Stochastic optimization models for offshore wind farm maintenance

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Abstract

The world is fast moving away from fossil fuel, to a more renewable and sustainable energy future.The offshore wind industry is a major player in the drive for renewable energy. In order for sustainability to be achieved,the cost of operating and maintaining an offshore wind farm has to be minimized. The O&M cost of an offshore wind farm accounts for roughly 20% to 30% of the total lifetime cost of a wind farm.

In this thesis report,a stochastic model is formulated in integer programming for a single wind farm with twenty turbines, ten feasible routes and a set of periods.The model is developed to handle both small and large data sets from a wind farm.

Several case scenarios were considered in order to test the performance of the model. Simulation results proved that the model can solve smaller data sets in fewer minutes by arriving at an optimum solution, while it takes longer runtime in solving larger data sets,with feasible solutions.In addition,the result of the simulated cases at a runtime of 10mins, showed that the model can be used as a decision making tool for maintenance scheduling.The model is able to determine which turbine should be maintained in a set period,giving the right data set.

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Chapter 1

Introduction to Offshore Wind Energy

Due to the high demand in electricity by a growing population of the world, comes the need to harness other forms of energy. The need for greener energy sources has made wind energy the most sort-out form of renewable energy. Onshore wind energy has been the dominant source of wind energy up on till the early 90s, when the first offshore wind turbine was installed in Denmark. A total of 11 wind turbines were installed in the Vindeby offshore wind farm with installation capacities of 5MW [14]. From the early 90s till date, the number of offshore wind projects have risen tremendously with a lot of countries investing heavily in offshore wind energy. This growth is expected to further increase in the nearest future. The growth recorded can be attributed to a number of factors which is mainly centred around the need to reduce global emission. The European commission in 2009 passed a legislation, which plans to raise the energy consumption from renewable energy across member states by 20% in 2020 [3]. This of which explains the growth in installed offshore wind capacity across Europe.The figure [4] shows the global cumulative offshore wind capacity in 2016.

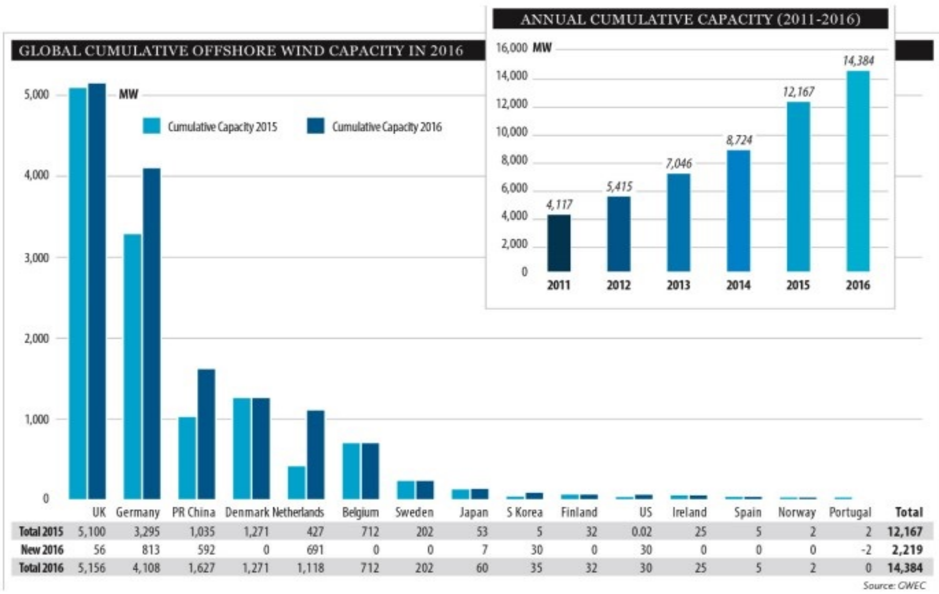

Figure 1.1: Global offshore wind capacity in 2016[4]

The majority of offshore wind farms in the UK are located in the north-sea due to depths below 50 meters and high wind speeds. There is a greater need to go further away from the shoreline into deeper waters. The further away the wind farm is from land, the more expensive and challenging it is to operate and carry out routing maintenance.

An offshore wind farm comprises of wind turbines ranging from 50 to as many as 200 at a particular location depending on the square area available. Today's offshore wind turbines generate more power than their onshore counterparts owing to the abundance of wind energy offshore. Unlike Onshore wind farms, the problem of noise pollution, Aesthetics, and restriction to land area are not applicable in offshore wind farms. When it comes to the maintenance and operation of offshore wind farms, a lot of planning and scheduling comes into play.Carrying out maintenance activities on an offshore wind farm is capital intensive and requires weather window period for this to occur. There are two major types of maintenance operations for all types of equipment and of which can be applicable to offshore wind farms , namely the preventive maintenance and the corrective(repairs) maintenance operations.The former is based on reducing the outcome of failure to the wind turbines and has both a planned routine schedule and a condition-based maintenance, while the later is carried out due to unforeseen failure to the system or a complete breakdown of the turbine.A combination of the two maintenance types has been shown in some literatures to be very cost effective. The operator of the offshore wind farm is faced with several challenges, one of which is the maintenance scheduling problem.The complexity of this problem is due to uncertainty of some variables like weather condition, wave height, spot rate, wind speeds, electricity market price, etc. Other challenges may arise from choosing the best vessel routes from the base station to the wind farm. Also the optimum number of vessels required to carry out the proposed maintenance activity. This would be our centre of discussion for the rest of the chapters.

Chapter 2

Background

The offshore wind farm operator is faced with the challenge of lowering operation and maintenance costs while trying to maximize production output. There is a trade-off between income and O&M cost. In this report, the following maintenance activities are considered: preventive maintenance and corrective maintenance. The preventive maintenance comprises of both planned preventive and condition-based preventive maintenance. Preventive maintenance is carried out in order to avert any form of failure to the wind turbines. These activities involve changing spare-parts (worn-out bolts, oil filters), visual inspections, etc. On the other hand, the corrective maintenance is carried out when a failure to the wind turbine has occurred. These activities usually involve heavy lift vessels for replacing turbine gearbox, damaged rotor head, etc. There are costs associated with these maintenance activities and they vary from each other.

2.1 Preventive Maintenance

The preventive maintenance activity , as the name implies, helps reduce the risk of failure of the turbine.This maintenance activity falls on the shoulders of the wind farm operator or owner. For a planned preventive maintenance activity, the wind farm operator prepares a schedule based on the age of degradation of the turbine material or expected production output.The schedule can be prepared on daily,monthly, or yearly basis.A wide range of maintenance activities are carried out which include: servicing, lubrication,hard time(HT),and failure finding(FF)[18]. Servicing of turbines are done based on the manufacturer's instruction and involves changing consumables such as oil,etc. As for lubrication,it is also carried out on periodic basis according to the manufacturer's instruction.Other activities like the "Hard

Time" and "Failure Finding" comprises of replacing spare parts and finding hidden failure using non-destructive technique. Preventive maintenance can sometimes be carried out during corrective maintenance activities or while the turbine is still in operation [18].

2.2 Corrective Maintenance

The corrective maintenance, which is otherwise known as failure maintenance, is an activity carried out when there is a high probability of turbine failure or total failure of the turbine.This maintenance activity is mostly unscheduled and thus,requires swift action by the maintenance team in getting the turbine back into operation.One major challenge is the weather condition. This can hinder or delay maintenance operations, thereby resulting in higher downtime cost for the wind farm operator. Another challenge is the availability of turbine spare-parts. This in turn can also delay the maintenance operation. The common parts of a turbine that usually requires corrective maintenance in the advent of failure can be categorized into three failure groups namely: pitch/hydraulic systems, other components and the generator [1].The figure 2.1,2.2 and 2.3 gives an overview of the various components that make up each failure group.

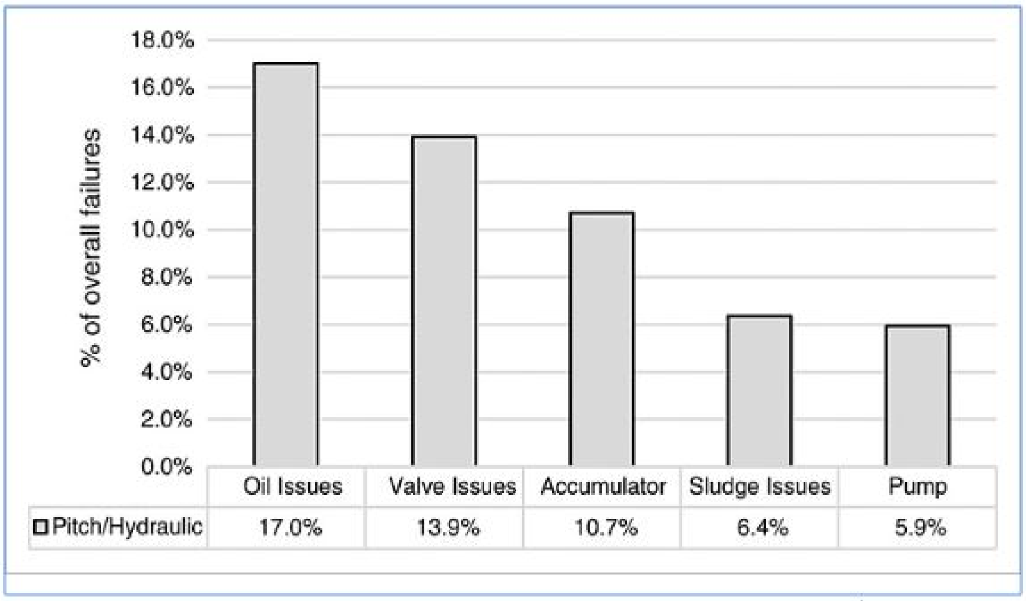

Figure 2.1: Pitch/hydraulic failure modes [1]

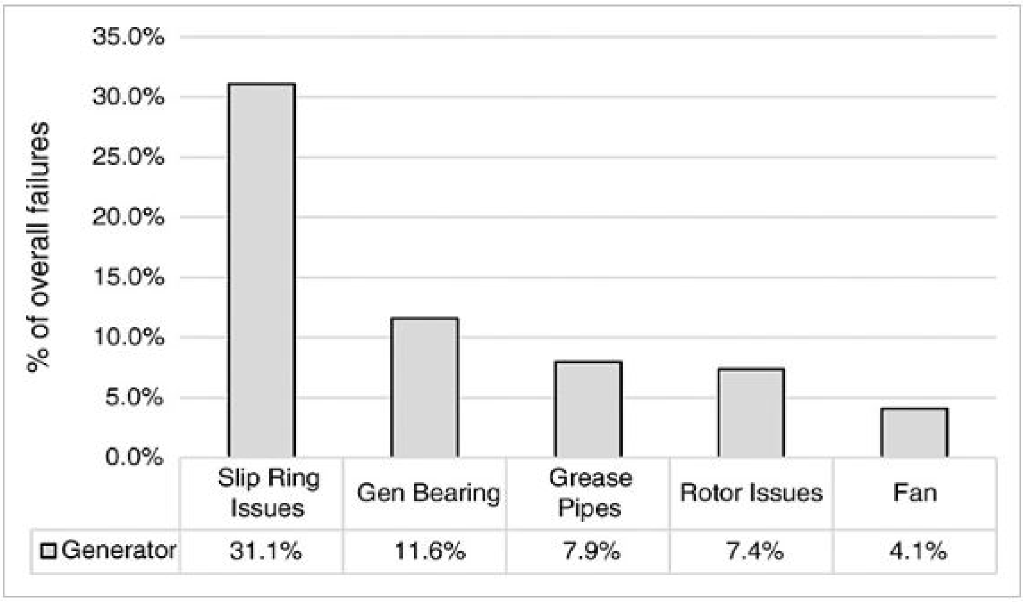

Figure 2.2: Generator failure modes [1]

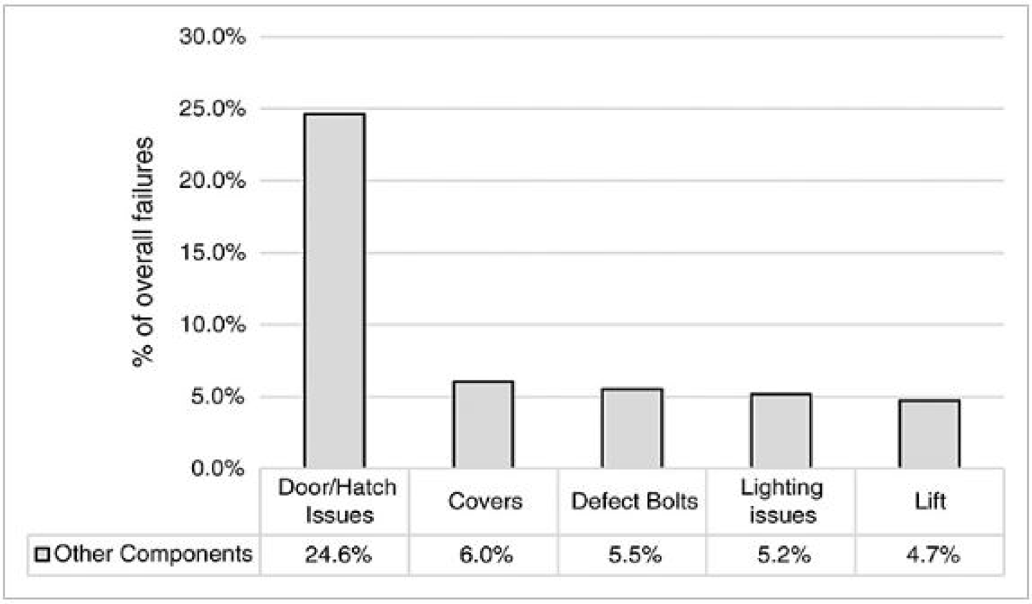

Figure 2.3: Other components failure modes. [1]

In each failure group, the percentage of failure components helps the wind farm operator in making better maintenance schedule in other to prevent failure. For the pitch/Hydraulic failure group, the major failure contributor is the oil issues.Thus, with better maintenance scheduling, failure due to oil issues can be averted. Other failure groups show similar trend as the latter group.

2.3 Maintenance cost for Offshore Wind Farm

For an offshore wind farm, the O&M cost accounts for 14% to 30% of the overall life circle cost[17].There is therefore the need to find a cost effective strategy in achieving a reduction in the O&M cost of an OWF. The maintenance cost comprises mainly of the downtime cost, personnel cost, equipment cost, vessel routing cost,preventive maintenance and failure cost.

2.3.1 Downtime cost

The downtime cost is the cost incurred when the turbine is out of service and revenue is lost.The cost differs for the two types of maintenance activity. Less revenue is lost during preventive maintenance activities, while there is a prolonged period of production outage (higher revenue loss)during corrective or failure maintenance activities. The electricity price and weather conditions play a major role in determining the downtime cost. Taking into account the vessel capacity, there is a trade-off between the downtime cost and vessel capacity[16].

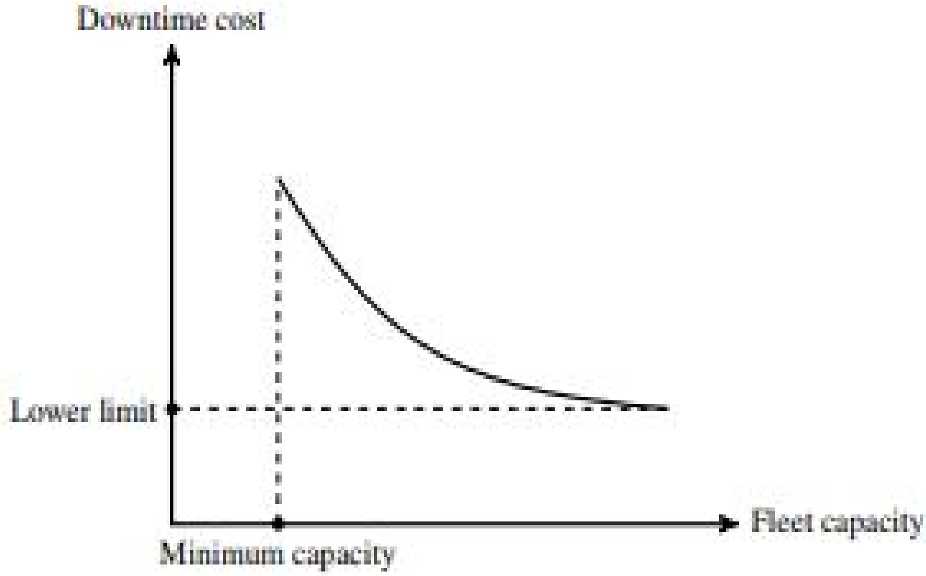

Figure 2.4: Downtime cost as a function of the vessel capacity[16].

As illustrated in figure 2.4, a large fleet capacity will reduces production losses caused by non-operational turbines, therefore also lowering the downtime cost.

2.3.2 Routing cost

The routing cost can be said to comprise mainly of the vessel travel cost and the personnel cost.It is very important that the decision maker finds the optimal route for maintaining a set of turbines, so as to lower the overall maintenance cost. Constraints such as vessel availability,weather condition,no of technicians and distance from maintenance base,are taken in to account when finding the optimal vessel route[8].

2.4 maintenance vessels

These are vessels used to execute maintenance activity.For offshore wind farm maintenance, the most commonly used vessels are floating vessels and helicopters. Unlike land based maintenance vessels, the cost of offshore vessels are high. The floating vessels consist of crew transfer vessels(CTV), crane floating vessels, house/accommodation vessels, etc. CTV's are relatively small vessels used for carrying out preventive maintenance activities like turbine inspections and small repairs. They usually accommodate a small crew and maintenance tools.CTV's are required to carry upto 30tons of load and can reach a top speed of 30 Knots.The figure 2.5, shows a typical CTV servicing an offshore wind turbine.The accommodation vessels as shown in figure 2.7, are used to house the personnels who carry out maintenance activities on the wind farm.These vessels can stay offshore for upto a month[13]. The figure 2.8 shows a personnel crew carrying out maintenance on a turbine using a helicopter. The use of helicopters help to reduce downtime cost and provides a quicker response in the advent of a failure occurrence.An average helicopter for OWF maintenance would accommodate a crew of 10 to 15 personnels[15].

Figure 2.5: crew transfer vessel[10].

Figure 2.6: Offshore crane vessel for heavy lift[19].

Figure 2.7: Accommodation vessel[13].

Figure 2.8: Helicopters [15].

Chapter 3

Literature Review

The operation and maintenance of an offshore wind farm can be quite challenging due to several uncertainties such as weather conditions, cost of electricity, challenges due to logistics, and scheduling period for maintenance,etc. Currently, the cost of operating an offshore wind farm is very high compared to that of an onshore wind farm. There is a need to minimise this cost in other to make offshore wind competitive to other renewable forms of energy. The solution to the challenges faced in the offshore wind lies in the need for effective optimization. There are several aspects of offshore wind that require optimization, but this report focuses mainly on the maintenance scheduling of offshore wind farms.

In carrying maintenance in an offshore wind farm, vessels comprising of helicopters and ships are used to transport both workers and equipment to and from the wind farm. The cost of purchasing or leasing these vessels are usually high. Scheduled maintenance is usually carried out by the wind farm operator. The maintenance of the offshore wind turbines can be classified into two methods namely: corrective maintenance and preventive maintenance. The corrective maintenance process is carried out when there is a failure or a breakdown in the wind turbine. On the other hand, the preventive maintenance, just as the name goes, tries to avert any occurrence of failure or breakdown to the turbine. The latter is done so as to keep the number of failures at a reasonable level, thus extending the life of the turbine[9]. In other to reduce the cost of operating and maintaining an offshore wind turbine, one has to carry out proper preventive maintenance scheduling so as to prevent the occurrence of a failure, since corrective maintenance is very expensive. For maintenance operation to be carried out on an offshore wind farm, the operator requires a weather window with minimum travel distance to and from the wind farm [9]. The shorter the distance required for the vessel to travel from the base station, the faster it will be to carry out the maintenance operation within the window period. It is also very necessary to keep the cost of vessels at minimum, if we are to lower the cost of energy from offshore wind farms. Therefore, the vessel fleet optimization problem is essential in the optimization of maintenance scheduling for offshore wind farms.

3.1 Optimisation of maintenance scheduling and routing for offshore wind farms using other models

A mathematical model for the optimisation of maintenance scheduling and routing of offshore wind farms was proposed by [11].The model made use of a decomposition solution method by considering more than one offshore wind farm. The main objective of the model is to find the optimal maintenance schedule and routing which aims to minimize the maintenance cost including other related costs like travel, technician and penalty costs selected in the optimal solution [11]. The maintenance model illustrated in figure 3.1 makes use of a Mixed Integer Linear Program(MILP) to find the optimal routing for a set of turbines and the Integer Linear Program(ILP) to select the best routing from all feasible routes.

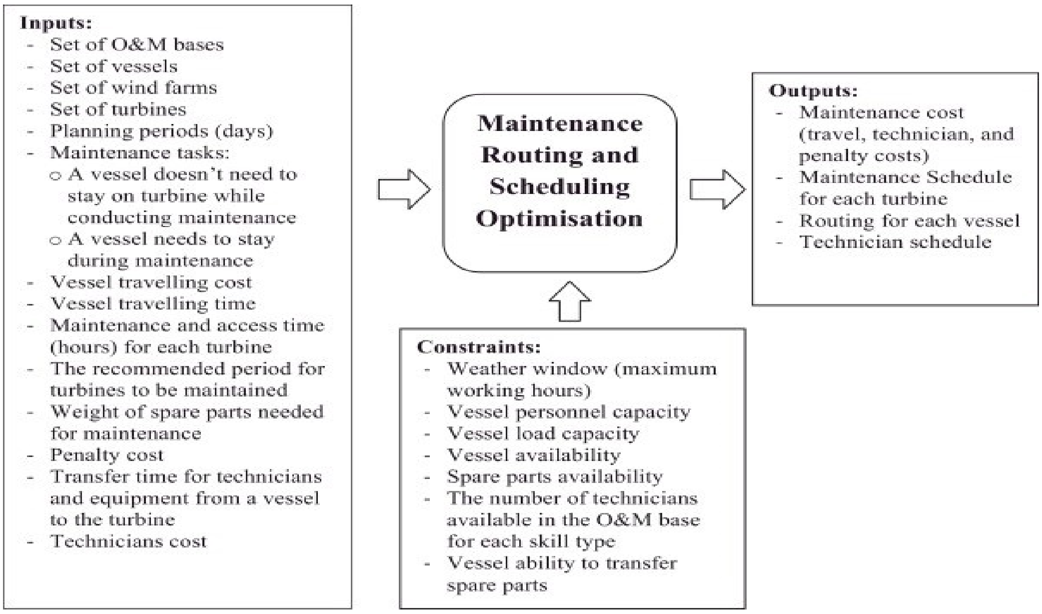

Figure 3.1: Model for maintenance routing and scheduling optimisation [11]

The maintenance routing and scheduling problem for an offshore wind farm was earlier discussed by [5].They proposed an RSPMFOWF problem which applies the concept of "maintenance grouping" ,i.e it combines both the corrective and preventive maintenance into a single maintenance operation.The maintenance operation which involves repairs, installation and inspection are carried out in one visit within the time limit [5].The number of wind turbines considered by the RSPMFOWF problem were less than 8 offshore wind turbines. Above of which the model finds it difficult in solving the problem that consists of finding a single route and scheduling for each vessel to carry out maintenance on a set of offshore wind turbines over a planing period [11].Penalty cost was also taken into account by the model, if the maintenance is done outside the recommended period. The arc flow model which was first introduced by [2] or ship routing and scheduling problem, has now been used by [20]for finding the optimal vessel routing in other to minimize maintenance cost.This model was then decomposed into a path-flow model using Dantzig-wolfe decomposition. A deterministic model was proposed by [9]for the vessel fleet composition problem with the aim of determining the minimum vessel fleet cost capable of maximising maintenance activities during the planning period.The model assumed some of the uncertain parameters like wave height and wind speed as known. Activity bundles were also introduced in this model, so as to include overlaps from either the preventive or corrective maintenance activities within the hard time window period. For the optimal vessel fleet and maintenance scheduling problem, a discrete optimization model was introduced by [8]. The model is partitioned into two problems(levels) namely: the tactical level for determining the optimal fleet and the operational level for scheduling maintenance operations needed at the offshore wind farm throughout the time horizon [8].From the above literatures, it was observed that the models did not take into consideration uncertainties such as weather conditions, electricity prices and the uncertainty as to how often the maintenance operation should be carried out, without increasing the cost of operating the wind farm. Due to the randomness of these uncertainty variables, a stochastic optimisation model would show better results in the optimisation of offshore wind farm maintenance.

3.2 Stochastic optimization models for OWF maintenance

Stochastic models are non-deterministic mathematical models with a set of random outcomes. The set of random possible outcomes are predicted by the model based on probability of occurrence. The stochastic model in offshore wind maintenance depicts a real life scenario unlike the deterministic model. Very few publications on the use of stochastic models for offshore wind maintenance are available for reference.One of such publication from [7] focuses on both maintenance scheduling and vessel routing problem by proposing a three-stage stochastic programming model. The problem was initially modelled as a static, deterministic, mixed-integer, routing problem and later transformed into a stochastic model by the inclusion of some uncertainty variables. The first and second stages of the stochastic model focused on the vessel fleet size and mix, while the third stage was based on the execution of maintenance activities at the wind farm.The objective was to minimize the cost of the vessel fleet size used in carrying out maintenance activities on an offshore wind farm. A meta-heuristics approach was used by [12] in solving the a stochastic fleet size and mix problem for offshore wind farm maintenance.

Chapter 4

Problem Description

Wind farm operators are usually faced with tough decision choices when it come to schedule maintenance of offshore wind farms. The choices of when a turbine should be maintained and how often maintenance activities should be carried out, taking into consideration factors such as: maintenance cost, failure or corrective maintenance cost, and the income generated from the wind farm,forms the basis of this report. There is a need to achieve an optimal maintenance schedule, whereby the expected net profit from the wind farm is maximized. There is a trade-off between the number of maintenance periods and turbine failure. Higher number of maintenance periods will result in lower probability of turbine failure.
A proposed model for maintenance scheduling is derived from a publication on the "optimisation of maintenance routing and scheduling for offshore wind farms" by [11].In this proposed model, it is assumed that the optimal routing for a set of turbines is known. The model takes into account the set of turbines, set of periods and set of feasible routes as inputs. In addition, the following parameter are considered:preventive maintenance cost, corrective maintenance or failure cost,routing cost,probability of available turbine,maximum turbine life without maintenance.The travel cost, personnel cost and penalty cost are all included in the routing cost. The probability parameter introduces a stochastic behaviour to the deterministic model. It poses the question on the availability of each turbine at the wind farm with regards to turbine generated revenue and failure cost.
The preventive maintenance cost and corrective maintenance cost parameters consist of both the actual cost of repair or replacement of equipments and the downtime cost incurred during the period of maintenance. When a preventive maintenance is carried out, we incur a downtime cost which is normally during the period of turbine shut-down. For corrective maintenance, the downtime cost is usually from the time of failure to the time the tur-

bine is back and running. We incur higher downtime cost during corrective maintenance activities than preventive maintenance activities.
Another parameter taken into consideration in the model is the maximum turbine life without maintenance.It is assumed that the turbine can operate without maintenance for a duration of 20 to 40 periods. This is equivalent to a time period of 5 to 10 years,i.e four planned periods per year.
The model takes into consideration a single offshore wind farm, with varying number of turbines.The periods are of equal length, and are implemented in the model using the rolling horizon planning method.This gives the wind farm operator the ability to make better decisions with regards to short term and long term maintenance decision.The decision includes the best route to maintain a set of turbines,what period is suitable to carry out maintenance on the turbine, and how often should the turbine be maintained within the life time of the wind farm for long term decisions.

Chapter 5

Mathematical Model

This chapter presents a stochastic mathematical model formulated in Integer programming for offshore wind farm maintenance at varying periods.In order to obtain the set of feasible routes for carrying out maintenance activities, An existing model developed by[11] is used.Assumptions made in the model are explained in section 5.1. Section 5.2 gives a detailed explanation of the set of indices, model parameters, and variables. Section 5.3 explains highlight and explains the model objective functions and constraints.

5.1 Assumptions

The model considers a single wind farm with a set of turbines. The distance of the wind farm from the shore is not considered.A set of feasible routes is assumed to have been derived from the model in [11].The routes are said to have distinct number of turbines, with no two routes covering the same set of turbines. As stated in chapter 4, the model provides the wind farm operator with a better maintenance schedule on how often to carry-out turbine maintenance within a given set of periods. The model covers both short term and long term planning periods.

There are four maintenance periods per year, with the maximum operational period of a turbine without maintenance set at 40 periods(10 years).The number of planned maintenance period per year can be way larger than four periods, depending on the decision maker. This comes at a price, as higher maintenance periods will result in higher maintenance cost.

The uncertainty variable considered in the model is that of turbine failure. It looks at the probability of the turbine remaining active at each given period. Other uncertainties such as electricity price, weather condition, were not directly implemented in the model. The electricity price is assumed to reflect the randomness of the generated income and maintenance cost model data. There were no penalty costs for not completing the maintenance activity at the a given period. It was assumed that all maintenance activities were carried out within the allocated period.

5.2 Model description

The sets and parameters are represented in in upper-case letters while the decision variables are in lower-case letters.

indices:

j	turbine
r	route
t	current period
k	last period

Sets:

J	set of turbines
R	set of feasible routes
S	set of periods , S:$\{1, ..., \|S\|\}$

Parameters:

T	Maximum period without maintenance
E_j	Income generated from turbine j
C_{rt}	Routing cost of feasible routes r in period t
M_{jt}	Preventive maintenance cost of turbine j in period t.
${M_{jt}}^c$	maintenance cost of turbine j in period t
P_{jtk}	Probability that turbine j is active to be maintained in period t,if it was last maintained in period k

Variables:

x_{jrt} = 1,turbine j is maintained in route r in period t, = 0, Otherwise

y_{jtk} = 1, if k is the last period before period t in which turbine j was maintained, = 0, Otherwise

z_{jt} = 1,if turbine j is maintained in period t, = 0, Otherwise

w_{rt} = 1,route r is in period t, = 0, Otherwise

ν_{jtk} = 1,if turbine j was last maintained in period k, and is maintained in period t, = 0, Otherwise

5.3 Model Formulation

The stochastic model is formulated and explained in this section.It includes the objective function and model constraints. A plain version of the model can be found in the appendix of this report.

5.3.1 Objective function

$$Max\, N = \sum_j \sum_t \sum_k P_{jtk} E_j y_{jtk} \tag{5.1}$$

$$- \sum_r \sum_t C_{rt} w_{rt} \tag{5.2}$$

$$- \sum_j \sum_t M_{jt} z_{jt} \tag{5.3}$$

$$- \sum_j \sum_t \sum_{k=1}^{t} (1 - P_{jtk}) \nu_{jtk} (M^c_{jt} - M_{jt}) \tag{5.4}$$

The objective function N maximizes the expected net profit from a wind farm with a set of turbines being maintained over a set of periods. The expected net profit is the difference between the total income generated from turbine j in a wind farm and the sum of the maintenance and routing costs at the period t.Equation 5.1 shows the total income generated at turbine j in periods t and k, multiplied by the probability of turbine activeness. The second part (5.2) gives the total routing cost of each route of turbines at period t. The third part (5.3) gives the preventive maintenance cost. The last part (5.4) gives the failure probability multiplied by the difference between the corrective maintenance cost and preventive maintenance cost.

5.3.2 Constraints

Maintenance periods
Constraint (5.5) ensures that the turbine j is maintained not more than once in period t.

$$\sum_{k=1}^{t} y_{jtk} \leq 1 \qquad j \in J, t \in S \tag{5.5}$$

The constraint (5.6) makes it possible for turbine j to be maintained in two consecutive periods.

$$y_{jtk} \leq z_{jk} \tag{5.6}$$

The constraint (5.7) tries to ensure that the difference between the previous period k in which j was maintained and the sum of subsequent previous periods do not exceed the last period k before t in which j was maintained.

$$y_{jtk} \geq z_{jk} - \sum_{l=k+1}^{t} z_{jl} \tag{5.7}$$

The decision maker will find this constraint very useful, as it makes sure that sum of turbine j to be maintained in period t with respect to all the routes r in R have to be equal to the same number of turbine j to be maintained in period t. Constraint (5.8) is an equality constraint.

$$\sum_{r \in R_j} x_{jrt} = z_{jt} \tag{5.8}$$

The constraint (5.9) ensures that the route used in maintaining turbine j in period t is either less than or equal to the available routes in period t. It makes sure that no two routes can service the same turbine in a particular period t.

$$x_{jrt} \leq w_{rt} \tag{5.9}$$

The turbine j can be maintained in two or more consecutive periods. The constraint (5.10) makes sure that this is possible.

$$\nu_{jtk} \leq y_{jtk} \tag{5.10}$$

Constraint(5.11) creates an upper-bound in period t for turbine j being maintained.

$$\nu_{jtk} \leq z_{jt} \tag{5.11}$$

The constraint(5.12)creates an lower-bound in period t for turbine j being maintained

$$\nu_{jtk} \geq y_{jtk} + z_{jt} - 1 \tag{5.12}$$

Binary constraints

Constraints (5.13) to (5.17) creates a non-negative and binary constraints on the decision variables.

$$x_{jrt} = \{0, 1\} \tag{5.13}$$

$$y_{jtk} = \{0, 1\} \tag{5.14}$$

$$z_{jt} = \{0, 1\} \tag{5.15}$$

$$w_{rt} = \{0, 1\} \tag{5.16}$$

$$\nu_{jtk} = \{0, 1\} \tag{5.17}$$

Chapter 6

Model Simulation

This chapter focuses on the implementation of the stochastic model discussed in section 5.3. It is implemented using an optimization solver in AMPL called CPLEX. The goal is to check the robustness of the model to both small and large data, to see how quickly it generates a solution(solution time),usefulness of the model in maintenance scheduling,and investigate the optimality gap after a solution has been reached. The computer which will be used in carrying out the simulation in AMPL is a Toshiba satellite C55-A,intel core i3-3120M,CPU @ 2.50GHz, and 6GB RAM in windows 10.The cost data used in the experimental section was generated randomly to depict a real life scenario.

6.1 AMPL solver

AMPL is a programming language used in developing and applying mathematical programming models on a computer.It is generally used for small and large scale optimization problems.In addition to solving optimization problems, it also offers an interactive command environment for carrying out such actions. This makes it easy to access and use different solvers for different mathematical programming problems.
There are several solvers available in AMPL depending on the problem to be solved. The CPLEX solver is a widely used and a well known solver, especially for large-scale problems.It is preferred when solving integer problems. The AMPL program with a CPLEX solver makes use of the following sequence for solving mathematical programming problems[6].

- Model formulation which includes objective function, constraints and variables,in its standard form.

- Data collection for specific problem and create a data file.
- create a model file and generate the objective function and constraints from the model and data.
- Solve the problem by including the CPLEX solver in the run file and running the program.
- Analyse the results.
- Refine the model and data.
- Repeat procedure.

6.2 Experimental cases

Using the rolling horizon method,four data sets over the first 10, 20, 30, and 40 periods were considered.The wind farm was assumed to have 20 turbines and 10 feasible routes. The parameter cost data used in the simulation of the model was randomly generated to fit a real life cost scenario.The cost is in Euro per KWperiod.
The income data for each turbine was randomly generated within the range of 9 Euro to 15 Euro. The randomness in the income implies that there are shortages in power generation in some turbines, than others. This can be due to factors such as wake effect in wind farms, weather conditions.This parameter data is kept fixed in the four experimental data sets used.
The routing cost data and those of preventive and corrective cost data were also randomly generated with respect to the periods. The routing cost ranges from as low as 7 Euro to as high as 17 Euro per Kw period. The randomness introduced in the cost data represents the electricity price at the different periods. The preventive cost data has a range from 0.5 Euro to 2.00 Euro.On the other hand, the corrective cost data is made to be atleast twice that of the preventive cost. The cost range is from 2 Euro to 4 Euro.The assumptions made is based on a real life scenario. The cost of corrective maintenance would be greater than that of preventive maintenance.
The probability parameter is implemented in the AMPL model, using the following equation.

$$P(t) = \exp(\frac{t-k}{t-k-T} \qquad t \in [1,T], P(t) \in (0,1) \tag{6.1}$$

Where t is the actual period, k is the previous period and T is the maximum period a turbine can operate without maintenance.The probability decreases along the periods if the turbine is yet to be maintained.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(P(t)\right) < 0 \tag{6.2}$$

$$\lim_{t \to T} P(t) = 0 \tag{6.3}$$

In order to test the performance of the model to both small and big data cases, four different data cases were simulated.The table 6.1 shows the different cases with sets of turbines,routes and periods. The data sets for these cases can be found in the Appendix (II - V) of this report.

Table 6.1: Simulation cases

Cases	Turbines	Routes	Periods
case 1	20	10	10
case 2	20	10	20
case 3	20	10	30
case 4	20	10	40

The following questions will need to be answered in the next chapter.

- How useful is the model to the windfarm operator.
- How long will it take to arrive at an optimum solution, if any exists.
- What is the typical outcome

Chapter 7

Results and Analysis

As discussed in the previous chapter 6 of this report,we will like to test the performance of the model with respect to the simulation runtime.Four cases were simulated with respect to four different runtime in AMPl using the CPLEX solver.

7.1 Objective function result

The objective functions derived from simulating each experimental case at the different simulation runtime is shown in Table 7.1. As shown in the table, Case 1 has an optimal solution within one minute of runtime.As the data set increases for other cases, the longer the convergence time to reach an optimal solution. The objective function is seen to be increasing gradually over the runtime period for cases 2 to 4. At the end of each runtime, a feasible solution is outputted, if there exists no optimal solution yet. A better way of displaying the solutions over the runtime is shown in Figure 7.1. As shown, an optimal solution is reached when there are no more changes in the objective function along the runtime.

Table 7.1: Objective function after 1min,10mins,30mins and 60mins

	Objective Function			
Cases	1mins	10mins	30mins	60mins
case 1	2198.39	2198.39	2198.39	2198.39
case 2	4404.06	4411.17	4412.01	4414.815
case 3	6484.699	6608.48	6613.245	6623.438
case 4	7780.396	8797.97	8825.038	8825.038

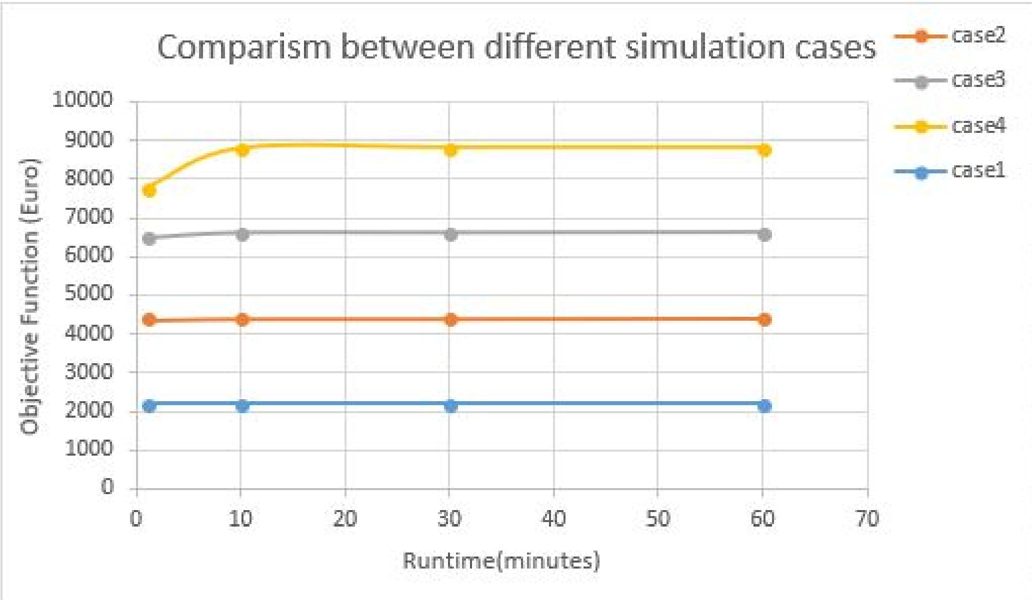

Figure 7.1: Objective function with respect to simulation runtime

7.2 Relative mixed integer optimum gap result

The Relmipgap is very important as it lets us know how close our feasible solution is to the optimum solution. Its unit is in percentage. The Table

7.2 shows the different relative optimality gaps for all four cases over several runtime. The Relmipgap is seen to be decreasing over an increasing runtime. When an optimal solution is attained, there is no longer a change in the Relmipgap, as seen in case 1.Therefore, the smaller the Relmipgap,the closer we are to the optimum solution.This is shown in the Figure 7.2.

Table 7.2: Relative optimal gap at 1min,10mins,30mins and 60mins

	Relative optimal gap(%).			
Cases	1mins	10mins	30mins	60mins
case 1	0.0099	0.0099	0.0099	0.0099
case 2	0.573	0.25	0.19	0.095
case 3	2.50	0.53	0.44	0.27
case 4	14.07	0.79	0.46	0.455

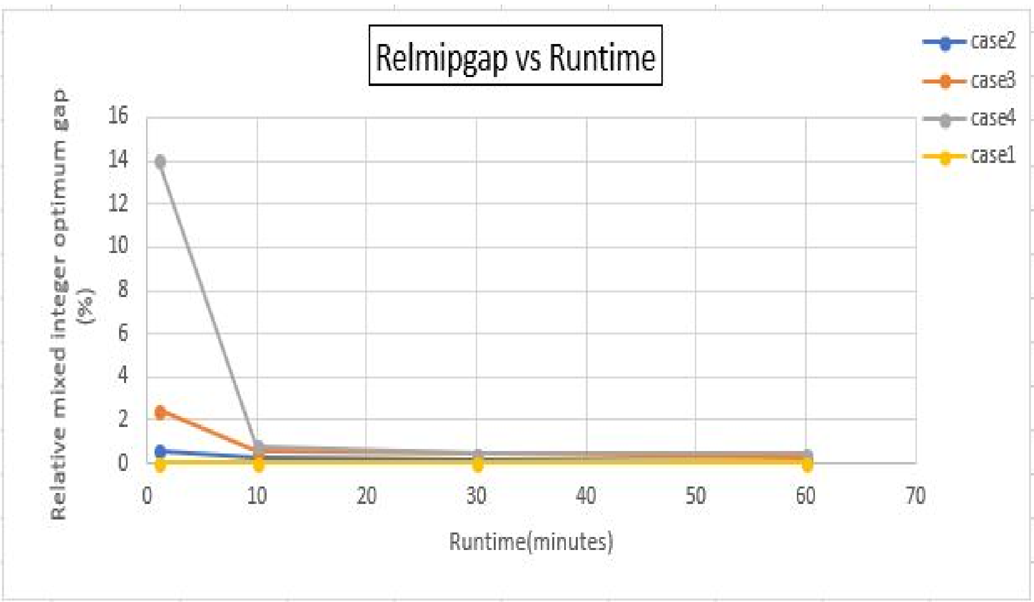

Figure 7.2: Relative mixed integer optimum gap with respect to simulation runtime

7.3 Branch and bound nodes

The Table 7.3 gives the result of the branch and bound nodes at the end of each runtime. In general, the branch and bound is a Breath First Search(BFS) for optimal solutions. Since this is a maximization problem, the B&B compares each feasible solution at the nodes until an optimum solution is found. From the Table 7.3, the B&B nodes are increasing with increasing runtime. Except in case 1, where an optimum solution has already been achieved.

Table 7.3: Branch and bound nodes at 1min,10mins,30mins and 60mins

	Branch and bound nodes			
Cases	1mins	10mins	30mins	60mins
case 1	307	307	307	307
case 2	10	3811	12129	28746
case 3	0	1204	2680	8090
case 4	0	143	1128	1620

7.4 Maintenance decision results after 10mins runtime

This section shows the simulation result of the four different cases at a runtime of 10mins.The model,for each data sets,determines which turbine need to be maintained, and in what period it needs to be carried out.It tries to answer the question posed by the decision maker, as to how often should the turbine be maintained within a set period.

7.4.1 Case 1

The result of the decision variable z is shown in the Table 7.4. The decision variable is binary(0,1),where = 1, if the turbine is maintained in period t, = 0, otherwise. This helps the wind farm operator to know which turbine requires maintenance and in what period is it needed.

Table 7.4: Maintenance scheduling for 10 periods

z [*,*]

:	1	2	3	4	5	6	7	8	9	10	:=
tub1	1	0	0	1	0	1	0	1	0	0	
tub10	1	0	0	1	0	0	0	1	0	0	
tub11	1	0	0	0	0	1	0	0	0	0	
tub12	1	0	0	0	0	1	0	0	0	0	
tub13	1	0	0	0	1	0	0	0	0	0	
tub14	1	0	0	0	1	0	0	0	0	0	
tub15	1	0	0	0	1	0	0	1	0	0	
tub16	1	0	0	0	0	1	0	0	0	0	
tub17	1	0	0	1	0	0	0	1	0	0	
tub18	1	0	0	1	0	0	0	1	0	0	
tub19	1	0	0	1	0	0	0	1	0	0	
tub2	1	0	0	1	0	1	0	0	0	0	
tub20	1	0	0	1	0	1	0	1	0	0	
tub3	1	0	0	0	0	1	0	0	0	0	
tub4	1	0	0	1	0	0	0	1	0	0	
tub5	1	0	0	0	1	1	0	0	0	0	
tub6	1	0	0	1	1	0	0	1	0	0	
tub7	1	0	0	1	0	0	0	1	0	0	
tub8	1	0	0	0	1	0	0	0	0	0	
tub9	1	0	0	0	0	1	0	0	0	0	;

7.4.2 Case 2

The result of the maintenance schedule for a set of 20 periods is shown in Table 7.5. The decision variable z gives the wind farm operator the necessary information on which turbine to maintain and at what period.At the first period, the model maintains all the turbines. In subsequent periods, maintenance is carried out randomly by the model based on information from the data set.

Table 7.5: Maintenance scheduling for 20 periods

```
z [*,*]
:       1   2   3   4   5   6   7   8   9  10    :=
tub1    1   0   0   1   0   0   1   0   0   1
tub10   1   0   0   1   0   0   1   0   0   1
tub11   1   0   0   0   0   1   0   0   0   0
tub12   1   0   0   0   0   1   0   0   0   0
tub13   1   0   0   0   0   0   1   0   0   0
tub14   1   0   0   0   0   0   1   0   0   0
tub15   1   0   0   1   0   0   1   0   0   1
tub16   1   0   0   0   0   1   0   0   0   0
tub17   1   0   0   1   0   0   0   1   0   0
tub18   1   0   0   1   0   0   0   1   0   0
tub19   1   0   0   1   0   0   0   1   0   0
tub2    1   0   0   1   0   0   1   0   0   1
tub20   1   0   0   1   0   1   0   1   0   0
tub3    1   0   0   0   0   1   0   0   0   1
tub4    1   0   0   1   0   0   0   1   0   0
tub5    1   0   0   0   0   1   1   0   0   1
tub6    1   0   0   1   0   0   0   1   0   0
tub7    1   0   0   1   0   0   0   1   0   0
tub8    1   0   0   0   0   1   0   0   0   0
tub9    1   0   0   0   0   1   1   0   0   1

:      11  12  13  14  15  16  17  18  19  20     :=
tub1    0   0   1   0   0   0   1   0   0   0
tub10   1   0   0   1   0   1   0   1   0   0
tub11   0   0   1   0   0   0   1   0   0   0
tub12   1   0   0   1   0   0   1   0   0   0
tub13   1   0   0   1   0   0   0   1   0   0
tub14   1   0   0   1   0   1   0   1   0   0
tub15   0   0   0   0   0   1   0   1   0   0
tub16   1   0   0   1   0   0   1   0   0   0
tub17   0   0   1   0   0   1   1   0   0   0
tub18   1   0   0   1   0   0   0   1   0   0
tub19   1   0   0   1   0   1   0   0   0   0
tub2    0   0   1   0   0   0   1   0   0   0
tub20   0   0   1   0   0   0   1   0   0   0
tub3    0   0   1   0   0   0   1   0   0   0
tub4    1   0   0   1   0   1   0   0   0   0
tub5    0   0   1   0   0   0   1   0   0   0
tub6    1   0   0   1   0   0   1   0   0   0
tub7    1   0   0   1   0   1   0   0   0   0
tub8    1   0   1   0   0   1   0   1   0   0
tub9    0   0   1   0   0   0   0   1   0   0
;
```

7.4.3 Case 3

The result below shows the maintenance scheduling of twenty turbines over a set of 30 periods.As the data set grows, we see how the model selects, which turbine to maintain and at what period of time.Just as discussed in previous subsections, the information contained in the table will help the wind farm operator in making better maintenance decisions, thereby maximizing expected net profit from the wind farm.

```
Maintenance scheduling for 30 periods

z [*,*] (tr)
# $2 = tub10
# $3 = tub11
# $4 = tub12
# $5 = tub13
# $6 = tub14
# $7 = tub15
# $8 = tub16
# $9 = tub17
# $10 = tub18
# $11 = tub19
# $12 = tub2
# $13 = tub20
# $14 = tub3
# $15 = tub4
# $16 = tub5
# $17 = tub6
# $18 = tub7
# $19 = tub8

:   tub1  $2  $3  $4  $5  $6  $7  $8  $9 :=
1     1    1   1   1   1   1   1   1   1
2     0    0   0   0   0   0   0   0   0
3     0    0   0   0   0   0   0   0   0
4     1    1   0   0   0   0   0   0   1
5     0    0   0   0   1   1   1   0   0
6     1    0   1   1   0   0   0   1   0
7     0    1   0   0   0   0   1   0   1
8     0    0   0   0   0   0   0   0   0
9     1    0   0   1   0   1   1   1   0
10    0    1   1   0   0   0   0   0   1
```

11	0	0	0	0	0	0	0	0	0
12	0	1	0	0	1	1	1	0	0
13	1	0	1	0	0	0	0	1	1
14	0	0	0	1	1	0	0	1	0
15	0	1	0	0	0	1	1	0	0
16	0	0	0	0	0	0	0	0	0
17	1	1	1	1	1	1	0	1	1
18	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0
20	0	0	1	0	0	0	1	1	1
21	1	1	0	1	0	1	0	1	0
22	0	0	0	0	0	0	0	0	0
23	1	0	0	0	1	1	1	0	0
24	0	1	1	0	0	0	0	1	1
25	1	0	0	1	1	0	1	0	0
26	0	0	0	0	0	0	0	0	0
27	0	1	0	0	0	1	1	0	0
28	1	0	1	1	0	0	0	1	1
29	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0

:	$10	$11	$12	$13	$14	$15	$16	$17	$18	$19	tub9:=
1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0
4	1	1	1	1	0	1	0	1	1	0	0
5	0	0	0	0	0	0	1	0	0	1	1
6	0	0	1	1	1	0	0	1	0	0	0
7	0	1	0	0	0	1	0	0	1	0	0
8	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	1	0	0	1	0	0	1	1
10	0	1	1	0	0	1	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0	0
12	1	0	0	0	1	0	1	1	0	1	0
13	0	0	1	1	0	0	0	0	0	0	1
14	0	1	0	0	0	1	0	0	1	1	0
15	1	0	0	0	1	0	1	1	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0
17	1	1	1	1	1	1	1	1	1	1	1
18	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0

```
20   0   0   1   0   1   0   1   1   0   0   0
21   1   1   0   1   0   1   0   0   1   1   0
22   0   0   0   0   0   0   0   0   0   0   0
23   1   0   1   0   1   0   1   1   0   0   1
24   0   0   0   0   0   0   0   0   0   1   0
25   0   1   0   0   0   0   0   1   1   0   1
26   0   0   0   0   0   0   0   0   0   0   0
27   1   1   1   0   1   1   0   1   0   0   0
28   0   0   0   1   0   0   1   0   0   1   1
29   0   0   0   0   0   0   0   0   0   0   0
30   0   0   0   0   0   0   0   0   0   0   0 ;
```

7.4.4 Case 4

The maintenance scheduling result shown below, gives the wind farm operator useful information as to how the model handles large data sets.

```
Maintenance scheduling for 40 periods

z [*,*] (tr)
# $2 = tub10
# $3 = tub11
# $4 = tub12
# $5 = tub13
# $6 = tub14
# $7 = tub15
# $8 = tub16
# $9 = tub17
# $10 = tub18
# $11 = tub19
# $12 = tub2
# $13 = tub20
# $14 = tub3
# $15 = tub4
# $16 = tub5
# $17 = tub6
# $18 = tub7
# $19 = tub8

:  tub1  $2  $3  $4  $5  $6  $7  $8  $9 :=
1    1    1   1   1   1   1   1   1   1
```

2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	1	0	0	0	0	1	0	1
5	0	0	0	0	0	0	0	0	0
6	1	0	1	1	0	0	0	1	1
7	1	1	0	0	1	1	1	1	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	1	1	1	1	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
13	1	1	1	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0
15	0	0	0	1	1	0	0	1	0
16	0	1	0	0	0	1	1	0	1
17	1	0	1	1	0	0	0	1	0
18	0	0	0	0	0	0	0	0	0
19	1	1	0	0	1	1	1	0	0
20	1	0	0	0	0	0	0	0	1
21	0	0	1	1	0	0	0	1	0
22	0	0	0	0	0	0	0	0	0
23	1	1	0	0	1	1	1	0	0
24	0	0	1	0	0	0	0	1	1
25	1	0	0	1	1	0	1	0	0
26	0	0	0	0	0	0	0	0	0
27	0	1	0	0	0	1	1	0	0
28	1	0	1	1	0	0	0	1	1
29	0	0	0	0	0	0	0	0	0
30	0	1	0	0	1	1	0	1	0
31	1	0	1	1	0	0	0	0	1
32	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0
34	1	0	0	1	0	1	1	1	0
35	0	1	1	0	1	0	0	0	1
36	0	0	0	0	0	0	0	0	0
37	1	0	1	1	0	0	0	1	1
38	0	1	0	0	1	1	1	0	0
39	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0

```
:  $10 $11 $12 $13 $14 $15 $16 $17 $18 $19  tub9:=
```

1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0
4	1	1	1	1	0	1	0	1	1	0	0
5	0	0	0	0	0	0	0	0	0	0	0
6	0	0	1	1	1	0	1	0	0	1	1
7	1	1	0	0	0	1	0	1	1	0	1
8	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
10	1	1	1	1	1	1	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0
13	1	1	1	1	1	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0
15	1	0	0	0	0	1	0	1	0	0	0
16	0	1	0	0	0	1	0	0	1	1	0
17	0	0	1	1	1	0	1	1	0	0	1
18	0	0	0	0	0	0	0	0	0	0	0
19	1	0	0	0	0	0	1	0	0	1	1
20	0	1	0	1	0	1	0	1	1	0	0
21	0	0	1	1	1	0	0	0	0	1	1
22	0	0	0	0	0	0	0	0	0	0	0
23	1	0	0	0	0	0	1	1	0	0	0
24	0	0	1	0	1	0	0	0	0	1	0
25	0	1	0	0	0	0	0	1	1	0	1
26	0	0	0	0	0	0	0	0	0	0	0
27	1	1	1	0	1	1	0	1	0	0	0
28	0	0	0	1	0	0	1	0	0	1	1
29	0	0	0	0	0	0	0	0	0	0	0
30	1	1	0	0	0	1	0	0	1	0	0
31	0	0	1	1	1	0	1	1	0	1	1
32	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0
34	1	0	0	1	0	0	0	0	1	0	1
35	0	1	1	0	1	1	1	1	1	1	0
36	0	0	0	0	0	0	0	0	0	0	0
37	0	0	1	1	1	0	0	0	0	0	1
38	1	0	0	0	0	0	1	1	0	1	0
39	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0 ;

Chapter 8

Concluding Remarks and Recommendation

The offshore wind farm industry is fast growing and very expensive in terms of O&M costs.There is a need for proper maintenance scheduling, so as to lower the cost of maintenance while maximizing expected net profit from the wind farm.
Having taken into consideration the useful parameters for offshore wind farm maintenance,we developed a working stochastic model that lets the wind farm operator know when best to carry out turbine maintenance.
The simulation results show that the model can handle both small and large data sets efficiently. The runtime for small data sets are usually in fewer minutes and guarantee an optimum solution.Unlike for larger data sets,where the model takes longer time in reaching an optimal solution, but still gives feasible solutions in shorter runtime.In addition, the Relmipgap proofs to be a useful tool is determining the deviation of our feasible solution from the optimum solution. The table results from all four cases show the robustness of the model as it determines which turbine requires maintenance over a set of period.
The model formulated in this report only considered one uncertainty parameter.We tried to make the model as simple as possible but yet robust. For further work, i recommend taking into account more uncertainties like weather condition,electricity price,etc.

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APPENDIX I: Model file

```
set turbine;
set route;
param no_period;
set period:={1..no_period};
param turbine_route{turbine, route}binary;
param income{turbine}>0;
param routing_cost{route,period}>=0;
param preventive_cost{turbine,period}>=0;
param corrective_cost{turbine,period}>=0;
param T{turbine}default(40); #max lifetime of turbine
param P{j in turbine,t in period,k in 1..t}>=0,<= 1,
= exp((t-k)/(t-k-T[j]));
var x{j in turbine,r in route,t in period}binary;
var y{j in turbine, t in period,k in 1..t}binary;
var z{j in turbine, t in period}binary;
var w{r in route,t in period}binary;
var v{j in turbine, t in period,k in 1..t}binary;

#objective function
maximize expected_net_profit:
sum{j in turbine,t in period,k in 1..t} P[j,t,k]*income[j]*y[j,t,k] -
sum{r in route,t in period} routing_cost[r,t]*w[r,t] -
sum{j in turbine,t in period}preventive_cost[j,t]*z[j,t] -
sum{j in turbine,t in period,k in 1..t}((1-P[j,t,k])*v[j,t,k]*
(corrective_cost[j,t]-preventive_cost[j,t]));

#constraints
subject to previous_period{j in turbine,t in  period}:
sum{k in 1..t}y[j,t,k]<=1 ;

subject to maintenance_routing{j in turbine,t in period}:
```

```
sum{r in route}x[j,r,t]*turbine_route[j,r] = z[j,t];

subject to turbine_prev_period{t in period, k in 1..t, j in turbine}:
y[j,t,k]<= z[j,k];

subject to turbine_maintenace_period{t in period, j in turbine,k in 1..t}:
 y[j,t,k] >= z[j,k] - sum{l in period: l>k}z[j,l];

subject to routing{j in turbine,r in route, t in period}:
x[j,r,t] <=turbine_route[j,r]*w[r,t];

subject to  successive_period{j in turbine,t in period, k in 1..t}:
v[j,t,k] <= y[j,t,k];

subject to  present_period{t in period,k in 1..t, j in turbine}:
 v[j,t,k] <= z[j,t];

subject to maintenace_period{j in turbine, t in period, k in 1..t}:
v[j,t,k] >= y[j,t,k] + z[j,t] - 1;
```

APPENDIX II: Data set 1

```
set route:= R1 R2 R3 R4 R5 R6 R7 R8 R9 R10;
set turbine :=tub1 tub2 tub3 tub4 tub5 tub6 tub7 tub8 tub9 tub10 tub11
tub12 tub13 tub14 tub15 tub16 tub17 tub18 tub19 tub20;
param no_period default 10;

param income                                :=

tub1         12.6     tub11      11.00
tub2         11.16    tub12      11.90
tub3         10.53    tub13      9.45
tub4         9.04     tub14      10.67
tub5         14.37    tub15      14.00
tub6         12.86    tub16      15.00
tub7         11.80    tub17      12.98
tub8         10.34    tub18      13.45
tub9         9.0      tub19      13.89
tub10        13.54    tub20      14.55       ;

param turbine_route :    R1      R2      R3    R4   R5    R6    R7    R8   R9   R10   :=

tub1                     1        0       1     1    0     1     1     0    1    0
tub2                     0        1       0     1    0     1     1     1    1    0
tub3                     1        1       0     0    1     1     1     0    1    0
tub4                     0        0       0     1    0     1     0     1    0    1
tub5                     0        1       1     0    1     0     1     0    1    0
tub6                     1        1       0     1    1     1     1     0    1    1
tub7                     1        0       1     1    1     0     0     1    0    1
tub8                     0        1       1     0    1     1     1     1    1    1
tub9                     1        0       1     0    0     0     1     0    1    0
tub10                    0        1       0     1    1     1     1     1    0    1
tub11                    0        1       0     0    1     0     0     1    1    0
```

```
tub12                  1        0      1    0    1    0    0    0    1    1
tub13                  1        0      0    0    0    0    1    0    0    1
tub14                  0        0      1    0    1    1    1    1    0    1
tub15                  1        1      1    1    0    1    1    1    0    0
tub16                  0        1      1    0    0    0    0    0    1    1
tub17                  0        1      0    1    0    0    0    1    1    0
tub18                  0        0      1    1    0    1    1    0    0    1
tub19                  1        0      0    1    1    1    0    1    0    1
tub20                  0        0      1    1    1    0    0    0    1    0   ;

param  :  1   2       3       4      5      6      7     8       9      10   :
routing
_cost

R1      15.62 10.23   16.87   11.99  7.99    8.11   7.98  12.98   7.39   12.24
R2      13.38 11.76   15.11   7.00   12.77   8.23  11.12  11.98   12.46  15.99
R3       2.33 12.77   12.23   12.22  16.33   9.76  12.46  11.12   8.39   12.34
R4      7.15  10.23   14.23   11.14  12.67 12.98  14.47  8.08    12.34  11.34
R5      11.23 15.66   8.15    10.23  14.87 11.87  7.92   12.23   11.34   9.02
R6      14.34  7.14   10.11   14.67  15.63 14.87  8.35   14.48   14.34   8.34
R7      10.23  9.14   7.10    13.66   7.98 12.66  9.33   11.23    9.35   7.11
R8      12.21  13.38   8.98   10.45   8.11  7.08  7.34   17.00   15.44   7.12
R9      11.76 10.34   15.88   15.98  13.77  7.45  12.83  12.23   13.45   9.13
R10     12.77 13.00   11.11   14.78  12.45 11.45  10.23   9.23   17.00  10.55


param  :     1      2    3      4     5     6     7      8     9      10   :=
preventive
_cost
 tub1       1.61   1.36  2.00   1.93  2.00  1.21  0.65   1.11  0.98   1.45
 tub2       1.26   1.22  1.84   0.55  0.81  0.95  1.10   2.00  1.11   1.84
 tub3       0.94   0.87  1.48   0.87  1.45  1.12  1.45   1.46  2.00   0.57
 tub4       0.79   0.65  1.36   0.98  0.67  0.88  1.24   1.13  1.76   1.57
 tub5       1.65   0.50  0.87   1.98  1.34  1.87  1.01   2.00  1.23   1.91
 tub6       2.00   1.87  1.11   0.98  0.76  1.98  1.23   1.01  1.90   1.56
 tub7       1.20   0.58  1.90   0.99  0.87  0.76  1.57   1.98  1.09   1.34
 tub8       0.78   0.67  1.98   2.00  1.12  1.87  1.65   1.27  1.09   1.67
 tub9       0.67   1.89  1.78   0.76  0.98  0.99  0.66   0.76  1.78   1.76
 tub10      2.00   1.23  1.87   1.98  2.00  2.00  1.67   1.65  0.76   0.77
 tub11      1.83   2.00  1.11   1.45  1.11  1.10  1.56   0.57  1.37   1.18
 tub12      1.23   1.22  1.24   1.57  1.78  0.68  1.73   1.93  2.00   1.34
```

```
tub13     0.98   1.34  1.55   1.56  1.56  1.67  1.09   1.12  1.11   1.87
tub14     1.33   1.35  1.45   1.20  1.98  1.90  1.56   1.73  1.34   1.11
tub15     1.98   1.87  1.71   1.99  1.34  2.00  1.28   1.02  1.23   2.00
tub16     2.00   1.47  0.87   2.00  1.23  1.12  0.77   1.48  1.88   1.97
tub17     0.55   1.23  0.57   0.68  1.25  1.45  0.57   1.66  1.33   1.33
tub18     0.65   0.76  2.00   0.78  1.99  1.84  1.93   1.22  1.46   1.45
tub19     0.76   0.65  1.29   0.99  0.78  1.65  1.32   0.88  2.00   1.34
tub20     0.99   0.98  1.09   1.12  2.00  0.77  1.45   1.12  0.88   1.66 ;

param  :     1      2       3      4     5     6     7     8     9   10 :=
corrective
_cost
tub1        3.98   2.09    2.34   2.30  3.00  4.00  3.81  3.12  2.99 3.12
tub2        2.98   4.00    4.00   3.34  2.98  3.46  3.90  2.44  3.44 2.47
tub3        2.94   3.98    2.43   3.86  2.70  2.77  2.11  3.12  3.65 3.93
tub4        3.22   2.89    2.13   3.50  2.55  3.21  3.87  2.99  3.11 3.25
tub5        3.12   3.67    3.21   4.00  2.99  3.45  2.43  3.45  4.00 3.12
tub6        2.88   3.12    2.01   3.98  2.23  3.11  4.00  4.00  2.67 2.37
tub7        3.00   2.90    2.56   3.19  3.12  2.89  2.55  2.56  2.20 3.99
tub8        3.88   2.56    2.22   3.20  3.77  3.64  3.56  2.34  3.99 2.99
tub9        2.55   3.89    3.33   2.50  2.55  3.11  3.27  3.88  3.73 3.45
tub10       2.67   2.67    2.65   2.16  2.13  2.88  3.19  2.88  2.55 2.44
tub11       3.10   3.78    3.11   3.33  2.38  2.32  3.88  3.77  3.98 3.11
tub12       3.48   4.00    2.99   3.23  3.37  3.98  2.34  3.87  3.29 4.00
tub13       2.50   2.12    3.78   3.88  3.87  3.90  2.49  3.22  3.29 3.22
tub14       2.35   3.87    3.67   2.87  4.00  2.87  2.99  2.98  3.22 2.46
tub15       4.00   2.46    2.45   2.48  3.87  3.33  4.00  3.22  4.00 3.09
tub16       2.99   3.66    2.44   3.47  3.98  3.23  2.39  3.87  2.88 3.03
tub17       3.00   2.46    4.00   2.99  4.00  2.88  3.48  3.22  3.11 3.46
tub18       2.49   3.11    2.77   3.84  3.22  3.77  3.49  2.11  3.98 3.67
tub19       3.99   2.55    2.47   3.43  2.99  2.87  3.22  2.77  3.09 3.46
tub20       4.00   3.47    3.43   2.38  2.65  3.98  4.00  3.99  3.33 4.00 ;
```

APPENDIX III: Data set 2

```
set route:= R1 R2 R3 R4 R5 R6 R7 R8 R9 R10;
set turbine := tub1 tub2 tub3 tub4 tub5 tub6 tub7 tub8 tub9 tub10
tub11 tub12  tub13  tub14  tub15  tub16  tub17 tub18 tub19  tub20;
param no_period default 20;

param income                              :=

tub1         12.6     tub11      11.00
tub2         11.16    tub12      11.90
tub3         10.53    tub13      9.45
tub4         9.04     tub14      10.67
tub5         14.37    tub15      14.00
tub6         12.86    tub16      15.00
tub7         11.80    tub17      12.98
tub8         10.34    tub18      13.45
tub9         9.0      tub19      13.89
tub10        13.54    tub20      14.55       ;

param turbine_route :    R1   R2     R3   R4  R5   R6   R7   R8  R9  R10 :=

tub1                     1     0      1    1   0    1    1    0   1   0
tub2                     0     1      0    1   0    1    1    1   1   0
tub3                     1     1      0    0   1    1    1    0   1   0
tub4                     0     0      0    1   0    1    0    1   0   1
tub5                     0     1      1    0   1    0    1    0   1   0
tub6                     1     1      0    1   1    1    1    0   1   1
tub7                     1     0      1    1   1    0    0    1   0   1
tub8                     0     1      1    0   1    1    1    1   1   1
tub9                     1     0      1    0   0    0    1    0   1   0
tub10                    0     1      0    1   1    1    1    1   0   1
tub11                    0     1      0    0   1    0    0    1   1   0
```

```
tub12                      1      0      1     0    1     0     0     0    1    1
tub13                      1      0      0     0    0     0     1     0    0    1
tub14                      0      0      1     0    1     1     1     1    0    1
tub15                      1      1      1     1    0     1     1     1    0    0
tub16                      0      1      1     0    0     0     0     0    1    1
tub17                      0      1      0     1    0     0     0     1    1    0
tub18                      0      0      1     1    0     1     1     0    0    1
tub19                      1      0      0     1    1     1     0     1    0    1
tub20                      0      0      1     1    1     0     0     0    1    0 ;

param
routing
_cost :  1    2     3      4      5       6      7      8       9      10

R1      15.62 10.23 16.87 11.99   7.99    8.11   7.98   12.98   7.39   12.24
R2      13.38 11.76 15.11 7.00    12.77   8.23   11.12  11.98   12.46  15.99
R3      12.33 12.77 12.23 12.22   16.33   9.76   12.46  11.12   8.39   12.34
R4       7.15 10.23 14.23 11.14   12.67   12.98  14.47  8.08    12.34  11.34
R5      11.23 15.66  8.15 10.23   14.87   11.87  7.92   12.23   11.34   9.02
R6      14.34  7.14 10.11 14.67   15.63   14.87  8.35   14.48   14.34   8.34
R7      10.23  9.14  7.10 13.66   7.98    12.66  9.33   11.23    9.35   7.11
R8      12.21  13.38 8.98 10.45   8.11    7.08   7.34   17.00   15.44   7.12
R9      11.76 10.34 15.88 15.98   13.77   7.45   12.83  12.23   13.45   9.13
R10     12.77 13.00 11.11 14.78   12.45   11.45  10.23   9.23   17.00  10.55

(continue) 11     12     13      14      15      16     17    18      19      20 :=

R1        8.37    12.39 13.58  12.48  12.23  10.11  12.34 10.23   9.03  15.22
R2        9.57    16.47 12.09  15.77  11.23  12.39  14.45 14.59   8.10   7.44
R3       10.37  10.98  11.30  12.34  10.45  13.44   9.45 17.00  12.90   8.40
R4       16.34  11.29   9.45  14.44  11.56   9.08   8.54 13.45  11.29   9.01
R5       15.89   8.23  14.00  11.32   7.00   8.34  12.44 11.34  14.22  12.33
R6       12.39   7.44  12.49   9.54  16.33  10.11  15.21 15.67   9.22  14.98
R7       10.00   8.09  17.00   7.09   8.71  12.54  10.04  7.09   7.00  17.00
R8       11.23   9.55  12.34  12.45  11.12   7.13  12.59  8.59  17.00  13.33
R9       14.88  12.09   8.49  14.77   9.23  15.34   7.10  8.11  12.33  15.49
R10       9.09  14.33   7.33   8.43   8.11  13.43   8.22 10.11  15.33  15.32 ;


param
preventive
```

_cost:	1	2	3	4	5	6	7	8	9	10
tub1	1.61	1.36	2.00	1.93	2.00	1.21	0.65	1.11	0.98	1.45
tub2	1.26	1.22	1.84	0.55	0.81	0.95	1.10	2.00	1.11	1.84
tub3	0.94	0.87	1.48	0.87	1.45	1.12	1.45	1.46	2.00	0.57
tub4	0.79	0.65	1.36	0.98	0.67	0.88	1.24	1.13	1.76	1.57
tub5	1.65	0.50	0.87	1.98	1.34	1.87	1.01	2.00	1.23	1.91
tub6	2.00	1.87	1.11	0.98	0.76	1.98	1.23	1.01	1.90	1.56
tub7	1.20	0.58	1.90	0.99	0.87	0.76	1.57	1.98	1.09	1.34
tub8	0.78	0.67	1.98	2.00	1.12	1.87	1.65	1.27	1.09	1.67
tub9	0.67	1.89	1.78	0.76	0.98	0.99	0.66	0.76	1.78	1.76
tub10	2.00	1.23	1.87	1.98	2.00	2.00	1.67	1.65	0.76	0.77
tub11	1.83	2.00	1.11	1.45	1.11	1.10	1.56	0.57	1.37	1.18
tub12	1.23	1.22	1.24	1.57	1.78	0.68	1.73	1.93	2.00	1.34
tub13	0.98	1.34	1.55	1.56	1.56	1.67	1.09	1.12	1.11	1.87
tub14	1.33	1.35	1.45	1.20	1.98	1.90	1.56	1.73	1.34	1.11
tub15	1.98	1.87	1.71	1.99	1.34	2.00	1.28	1.02	1.23	2.00
tub16	2.00	1.47	0.87	2.00	1.23	1.12	0.77	1.48	1.88	1.97
tub17	0.55	1.23	0.57	0.68	1.25	1.45	0.57	1.66	1.33	1.33
tub18	0.65	0.76	2.00	0.78	1.99	1.84	1.93	1.22	1.46	1.45
tub19	0.76	0.65	1.29	0.99	0.78	1.65	1.32	0.88	2.00	1.34
tub20	0.99	0.98	1.09	1.12	2.00	0.77	1.45	1.12	0.88	1.66

(continue)	11	12	13	14	15	16	17	18	19	20 :=
tub1	1.36	1.20	1.09	1.11	2.00	1.87	1.91	2.00	1.28	1.05
tub2	0.57	1.39	1.29	2.00	1.37	1.23	0.71	1.11	1.38	1.11
tub3	0.55	1.36	1.38	1.29	0.98	1.11	0.88	1.19	1.22	0.77
tub4	1.00	1.35	1.33	0.56	0.77	2.00	1.28	1.92	1.09	0.83
tub5	2.00	0.57	1.09	1.09	0.54	1.87	1.22	1.35	1.03	0.99
tub6	1.11	0.50	2.00	1.19	0.87	0.55	1.28	2.00	2.00	1.28
tub7	1.23	0.61	1.19	0.99	1.77	0.82	0.97	1.47	0.98	1.76
tub8	0.77	0.81	0.98	1.11	1.76	0.67	1.22	0.55	0.55	2.00
tub9	1.12	1.11	0.76	1.88	1.09	0.50	1.34	0.83	0.60	1.23
tub10	0.99	1.60	0.55	2.00	0.99	1.10	1.56	0.76	0.74	1.11
tub11	1.61	1.36	2.00	1.93	2.00	1.21	0.65	1.11	0.98	1.45
tub12	1.26	1.22	1.84	0.55	0.81	0.95	1.10	2.00	1.11	1.84
tub13	0.94	0.87	1.48	0.87	1.45	1.12	1.45	1.46	2.00	0.57
tub14	0.79	0.65	1.36	0.98	0.67	0.88	1.24	1.13	1.76	1.57
tub15	1.65	0.50	0.87	1.98	1.34	1.87	1.01	2.00	1.23	1.91
tub16	2.00	1.87	1.11	0.98	0.76	1.98	1.23	1.01	1.90	1.56

```
 tub17       1.20   0.58  1.90   0.99   0.87  0.76 1.57 1.98  1.09  1.34
 tub18       0.78   0.67  1.98   2.00   1.12  1.87 1.65 1.27  1.09  1.67
 tub19       0.67   1.89  1.78   0.76   0.98  0.99 0.66 0.76  1.78  1.76
 tub20       2.00   1.23  1.87   1.98   2.00  2.00 1.67 1.65  0.76  0.77 ;

param
corrective
_cost:     1      2        3      4      5      6      7      8      9      10

 tub1     3.98   2.09    2.34   2.30  3.00  4.00  3.81  3.12  2.99   3.12
 tub2     2.98   4.00    4.00   3.34  2.98  3.46  3.90  2.44  3.44   2.47
 tub3     2.94   3.98    2.43   3.86  2.70  2.77  2.11  3.12  3.65   3.93
 tub4     3.22   2.89    2.13   3.50  2.55  3.21  3.87  2.99  3.11   3.25
 tub5     3.12   3.67    3.21   4.00  2.99  3.45  2.43  3.45  4.00   3.12
 tub6     2.88   3.12    2.01   3.98  2.23  3.11  4.00  4.00  2.67   2.37
 tub7     3.00   2.90    2.56   3.19  3.12  2.89  2.55  2.56  2.20   3.99
 tub8     3.88   2.56    2.22   3.20  3.77  3.64  3.56  2.34  3.99   2.99
 tub9     2.55   3.89    3.33   2.50  2.55  3.11  3.27  3.88  3.73   3.45
 tub10    2.67   2.67    2.65   2.16  2.13  2.88  3.19  2.88  2.55   2.44
 tub11    3.10   3.78    3.11   3.33  2.38  2.32  3.88  3.77  3.98   3.11
 tub12    3.48   4.00    2.99   3.23  3.37  3.98  2.34  3.87  3.29   4.00
 tub13    2.50   2.12    3.78   3.88  3.87  3.90  2.49  3.22  3.29   3.22
 tub14    2.35   3.87    3.67   2.87  4.00  2.87  2.99  2.98  3.22   2.46
 tub15    4.00   2.46    2.45   2.48  3.87  3.33  4.00  3.22  4.00   3.09
 tub16    2.99   3.66    2.44   3.47  3.98  3.23  2.39  3.87  2.88   3.03
 tub17    3.00   2.46    4.00   2.99  4.00  2.88  3.48  3.22  3.11   3.46
 tub18    2.49   3.11    2.77   3.84  3.22  3.77  3.49  2.11  3.98   3.67
 tub19    3.99   2.55    2.47   3.43  2.99  2.87  3.22  2.77  3.09   3.46
 tub20    4.00   3.47    3.43   2.38  2.65  3.98  4.00  3.99  3.33   4.00

(continue) 11     12      13      14      15      16     17     18     19     20    :=

 tub1     2.98  2.37   3.78   3.44  3.11    2.67   3.33   2.88  2.10  3.33
 tub2     2.33  2.09   3.11   3.12  2.76    3.11   2.22   3.99  2.49  2.67
 tub3     2.90  3.88   3.90   2.66  2.90    3.76   2.83   3.12  2.14  2.38
 tub4     3.00  2.99   2.50   2.10  2.56    2.33   4.00   2.37  3.78  4.00
 tub5     4.00  3.90   2.19   2.88  2.18    3.99   3.56   2.22  2.88  3.67
 tub6     2.98  3.11   3.66   3.11  3.99    2.91   2.44   3.12  3.66  2.30
 tub7     3.77  2.77   4.00   3.50  3.34    4.00   3.18   2.67  3.10  2.22
 tub8     3.44  2.32   3.09   2.77  2.99    2.77   2.73   4.00  2.37  2.83
 tub9     2.67  3.12   3.12   3.99  3.45    3.11   3.01   3.22  3.12  3.11
```

tub10	2.33	3.37	4.00	2.45	3.20	2.36	2.77	3.77	2.90	2.99
tub11	3.98	2.09	2.34	2.30	3.00	4.00	3.81	3.12	2.99	3.12
tub12	2.98	4.00	4.00	3.34	2.98	3.46	3.90	2.44	3.44	2.47
tub13	2.94	3.98	2.43	3.86	2.70	2.77	2.11	3.12	3.65	3.93
tub14	3.22	2.89	2.13	3.50	2.55	3.21	3.87	2.99	3.11	3.25
tub15	3.12	3.67	3.21	4.00	2.99	3.45	2.43	3.45	4.00	3.12
tub16	2.88	3.12	2.01	3.98	2.23	3.11	4.00	4.00	2.67	2.37
tub17	3.00	2.90	2.56	3.19	3.12	2.89	2.55	2.56	2.20	3.99
tub18	3.88	2.56	2.22	3.20	3.77	3.64	3.56	2.34	3.99	2.99
tub19	2.55	3.89	3.33	2.50	2.55	3.11	3.27	3.88	3.73	3.45
tub20	2.67	2.67	2.65	2.16	2.13	2.88	3.19	2.88	2.55	2.44 ;

APPENDIX IV: Data set 3

```
set route:= R1 R2 R3 R4 R5 R6 R7 R8 R9 R10;
set turbine := tub1 tub2 tub3 tub4 tub5 tub6 tub7 tub8 tub9 tub10
tub11 tub12  tub13  tub14  tub15  tub16  tub17 tub18 tub19  tub20;
param no_period default 30;

param income                            :=

tub1         12.6     tub11      11.00
tub2         11.16    tub12      11.90
tub3         10.53    tub13      9.45
tub4         9.04     tub14      10.67
tub5         14.37    tub15      14.00
tub6         12.86    tub16      15.00
tub7         11.80    tub17      12.98
tub8         10.34    tub18      13.45
tub9         9.0      tub19      13.89
tub10        13.54    tub20      14.55    ;

param turbine_route :    R1   R2    R3   R4  R5   R6   R7   R8  R9  R10 :=

tub1                     1    0     1    1   0    1    1    0   1   0
tub2                     0    1     0    1   0    1    1    1   1   0
tub3                     1    1     0    0   1    1    1    0   1   0
tub4                     0    0     0    1   0    1    0    1   0   1
tub5                     0    1     1    0   1    0    1    0   1   0
tub6                     1    1     0    1   1    1    1    0   1   1
tub7                     1    0     1    1   1    0    0    1   0   1
tub8                     0    1     1    0   1    1    1    1   1   1
tub9                     1    0     1    0   0    0    1    0   1   0
tub10                    0    1     0    1   1    1    1    1   0   1
tub11                    0    1     0    0   1    0    0    1   1   0
```

```
tub12                    1     0      1    0   1    0    0    0   1   1
tub13                    1     0      0    0   0    0    1    0   0   1
tub14                    0     0      1    0   1    1    1    1   0   1
tub15                    1     1      1    1   0    1    1    1   0   0
tub16                    0     1      1    0   0    0    0    0   1   1
tub17                    0     1      0    1   0    0    0    1   1   0
tub18                    0     0      1    1   0    1    1    0   0   1
tub19                    1     0      0    1   1    1    0    1   0   1
tub20                    0     0      1    1   1    0    0    0   1   0 ;

param
routing
_cost :  1    2     3      4      5       6      7      8       9      10

R1      15.62 10.23 16.87 11.99   7.99    8.11   7.98   12.98   7.39   12.24
R2      13.38 11.76 15.11 7.00    12.77   8.23   11.12  11.98   12.46  15.99
R3      12.33 12.77 12.23 12.22   16.33   9.76   12.46  11.12   8.39   12.34
R4       7.15 10.23 14.23 11.14   12.67   12.98  14.47  8.08    12.34  11.34
R5      11.23 15.66  8.15 10.23   14.87   11.87  7.92   12.23   11.34   9.02
R6      14.34  7.14 10.11 14.67   15.63   14.87  8.35   14.48   14.34   8.34
R7      10.23  9.14  7.10 13.66   7.98    12.66  9.33   11.23    9.35   7.11
R8      12.21  13.38 8.98 10.45   8.11    7.08   7.34   17.00   15.44   7.12
R9      11.76 10.34 15.88 15.98   13.77   7.45   12.83  12.23   13.45   9.13
R10     12.77 13.00 11.11 14.78   12.45   11.45  10.23   9.23   17.00  10.55

(continue) 11     12     13      14      15      16     17    18      19     20

R1         8.37   12.39 13.58  12.48  12.23  10.11  12.34 10.23   9.03  15.22
R2         9.57   16.47 12.09  15.77  11.23  12.39  14.45 14.59   8.10   7.44
R3        10.37  10.98  11.30  12.34  10.45  13.44   9.45 17.00  12.90   8.40
R4        16.34  11.29   9.45  14.44  11.56   9.08   8.54 13.45  11.29   9.01
R5        15.89   8.23  14.00  11.32   7.00   8.34  12.44 11.34  14.22  12.33
R6        12.39   7.44  12.49   9.54  16.33  10.11  15.21 15.67   9.22  14.98
R7        10.00   8.09  17.00   7.09   8.71  12.54  10.04  7.09   7.00  17.00
R8        11.23   9.55  12.34  12.45  11.12   7.13  12.59  8.59  17.00  13.33
R9        14.88  12.09   8.49  14.77   9.23  15.34   7.10  8.11  12.33  15.49
R10        9.09  14.33   7.33   8.43   8.11  13.43   8.22 10.11  15.33  15.32

(continue) 21     22       23       24      25     26     27      28      29   30 :=

R1          15.62 10.23   16.87  11.99   7.99  8.37   12.39   13.58 12.48 12.23
```

```
R2          13.38 11.76   15.11  7.00    12.77  9.57   16.47   12.09 15.77 11.23
R3          12.33 12.77   12.23  12.22   16.33 10.37   10.98   11.30 12.34 10.45
R4          7.15  10.23   14.23  11.14   12.67 16.34   11.29    9.45 14.44 11.56
R5          11.23 15.66   8.15   10.23   14.87 15.89    8.23   14.00 11.32  7.00
R6          14.34  7.14   10.11  14.67   15.63 12.39    7.44   12.49  9.54 16.33
R7          10.23  9.14   7.10   13.66    7.98 10.00    8.09   17.00  7.09  8.71
R8          12.21  13.38   8.98  10.45    8.11 11.23    9.55   12.34 12.45 11.12
R9          11.76 10.34   15.88  15.98   13.77 14.88   12.09    8.49 14.77  9.23
R10         12.77 13.00   11.11  14.78   12.45  9.09   14.33    7.33  8.43  8.11 ;


param
preventive
_cost:      1      2    3      4     5     6     7      8     9      10

 tub1      1.61   1.36  2.00   1.93  2.00  1.21  0.65   1.11  0.98   1.45
 tub2      1.26   1.22  1.84   0.55  0.81  0.95  1.10   2.00  1.11   1.84
 tub3      0.94   0.87  1.48   0.87  1.45  1.12  1.45   1.46  2.00   0.57
 tub4      0.79   0.65  1.36   0.98  0.67  0.88  1.24   1.13  1.76   1.57
 tub5      1.65   0.50  0.87   1.98  1.34  1.87  1.01   2.00  1.23   1.91
 tub6      2.00   1.87  1.11   0.98  0.76  1.98  1.23   1.01  1.90   1.56
 tub7      1.20   0.58  1.90   0.99  0.87  0.76  1.57   1.98  1.09   1.34
 tub8      0.78   0.67  1.98   2.00  1.12  1.87  1.65   1.27  1.09   1.67
 tub9      0.67   1.89  1.78   0.76  0.98  0.99  0.66   0.76  1.78   1.76
 tub10     2.00   1.23  1.87   1.98  2.00  2.00  1.67   1.65  0.76   0.77
 tub11     1.83   2.00  1.11   1.45  1.11  1.10  1.56   0.57  1.37   1.18
 tub12     1.23   1.22  1.24   1.57  1.78  0.68  1.73   1.93  2.00   1.34
 tub13     0.98   1.34  1.55   1.56  1.56  1.67  1.09   1.12  1.11   1.87
 tub14     1.33   1.35  1.45   1.20  1.98  1.90  1.56   1.73  1.34   1.11
 tub15     1.98   1.87  1.71   1.99  1.34  2.00  1.28   1.02  1.23   2.00
 tub16     2.00   1.47  0.87   2.00  1.23  1.12  0.77   1.48  1.88   1.97
 tub17     0.55   1.23  0.57   0.68  1.25  1.45  0.57   1.66  1.33   1.33
 tub18     0.65   0.76  2.00   0.78  1.99  1.84  1.93   1.22  1.46   1.45
 tub19     0.76   0.65  1.29   0.99  0.78  1.65  1.32   0.88  2.00   1.34
 tub20     0.99   0.98  1.09   1.12  2.00  0.77  1.45   1.12  0.88   1.66

 (continue)  11     12     13     14     15     16    17    18     19     20

 tub1        1.36   1.20  1.09   1.11   2.00   1.87 1.91 2.00   1.28   1.05
 tub2        0.57   1.39  1.29   2.00   1.37   1.23 0.71 1.11   1.38   1.11
 tub3        0.55   1.36  1.38   1.29   0.98   1.11 0.88 1.19   1.22   0.77
```

tub4	1.00	1.35	1.33	0.56	0.77	2.00	1.28	1.92	1.09	0.83
tub5	2.00	0.57	1.09	1.09	0.54	1.87	1.22	1.35	1.03	0.99
tub6	1.11	0.50	2.00	1.19	0.87	0.55	1.28	2.00	2.00	1.28
tub7	1.23	0.61	1.19	0.99	1.77	0.82	0.97	1.47	0.98	1.76
tub8	0.77	0.81	0.98	1.11	1.76	0.67	1.22	0.55	0.55	2.00
tub9	1.12	1.11	0.76	1.88	1.09	0.50	1.34	0.83	0.60	1.23
tub10	0.99	1.60	0.55	2.00	0.99	1.10	1.56	0.76	0.74	1.11
tub11	1.61	1.36	2.00	1.93	2.00	1.21	0.65	1.11	0.98	1.45
tub12	1.26	1.22	1.84	0.55	0.81	0.95	1.10	2.00	1.11	1.84
tub13	0.94	0.87	1.48	0.87	1.45	1.12	1.45	1.46	2.00	0.57
tub14	0.79	0.65	1.36	0.98	0.67	0.88	1.24	1.13	1.76	1.57
tub15	1.65	0.50	0.87	1.98	1.34	1.87	1.01	2.00	1.23	1.91
tub16	2.00	1.87	1.11	0.98	0.76	1.98	1.23	1.01	1.90	1.56
tub17	1.20	0.58	1.90	0.99	0.87	0.76	1.57	1.98	1.09	1.34
tub18	0.78	0.67	1.98	2.00	1.12	1.87	1.65	1.27	1.09	1.67
tub19	0.67	1.89	1.78	0.76	0.98	0.99	0.66	0.76	1.78	1.76
tub20	2.00	1.23	1.87	1.98	2.00	2.00	1.67	1.65	0.76	0.77

(continue)	21	22	23	24	25	26	27	28	29	30 :=
tub1	1.83	2.00	1.11	1.45	1.11	1.10	1.56	0.57	1.37	1.18
tub2	1.23	1.22	1.24	1.57	1.78	0.68	1.73	1.93	2.00	1.34
tub3	0.98	1.34	1.55	1.56	1.56	1.67	1.09	1.12	1.11	1.87
tub4	1.33	1.35	1.45	1.20	1.98	1.90	1.56	1.73	1.34	1.11
tub5	1.98	1.87	1.71	1.99	1.34	2.00	1.28	1.02	1.23	2.00
tub6	2.00	1.47	0.87	2.00	1.23	1.12	0.77	1.48	1.88	1.97
tub7	0.55	1.23	0.57	0.68	1.25	1.45	0.57	1.66	1.33	1.33
tub8	0.65	0.76	2.00	0.78	1.99	1.84	1.93	1.22	1.46	1.45
tub9	0.76	0.65	1.29	0.99	0.78	1.65	1.32	0.88	2.00	1.34
tub10	0.99	0.98	1.09	1.12	2.00	0.77	1.45	1.12	0.88	1.66
tub11	1.36	1.20	1.09	1.11	2.00	1.87	1.91	2.00	1.28	1.05
tub12	0.57	1.39	1.29	2.00	1.37	1.23	0.71	1.11	1.38	1.11
tub13	0.55	1.36	1.38	1.29	0.98	1.11	0.88	1.19	1.22	0.77
tub14	1.00	1.35	1.33	0.56	0.77	2.00	1.28	1.92	1.09	0.83
tub15	2.00	0.57	1.09	1.09	0.54	1.87	1.22	1.35	1.03	0.99
tub16	1.11	0.50	2.00	1.19	0.87	0.55	1.28	2.00	2.00	1.28
tub17	1.23	0.61	1.19	0.99	1.77	0.82	0.97	1.47	0.98	1.76
tub18	0.77	0.81	0.98	1.11	1.76	0.67	1.22	0.55	0.55	2.00
tub19	1.12	1.11	0.76	1.88	1.09	0.50	1.34	0.83	0.60	1.23
tub20	0.99	1.60	0.55	2.00	0.99	1.10	1.56	0.76	0.74	1.11 ;

param
corrective

_cost:	1	2	3	4	5	6	7	8	9	10
tub1	3.98	2.09	2.34	2.30	3.00	4.00	3.81	3.12	2.99	3.12
tub2	2.98	4.00	4.00	3.34	2.98	3.46	3.90	2.44	3.44	2.47
tub3	2.94	3.98	2.43	3.86	2.70	2.77	2.11	3.12	3.65	3.93
tub4	3.22	2.89	2.13	3.50	2.55	3.21	3.87	2.99	3.11	3.25
tub5	3.12	3.67	3.21	4.00	2.99	3.45	2.43	3.45	4.00	3.12
tub6	2.88	3.12	2.01	3.98	2.23	3.11	4.00	4.00	2.67	2.37
tub7	3.00	2.90	2.56	3.19	3.12	2.89	2.55	2.56	2.20	3.99
tub8	3.88	2.56	2.22	3.20	3.77	3.64	3.56	2.34	3.99	2.99
tub9	2.55	3.89	3.33	2.50	2.55	3.11	3.27	3.88	3.73	3.45
tub10	2.67	2.67	2.65	2.16	2.13	2.88	3.19	2.88	2.55	2.44
tub11	3.10	3.78	3.11	3.33	2.38	2.32	3.88	3.77	3.98	3.11
tub12	3.48	4.00	2.99	3.23	3.37	3.98	2.34	3.87	3.29	4.00
tub13	2.50	2.12	3.78	3.88	3.87	3.90	2.49	3.22	3.29	3.22
tub14	2.35	3.87	3.67	2.87	4.00	2.87	2.99	2.98	3.22	2.46
tub15	4.00	2.46	2.45	2.48	3.87	3.33	4.00	3.22	4.00	3.09
tub16	2.99	3.66	2.44	3.47	3.98	3.23	2.39	3.87	2.88	3.03
tub17	3.00	2.46	4.00	2.99	4.00	2.88	3.48	3.22	3.11	3.46
tub18	2.49	3.11	2.77	3.84	3.22	3.77	3.49	2.11	3.98	3.67
tub19	3.99	2.55	2.47	3.43	2.99	2.87	3.22	2.77	3.09	3.46
tub20	4.00	3.47	3.43	2.38	2.65	3.98	4.00	3.99	3.33	4.00

(continue)	11	12	13	14	15	16	17	18	19	20
tub1	2.98	2.37	3.78	3.44	3.11	2.67	3.33	2.88	2.10	3.33
tub2	2.33	2.09	3.11	3.12	2.76	3.11	2.22	3.99	2.49	2.67
tub3	2.90	3.88	3.90	2.66	2.90	3.76	2.83	3.12	2.14	2.38
tub4	3.00	2.99	2.50	2.10	2.56	2.33	4.00	2.37	3.78	4.00
tub5	4.00	3.90	2.19	2.88	2.18	3.99	3.56	2.22	2.88	3.67
tub6	2.98	3.11	3.66	3.11	3.99	2.91	2.44	3.12	3.66	2.30
tub7	3.77	2.77	4.00	3.50	3.34	4.00	3.18	2.67	3.10	2.22
tub8	3.44	2.32	3.09	2.77	2.99	2.77	2.73	4.00	2.37	2.83
tub9	2.67	3.12	3.12	3.99	3.45	3.11	3.01	3.22	3.12	3.11
tub10	2.33	3.37	4.00	2.45	3.20	2.36	2.77	3.77	2.90	2.99
tub11	3.98	2.09	2.34	2.30	3.00	4.00	3.81	3.12	2.99	3.12
tub12	2.98	4.00	4.00	3.34	2.98	3.46	3.90	2.44	3.44	2.47
tub13	2.94	3.98	2.43	3.86	2.70	2.77	2.11	3.12	3.65	3.93

```
 tub14   3.22  2.89   2.13   3.50  2.55   3.21   3.87   2.99  3.11  3.25
 tub15   3.12  3.67   3.21   4.00  2.99   3.45   2.43   3.45  4.00  3.12
 tub16   2.88  3.12   2.01   3.98  2.23   3.11   4.00   4.00  2.67  2.37
 tub17   3.00  2.90   2.56   3.19  3.12   2.89   2.55   2.56  2.20  3.99
 tub18   3.88  2.56   2.22   3.20  3.77   3.64   3.56   2.34  3.99  2.99
 tub19   2.55  3.89   3.33   2.50  2.55   3.11   3.27   3.88  3.73  3.45
 tub20   2.67  2.67   2.65   2.16  2.13   2.88   3.19   2.88  2.55  2.44


(continue) 21   22    23  24    25   26    27    28    29  30 :=

 tub1    3.10 3.78  3.11 3.33  2.38  2.32  3.88  3.77 3.98 3.11
 tub2    3.48 4.00  2.99 3.23  3.37  3.98  2.34  3.87 3.29 4.00
 tub3    2.50 2.12  3.78 3.88  3.87  3.90  2.49  3.22 3.29 3.22
 tub4    2.35 3.87  3.67 2.87  4.00  2.87  2.99  2.98 3.22 2.46
 tub5    4.00 2.46  2.45 2.48  3.87  3.33  4.00  3.22 4.00 3.09
 tub6    2.99 3.66  2.44 3.47  3.98  3.23  2.39  3.87 2.88 3.03
 tub7    3.00 2.46  4.00 2.99  4.00  2.88  3.48  3.22 3.11 3.46
 tub8    2.49 3.11  2.77 3.84  3.22  3.77  3.49  2.11 3.98 3.67
 tub9    3.99 2.55  2.47 3.43  2.99  2.87  3.22  2.77 3.09 3.46
 tub10   4.00 3.47  3.43 2.38  2.65  3.98  4.00  3.99 3.33 4.00
 tub11   2.98 2.37  3.78 3.44  3.11  2.67  3.33  2.88 2.10 3.33
 tub12   2.33 2.09  3.11 3.12  2.76  3.11  2.22  3.99 2.49 2.67
 tub13   2.90 3.88  3.90 2.66  2.90  3.76  2.83  3.12 2.14 2.38
 tub14   3.00 2.99  2.50 2.10  2.56  2.33  4.00  2.37 3.78 4.00
 tub15   4.00 3.90  2.19 2.88  2.18  3.99  3.56  2.22 2.88 3.67
 tub16   2.98 3.11  3.66 3.11  3.99  2.91  2.44  3.12 3.66 2.30
 tub17   3.77 2.77  4.00 3.50  3.34  4.00  3.18  2.67 3.10 2.22
 tub18   3.44 2.32  3.09 2.77  2.99  2.77  2.73  4.00 2.37 2.83
 tub19   2.67 3.12  3.12 3.99  3.45  3.11  3.01  3.22 3.12 3.11
 tub20   2.33 3.37  4.00 2.45  3.20  2.36  2.77  3.77 2.90 2.99 ;
```

APPENDIX V: Data set 4

```
set route:= R1 R2 R3 R4 R5 R6 R7 R8 R9 R10;
set turbine := tub1 tub2 tub3 tub4 tub5 tub6 tub7 tub8 tub9 tub10
tub11 tub12  tub13  tub14  tub15  tub16  tub17 tub18 tub19  tub20;
param no_period default 40;

param income                            :=

tub1         12.6     tub11      11.00
tub2         11.16    tub12      11.90
tub3         10.53    tub13      9.45
tub4         9.04     tub14      10.67
tub5         14.37    tub15      14.00
tub6         12.86    tub16      15.00
tub7         11.80    tub17      12.98
tub8         10.34    tub18      13.45
tub9         9.0      tub19      13.89
tub10        13.54    tub20      14.55    ;

param turbine_route :    R1   R2     R3   R4  R5   R6   R7   R8  R9  R10 :=

tub1                     1     0      1    1   0    1    1    0   1   0
tub2                     0     1      0    1   0    1    1    1   1   0
tub3                     1     1      0    0   1    1    1    0   1   0
tub4                     0     0      0    1   0    1    0    1   0   1
tub5                     0     1      1    0   1    0    1    0   1   0
tub6                     1     1      0    1   1    1    1    0   1   1
tub7                     1     0      1    1   1    0    0    1   0   1
tub8                     0     1      1    0   1    1    1    1   1   1
tub9                     1     0      1    0   0    0    1    0   1   0
tub10                    0     1      0    1   1    1    1    1   0   1
tub11                    0     1      0    0   1    0    0    1   1   0
```

```
tub12                    1     0      1    0   1    0    0    0   1   1
tub13                    1     0      0    0   0    0    1    0   0   1
tub14                    0     0      1    0   1    1    1    1   0   1
tub15                    1     1      1    1   0    1    1    1   0   0
tub16                    0     1      1    0   0    0    0    0   1   1
tub17                    0     1      0    1   0    0    0    1   1   0
tub18                    0     0      1    1   0    1    1    0   0   1
tub19                    1     0      0    1   1    1    0    1   0   1
tub20                    0     0      1    1   1    0    0    0   1   0 ;

param
routing
_cost :  1    2     3      4      5       6      7      8       9      10

R1      15.62 10.23 16.87 11.99   7.99    8.11   7.98   12.98   7.39   12.24
R2      13.38 11.76 15.11 7.00    12.77   8.23   11.12  11.98   12.46  15.99
R3      12.33 12.77 12.23 12.22   16.33   9.76   12.46  11.12   8.39   12.34
R4       7.15 10.23 14.23 11.14   12.67   12.98  14.47  8.08    12.34  11.34
R5      11.23 15.66  8.15 10.23   14.87   11.87  7.92   12.23   11.34   9.02
R6      14.34  7.14 10.11 14.67   15.63   14.87  8.35   14.48   14.34   8.34
R7      10.23  9.14  7.10 13.66   7.98    12.66  9.33   11.23    9.35   7.11
R8      12.21  13.38 8.98 10.45   8.11    7.08   7.34   17.00   15.44   7.12
R9      11.76 10.34 15.88 15.98   13.77   7.45   12.83  12.23   13.45   9.13
R10     12.77 13.00 11.11 14.78   12.45   11.45  10.23   9.23   17.00  10.55

(continue) 11     12     13     14      15     16     17    18      19     20

R1         8.37   12.39 13.58  12.48  12.23  10.11  12.34 10.23   9.03  15.22
R2         9.57   16.47 12.09  15.77  11.23  12.39  14.45 14.59   8.10   7.44
R3        10.37  10.98  11.30  12.34  10.45  13.44   9.45 17.00  12.90   8.40
R4        16.34  11.29   9.45  14.44  11.56   9.08   8.54 13.45  11.29   9.01
R5        15.89   8.23  14.00  11.32   7.00   8.34  12.44 11.34  14.22  12.33
R6        12.39   7.44  12.49   9.54  16.33  10.11  15.21 15.67   9.22  14.98
R7        10.00   8.09  17.00   7.09   8.71  12.54  10.04  7.09   7.00  17.00
R8        11.23   9.55  12.34  12.45  11.12   7.13  12.59  8.59  17.00  13.33
R9        14.88  12.09   8.49  14.77   9.23  15.34   7.10  8.11  12.33  15.49
R10        9.09  14.33   7.33   8.43   8.11  13.43   8.22 10.11  15.33  15.32

(continue) 21     22      23      24      25     26     27      28      29    30

R1          15.62 10.23   16.87  11.99   7.99  8.37   12.39   13.58 12.48 12.23
```

```
R2         13.38 11.76   15.11  7.00    12.77  9.57  16.47   12.09 15.77 11.23
R3         12.33 12.77   12.23  12.22   16.33 10.37  10.98   11.30 12.34 10.45
R4         7.15  10.23   14.23  11.14   12.67 16.34  11.29    9.45 14.44 11.56
R5         11.23 15.66   8.15   10.23   14.87 15.89   8.23   14.00 11.32  7.00
R6         14.34  7.14   10.11  14.67   15.63 12.39   7.44   12.49  9.54 16.33
R7         10.23  9.14   7.10   13.66    7.98 10.00   8.09   17.00  7.09  8.71
R8         12.21  13.38   8.98  10.45    8.11 11.23   9.55   12.34 12.45 11.12
R9         11.76 10.34   15.88  15.98   13.77 14.88  12.09    8.49 14.77  9.23
R10        12.77 13.00   11.11  14.78   12.45  9.09  14.33    7.33  8.43  8.11

(continue) 31     32     33      34    35     36     37     38     39    40 :=

R1          8.11   7.98   12.98   7.39  12.24  10.11   12.34 10.23   9.03 15.22
R2          8.23   11.12  11.98   12.46 15.99  12.39   14.45 14.59   8.10  7.44
R3          9.76   12.46  11.12   8.39  12.34  13.44    9.45 17.00  12.90  8.40
R4         12.98  14.47  8.08    12.34  11.34   9.08    8.54 13.45  11.29  9.01
R5         11.87  7.92   12.23   11.34  9.02    8.34   12.44 11.34  14.22 12.33
R6         14.87  8.35   14.48   14.34  8.34   10.11   15.21 15.67   9.22 14.98
R7         12.66  9.33   11.23    9.35  7.11   12.54   10.04  7.09   7.00 17.00
R8          7.08  7.34   17.00   15.44  7.12    7.13   12.59  8.59  17.00 13.33
R9          7.45   12.83  12.23  13.45  9.13   15.34    7.10  8.11  12.33 15.49
R10        11.45  10.23   9.23   17.00  10.55  13.43    8.22 10.11  15.33 15.32 ;


param
preventive
_cost:      1      2     3      4     5     6     7      8     9      10

 tub1      1.61   1.36  2.00   1.93  2.00  1.21  0.65   1.11  0.98   1.45
 tub2      1.26   1.22  1.84   0.55  0.81  0.95  1.10   2.00  1.11   1.84
 tub3      0.94   0.87  1.48   0.87  1.45  1.12  1.45   1.46  2.00   0.57
 tub4      0.79   0.65  1.36   0.98  0.67  0.88  1.24   1.13  1.76   1.57
 tub5      1.65   0.50  0.87   1.98  1.34  1.87  1.01   2.00  1.23   1.91
 tub6      2.00   1.87  1.11   0.98  0.76  1.98  1.23   1.01  1.90   1.56
 tub7      1.20   0.58  1.90   0.99  0.87  0.76  1.57   1.98  1.09   1.34
 tub8      0.78   0.67  1.98   2.00  1.12  1.87  1.65   1.27  1.09   1.67
 tub9      0.67   1.89  1.78   0.76  0.98  0.99  0.66   0.76  1.78   1.76
 tub10     2.00   1.23  1.87   1.98  2.00  2.00  1.67   1.65  0.76   0.77
 tub11     1.83   2.00  1.11   1.45  1.11  1.10  1.56   0.57  1.37   1.18
 tub12     1.23   1.22  1.24   1.57  1.78  0.68  1.73   1.93  2.00   1.34
 tub13     0.98   1.34  1.55   1.56  1.56  1.67  1.09   1.12  1.11   1.87
```

tub14	1.33	1.35	1.45	1.20	1.98	1.90	1.56	1.73	1.34	1.11
tub15	1.98	1.87	1.71	1.99	1.34	2.00	1.28	1.02	1.23	2.00
tub16	2.00	1.47	0.87	2.00	1.23	1.12	0.77	1.48	1.88	1.97
tub17	0.55	1.23	0.57	0.68	1.25	1.45	0.57	1.66	1.33	1.33
tub18	0.65	0.76	2.00	0.78	1.99	1.84	1.93	1.22	1.46	1.45
tub19	0.76	0.65	1.29	0.99	0.78	1.65	1.32	0.88	2.00	1.34
tub20	0.99	0.98	1.09	1.12	2.00	0.77	1.45	1.12	0.88	1.66

(continue)	11	12	13	14	15	16	17	18	19	20
tub1	1.36	1.20	1.09	1.11	2.00	1.87	1.91	2.00	1.28	1.05
tub2	0.57	1.39	1.29	2.00	1.37	1.23	0.71	1.11	1.38	1.11
tub3	0.55	1.36	1.38	1.29	0.98	1.11	0.88	1.19	1.22	0.77
tub4	1.00	1.35	1.33	0.56	0.77	2.00	1.28	1.92	1.09	0.83
tub5	2.00	0.57	1.09	1.09	0.54	1.87	1.22	1.35	1.03	0.99
tub6	1.11	0.50	2.00	1.19	0.87	0.55	1.28	2.00	2.00	1.28
tub7	1.23	0.61	1.19	0.99	1.77	0.82	0.97	1.47	0.98	1.76
tub8	0.77	0.81	0.98	1.11	1.76	0.67	1.22	0.55	0.55	2.00
tub9	1.12	1.11	0.76	1.88	1.09	0.50	1.34	0.83	0.60	1.23
tub10	0.99	1.60	0.55	2.00	0.99	1.10	1.56	0.76	0.74	1.11
tub11	1.61	1.36	2.00	1.93	2.00	1.21	0.65	1.11	0.98	1.45
tub12	1.26	1.22	1.84	0.55	0.81	0.95	1.10	2.00	1.11	1.84
tub13	0.94	0.87	1.48	0.87	1.45	1.12	1.45	1.46	2.00	0.57
tub14	0.79	0.65	1.36	0.98	0.67	0.88	1.24	1.13	1.76	1.57
tub15	1.65	0.50	0.87	1.98	1.34	1.87	1.01	2.00	1.23	1.91
tub16	2.00	1.87	1.11	0.98	0.76	1.98	1.23	1.01	1.90	1.56
tub17	1.20	0.58	1.90	0.99	0.87	0.76	1.57	1.98	1.09	1.34
tub18	0.78	0.67	1.98	2.00	1.12	1.87	1.65	1.27	1.09	1.67
tub19	0.67	1.89	1.78	0.76	0.98	0.99	0.66	0.76	1.78	1.76
tub20	2.00	1.23	1.87	1.98	2.00	2.00	1.67	1.65	0.76	0.77

(continue)	21	22	23	24	25	26	27	28	29	30
tub1	1.83	2.00	1.11	1.45	1.11	1.10	1.56	0.57	1.37	1.18
tub2	1.23	1.22	1.24	1.57	1.78	0.68	1.73	1.93	2.00	1.34
tub3	0.98	1.34	1.55	1.56	1.56	1.67	1.09	1.12	1.11	1.87
tub4	1.33	1.35	1.45	1.20	1.98	1.90	1.56	1.73	1.34	1.11
tub5	1.98	1.87	1.71	1.99	1.34	2.00	1.28	1.02	1.23	2.00
tub6	2.00	1.47	0.87	2.00	1.23	1.12	0.77	1.48	1.88	1.97
tub7	0.55	1.23	0.57	0.68	1.25	1.45	0.57	1.66	1.33	1.33

```
 tub8       0.65  0.76  2.00   0.78  1.99  1.84  1.93   1.22  1.46   1.45
 tub9       0.76  0.65  1.29   0.99  0.78  1.65  1.32   0.88  2.00   1.34
 tub10      0.99  0.98  1.09   1.12  2.00  0.77  1.45   1.12  0.88   1.66
 tub11      1.36  1.20  1.09   1.11  2.00  1.87  1.91   2.00  1.28   1.05
 tub12      0.57  1.39  1.29   2.00  1.37  1.23  0.71   1.11  1.38   1.11
 tub13      0.55  1.36  1.38   1.29  0.98  1.11  0.88   1.19  1.22   0.77
 tub14      1.00  1.35  1.33   0.56  0.77  2.00  1.28   1.92  1.09   0.83
 tub15      2.00  0.57  1.09   1.09  0.54  1.87  1.22   1.35  1.03   0.99
 tub16      1.11  0.50  2.00   1.19  0.87  0.55  1.28   2.00  2.00   1.28
 tub17      1.23  0.61  1.19   0.99  1.77  0.82  0.97   1.47  0.98   1.76
 tub18      0.77  0.81  0.98   1.11  1.76  0.67  1.22   0.55  0.55   2.00
 tub19      1.12  1.11  0.76   1.88  1.09  0.50  1.34   0.83  0.60   1.23
 tub20      0.99  1.60  0.55   2.00  0.99  1.10  1.56   0.76  0.74   1.11

(continue) 31      32    33     34    35     36    37     38    39     40 :=

 tub1       1.61   1.36  2.00   1.93  2.00  1.21  0.65   1.11  0.98   1.45
 tub2       1.26   1.22  1.84   0.55  0.81  0.95  1.10   2.00  1.11   1.84
 tub3       0.94   0.87  1.48   0.87  1.45  1.12  1.45   1.46  2.00   0.57
 tub4       0.79   0.65  1.36   0.98  0.67  0.88  1.24   1.13  1.76   1.57
 tub5       1.65   0.50  0.87   1.98  1.34  1.87  1.01   2.00  1.23   1.91
 tub6       2.00   1.87  1.11   0.98  0.76  1.98  1.23   1.01  1.90   1.56
 tub7       1.20   0.58  1.90   0.99  0.87  0.76  1.57   1.98  1.09   1.34
 tub8       0.78   0.67  1.98   2.00  1.12  1.87  1.65   1.27  1.09   1.67
 tub9       0.67   1.89  1.78   0.76  0.98  0.99  0.66   0.76  1.78   1.76
 tub10      2.00   1.23  1.87   1.98  2.00  2.00  1.67   1.65  0.76   0.77
 tub11      1.83   2.00  1.11   1.45  1.11  1.10  1.56   0.57  1.37   1.18
 tub12      1.23   1.22  1.24   1.57  1.78  0.68  1.73   1.93  2.00   1.34
 tub13      0.98   1.34  1.55   1.56  1.56  1.67  1.09   1.12  1.11   1.87
 tub14      1.33   1.35  1.45   1.20  1.98  1.90  1.56   1.73  1.34   1.11
 tub15      1.98   1.87  1.71   1.99  1.34  2.00  1.28   1.02  1.23   2.00
 tub16      2.00   1.47  0.87   2.00  1.23  1.12  0.77   1.48  1.88   1.97
 tub17      0.55   1.23  0.57   0.68  1.25  1.45  0.57   1.66  1.33   1.33
 tub18      0.65   0.76  2.00   0.78  1.99  1.84  1.93   1.22  1.46   1.45
 tub19      0.76   0.65  1.29   0.99  0.78  1.65  1.32   0.88  2.00   1.34
 tub20      0.99   0.98  1.09   1.12  2.00  0.77  1.45   1.12  0.88   1.66 ;

param
corrective
_cost:     1      2        3      4     5     6     7     8     9     10
```

tub1	3.98	2.09	2.34	2.30	3.00	4.00	3.81	3.12	2.99	3.12
tub2	2.98	4.00	4.00	3.34	2.98	3.46	3.90	2.44	3.44	2.47
tub3	2.94	3.98	2.43	3.86	2.70	2.77	2.11	3.12	3.65	3.93
tub4	3.22	2.89	2.13	3.50	2.55	3.21	3.87	2.99	3.11	3.25
tub5	3.12	3.67	3.21	4.00	2.99	3.45	2.43	3.45	4.00	3.12
tub6	2.88	3.12	2.01	3.98	2.23	3.11	4.00	4.00	2.67	2.37
tub7	3.00	2.90	2.56	3.19	3.12	2.89	2.55	2.56	2.20	3.99
tub8	3.88	2.56	2.22	3.20	3.77	3.64	3.56	2.34	3.99	2.99
tub9	2.55	3.89	3.33	2.50	2.55	3.11	3.27	3.88	3.73	3.45
tub10	2.67	2.67	2.65	2.16	2.13	2.88	3.19	2.88	2.55	2.44
tub11	3.10	3.78	3.11	3.33	2.38	2.32	3.88	3.77	3.98	3.11
tub12	3.48	4.00	2.99	3.23	3.37	3.98	2.34	3.87	3.29	4.00
tub13	2.50	2.12	3.78	3.88	3.87	3.90	2.49	3.22	3.29	3.22
tub14	2.35	3.87	3.67	2.87	4.00	2.87	2.99	2.98	3.22	2.46
tub15	4.00	2.46	2.45	2.48	3.87	3.33	4.00	3.22	4.00	3.09
tub16	2.99	3.66	2.44	3.47	3.98	3.23	2.39	3.87	2.88	3.03
tub17	3.00	2.46	4.00	2.99	4.00	2.88	3.48	3.22	3.11	3.46
tub18	2.49	3.11	2.77	3.84	3.22	3.77	3.49	2.11	3.98	3.67
tub19	3.99	2.55	2.47	3.43	2.99	2.87	3.22	2.77	3.09	3.46
tub20	4.00	3.47	3.43	2.38	2.65	3.98	4.00	3.99	3.33	4.00

(continue)	11	12	13	14	15	16	17	18	19	20
tub1	2.98	2.37	3.78	3.44	3.11	2.67	3.33	2.88	2.10	3.33
tub2	2.33	2.09	3.11	3.12	2.76	3.11	2.22	3.99	2.49	2.67
tub3	2.90	3.88	3.90	2.66	2.90	3.76	2.83	3.12	2.14	2.38
tub4	3.00	2.99	2.50	2.10	2.56	2.33	4.00	2.37	3.78	4.00
tub5	4.00	3.90	2.19	2.88	2.18	3.99	3.56	2.22	2.88	3.67
tub6	2.98	3.11	3.66	3.11	3.99	2.91	2.44	3.12	3.66	2.30
tub7	3.77	2.77	4.00	3.50	3.34	4.00	3.18	2.67	3.10	2.22
tub8	3.44	2.32	3.09	2.77	2.99	2.77	2.73	4.00	2.37	2.83
tub9	2.67	3.12	3.12	3.99	3.45	3.11	3.01	3.22	3.12	3.11
tub10	2.33	3.37	4.00	2.45	3.20	2.36	2.77	3.77	2.90	2.99
tub11	3.98	2.09	2.34	2.30	3.00	4.00	3.81	3.12	2.99	3.12
tub12	2.98	4.00	4.00	3.34	2.98	3.46	3.90	2.44	3.44	2.47
tub13	2.94	3.98	2.43	3.86	2.70	2.77	2.11	3.12	3.65	3.93
tub14	3.22	2.89	2.13	3.50	2.55	3.21	3.87	2.99	3.11	3.25
tub15	3.12	3.67	3.21	4.00	2.99	3.45	2.43	3.45	4.00	3.12
tub16	2.88	3.12	2.01	3.98	2.23	3.11	4.00	4.00	2.67	2.37
tub17	3.00	2.90	2.56	3.19	3.12	2.89	2.55	2.56	2.20	3.99
tub18	3.88	2.56	2.22	3.20	3.77	3.64	3.56	2.34	3.99	2.99

tub19	2.55	3.89	3.33	2.50	2.55	3.11	3.27	3.88	3.73	3.45
tub20	2.67	2.67	2.65	2.16	2.13	2.88	3.19	2.88	2.55	2.44

(continue)	21	22	23	24	25	26	27	28	29	30
tub1	3.10	3.78	3.11	3.33	2.38	2.32	3.88	3.77	3.98	3.11
tub2	3.48	4.00	2.99	3.23	3.37	3.98	2.34	3.87	3.29	4.00
tub3	2.50	2.12	3.78	3.88	3.87	3.90	2.49	3.22	3.29	3.22
tub4	2.35	3.87	3.67	2.87	4.00	2.87	2.99	2.98	3.22	2.46
tub5	4.00	2.46	2.45	2.48	3.87	3.33	4.00	3.22	4.00	3.09
tub6	2.99	3.66	2.44	3.47	3.98	3.23	2.39	3.87	2.88	3.03
tub7	3.00	2.46	4.00	2.99	4.00	2.88	3.48	3.22	3.11	3.46
tub8	2.49	3.11	2.77	3.84	3.22	3.77	3.49	2.11	3.98	3.67
tub9	3.99	2.55	2.47	3.43	2.99	2.87	3.22	2.77	3.09	3.46
tub10	4.00	3.47	3.43	2.38	2.65	3.98	4.00	3.99	3.33	4.00
tub11	2.98	2.37	3.78	3.44	3.11	2.67	3.33	2.88	2.10	3.33
tub12	2.33	2.09	3.11	3.12	2.76	3.11	2.22	3.99	2.49	2.67
tub13	2.90	3.88	3.90	2.66	2.90	3.76	2.83	3.12	2.14	2.38
tub14	3.00	2.99	2.50	2.10	2.56	2.33	4.00	2.37	3.78	4.00
tub15	4.00	3.90	2.19	2.88	2.18	3.99	3.56	2.22	2.88	3.67
tub16	2.98	3.11	3.66	3.11	3.99	2.91	2.44	3.12	3.66	2.30
tub17	3.77	2.77	4.00	3.50	3.34	4.00	3.18	2.67	3.10	2.22
tub18	3.44	2.32	3.09	2.77	2.99	2.77	2.73	4.00	2.37	2.83
tub19	2.67	3.12	3.12	3.99	3.45	3.11	3.01	3.22	3.12	3.11
tub20	2.33	3.37	4.00	2.45	3.20	2.36	2.77	3.77	2.90	2.99

(continue)	31	32	33	34	35	36	37	38	39	40 :=
tub1	3.98	2.09	2.34	2.30	3.00	4.00	3.81	3.12	2.99	3.12
tub2	2.98	4.00	4.00	3.34	2.98	3.46	3.90	2.44	3.44	2.47
tub3	2.94	3.98	2.43	3.86	2.70	2.77	2.11	3.12	3.65	3.93
tub4	3.22	2.89	2.13	3.50	2.55	3.21	3.87	2.99	3.11	3.25
tub5	3.12	3.67	3.21	4.00	2.99	3.45	2.43	3.45	4.00	3.12
tub6	2.88	3.12	2.01	3.98	2.23	3.11	4.00	4.00	2.67	2.37
tub7	3.00	2.90	2.56	3.19	3.12	2.89	2.55	2.56	2.20	3.99
tub8	3.88	2.56	2.22	3.20	3.77	3.64	3.56	2.34	3.99	2.99
tub9	2.55	3.89	3.33	2.50	2.55	3.11	3.27	3.88	3.73	3.45
tub10	2.67	2.67	2.65	2.16	2.13	2.88	3.19	2.88	2.55	2.44
tub11	3.10	3.78	3.11	3.33	2.38	2.32	3.88	3.77	3.98	3.11
tub12	3.48	4.00	2.99	3.23	3.37	3.98	2.34	3.87	3.29	4.00

tub13	2.50	2.12	3.78	3.88	3.87	3.90	2.49	3.22	3.29	3.22
tub14	2.35	3.87	3.67	2.87	4.00	2.87	2.99	2.98	3.22	2.46
tub15	4.00	2.46	2.45	2.48	3.87	3.33	4.00	3.22	4.00	3.09
tub16	2.99	3.66	2.44	3.47	3.98	3.23	2.39	3.87	2.88	3.03
tub17	3.00	2.46	4.00	2.99	4.00	2.88	3.48	3.22	3.11	3.46
tub18	2.49	3.11	2.77	3.84	3.22	3.77	3.49	2.11	3.98	3.67
tub19	3.99	2.55	2.47	3.43	2.99	2.87	3.22	2.77	3.09	3.46
tub20	4.00	3.47	3.43	2.38	2.65	3.98	4.00	3.99	3.33	4.00 ;