kinetic energy to electricity which is then connected to the electricity grid. When the steam reaches the condenser it still contains large amounts of thermal energy and water is used to cool it off. The cooling water is taken from the sea and is then returned. The increase in temperature in the cooling water is around 10 degrees. The water in the turbine is contained in a closed system and it never mixes with the cooling water thus avoiding radioactive contamination. When the steam has cooled off to water in the condenser it is led through feed-water pumps to be pressurized before it passes into the reactor again. The flow of the feed-water is adjusted so that the water entering the reactor replaces the amount of steam leaving it. It is very important to keep the water level in the reactor constant at all times and the feed-water pumps are essential for this process.

In this thesis we have studied the feed water pump system of the nuclear reactor. At Forsmark 1 the turbines have three feed-water pumps each. For the reactor to run at full capacity at least two of the three pumps connected to each turbine must be in use. If only one pump is in use there is a loss of 50% of the production available in that turbine. The loss of production is very costly and therefore it is important to keep enough pumps working to avoid this. The failures on the feed-water pumps are mostly due to failures on the shaft seals of which there are two in each pump. The shaft seals are expensive components that are currently replaced when failure occurs and no preventive maintenance is performed [3]. By optimizing the maintenance schedule for the shaft seals of the reactor the cost of retaining the reliability and availability of the reactor can be improved.

1.4 Outline and motivation

This thesis seeks to examine an opportunistic model combining corrective and preventive maintenance, and to compare it with common maintenance planning methods and policies with respect to the reliability of the turbine. The mathematical models developed and described are based on Mixed Integer Linear Programming, MILP as described in [4]. In Section 2 an example of a MILP is introduced along with a principal solution method. Section 3 presents a number of MILP models for somewhat differing maintenance situations as well as a comparison of the models described with two common maintenance policies. These models were solved using the numerical setup and software which are described in Section 4. The results are presented in Section 5 and discussed in Section 6.

Chapter 2

Integer linear programming

Mixed integer linear programming is used to model and solve many types of optimization problems that can be modelled using linear relations and integer requirements, for example airline crew scheduling and how to cut shapes from sheets of plastic with minimum waste. A general MILP-problem is described as to

$$\begin{aligned} &\text{minimize} \quad d^{\mathrm{T}}x, \\ &\text{subject to} \quad Ax \le b, \\ &\qquad\qquad\quad x \ge 0^n, \qquad \text{and integer} \end{aligned} \tag{2.1}$$

where $x \in \mathbb{R}^n$ is a vector of variables and $d \in \mathbb{R}^n$, $A \in \mathbb{R}^{m\times n}$, and $b \in \mathbb{R}^m$ are vectors and matrices, respectively, of parameters. A simple example of an ILP is given by the problem to

$$\begin{aligned} \text{minimize} \quad & -2x_1 - 3x_2, \\ \text{subject to} \quad & x_1 + x_2 \le 4.5, \\ & -2.65x_1 + x_2 \le -0.3, \\ & x \ge 0^2, \qquad \text{and integer} \end{aligned} \tag{2.2}$$

The set of feasible solutions to this program lies within the polyhedron defined by the x_1 and x_2 axes and the constraint lines illustrated in Figure 2.1. For this example, the continuous solution is given by (x_1, x_2)=$(1.15, 3.35)$, (i.e., when the integrality constraints are relaxed), while the integer solution is given by (x_1, x_2)=$(2, 2)$; these are not very close. The continuous optimal value is 12.35 and the integral optimal value is 10. To find a (feasible) solution to an ILP is much harder than finding a solution to the corresponding continuous program. Since the ILP is very similar to an LP one might be tempted to round the solution obtained to the LP to find a good solution to the ILP. This is however not a generally good idea as the example shows.

If the variables in the ILP are binary a Binary Linear Program (BLP) is to be solved. This type of problem arises when the variables are of type

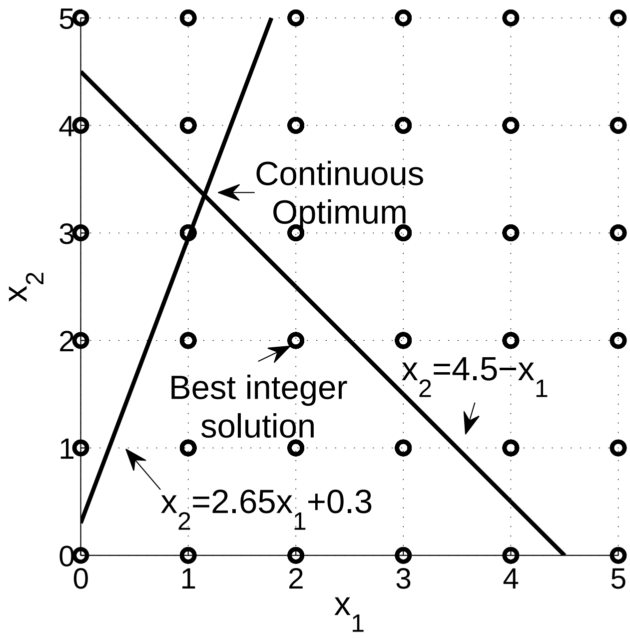

Figure 2.1: *Illustration of the ILP described in example 2.2*

on/off, as for example, whether or not maintenance should be performed at a certain time or whether or not a salesman travels directly between two specific cities. The maintenance problem in this thesis is analyzed using a BLP.

There exists different methods for solving this type of problem. The principal method used here is called “branch and bound” . In Figure 2.2 a branch and bound search tree for solving the example problem (2.3).

$$
\begin{aligned}
\text{minimize} \;\; & 7x_1 + 11x_2 + 4x_3 + 13x_4, \\
\text{subject to} \;\; & 3x_1 + 6x_2 + 5x_3 + 14x_4 \geq 7, \\
& x \geq 0^4, \qquad \text{and binary}
\end{aligned}
\tag{2.3}
$$

The search tree is examined by relaxing the integrality constraints on the variables and recursively fixing the values of variables yielding fractional values in the solution for the relaxed program. The solutions obtained at the respective nodes decide in which direction the search should continue and which directions that can yield no better solutions and thus can be discarded.

The solution of the program (2.3) using the branch and bound algorithm proceeds as follows. The search starts at node 0, in which the integrality

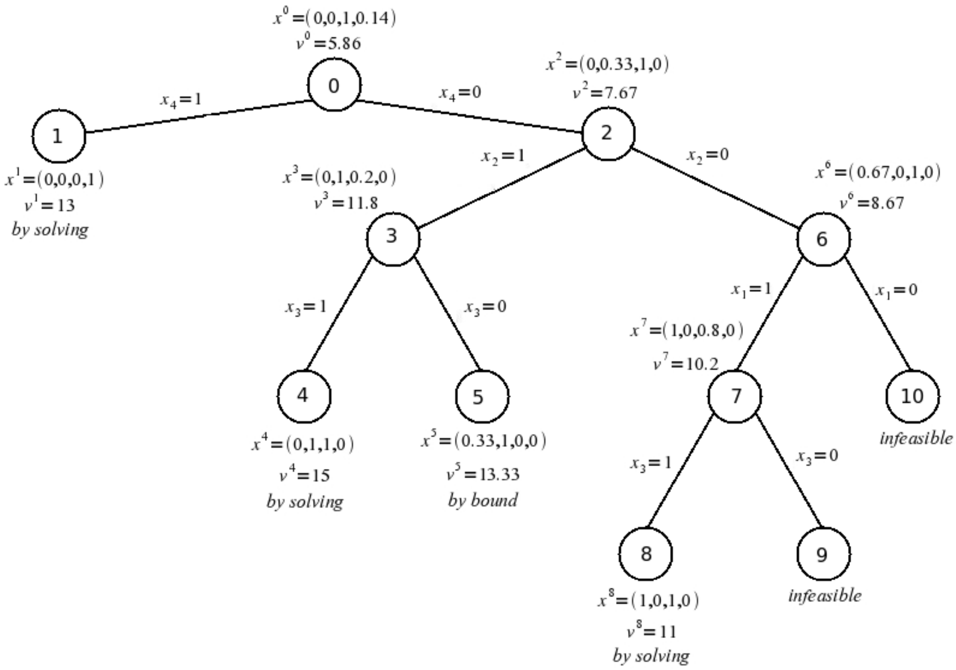

Figure 2.2: Illustration of the branch and bound algorithm applied to the program (2.3)

constraints on all variables are relaxed. The optimal value of the relaxed problem forms a lower bound for the binary linear program. From node 0 we choose to branch on variable x_4 since its value is fractional. By fixing the value on x_4 to one and zero, respectively, we define the nodes 1 and 2. At node 1 we solve the program (2.3) complemented with the constraint $x_4 = 1$. The solution reached turns out to be a feasible solution to the original program (2.3) since all values of the variables are binary. This branch of the search tree does not have to be examined further. Node 2 (defined by (2.3) and the constraint $x_4 = 0$) on the other hand results in a solution that is not binary. Here we branch on the variable x_2. From here we continue to node 3 which also results in a solution that is not binary. Further branching on variable x_3 from node 3 yields a solution at node 4 which, however, is not as good as the solution reached at node 1. At node 5 a solution is reached which has a value that exceeds the upper bound for the feasible solution reached in node 1. These two branches from nodes 4 and 5 are terminated here and the search continues at node 6. Here we branch on the variable x_1. The two branches created lead to node 7 where branching continues on the variable x_1, and to node 10, which only yields an infeasible solution. Branching from node 7 yields an infeasible solution at branch 9 and a feasible solution at node 8 which is better than the solution found at node 1. The optimal solution to the problem is $x = (1, 0, 1, 0)$ with the objective value 11. For a formal description of MILP and the “branch and bound” method, see [6]. The complexity of general and specific MILP is described in [4].

Chapter 3

Mathematical models of maintenance planning optimization for feed-water pump systems in nuclear power plants

We model replacements of shaft seals during a finite time period with discrete time steps. The life of a shaft seal is assumed to be deterministic and the time required to replace a shaft seal is considered to be exactly one time step. The optimization problems modelled and solved considers three scenarios: One in which at least two pumps must be working at all points in time, another in which the turbine can be kept running with only one working pump at 50 % loss of the turbine capacity, and the last model for which the shaft seals in the pumps suffer a reduction in remaining life or a cost each time the pump is switched on or off.

3.1 Model 1: At least two of three pumps always in use

This model considers three feed-water pumps with two shaft seals each. At least two of the three pumps must be running at all points in time since the turbine should be working at full effect.

The shaft seals are ageing when the pump is in use and thus need to be replaced before their remaining life has expired. There is a cost associated with the replacement of the shaft seals and a work cost for opening the pump to perform the maintenance. We define the following sets and parameters:

$$
\begin{array}{lcll}
\mathcal{I} & = & \{1,2,3\}, & \text{the set of pumps,} \\
\mathcal{J} & = & \{1,2\}, & \text{the set of shaft seals per pump,} \\
\mathcal{T} & = & \{1,..,T\}, & \text{the set of time steps, and} \\
U & \in & \mathbb{N}, & \text{the life in number of time steps of a new shaft seal.}
\end{array}
$$

The model is a MILP with three sets of binary variables, two of which concerns maintenance and replacement. They are defined as

$$x_{ijt} = \begin{cases} 1, & \text{if shaft seal } j \text{ in pump } i \text{ is replaced at time } t, \\ 0, & \text{otherwise,} \qquad\qquad\qquad i \in \mathcal{I}\ ,\ j \in \mathcal{J}, t \in \mathcal{T}. \end{cases} \tag{3.1}$$

and

$$y_{it} = \begin{cases} 1, & \text{if pump } i \text{ is opened for maintenance at time } t, \\ 0, & \text{otherwise,} \qquad\qquad\qquad i \in \mathcal{I}, t \in \mathcal{T}. \end{cases} \tag{3.2}$$

The third set of binary variables concerns whether the pumps are running or not. These variables are defined as

$$q_{it} = \begin{cases} 1, & \text{if pump } i \text{ is in use at time } t, \\ 0, & \text{otherwise,} \qquad\qquad i \in \mathcal{I}, t \in \mathcal{T}. \end{cases} \tag{3.3}$$

The variables q_{it} are used together with x_{ijt} and y_{it} to calculate the remaining life of the respective shaft seals since these are ageing only when the pump is in use. The remaining lives, l_{ijt}, depend on the values of these variables and are defined as

$$l_{ijt} = \quad \text{The remaining life of shaft seal } j \text{ in pump } i \text{ at time } t, \quad i \in \mathcal{I}\ ,\ j \in \mathcal{J}, t \in \mathcal{T}. \tag{3.4}$$

The cost, a, for performing maintenance on a pump and the price, c, of a new shaft seal are assumed to be constant over time. The objective is then defined as that to

$$\text{minimize} \quad \sum_{t=1}^{T}\sum_{i=1}^{3}\left(ay_{it} + c\sum_{j=1}^{2} x_{ijt}\right). \tag{3.5}$$

No shaft seal can be replaced without the pump being opened for maintenance, which is described by the constraints,

$$x_{ijt} \leq y_{it}, \qquad i \in \mathcal{I}, \quad j \in \mathcal{J}, \quad t \in \mathcal{T}. \tag{3.6}$$

A pump can not be running when maintenance is performed on it, i.e.,

$$y_{it} + q_{it} \leq 1, \qquad i \in \mathcal{I}, \quad t \in \mathcal{T}. \tag{3.7}$$

At each point in time there must be at least n pumps running for the turbine to operate at full effect, i.e.,

$$\sum_{i=1}^{3} q_{it} \geq n, \qquad i \in \mathcal{I}, \quad t \in \mathcal{T}. \tag{3.8}$$

In Model 1 $n = 2$, i.e., at least two pumps must be running at the same time. The remaining life, l_{ijt}, of shaft seal j in pump i at time t must be at least equal to one for the pump to operate and it cannot exceed the life of a new shaft seal, i.e.,

$$1 \leq l_{ijt} \leq U, \qquad i \in \mathcal{I}, \quad j \in \mathcal{J}, \quad t \in \mathcal{T}. \tag{3.9}$$

If shaft seal j of pump i is replaced at time t, the remaining life l_{ijt} equals U, which is expressed by the constraints

$$l_{ijt} \geq U x_{ijt}, \qquad i \in \mathcal{I}, \quad j \in \mathcal{J}, \quad t \in \mathcal{T}. \tag{3.10}$$

The remaining life of a shaft seal is also dependent on whether the pump is running or not. The following constraints express that the life of a shaft seal may decrease from time $t-1$ to time t only if the pump is running and maintenance is not performed at time t:

$$l_{ijt} \leq U x_{ijt} + l_{ij(t-1)} - q_{it}, \qquad i \in \mathcal{I}, \quad j \in \mathcal{J}, \quad t \in \mathcal{T} \setminus \{1\}. \tag{3.11}$$

If the pump is running, i.e., if $q_{it} = 1$, the remaining lives of the shaft seals are decreased by one and when maintenance is performed the remaining lives are increased to U. The remaining lives of the shaft seals may be decreased by at most one unit between consecutive time steps since the wear of the seal is constant when the pump is in use. This is modelled by the constraints

$$l_{ij(t-1)} - l_{ijt} \leq 1, \qquad i \in \mathcal{I}, \quad j \in \mathcal{J}, \quad t \in \mathcal{T} \setminus \{1\}. \tag{3.12}$$

Model 1 is thus defined as to minimize (3.5) subject to the constraints (3.6)–(3.12) and

$$\begin{array}{rlllll} x_{ijt}, y_{it}, q_{it} & \in \{0,1\}, & i \in \mathcal{I}, & j \in \mathcal{J}, & t \in \mathcal{T} \\ l_{ijt} & \geq 0, & i \in \mathcal{I}, & j \in \mathcal{J}, & t \in \mathcal{T}. \end{array} \tag{3.13}$$

If the remaining lives of all shaft seals are equal at time $t = 1$ the model, (3.5)–(3.12), becomes symmetric, meaning that running pumps 1 and 2 at time step 1 is equivalent to running pumps 1 and 3 or pumps 2 and 3 during time step 1. In order to decrease the number of feasible solutions to the MILP (3.5)–(3.13) this symmetry should be erased. To break this symmetry the model was forced to run pumps number one and two during the first two time steps. The choice of two time steps was made to further decrease the symmetry. The constraints describing this are given by:

$$q_{it} = 1, \qquad i \in \mathcal{I}, \ t = 1, 2. \tag{3.14}$$

These constraints will reduce the number of feasible solutions without excluding all optimal solutions.

3.1.1 Model 1a: Modelling with constant costs over time

Model 1a is described as to minimize (3.5) subject to the constraints (3.5)–(3.13). The following models are based on this formulation of the optimization problem.

3.1.2 Model 1b: Modelling with decreasing costs with respect to time

The model (3.5)–(3.13), will typically possess several optimal solutions. In practice, maintenance occasions are preferably placed as late as possible within the time period considered. To shift the maintenance occasions towards later but feasible points in time a small decrease in the maintenance cost over time was included in the model, resulting in the objective function to

$$\text{minimize} \sum_{t=1}^{T} \sum_{i=1}^{3} \left(a y_{it} + \big(c + \varepsilon\,(T-t)\big) \sum_{j=1}^{2} x_{ijt} \right), \tag{3.15}$$

where the value of $\varepsilon > 0$ was chosen small enough so as not to affect the total numbers of maintenance occasions and shaft seal replacements during the planning period. Model 1b is defined as to minimize (3.15) subject to the constraints (3.6)–(3.13).

3.2 Model 2: Loss of capacity due to only one pump being in use

Model 1 was modified to reflect the possibility to run only one of the pumps but at a reduction of 50% of the capacity of the turbine. Running all three pumps does not generate a higher capacity than running two pumps. Model 1 was complemented by the variables representing the efficiency of the system of pumps and a set of constraints to consider this. The revenue from the electricity produced by the plant was estimated to $d = 200$ SEK/MWh. The maximum power output of the turbine is $P = 500$MW. The efficiency, p_t, of the pump system is dependent on the number of pumps in use, i.e,

$$p_t \leq \frac{1}{2} \sum_{i \in \mathcal{I}} q_{it}, \qquad t \in \mathcal{T}. \tag{3.16}$$

The effect produced by the turbine is not higher when more than two pumps are operating simultaneously and it cannot be negative, i.e.,

$$0 \leq p_t \leq 1, \qquad t \in \mathcal{T}. \tag{3.17}$$

The constraints (3.8) were used with $n = 1$ instead of $n = 2$ as was the case in Model 1. A cost is added when only one pump is running. This cost is due to the decreased power output of the turbine and it is dependent on the electricity price. This cost was added to the objective function (3.5) in Model 1. In this model the price of electricity is considered to be constant over the planning period.

$$\text{minimize} \sum_{t \in \mathcal{T}} \left(Pd\,(1 - p_t) + \sum_{i \in \mathcal{I}} \left(a y_{it} + c \sum_{j \in \mathcal{J}} x_{ijt} \right) \right) \tag{3.18}$$

Model 2 is then defined as to minimize (3.18) subject to the constraints (3.6)–(3.13) and (3.16)–(3.17)

3.3 Model 3: Considering a cost for switching the pumps on and off

Model 1 was modified by adding a cost associated with switching the pumps on and off. Two cases were considered, one where the cost was added in the objective function and one where the cost is represented by a decrease in remaining life (a faster ageing) of the shaft seals. Two binary variables were added to keep track of when the pumps were switched on or off. They are described as

$$r_{it} = \begin{cases} 1, & \text{if pump } i \text{ is switched on at time } t, \\ 0, & \text{otherwise,} \qquad\qquad i \in \mathcal{I}, t \in \mathcal{T}. \end{cases} \tag{3.19}$$

and

$$s_{it} = \begin{cases} 1, & \text{if pump } i \text{ is switched off at time } t, \\ 0, & \text{otherwise,} \qquad\qquad i \in \mathcal{I}, t \in \mathcal{T}. \end{cases} \tag{3.20}$$

To the set of constraints (3.6)–(3.12) were added constraints concerning these variables. They are described as

$$r_{it} \geq q_{it} - q_{i(t-1)}, \qquad i \in \mathcal{I}, j \in \mathcal{J},\ t \in \mathcal{T} \setminus \{1\}, \tag{3.21}$$

$$s_{it} \geq q_{i(t-1)} - q_{it}, \qquad i \in \mathcal{I}, j \in \mathcal{J},\ t \in \mathcal{T} \setminus \{1\}. \tag{3.22}$$

This means that for $t \geq 2$, q_{it} and $q_{i(t-1)}$ are used to determine whether the state of the pump has changed. If this is the case, one of the variables r_{it} and s_{it} will receive the value one, and if not, both variables will receive the value zero.

3.3.1 Model 3a: Cost for switching the pumps on and off added in the objective function

Model 3a adds a cost in the objective function each time a pump is switched on or off. This cost is associated with the work required for switching a pump on or off. The costs used in the calculations were set to $d_{\text{on}} = 500$ SEK and $d_{\text{off}} = 500$ SEK. The objective function 3.5 was modified to include the new variables and their associated costs yielding the objective to

$$\text{minimize} \sum_{t=1}^{T}\sum_{i=1}^{3}\left(ay_{it} + d_{\text{on}}r_{it} + d_{\text{off}}s_{it} + c\sum_{j=1}^{2}x_{ijt}\right) \tag{3.23}$$

Model 3a can thus be described by (3.23), (3.6)–(3.12) and

$$r_{it}, s_{it} \quad \in \{0,1\}, \quad i \in \mathcal{I}, t \in \mathcal{T}. \tag{3.24}$$

3.3.2 Model 3b: Loss of life due to extra wear on shaft seals when switching pumps on and off

This model includes a decrease in remaining life of the shaft seals when a pump is switched on or off. This decrease can be associated with the extra wear the shaft seals are exposed to when the pumps are switched on or off. The model is similar to Model 1 with the same objective function (3.5) but with modified constraints. The loss of life for turning on and off the pumps was set to $g_{\text{on}} = 1$ and $g_{\text{off}} = 1$ time units, respectively. The constraints (3.11) and (3.12) were modified to take this into account. The remaining life of a shaft seal at time t is dependent on not only whether the shaft seal was replaced or whether the pump was running at time $t-1$ but also on whether or not the pump was switched on or off. The new constraints are given by

$$\begin{aligned} l_{ijt} \leq \quad & Ux_{ijt} + l_{ij(t-1)} - q_{it} - r_{i(t-1)}g_{\text{on}} - s_{i(t-1)}g_{\text{off}}, \\ & \qquad i \in \mathcal{I},\ j \in \mathcal{J},\ t \in \mathcal{T} \setminus \{1\}. \end{aligned} \tag{3.25}$$

Between consecutive time steps the remaining life can be decreased by at most one plus the eventual loss of life resulting from the pump being switched on or off.

$$\begin{aligned} l_{ij(t-1)} - l_{ijt} \leq \quad & 1 + r_{i(t-1)}g_{\text{on}} + s_{i(t-1)}g_{\text{off}}, \\ & \qquad i \in \mathcal{I},\ j \in \mathcal{J},\ t \in \mathcal{T} \setminus \{1\}. \end{aligned} \tag{3.26}$$

Model 3b can thus be described as to minimize (3.5) subject to the constraints (3.6)–(3.10), (3.21)–(3.22) and (3.24)–(3.26).

Chapter 4

Case study

4.1 A summary of the models and parameters considered

The models described in Section 3.1-3.3 were solved both with and without the symmetry breaking constraints (3.14) in order to examine how the symmetry of the problem affects the solutions reached and the corresponding solution time.

Description	Parameter	Value	Unit
Number of pumps	I	3	
Number of shaft seals in each pump	J	2	
Number of time steps in the model	T	55	Time steps
Life of a new shaft seal	U	22	Time steps
Cost of opening a pump	a	4800	SEK
Cost of a new shaft seal	c	86000	SEK
Decrease of cost with each time step	ε	0.5	SEK
Power of turbine	P	500	MWh
Cost of production loss	d	200	SEK/MWh
Cost for switching a pump on or off	d_{on}	500	SEK
Cost for switching a pump off	d_{off}	500	SEK
Reduction of life when switching a pump on	g_{on}	1	Time steps
Reduction of life when switching a pump off	g_{off}	1	Time steps

Table 4.1: Data for different scenario setups

4.2 Software used to perform the tests

The models described in Section 3 were implemented in the AMPL modelling language for mathematical programming and solved using the MILP solver

Cplex. Cplex employs a branch and bound solution strategy as described in Section 2. Matlab was used to process the output data from the solver and for the computations made to compare Model 1a with other maintenance planning policies (according to Section 3.4). The results from these tests are reported in Section 5.

4.3 A simulation of the use of Model 2 in comparison with two maintenance policies

A comparison between the maintenance planning described in Model 2 and other common maintenance philosophies was made to examine how well the models described in this thesis compare to other commonly used maintenance policies with respect to production vailability and total cost of maintenance. Model 2 was used with $n = 0$ in the constraints (3.8), i.e. when not running any pumps the turbine will not produce any electricity. The maintenance policies used in the comparisons in which a corrective model where shaft seals are replaced as they break and no opportunistic maintenance is performed. The other model used is a so called "replace all" model where both shaft seals in a pump are replaced when one breaks. The comparison was performed using stochastic lives of the components according to a gamma distribution. At each time step a new maintenance decision was made depending on the remaining lives of the components and on whether or not a shaft seal had broken during the previous time step.

Chapter 5

Results

The models described in Section 3 were examined using AMPL with the Cplex solver. Cplex found optimal feasible solutions to all the models with the exception of some of the sensitivity analysis of Model 3b. These computations were run for 6000 seconds to find a lower bound for the objective value. The maintenance plans for the different models are very similar and differed only on at which time step maintenance were performed while the number of maintenance occasions and shaft seals replaced was the same for all models and parameters, except Model 3b that resulted in more maintenance occasions when the loss of life when switching a pump on or off was increased. To study the stability of the models the values of some parameters were varied and the difference in maintenance schedules and the computation times were studied. The sensitivity studies showed that all the models are stable with respect to the CPU time required to find an optimal feasible solution and the maintenance schedules for the parameters tested. By varying the price of performing maintenance in Model 1, the price of electricity in Model 2, and the cost of switching a pump on and off in Model 3a, it was concluded that the models are all reasonably stable and that it takes large variations in these constants to make a difference in the maintenance schedules. When comparing Model 1 with two common types of maintenance planning policies it performed better than both of these when the cost of performing maintenance is around the same level as it is today, showing that this type of maintenance planning can improve the reliability and availability of the pumps as well as decrease the total cost of maintenance during the time period considered.

5.1 Model 1: At least two of three pumps must always be in use

The model defined by (3.5)–(3.13) was solved with and without the constraints (3.14) to examine how the symmetry of the model affects the computation time. Figure 5.1 shows the maintenance schedules for the feasible solutions found by Cplex using the branch and bound method described in Section 2, with ($\Diamond$) and without ($\circ$) the constraints (3.14). The figure shows

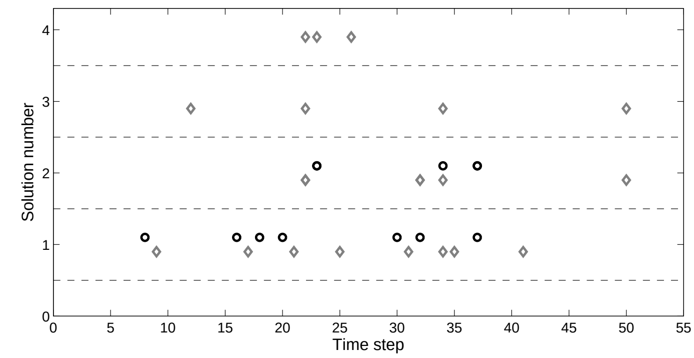

Figure 5.1: *The feasible maintenance schedules for Model 1a found by Cplex with ($\Diamond$) and without ($\circ$) the constraints* (3.14).

the four and two feasible solutions found by Cplex for the respective models. The inclusion of the constraints (3.14) yields a smaller number of feasible solutions before reaching an optimum compared to the model without the constraints (3.14). However, the CPU time spent to find an optimal solution is longer when including the constraints (3.14), as shown in Figure 5.2. Figure 5.3 shows the number of shaft seals replaced and the number of

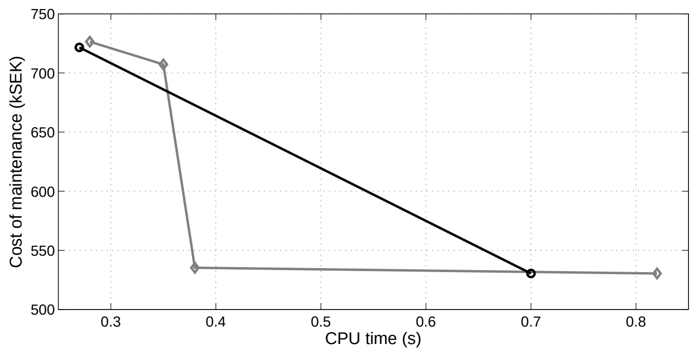

Figure 5.2: *Objective values for the feasible solutions to Model 1a with ($\Diamond$) and without ($\circ$) the constraints (3.14), for the four and two, respectively, feasible solutions found, which are illustrated in Figure 5.1.*

maintenance occasions as a function of the CPU-time needed to reach the respective solution. The numbers of maintenance occasions and shaft seals

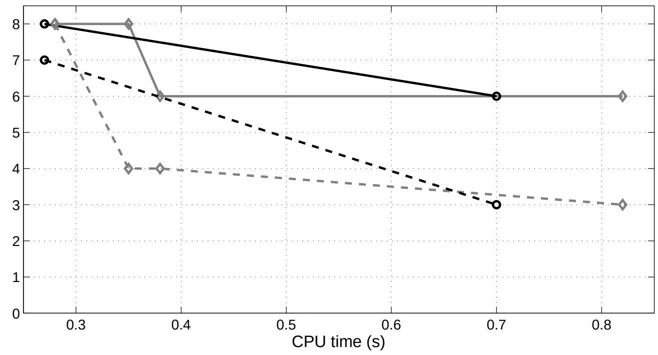

Figure 5.3: *The number of maintenance occasions (- - -) and the number of shaft seals replaced (—) for Model 1a with (◊) and without (∘) constraints (3.14), for the four and two, respectively, feasible solutions found, which are illustrated in Figure 5.1.*

replaced are decreasing constantly but not equally. The ratio between the number of shaft seals replaced and the number of maintenance occasion approaches 2 as the solution approaches optimum. This is expected, since the shaft seals possess the same remaining life at $t = 1$ and since they age equally when the pump is in use, it is therefore optimal that either none or both shaft seals of a pump are replaced at each maintenance occasion.

5.1.1 Model 1b: Adding a small cost that decreases with time

Figure 5.4 shows maintenance schedules for Model 1b defined by (3.6)–(3.13) and (3.15) with (◊) and without (∘) the cost terms $\varepsilon(T - t)$, $t \in \mathcal{T}$ which shifts the maintenance occasions towards later time points in the time spans given by the constraints (3.9)–(3.11) defining the remaining lives of the shaft seals. This makes sense since ε is the fictitious value by which the cost of replacement is decreased between consecutive time steps. When $\varepsilon > 0$ the maintenance occasions will move towards later time points the remaining lives of the components stay non-negative at all time points. The number of maintenance occasions and shaft seals replaced and hence the optimal total cost of maintenance is exactly the same as for Model 1a.

A good feasible solution, with the same number of maintenance occasions and shaft seals replaced, is reached in a CPU-time that is comparable to the CPU-time taken to reach the optimal feasible solution in Model 1a, as shown in Figure 5.5. All feasible solutions found, with the exception of the first have the same number of maintenance occasions and shaft seals replaced but differs in that the maintenance occasions are shifted towards

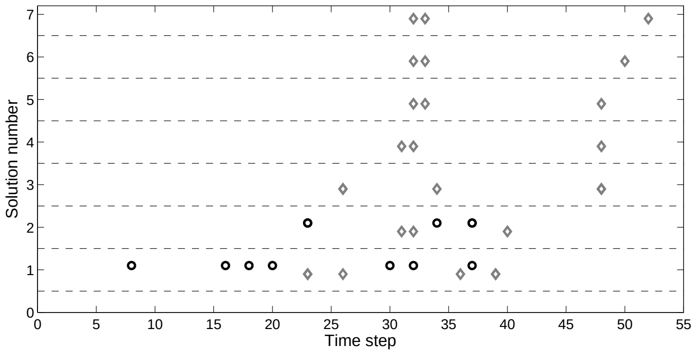

Figure 5.4: *The feasible maintenance schedules for Model 1b found by Cplex with* ($\Diamond$) *and without* ($\circ$) *the cost terms* $\varepsilon\,(T-t)\,, t \in \mathcal{T}$, *where* $\varepsilon = 0.5$.

later time points. An optimal feasible solution is reached after almost 10 seconds which is ten times longer CPU-time than it took to find the optimal feasible solution of Model 1a. Figure 5.6 shows the number of shaft seals replaced and the number of maintenance occasions needed. When ε was set to 0.5SEK more feasible solutions were found and an optimal solution was reached were the number of maintenance occasions and shaft seals replaced where the same as in the case when $\varepsilon = 0$. The CPU-time taken to reach the optimal solution in this model was longer than the time needed for Model 1a but still not unreasonable.

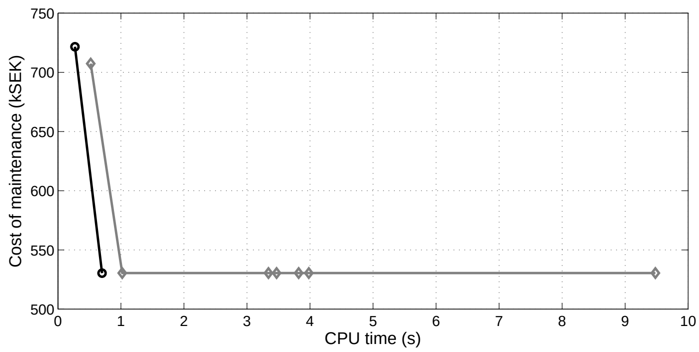

Figure 5.5: *Objective values for the feasible solutions to Model 1b with* ($\Diamond$) *and without* ($\circ$) *the cost terms* $\varepsilon (T - t), t \in \mathcal{T}$, *where* $\varepsilon = 0.5$, *for the two and seven, respectively, feasible solutions found, which are illustrated in Figure 5.4.*

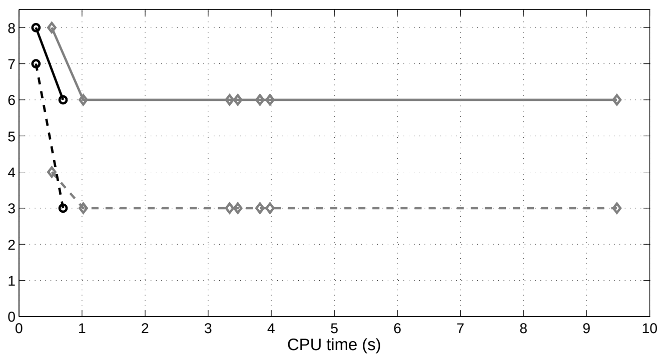

Figure 5.6: *The number of maintenance occasions (- - -) and the number of shaft seals replaced (—)for Model 1b with* ($\Diamond$) *and without* ($\circ$) *the cost terms* $\varepsilon (T - t), t \in \mathcal{T}$, *where* $\varepsilon = 0.5$, *for the two and seven, respectively, feasible solutions found, which are illustrated in Figure 5.4*

5.1.2 Sensitivity of Model 1a

To check the sensitivity of Model 1a with respect to cost relations it was solved for different values of the cost of a maintenance occasion a. The numbers of maintenance occasions and shaft seals replaced were the same for all values of a examined. There were a total of three maintenance occasions at which both shaft seals of a pump were replaced. These values represent the the minimum amount of maintenance that has to be performed for the turbine to be running during the time period considered.

The maintenance schedules differed for the different values of a but since the problem comprises symmetries there exists more than one optimal solution for each value of a and, hence, this is not surprising. The CPU-time required to reach an optimal solution to the model for the different values of a did only vary between three and seven seconds and there is no obvious relation between the CPU-time and the value of a. This indicates that Model 1a is stable and is not much affected by a change in the price of performing a maintenance occasion. The different values of a employed in the computations are given in Table 5.1.

a	1200	2400	4800	9600	19200	38400	76800

Table 5.1: The different values of a employed in the sensitivity calculations.

5.2 Model 2: Loss of capacity due to only one pump being in use

The model solved was defined by (3.6)–(3.12) and (3.16)–(3.18). The maintenance schedules for this model, as shown in Figure 5.7, differs from the other models. Both the model with ($\Diamond$) and without($\circ$) the constraints (3.14) reached a first feasible solution with only three maintenance occasions. Even though this is the same number of maintenance occasions as in the optimal solution of Model 1a, the cost of maintenance, as illustrated in Figure 5.8 is considerably larger due to the loss of production capacity when the turbine is run with only one working pump, i.e. at only half the production capacity. This solution is still feasible since the turbine can operate with only one pump in use.

The loss of effect when only one pump is in use yields a larger loss of income than the cost for the additional maintenance occasions required to keep two pumps running at all times. As seen in Figure 5.8 the loss of income from the turbine when less than two pumps are running is added to the cost of maintaining the pumps. This cost is increased rapidly when less than two pumps are in use and it is therefore worth performing maintenance on the

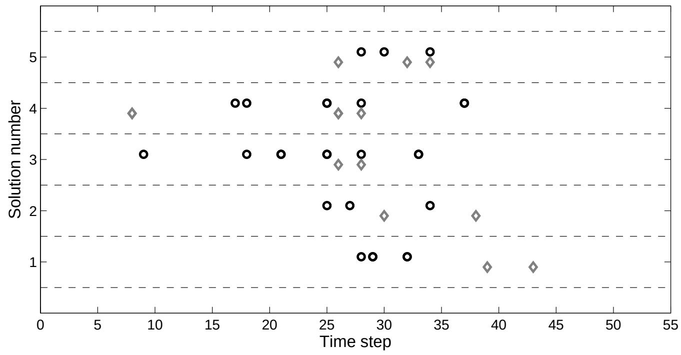

Figure 5.7: *The feasible maintenance schedules for Model 2 found by Cplex with (◊) and without (○) the constraints (3.14).*

pumps to keep at least two of them running at all times. In Figure 5.9 the

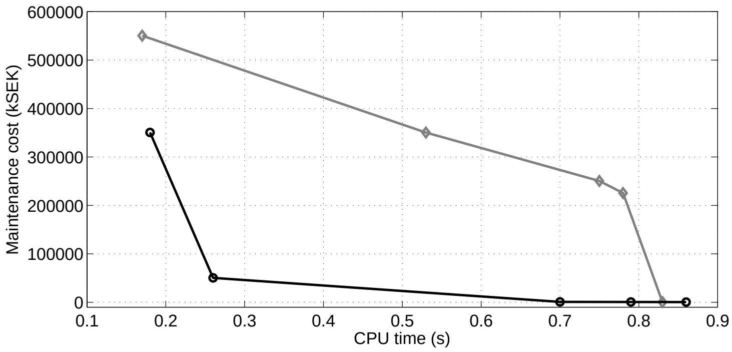

Figure 5.8: *Objective values for the feasible solutions to Model 2 with (◊) and without (○) the constraints (3.14) for the five feasible solutions illustrated in Figure 5.7.*

number of maintenance occasions and shaft seals replaced are shown. In the first solutions the numbers are low and not much maintenance is performed since few of the pumps are running. The number of maintenance occasions and shaft seals replaced then increase and peak before decreasing to the minimum of maintenance occasions needed to keep two pumps running at all times. At the optimal solution the number of maintenance occasions and shaft seals replaced are the same as for Model 1a even though the maintenance schedule differs.

The values of the Figures 5.7–5.8 are summarized in Table 5.2

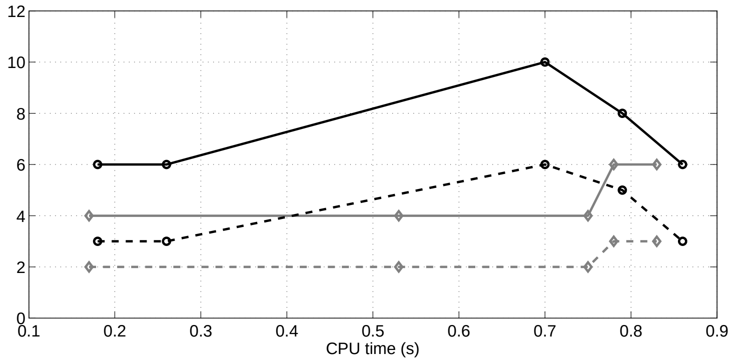

Figure 5.9: *The number of maintenance occasions (- - -) and the number of shaft seals replaced (—) for Model 2 with (◊) and without (○) constraints (3.14), for the five feasible solutions illustrated in Figure 5.7.*

5.2.1 Sensitivity of Model 2

When varying the income per MWh the maintenance schedule does not change much. This may be due to the maintenance schedule being already optimized to keep two pumps running at all points in time, and that the total cost for this is as small as possible even though the cost of production loss varies. It also shows that it is almost always more economical to run the turbines at full capacity even if this means that more maintenance has to be performed on the pumps. For a sufficiently low price of electricity it will not be economical to run two pumps at the same time. The reduction in maintenance costs will then balance the income lost when only one pump is running and only half the capacity of the turbine is available. The limit when this happens is only a fraction of the current price of electricity and our computations showed that the price has to be reduced to 0.05 SEK/MWh before this happens. This can be compared to the current price of 200 SEK/MWh. There is thus little chance that the full power output of the turbine will not be enough to cover the cost needed to maintain the full capacity of the turbine.

5.3 Model 3: Considering a cost for switching the pumps on and off

The two models both seek to minimize the number of times a pump is switched on or off. Model 3b was considerably faster to solve than Model 3a. This can be due to that the added constraints did tighten the feasible region while the model with a new objective function had a completely new surface. Common for the two models were the fact that the added

Model 2 w.o. constraints (3.14)	1	2	3	4	5
# time steps running one pump	14	2	0	0	0
# of shaft seals replaced	6	6	10	8	6
Cost of maintenance (MSEK)	0. 53	0.53	0.89	0.71	0.53
Cost of production loss (MSEK)	350	50	0	0	0
Total cost (MSEK)	350.53	50.53	0.89	0.71	0.53
Model 2 w. constraints (3.14)	1	2	3	4	5
# time steps running one pump	22	14	10	9	0
# of shaft seals replaced	4	4	4	6	6
Cost of maintenance (MSEK)	0.354	0.354	0.354	0.530	530
Cost of production loss (MSEK)	550	350	250	225	0
Total cost (MSEK)	550.35	350.35	250.35	225.53	0.53

Table 5.2: Data for different scenario setups without the constraints (3.14)

constraints (3.14) speeded up the solution procedure. This was not the case with the previous models.

5.3.1 Model 3a: Cost for switching on and off a pump added in the objective function

Model 3a is defined by (3.6)-(3.12) and (3.23). In Figure 5.10 the maintenance schedules for solutions found with ($\Diamond$) and without ($\circ$) the constraints (3.14) are shown as well as the number of times a pump was turned on or off in the respective solutions. In this case more solutions were produced before reaching an optimal solution when applying constraint (3.14). The CPU-time required to reach an optimal solution was however shorter with these constraints as seen in Figure 5.11. Figure 5.12 also shows that the minimum number of shaft seals replaced and maintenance occasions performed were reached sooner. In this case the added constraint led to an improved model. This model, being more complex than Model 1 required more CPU-time to reach an optimal solution.

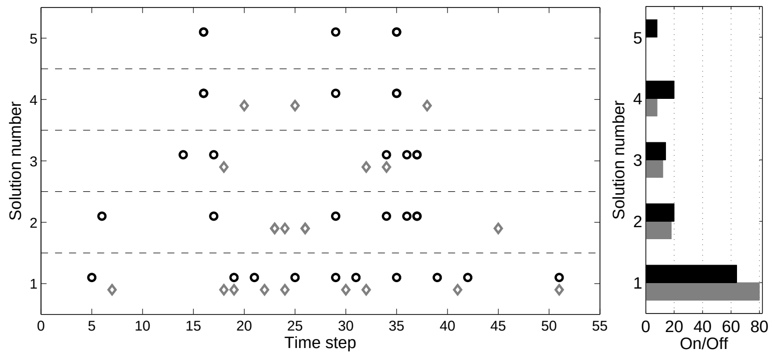

Figure 5.10: *The feasible maintenance schedules for Model 3a found by Cplex with (◊) and without (∘) constraints (3.14) and the number of times a pump was turned on or off in the maintenance schedule for the model with (■) and without (■) the constraints (3.14).*

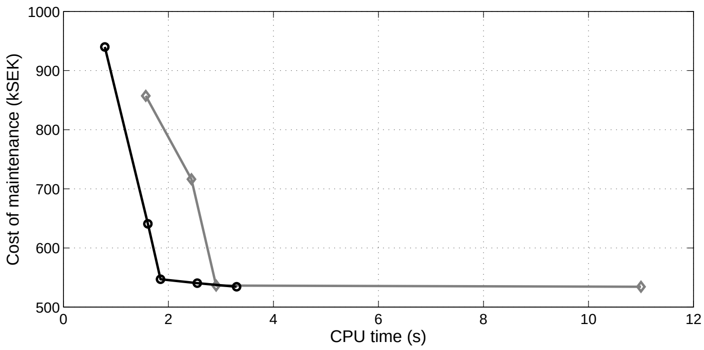

Figure 5.11: *Objective values for Model 3a with (◊) and without (∘) constraints (3.14), for the five and four, respectively, feasible solutions illustrated in Figure 5.10.*

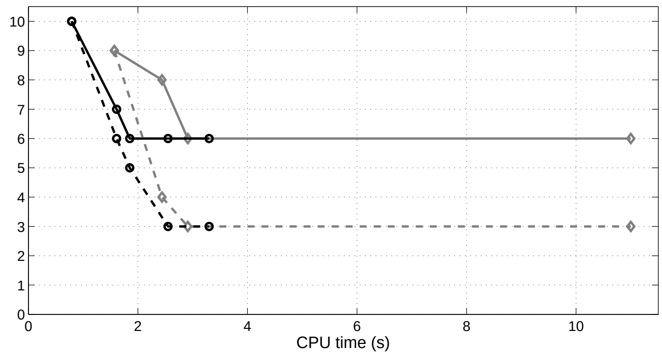

Figure 5.12: *The number of maintenance occasions (- - -) and the number of shaft seals replaced (—)for Model 3a with (◊) and without (○) constraints (3.14), for the five and four, respectively, feasible solutions illustrated in Figure 5.10.*

5.3.2 Model 3b: Loss of life due to extra wear on shaft seals when switching a pump on and off

The comparison was made over 100 scenarios and used stochastic lives of components distributed according to gamma distributions. The maintenance schedules of this model are shown in Figure 5.13, and as seen the model with (◊) the constraints (3.14) did only reach two feasible solutions within reasonable time compared to the six solutions reached by the model without (○) the constraints (3.14). The solution reached by the former model was however better than the by the latter, as seen in Figure 5.14, and it was also reached much faster. Figure 5.15 also shows the smaller number of shaft seals replaced and maintenance occasions performed that the model with the constraints (3.14) reached. The number of maintenance occasions and shaft seals changed were the same as in the previous models and thus the loss of life when switching a pumps on and off was not large enough to affect the number of maintenance occasions needed to keep the pumps running. This can also be seen when comparing the number of times a pump is switched on and off in Model 3a compared to Model 3b. In Model 3a a pump is switched off or on a total of eight times in the optimal solutions for the model both with and without the constraints (3.14) as seen in Figure 5.10 while in Model 3b the optimal solutions for the model both with and without the constraints (3.14) the pumps are turned on or off a total of twelve times. This is due to the extra wear on the pumps when turning them on or off. The wear is not large enough to require extra maintenance but the pumps running have to be interchanged to avoid the extra maintenance since the remaining lives of the shaft seals at the end of the planning period is smaller than in Model 3a.

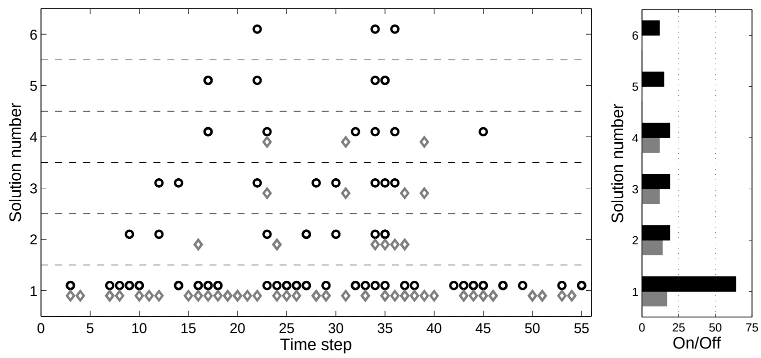

Figure 5.13: *The feasible maintenance schedules for Model 3b found by Cplex with (◊) and without (○) constraints (3.14) and the number of times a pump was turned on or off in the maintenance schedule for the model with (■) and without (■) the constraints (3.14).*

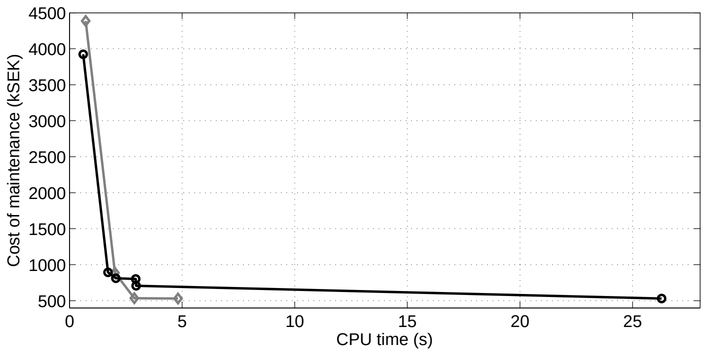

Figure 5.14: *Objective values for Model 3b with (◊) and without (○) constraints (3.14), for the six and four, respectively, feasible solutions illustrated in Figure 5.10.*

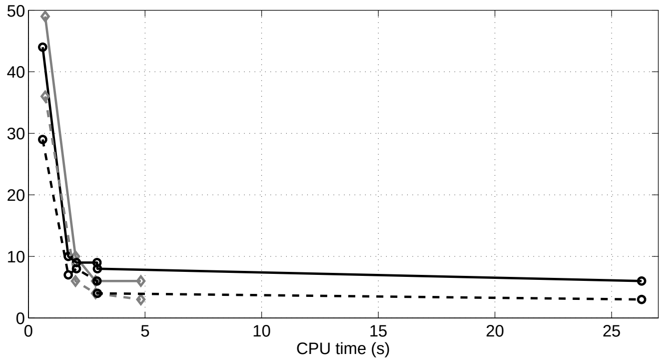

Figure 5.15: *The number of maintenance occasions (- - -) and the number of shaft seals replaced (—) for Model 3b with (◊) and without (○) constraints (3.14), for the six and four, respectively, feasible solutions illustrated in Figure 5.10.*

5.3.3 Sensitivity of Model 3a

When varying the cost of switching pump on and off it may be expected that the number of occasions a pump is switched on or off will decrease with increasing associated prices, d_{on} and d_{off}. However, the number of times a pump was switched on or off remained constant when varying the price. This number of switching pumps on or off, 8, is the smallest number of times that pumps has to be switched on or off to enable maintenance to be performed. The CPU-time taken to solve Model 3a with different values of

d_{on} and d_{off} did not vary much and since an optimal solution was reached for all values of d_{on} and d_{off} the model is considered stable.

5.3.4 Sensitivity of Model 3b

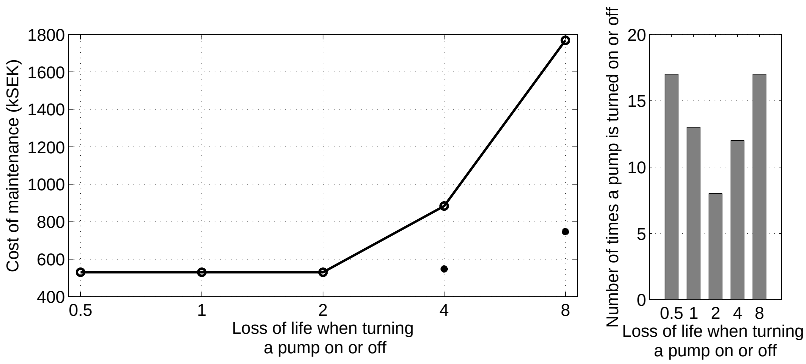

Figure 5.16: *Cost of maintenance and number of times a pump is switched on or off for different loss of life when turning a pump on or off. Where no optimal solution was reached the best solution found was compared with the lower bound found by Cplex after* 6000 *seconds.*

When the loss of life when switching a pump on or off is decreasing the number of times this can occur without affecting the number of times maintenance has to be performed on the shaft seals during the planning period is increasing.When the loss of life when switching a pump on or off the total cost of maintenance will increase due to the increased number of shaft seals that need to be replaced. This will also lead to an increase in the number of times a pump is turned on or off.

This is illustrated in Figure 5.16 where the total cost of maintenance for different values of g_{on} and g_{off} as well as the number of times a pump is switched on or off is shown. When the loss off life when switching on or off a pump, g_{on} and g_{off}, was increased to 4 or more the model did not reach an optimal solution and the lower bound calculated by Cplex is seen as $*$ in the graph. To find this bound the model was run for 6000 seconds. To the right in Figure 5.16 the number of times a pump is switched on or off for different values of g_{on} and g_{off} is shown. When $g_{\text{on}} = g_{\text{off}} = 2$ the number of times is reduced to 8 while larger or smaller values show a larger number of times a pump is turned on or off. In the first case this is due to that the loss of life is big enough to affect the number of maintenance occasions needed and in the latter case the loss is not big enough to affect the maintenance schedule and therefore no minimization of the number of times a pump is switched on or off is needed.

5.4 A simulation of the use of Model 2 in comparison with two maintenance policies

Model 2 describes an opportunistic maintenance policy that makes a decision on whether or not to replace one or two shaft seals in a pump depending on the cost of performing maintenance as well as on the condition of the shaft seals of the other two pumps. This model was compared to two different policies described in Section 4.3 in order to examine the availability and cost of maintenance for the different maintenance policies. The different maintenance policies used in the comparison are described as follows: in the first policy no opportunistic maintenance is performed and the shaft seals are replaced only when they break, and in the second policy (the "replace all" policy) both shaft seals in a pump are replaced when one shaft seal breaks. The third policy in the comparison is the opportunistic maintenance policy. The maintenance policies were modelled over 100 scenarios with 55 time steps each using Matlab, and the lives of the shaft seals were modelled by a Gamma(20000,4)-distribution which corresponds to 20 time steps as the maximum life of a shaft seal. With this modelling the shaft seals possess an expected life when they are new but they can break unexpectedly before that and the maintenance schedule has to be re-modelled accordingly. The mean of the cost of maintenance from these computations were used in order to calculate the availability and the total cost of maintenance for the different maintenance policies. The maintenance schedule when using each of the three policies was computed using Algorithm 1.

Algorithm 1 Maintenance cost of using a policy

```
t = 0,   cost = 0
give all shaft seals the life of a new shaft seal
while t ≤ T do
   check if any shaft seal is broke
   use the policy to determine which shaft seals to replace at time t
   if maintenance performed at time t then
      cost = cost + cost of maintenance + cost of replaced shaft seals
   end if
   t = t + 1
   uppdate the lives of the shaft seals at time t
end while
return cost
```

The availability and total cost of maintenance for the different maintenance policies were compared for the different values of the cost a for performing maintenance shown in Table 5.1 and the results were compared. The availability of the turbine, i.e. how often the turbine is running at full capacity was constant when using the corrective and the replace all maintenance philosophies, at 84% and 90.5%, respectively. The availability of these maintenance policies are thus not dependent on the cost a for performing maintenance. The reliability of the opportunistic model, however, varied with the cost a as shown in Figure 5.17. When the cost a is small the

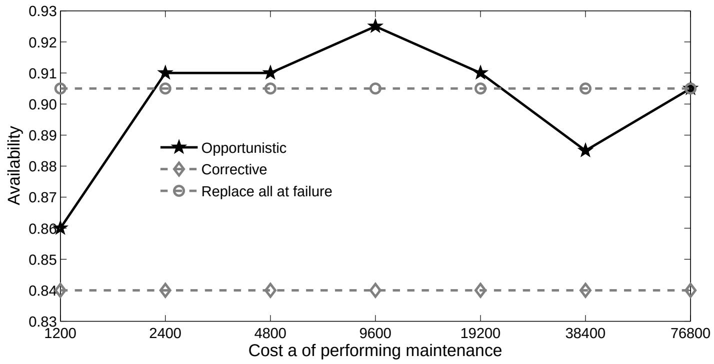

Figure 5.17: *The availability of the turbine for the different maintenance policies.*

opportunistic model will act more like the corrective model and shaft seal are only replaced when they break since the cost for each maintenance occasion is only a small share of the total cost of maintenance. In this case the most reliable maintenance policy is the opportunistic optimization model. When the cost a is large the availability of the turbine when using the opportunistic maintenance model will approach the reliability of the replace all model, since a large cost for performing maintenance makes it cheaper to minimize the number of maintenance occasions and thus replace both shaft seals of a pump at the same time. When the cost a is in the medium range, between 2400 and 19200 SEK, the opportunistic model is the maintenance policy with the highest availability of the turbine and hence the lowest total cost of maintenance when the cost for production loss is included. This can be due to that the opportunistic maintenance model can predict how many shaft seals will break during the next time step and thus replace shaft seals before they fail to avoid that two pumps are being shut down for maintenance at the same time. The corrective maintenance model did with its low availability prove to be the maintenance policy that resulted in the lowest reliability of the three models compared at all costs a of performing maintenance.

Chapter 6

Discussion

The availability of the production is very important in nuclear power plants, hence choosing a proper maintenance principle is important in order to achieve a high reliability. When comparing the different maintenance schedules it is clear that the opportunistic maintenance optimization model leads to a more reliable production as well as lower maintenance costs. The size of the problems solved depends very much on the number of parts that require maintenance. In this model, where only six components are considered, it is possible to reach an optimal solution for each problem. With a growing model size this might not longer be the case. The lenght of the time steps used in the models described here ($1000h$) makes it quite inaccurate since a replacement of a shaft seal most likely will take less time than this to complete. However, the size of the problem grows very fast with the number of time steps used and when choosing the length of the time steps this has to be taken into account. Other causes for production stops in the nuclear reactor that could give opportunities for maintenance on the feed-water pumps are not taken into account. The use of those opportunities can further decrease the risk of pumps breaking and causing production losses.

Chapter 7

Conclusion

In this thesis different philosophies of maintenance have been compared with respect to reliability of production and cost of maintenance. The calculations performed show that with the current price of performing maintenance the opportunistic maintenance optimization model is the most cost efficient decision principle since it results in a higher availability of the turbine compared to the other maintenance policies tested. The corrective maintenance model used today proved to be the least reliable in all cases while the "replace all" model is the best when the cost for each maintenance occasion is low. According to our experiments using the opportunistic model instead of the corrective model may deacrese the production losses due to failures of shaft seals in the feed-water pumps by 50%.

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