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RECOFF

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WP6: Operation and Maintenance
Task 3: Optimisation of the O&M costs to lower the energy costs

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Acknowledgement/Preface

This report has been prepared within the EU project RECOFF (RECommendations for OFFshore wind turbines); EU project number is ENK5-CT2000-00322. The project has been financially supported by Novem (the Netherlands Agency for Energy and the Environment) under the project number 0224-01-57-21-0007.

Abstract

A Probabilistic O&M Cost Optimisation model is presented, with which the operation and maintenance strategy of offshore windfarms can be improved. Basis for the application of this model is an extensive analysis of the fault detection and repair cycle offshore. A calculation model has been added.

CONTENTS

1. INTRODUCTION

As part of the RECOFF project RECommendations for OFFshore wind turbines, Task 3 of Work Package 6 (Operation and Maintenance) has been defined with the scope on the limiting of O&M cost by optimisation of operation and maintenance procedures. In other words: are there ways to reduce offshore O&M costs by means of new techniques or models?

In this report an O&M cost model is introduced and explained. This model is a probabilistic model based on an extensive analysis of the fault detection and repair cycle offshore.
A calculation model is included and elucidated.

2. GENERAL OBJECTIVE

The O&M Costs of offshore wind farms are, amongst others, influenced by:

- The complexity of the installation and the failure rate of the wind turbines and their components;
- The distance between the service buildings and the wind farms;
- The available maintenance facilities in the wind turbines;
- The accessibility of the farm and the individual wind turbines (environmental conditions);
- The loads due to wind, waves, and wake effects that lead to wear and failures.

In the planning stage of a wind farm it is useful to have data, information, and models available to analyse different scenarios for planning and optimising O&M procedures. Presently, such models and information are not publicly available. The analyses of the different scenarios go with large uncertainties in input and output. To deal with these uncertainties it is recommended to apply probabilistic techniques, to determine parameters and distribution functions, and to determine the key parameters that contribute most to the uncertainties of the O&M cost.

This document briefly describes the models, which have been developed by ECN to model the corrective maintenance aspects of offshore wind farms, viz. downtime, revenue losses and costs. Aspects, which have influence on these three aspects, are:

- the failure behaviour of the turbine;
- the repair strategy, especially the equipment to carry our repairs like boats and hoisting equipment; and
- the weather conditions at the site.

The models deal with the analyses of long-term wind and wave measurements. The wind and wave data are analysed in such a way that, for the different repair strategies, the waiting time due to bad weather can be determined.

A cost model is being used in addition to determine the direct costs for corrective maintenance (labour costs, material costs, and costs for equipment), the total downtime for the entire wind farm and the revenue losses.

The models have been implemented in MS Excel worksheets. The add-inn module @RISK is being used to consider the stochastic behaviour of the weather conditions and of the waiting time and to take into account the uncertainties in the input parameters, e.g. failure frequencies, costs, etc.

This report gives a brief description of the modelling approach and the relationship between the applied models.

3. INTRODUCTION INTO MODELLING O&M ASPECTS

3.1 General

Generally, the costs for maintaining an offshore wind farm will be determined by both corrective and preventive maintenance. In Fig. 3.1, the costs over the lifetime of the wind turbines are presented schematically. One can identify two major phases:

1. This phase usually includes the commissioning period and has duration of sometimes two, but mostly five years.
2. This phase applies to the remaining lifetime of a wind farm, which is approximately fifteen years and includes one or more major overhauls around year 7 to 13.

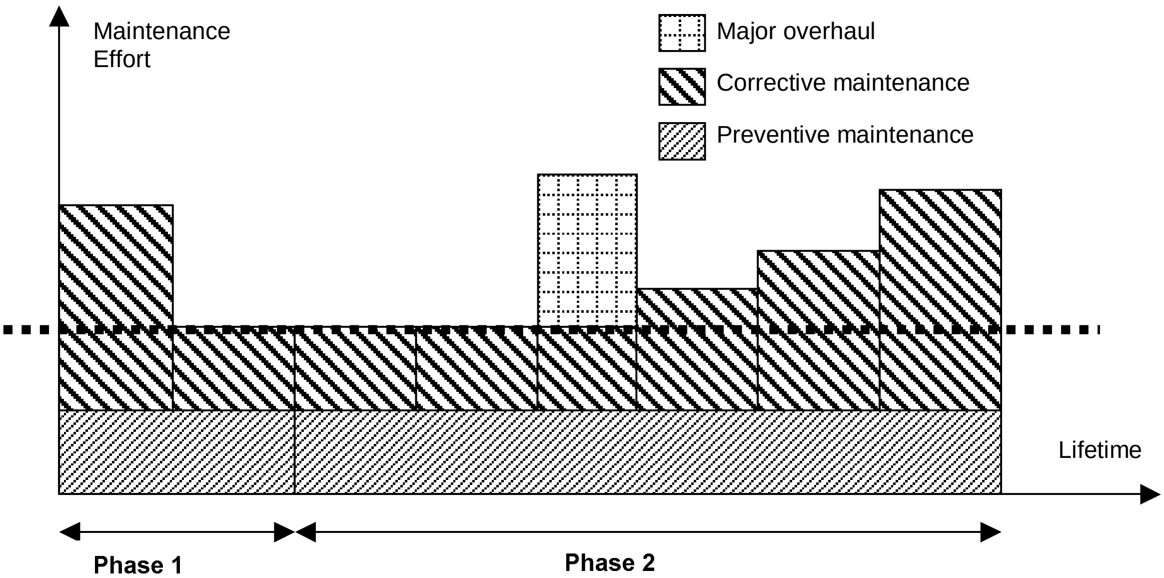

Fig. 3.1: *Schematic overview of the maintenance effort over the lifetime of a turbine. In reality, none of the lines is constant; the actual maintenance effort will vary from year to year.*

Phase 1: During the commissioning period, the burn-in problems usually require additional maintenance effort (and thus costs). Time should be spent on finding the right settings of software, changing minor production errors, etc. The turbine manufacturer usually provides a contract to the customer with a fixed price for the first five years of operation. The contract includes commissioning, preventive and corrective maintenance, warranties and machine damage.

Phase 2: After about 10 years of operation, it is very likely that some of the main systems of the turbines should be revised, e.g. pitch motors, hydraulic pumps, lubrication systems, etc. With the offshore turbines, no experience is available up to now on how often a major overhaul should be carried out. The exact point in time at which the overhaul(s) should take place is presently not known, perhaps after 7 years, 15 years, or not at all. The major overhaul in fact is to be considered as “condition based maintenance”. At the end of the lifetime it is likely that more corrective maintenance is required than in the beginning of the lifetime. It is presently unclear how much more this will be.

3.2 Modelling Procedure

To make an estimate of the effort that is needed to maintain an offshore wind farm, a possible model is available to determine the long term average effort and costs that are needed and to calculate the associated downtime and revenue losses. The model also takes into account the aspects which can be covered with warranties or all-inclusive contracts and which are sometimes not visible for the wind farm owners.

The process of cost modelling is illustrated in Fig. 3.2. To analyse the effort for preventive maintenance, a deterministic model is being used and will not be discussed further on. This document is focused on the probabilistic model to analyse the corrective maintenance aspects. The fact that the model is probabilistic offers the possibility to take into account the stochastic behaviour of the wind and wave climate at the site of the wind farm and uncertainties in e.g. the failure behaviour of the turbines.

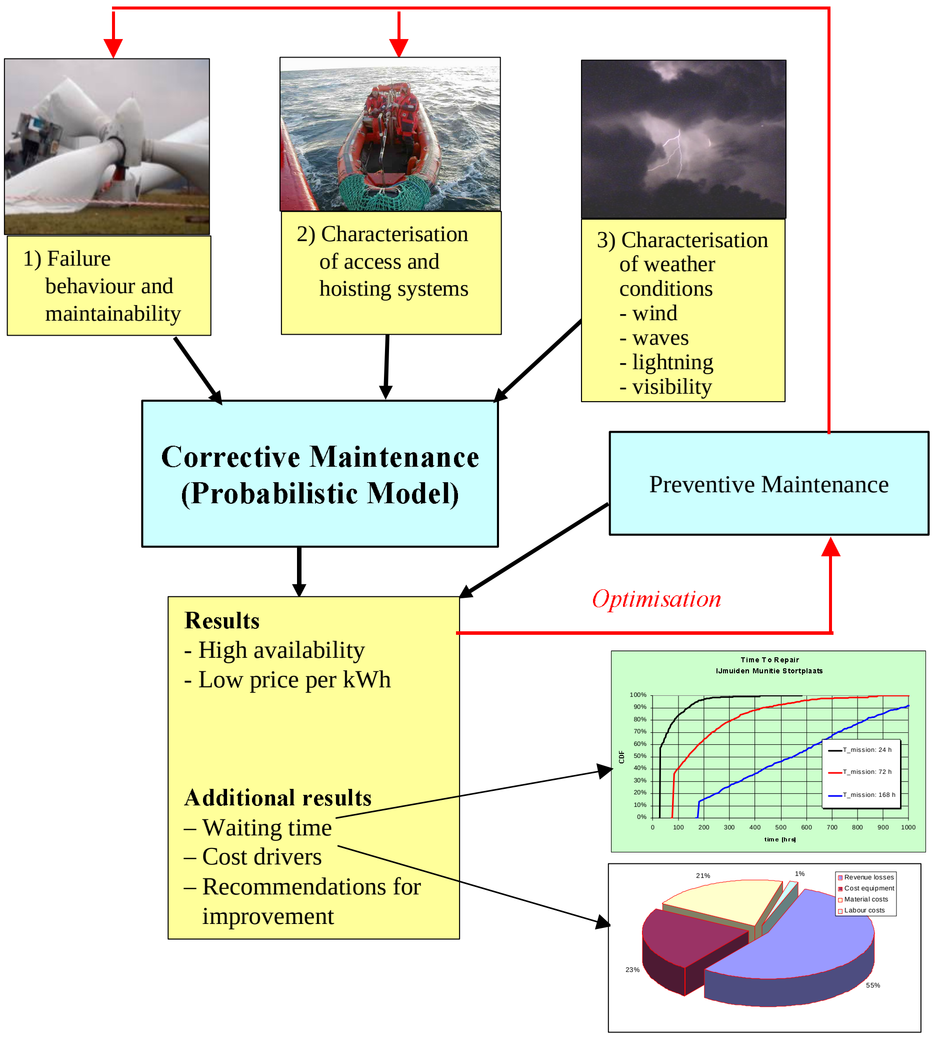

Fig. 3.2: *Cost model for determining the maintenance costs and the availability of an offshore wind farm*

3.3 Wind Turbine Failure and Resulting Repair Action

In this section, a description is given of a maintenance action needed to repair a wind turbine after it has failed. Aspects relevant for the model will be mentioned. In general it can be stated that the central operation office will be informed that an alarm has been triggered. Once the operator has notified the alarm, he has to decide whether the turbine can be restarted remotely or that a repair is necessary to determine whether the wind turbine can be restarted without maintenance or maintenance is required first. If repair is necessary the operator needs to organise the repair action, mobilise crew, a boat and if necessary spare parts and large hoisting equipment. This process is depicted in Fig. 3.3 and is the starting-point for the development of the structure of the cost model.

The Time To Repair (TTR) can be split up into four time intervals.

1. The interval *T_logistics* denotes the period of time between the wind turbine was shut down and the repair crew is organised and ready to travel to the turbine for repair. In this period, also the time needed to organise equipment and spare parts is considered. So the length of this interval depends on the availability of an inspection team, the availability of materials, and the availability of equipment for travelling and hoisting. The availability of personnel or equipment strongly depends on the company policy. Own personnel or third parties can do the maintenance, equipment can be owned or hired, etc.
2. Once the repair crew and the equipment for travelling are in principle ready for take off it might happen that the weather forecast during the period the mission has to be carried out *(T_mission-insp*) is such that it is not allowed or irresponsible to take off. This interval is denoted as *T_wait-insp*. The length of this interval is dependent on the duration of the mission and the device planned. For a helicopter only the wind speed is of importance, while for a (supply) boat both the wind speed and the wave height have to be less than specified maximum values. Due to its dependency on weather conditions (wind speed and or wave height) the duration of this interval shows large scatter and should be defined as a stochastic quantity. The treatment of the weather windows will be discussed in more detail in Section 3.6.
3. The interval *T_travel* denotes the time needed to travel to the wind turbine that has to be inspected.
4. The interval *T_repair* is the time needed to carry out the repair.

The total costs due to the above described maintenance action to repair lightning damage consist of:

- cost of equipment;
- cost of personnel for inspection and repair;
- cost of spare parts;
- loss of revenues determined by the total downtime (or: Time To Repair, TTR) and the wind speed during the downtime.

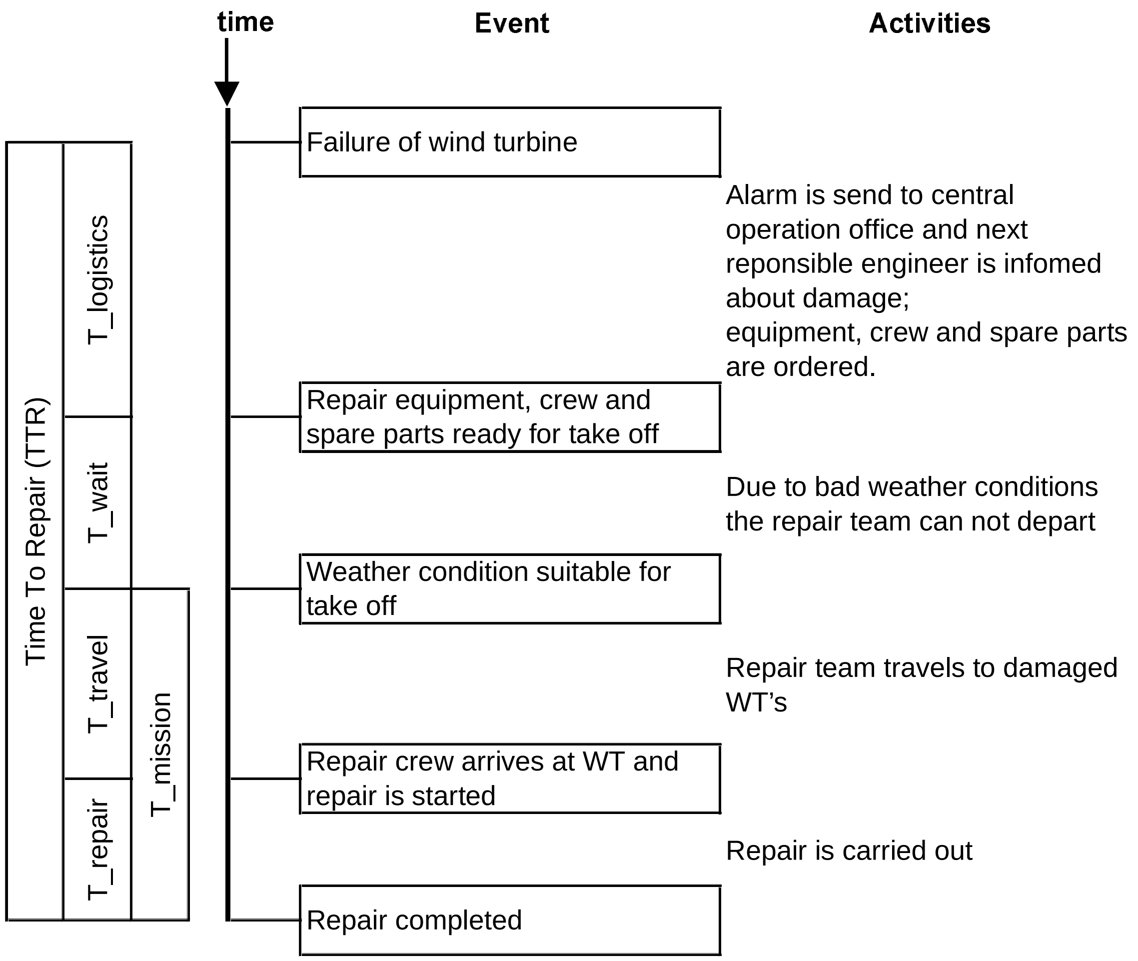

Fig. 3.3: *Repair process of lightning damage.*

3.4 Failure Behaviour of Turbine

For onshore wind turbines, a lot of operating experience has been collected and analysed. Since onshore wind energy is a mature branch of industry, reliable data is available. In Table 3.1 some key figures are presented, mainly derived from [1], [2], and [4].

Table 3.1: *Key figures for O&M onshore (Investment costs ≈ € 850/ kW)*

Failure rate	1,5 to 4 failures per year
Availability	> 98 %
Service contract	0,5 to 0,8 % of invest. costs per year 5 to 8 €/kW
Service contract incl. warranty	1,0 to 1,6 % of invest. costs per year 10 to 16 €/kW
Costs for corrective maint. year 5	0,5 to 0,8 % of invest. costs per year 5 to 8 €/kW
Costs for corrective maint. year 15	4 to 6 % of invest. costs per year 40 to 60 €/kW
Average O&M costs over lifetime	2 to 4 % of invest. costs per year
Insurance costs	5 to 8 €/kW (machine damage, third parties, revenue losses)
LPC (O&M costs)	5 to 10% of kWh price (of which half due to maintenance.) 0.5 (year 1) to 1.5 (year 10) €cent/kWh

From failure statistics as e.g. presented in [1] it is learned that most failures have to do with the control system and the electrical system, see Fig. 3.4.

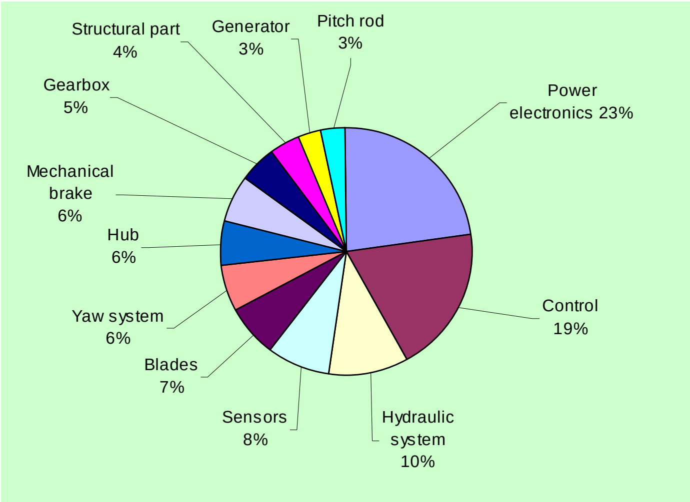

Fig. 3.4: *Distribution of failures per main system [1]*

The consequences of all failures are not equal. The *failure modes* determine what type of repair strategy is required and thus determine the costs. E.g. a generator may fail in various modes (failure of bearings, burned windings, wear of carbon brushes, etc.) and the repair actions can vary for instance between replacement of carbon brushes and replacement of the entire generator. In fact, for all components and for each failure mode the resulting repair actions need to be described in great detail. To model these maintenance actions and to analyse the costs and downtimes, the maintenance actions can be categorised into 3 to 6 categories. Four possible categories are given below.

Cat. 1: Inspection and repair.
Cat. 2: Replacements of small parts;
Cat. 3: Replacement of large components with internal crane;
Cat. 4: Replacement of rotor and nacelle with external crane;

In the modelling process, a failure rate is assigned to each component or system, and per component or system a sub division is made into the four categories. E.g., the failure rate of a generator is 2 per year, and 60 % of the failures is expected to fall into category 1 (inspection and repair), 30 % into category 2, and 10 % into category 3. The expected occurrence frequencies per year of the maintenance categories due to generator failures now become:

Cat. 1: 2*0.6 = 1.2
Cat. 2: 2*0.3 = 0.6
Cat. 3: 2*0.1 = 0.2
Cat. 4: 0

Subsequently, this is done for all repairable items. For each category a number of aspects need to be specified e.g., the materials and their costs, the costs of labour, and the costs of the equipment needed. Furthermore the time to repair, the logistic time of spare parts, the logistic time for equipment, etc. needs to be specified for each category.

3.5 Access and Hoisting Systems

Offshore wind farms are difficult to access. Onshore, repair can be done at almost any time. A technician can drive to the turbine, carry out repair and restart the turbine. Offshore, a boat or helicopter should be mobilized and repair can only be done if the weather conditions (wind speed and wave height) are good enough to travel to the turbine and to access the turbines.

If a certain access or hoisting system is going to be used for a certain maintenance action, at least the following aspects have influence on the repair costs and the downtime and should be considered in the cost model.

- weather window, especially wave height and wind speed, during which the systems can be used (aspects like fog and ice are of importance also, but are not considered in the current version of the cost model);
- costs of the system per hour or per day and the costs for mobilisation (MOB/DEMOB);
- logistics time for arranging the system;
- travelling speed;
- capabilities, e.g. the maximum number of maintenance technicians or personnel that can be transported, maximum hoisting capacity and height, maximum load that can be transferred.

3.6 Weather Windows

The maximum wave height H_s and wind speed V_w during which a certain maintenance action can be performed are of large influence on the downtime after a failure. If a failure occurs, repair can only start if the weather conditions are good. If not, the repair has to be postponed. It is not only sufficient that the right weather window occurs, the duration should also be long enough to make sure that the repair can be carried out.

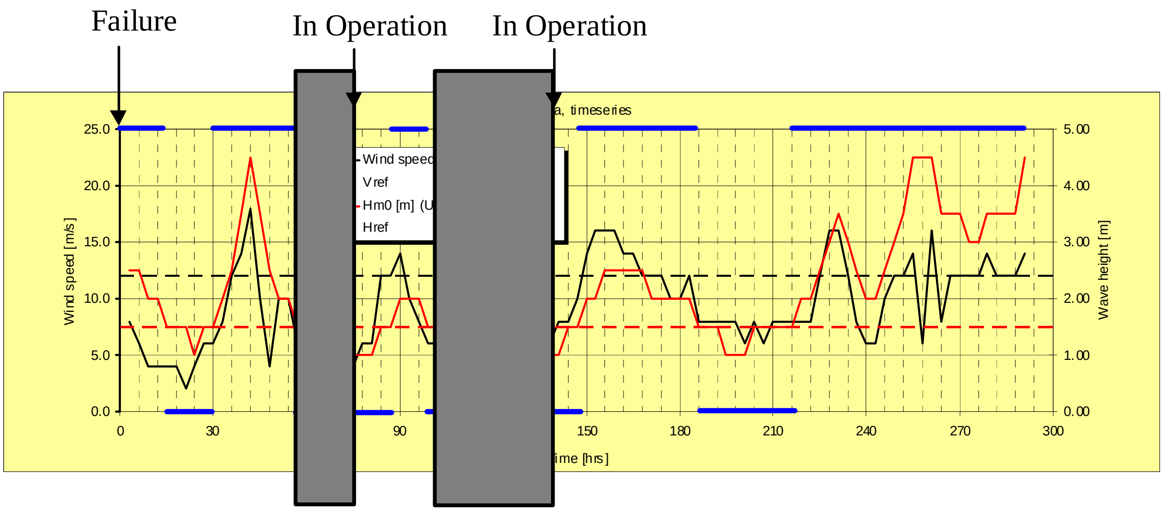

Fig. 3.5: *Example of determination of waiting time for a maintenance action that can be carried out if $H_s \leq 1.5$ m and $V_w \leq 12$ m/s and the duration is 20 hrs or 40 hrs.*

To model this, long term wind and wave data representative for the location of the wind farm should be analysed to search for the following variables:

1. number of times that suitable weather windows occur, i.e. H_s and V_w are below the maximum values;
2. duration of these suitable weather windows;
3. number of times that weather windows occur during which maintenance cannot be carried out;
4. duration of these weather windows that in fact determine the waiting time.

To illustrate this, a time series of wind and wave data is plotted in Fig. 2.5. Lets assume a repair action that can be carried out only if both $H_s \leq 1.5$ m and $V_w \leq 12$ m/s. If the failure occurs at t = 0, it takes approximately 96 hours before a repair action of 40 hours can be carried out. If the duration is only 20 hours, the waiting time is approximately 56 hours. Since the failure can occur at any point in time, the waiting time until a suitable weather window occurs in fact is a stochastic variable. If another device is going to be used for maintenance and repair, again all the waiting time needs to be determined and described as a stochastic variable.

Failure

Turbine in operation

Time To Repair (TTR)			
T_logistics	*T_wait*	*T_mission*	
		T_travel	*T_repair*
Arrangement of device, personnel and spare parts	Waiting due to bad weather conditions	Trip to failed WT	Repair of WT

Case study

- H_{max} = 1.5 m
- V_{max} = 12 m/s
- *T_logistics* = 0
- *T-mission* = 24 hr
  72 hr
  168 hr
- ***TTR*** =

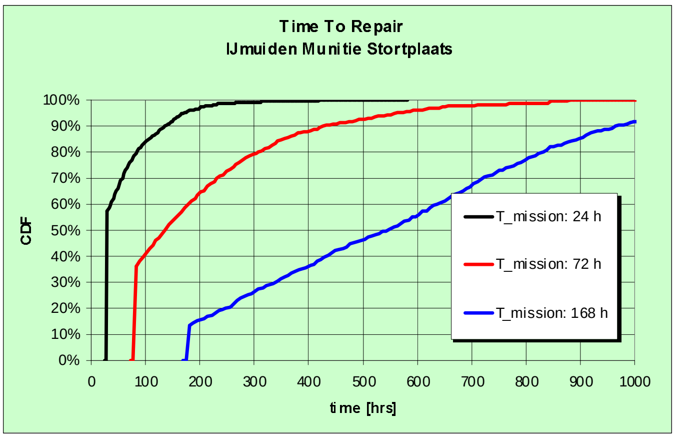

Fig. 3.6: *Example of cumulative density functions (CDF) to represent the time to repair. These CDF's are necessary to model the stochastic behaviour of waiting time for offshore wind farms and the associated downtime and costs.*

In Fig. 3.6, the determination of the time to repair (TTR) is given for three repair actions with a total mission time, *T_mission*, of 1 day, 3 days, and 1 week. To carry out the repair action, a device will be used which can operate if the significant wave height is less than 1.5 m and the wind speed is less than 12 m/s. (In this example, the logistics time, *T_logistics*, has been set to zero.) For this example, 20 years wind and wave data at the North Sea have been analysed and it is concluded among others that.

- In almost 60% of the cases, a repair with duration of 1 day can be carried out immediately and the time to repair equals the mission time. However, in approximately 10% of the cases, a total repair time of more than 130 hours is needed.
- Waiting for suitable weather windows with duration of one week may take a long time. In more than 50% of the cases, the total repair time will be 540 hours and more!

4. PROGRAM STRUCTURE

4.1 Overview of programs

In Chapter 3 it is outlined that to determine the cost of corrective maintenance, amongst others the time to repair (TTR) is of importance because this quantity determines not only the revenue losses but also other costs may increase with increasing waiting time. For instance the costs of equipment, when it has to stay in the harbour due to bad weather conditions after it has been mobilized and is ready for take off.

The TTR can be split up in several phases as already discussed in Chapter 3.

T_logistics: In the logistic phase, all arrangements are made for the spare parts, the personnel, and the device required. In case of a certain type of damage one or more specific devices (supplier, crane ship, helicopter, etc.) will be required for transportation of technicians and spare parts, and possibly for support during repair, for instance for hoisting.

T_wait: After all arrangements have been made during the logistic phase, it might happen that a device cannot leave the port due to bad weather conditions. It has to wait until the characteristic wave height H_s, and the wind speed V_w are more benign than the maximum values $H_{s,max}$ and $V_{w,max}$ required to carry out the mission.

T_mission: The mission phase comprises the time it takes to travel to the wind turbine (T_travel) and the time needed for the actual repair (T_repair).

The duration of the phase in which a device has to wait for suitable weather conditions, depends on the duration of the whole mission (T_mission) and the expected weather conditions during the mission. The waiting time (T_wait) is a stochastic quantity mainly due to dependence on the weather conditions, notably wave height and wind speed. The other phases, T_logistics and T_mission can be stochastic quantities also, but the variability in T_wait is by far the greatest. Hence TTR is a stochastic quantity mainly due to its dependence on T_wait. As an example the cumulative distribution function (CDF) of the TTR is depicted in Fig. 2.6 for three different missions with a device that can operate in a weather window with wind speed less than 12 m/s and wave height less than 1.5 m.

In the cost model at least the mean value of the waiting time is required, because it is used to determine the long-term average annual costs. However it is also possible to carry out a probabilistic cost analysis by which the uncertainty in the calculated long-term average annual cost can be quantified. That's why this option provides the opportunity to obtain insight in the most important uncertainties in the cost model. For the probabilistic version of the cost model a number of input variables are treated as a stochastic variable. This also holds for the waiting time, and hence the statistical variability in the waiting time has to be characterised. This can be done by characterising the cumulative distribution function (CDF) with its statistical parameters: the mean value and the standard deviation. To determine the mean value and the standard deviation of the waiting time the times series of the wind speed and the wave height have to be analysed. However it is not practical to work with measured time series in the costs model itself because of the large amount of data to be handled repeatedly. To avoid the problem of handling large amounts of data the mean value and the standard deviation of the waiting time are determined as a polynomial function of the mission time and the coefficients of these polynomials are used as input in the cost model to assess the waiting time. For this reason two pre-processing programs have been developed, WeWiCDF and Twait.

The program WeWiCDF analyses the time series of the wind speed and wave height for a certain weather window, defined by the maximum allowable wind speed $V_{w,max}$ and the maximum allowable significant wave height $H_{s,max}$. First, the time series are subdivided into two types of complementary time intervals. During the time intervals denoted as low, both the wind speed and the wave height are less than the maximum allowable value for the weather window considered, and hence repair might be possible when the length of the interval is long enough. On the other hand during the time intervals denoted as high, repair is not possible because the wind speed or the wave height exceed the maximum allowable value. In [2] it is shown that the number and the duration of these low and high intervals can be described by a Weibull distribution and the Weibull parameters are determined in the program WeWiCDF.

For a certain weather window, characterized by the Weibull parameters determined in WeWiCDF, the program Twait calculates the waiting time as function of the mission time by means of Monte Carlo simulations. For this purpose the Excel add-in @Risk is used. Furthermore the mean value and the standard deviation of the waiting time T_wait are determined as function of the mission times and these values are fitted by a 3rd or a 2nd order polynomial.

Besides data from Twait, data concerning the wind turbines and their failure behaviour, the wind farm and the O&M approach have to be defined in the cost model “CostDeter” and “CostProb” The working of and the data needed in the three programs are described in detail in the Chapters 4 through 6. The data flow between the different programs is depicted in Fig. 4.1.

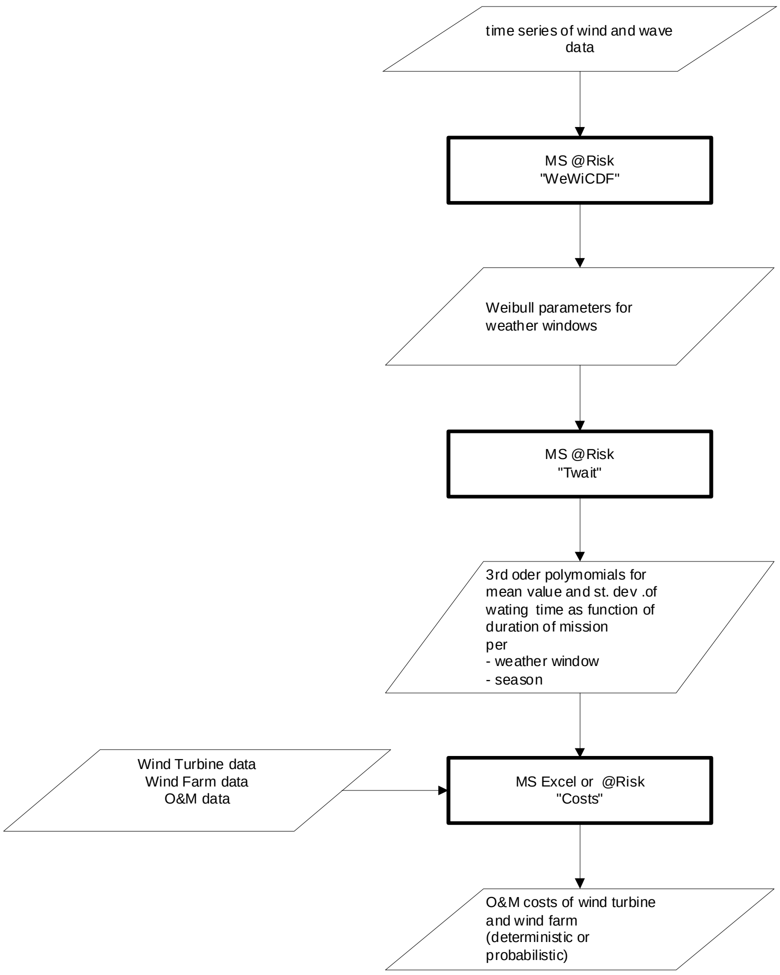

Figure 4.1 *Flow chart and relation between the programs that comprise the cost modeling*

4.2 Input needed for cost optimisation model.

The maintenance activities cost can be estimated with the previous described model. Necessary input for the calculation procedure as shown in fig 4.1 is explained here.

Long term wind and wave measurements of the specific location. On the basis of these data the weather windows can be calculated as a function of wave height and period and wind speed. Both annual and seasonal distributions are calculated. The weather windows are presented in Weibull distribution functions.
This information is further transformed into waiting times and repair times for given failures and problems. These times are determined as 3rd order polynomials for main values and standard deviations as a function of the mission duration (depending on type of failure and repair time) per weather window and per season.
When this information is available for a given site and given offshore wind farm, O&M costs can be estimated deterministically and stochastically.

In the deterministic cost model the level of repairable items the long-term yearly average costs and downtimes are being calculated in a straightforward way. Some work sheets that are being used in the model are explained below for illustration purposes.

Name of worksheet	**Function**
Log file	Sheet to record any modification in the model, relevant modifications in the input parameters, or changes in the scenario.
Equipment	Input sheets in which the various types of equipment can be defined that can be used for access of personnel and transportation and hoisting of spare parts. The definition includes among others the specification of the weather windows, costs, waiting time and mobilisation time.
Wind	Input sheet to define the average wind speed per year and per season. This information is used to calculate the capacity factors in the worksheet Wind Farm. These capacity factors are necessary to determine the energy output and the lost revenues.
Wind Farm	Input sheet with general information on the wind farm (name, capacity factor per season) and the turbine type (hub height, investment costs, etc.),
Fault Types	Input sheet in which the failure rate per main component should be defined and the severity. To define the severity, several classes can be defined to quantify the costs for personnel, materials, and equipment.
Twait	Input sheet with output of program **Twait**, viz. 2nd or 3rd order polynomials for the mean of the waiting time and the standard deviation.
Calculated Costs per annum or season_	Summary sheets with detailed calculation results and intermediate results per year and per season. They can be used to make various cross sections through the results, e.g. costs per device, costs per main system, etc.
Overview Results	Summary sheet with the calculation results, a.o. costs, downtime, and revenue losses; per annum and per season.

The model is based on deterministic input variables. For those input variables with inherent variability (f.i. the waiting time due to its dependence on the weather conditions) or with statistical uncertainty (f.i. the prices of equipment etc.) the mean value or the most likely value is used. In the probabilistic version of the cost model, the above-mentioned uncertainties can be taken into account by applying the @Risk module, so the uncertainty in the calculated results can be quantified and evaluated.

5. REFERENCES

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Abstract

A Probabilistic O&M Cost Optimisation model is presented, with which the operation and maintenance strategy of offshore windfarms can be improved. Basis for the application of this model is an extensive analysis of the fault detection and repair cycle offshore. A calculation model has been added.

Key words Offshore windfarm, O&M cost, probabilistic model

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