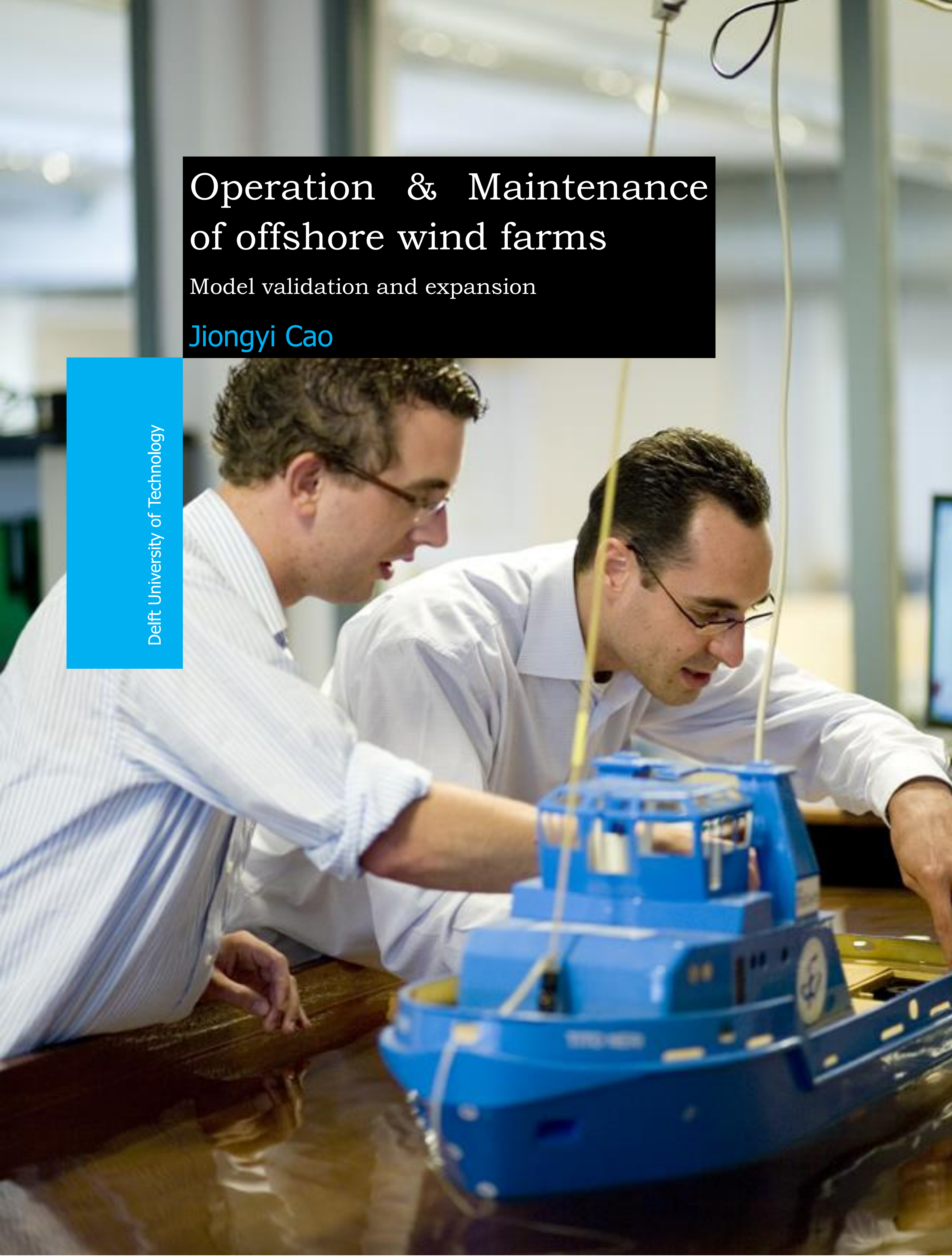
Operation & Maintenance of offshore wind farms

Model validation and expansion

Jiongyi Cao

Delft University of Technology



Operation & Maintenance of Offshore Wind Farms

Model Validation and Expansion

Master of Science Thesis

For the degree of Master of Science in Sustainable Energy Technology

at Delft University of Technology

Jiongyi Cao

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Faculty of Applied Sciences (TNW) · Delft University of Technology

Delft University of Technology
Department of
Aerospace Engineering

The undersigned hereby certify that they have read and recommend to the Faculty of Applied Sciences (TNW) for acceptance a thesis entitled
Operation & Maintenance of Offshore Wind Farms
By

Jiongyi Cao

in partial fulfillment of the requirements for the degree of
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Dated	May 2015	
Supervisor:	Dr.ir. M.B. Zaaijer	TU Delft
Thesis committee:	Prof.dr. G.J.W. van Bussel	TU Delft
	Dr.ir. M.B. Zaaijer	TU Delft
	Dr.ir. O. Morales-Nápoles	TU Delft

TU Delft Delft University of Technology

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Abstract

Wind energy is considered to be one of the most promising sustainable energies in the future. In Europe, wind energy industries have developed rapidly, over the last decade, wind power installation had a 10% annual growth rate. EWEA estimates a 230 GW installation of wind power in 2020 in Europe, among which 40 GW will be offshore wind power. Currently 117 GW wind power is installed, among which offshore wind accounts for 6.6 GW. Therefore, there is a large demand for wind farm construction both onshore and offshore.

In this thesis, firstly, work will focus on validation of TeamPlay, which is a statistic model for O&M of offshore wind farms. In this model, downtime and number of failures are determined by using expected values, and wind farm availability and cost of energy are calculated afterwards. Validations will be made after sufficient understanding of these maintenance theories and concepts. A specific offshore wind farm is selected as an example for validation. The official operation and failure data is collected and compared with results from the model. Finally, these results are analyzed and discussed.

After validation, the current model will be expanded with a model for using both vessels and helicopters for access in order to increase the accessibility and the overall availability of wind farms. Operation costs are expected to increase since helicopters have a higher daily rate than that of a vessel. The combined access model provides the operators with an additional option for accessing offshore wind farms. A more suitable selection can be made based on different operation strategies.

As an additional part of this thesis, spare parts stock is investigated. The number of components required in stock is calculated based on the lowest LPC of energy. With this stock model, TeamPlay gives a more accurate result for availability and levelised production costs of energy.

Jiongyi Cao
Delft, May 2015

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Acronyms

O&M	Operation and Maintenance
OWEZ	Offshore Wind Farm Egmond aan Zee
LPC	Levelised Production Costs
NPV	Net Present Value
MTTR	Mean Time To Repair
MTBF	Mean Time Between Failures
LRU	Line Replaceable Units
DU	Discardable Units
TAT	Turn Around Time
EWEA	The Europe Wind Energy Association

Chapter 1 Introduction

1.1 Wind energy development

Nowadays, with the depletion of fossil fuels, sustainable energy gathers increasing interests. The world needs to transform from its current unsustainable energy pattern to a future fueled by renewable energy. Among them, wind energy is considered as one of the most promising large-scale renewable sources to replace fossil fuels effectively. Over the last 13 years, the installed capacity of wind power has greatly increased with an annual growth rate of 10%, from 3.2 GW in 2000 to 11.2 GW in 2013 (Anonymous, 2014a). Since 2000, over 28% of new installed capacity has been wind power. Last year, this number even reached 32% (Anonymous, 2014a). In Europe, the total installed wind energy capacity is now 117.3 GW, among which 6.6 GW is offshore wind (Anonymous, 2014a). EWEA estimates that 230 GW of wind power will be installed by 2020, of which 40 GW will be offshore (Anonymous, 2012). Each European country has its own objectives. For example, in 2020, UK expects 13 GW of installed offshore capacity. Furthermore, Germany plans to have 10 GW installed by that time. The Netherlands has set a target for 5.1 GW installed capacity by 2020 (Anonymous, 2012).

In the development of onshore wind power, there are however some drawbacks. Onshore wind farms require approximately 0.1 km^2 per MW. Additionally, turbines produce noise around 100 dB when they are operating at rated speed (Zaaijer M.B., 2013a). These drawbacks become the most important reasons for the population to oppose wind power. Compared with onshore wind, offshore wind has some advantages. Offshore wind power has less visual impact, land usage and noise concerns. Moreover, higher average wind speed and lower turbulence intensity, all together make offshore wind more attractive.

Meanwhile, offshore wind is faced with some other challenges. One of the main barriers of large-scale implementation is the high cost of energy production. Currently, operation and maintenance cost of offshore wind farm accounts for 30% of the energy cost. Nowadays, researchers are engaged in optimizing O&M strategies to increase availability of wind farms and cut down the O&M cost. These efforts not only determine whether offshore wind is competitive or not, but also affect its potential implementation.

The current focus of researchers is set on creating simulation models that help optimize O&M strategies. Matthias Hofmann, for example, investigated a model based on a time-sequential event-based Monte Carlo technique (Hofmann M et al, 2013). He took into consideration weather uncertainty and other relevant aspects for operational phase. Furthermore different vessel concepts for accessing the wind farm are simulated by using this model. Second, Matti Scheu developed a MATLAB tool to simulate the operating phase with special emphasis toward the modeling of failure and repair (Scheu M et al, 2012). These simulation approaches are however quite time consuming, especially for large data cases. A statistical model might be more efficient for use in real operation. Such a statistical model, TeamPlay, is developed by Michiel B. Zaaijer, and is used to optimize the O&M strategies (Zaaijer M.B., 2013b). However, this model is not fully validated yet and is on suitable for one type of strategy.

1.2 Research objectives

Since this statistical model is now at its initial stage, the first objective is to validate the model. Efforts will be made to show whether the output generated from the model with current strategy is valid or not. This contains three parts. The first part is comparison between modelled result and reported data. The second part is validation from logical aspects. The third part is comparison with another model. Another objective is to expand the statistical model. A new combined access method, vessel and helicopter access, will be added. It will be assessed to see whether it is efficient and economically favorable. Moreover, stock management will also be added to make the model more realistic. The influence of stock management will be discussed. Finally, the improved model will be used in a case study to provide the optimized O&M strategies.

1.3 Approach and methodology

1.3.1 Research Approach

To achieve the objectives above, one needs first understand the basic offshore maintenance concepts. Some lectures and literatures related to wind energy provide with the background knowledge. One can prepare the background knowledge through study of literatures. Afterwards, one needs to collect related data to validate the model. The detailed working process can be seen in figure 1-1 below.

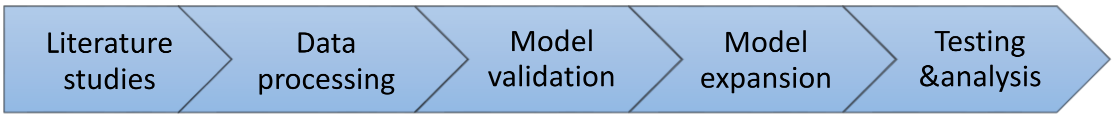


Figure 1-1 Working process

1.3.2 Literature studies

Literature studies are mainly concentrated on offshore maintenance theory. How the availability is affected will be investigated, then other possible alternatives can be summarized and used in the later model improvement.

1.3.3 Data processing

Data collection and processing is an important part of this report. Real operation data will be collected to provide with same inputs as much as possible. Also some calculations will be made to get further information from the initial data. Operation data of Windpark Egmond aan Zee (OWEZ) is chosen for the model validation.

1.3.4 Model validation

Model validation will focus on the availability comparison between reported data and model result. Specific categories will be compared, and analyses and discussions will be given.

1.3.5 Model expansion

New strategy will be added to the model to make the optimization more comprehensive with vessel and helicopter access strategy. The operator then can choose the access strategy according to real weather condition during the maintenance work. Stock management will also be discussed. It will provide the operator with the information of extra costs of stock and influence on cost of energy, and thus it gives the operator a more comprehensive result.

1.3.6 Testing and analysis

The new added strategies also need test and analysis about their economic aspects and efficiency. Some different scenarios will be used to test the new model. The result can provide users with an optimized result, and the users can make choice according to real situation.

1.4 Outline of the thesis report

In chapter 2, some background information of offshore wind development will be presented, including offshore wind history, basic maintenance concepts, etc. In chapter 3, the main activity is to figure out the train of thought of the model, such as how the inputs affect the outputs, what kinds of assumptions have been made, for an expected output, which kind of parameters should be controlled etc. Then, the data needed for the model as input will be collected, such as weather data, failure type, mean time to repair etc. In chapter 4, on the basis of studying the model and data collection, one can get outputs. The outputs will be first compared with the reported data to see whether it matches the real situation. Then the model will be evaluated logically to avoid evident unreasonable outcomes. Afterwards, outputs will be compared with that from another simulation model to see whether they match each other. Some differences are expected, so analyses will be naturally followed by justification. To achieve the second objective, in chapter 5, a new strategy, access by vessel and helicopter, will be introduced into to the model to expand it. Afterwards, evaluation will be made to see whether the new idea is efficient and economical. Chapter 6 will discuss the stock strategy, and a solution of stock of OWEZ will be given as an example. Chapter 7 will provide the conclusions and advices for future work.

Chapter 2 Offshore Wind Farms

2.1 Offshore wind history

The first attempt of building offshore wind turbines was made in 1990. The Windworld 220 KW machine, erected close to the Swedish harbor at Nogersund in the Blekinge region, was considered to be the first modern demonstration. This turbine was used to monitor the effect on the environment and public acceptance. During its operation period, it achieved an availability of 95%. Afterwards, the Danish built the first offshore wind farm in 1991. This wind farm was composed of 11 Bonus turbines with a rated power of 450 KW. It was located between 1.5 and 3 km off the Danish coast at Vindeby on the island of Lolland (Olsen F et al, 1993). In 2002, the first large-scale offshore wind farm, Horns Rev, was built in Denmark. It consisted of 80 Vestas turbine with a rated power of 2 MW, and the distance to shore is 14 km. The first offshore wind farm in the Netherlands was built in 2006, named OWEZ. It was composed of 36 Vestas turbines, and the farm capacity was 108 MW.

2.2 Offshore wind farm availability

Wind farms become larger and larger, which makes the situation more complicated. A large number of aspects will affect the availability of a wind farm. Besides the properties of the wind turbines, other external aspects also play a role in the actual availability. The schematic figure below shows in a clearer way.

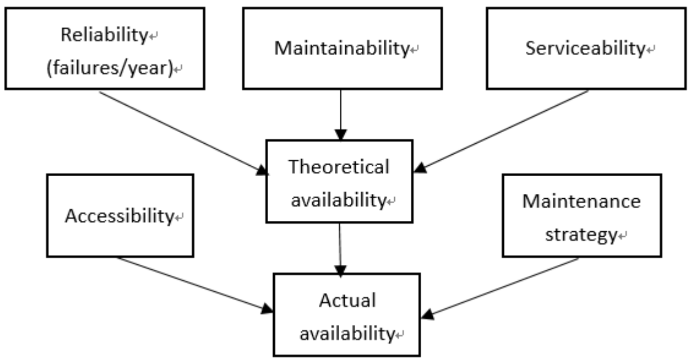


Figure 2-1 Theoretical and actual availability (van Bussel G.J.W., 2001)

Reliability is the probability that a system is able to work as prescribed over a certain time interval (Grievink J et al, 1993). For a wind turbine, reliability represents the percentage that it can function properly in a time period. Maintainability represents the ease of repair work. It can be expressed in terms of hours needed to complete a repair action. Serviceability represents the ease of scheduled service in a similar way. These three aspects together determine the theoretical availability of the wind farm. However, one should also consider the other two aspects, accessibility and maintenance strategy. Accessibility is the percentage of time that an offshore construction can be approached. It depends on the access methods that one chooses. Boat has a lower accessibility compared to offshore access system and helicopter. Maintenance strategy contains crew deployment, lifting equipment deployment and spare parts stock, etc. All aspects above determine the actual availability.

2.3 Offshore maintenance

Maintenance activities can be divided into two parts, corrective maintenance and preventive maintenance. See details in figure 2-1. Corrective maintenance is taken only after failures are detected (one failure is also possible). Preventive maintenance is taken to avoid failure. It is also composed of two parts, scheduled maintenance and condition-based maintenance. Scheduled maintenance is taken on fixed times, usually 2 times a year, and the chosen time is the most favorable accessible period with low wind speed and wave height. Condition-based maintenance is taken on the basis of the actual health of components, and the detections can be done by online monitoring systems.

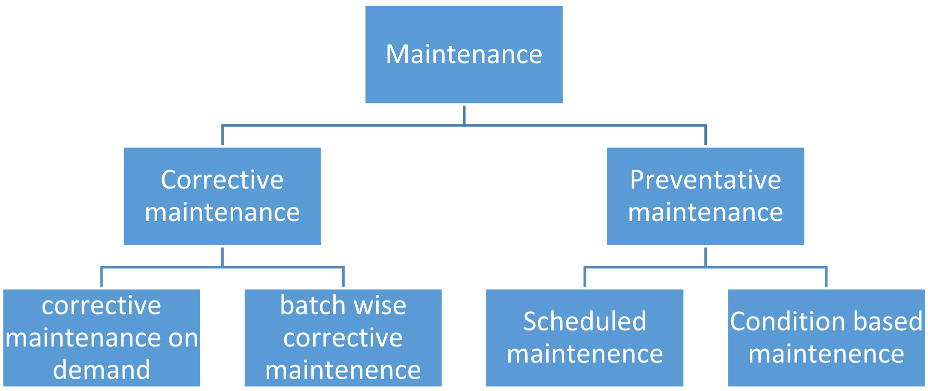


Figure 2-1 Maintenance policies (van Bussel G.J.W., 2013, with adaptations)

To choose the appropriate maintenance strategy, the intentions of carrying out maintenance have to be defined. There are two basic approaches, the reliability-based and cost-based approach. The first one is applied in systems that could not afford failure and damage, such as nuclear power plants. In these systems, reliability is much more important than costs. The other approach is cost-orientated. Failure and repair are taken into consideration before planning the next maintenance activity. Since major failures of offshore wind farms mainly lead to loss of production rather than damage to human beings, cost-based approach is preferred in offshore maintenance policy.

On the other hand, activities under cost-based approach may vary. Using corrective maintenance is the simplest strategy. However, when failures occur to some minor components, it will not lead to stop at once, but it will cause escalated damage to major components and lead to stop. These failures often happen during the periods with large wind loads, these periods happen to be inaccessible. Thus, using only corrective maintenance leads to larger repair cost and loss of production. As for preventive maintenance, when a scheduled maintenance is taking, extensive inspection to other components can be performed in a relatively low additional cost (Nielsen J.J et al, 2011). Therefore, a good strategy is not a single strategy but rather a comprehensive one.

2.4 Contribution of O&M to cost of energy

In operation and maintenance activities, many factors directly affect the cost. In operation phase, costs depend on taxes, liability insurance, administration fee and land rent. Taxes are paid to the local authority according to the net installed capacity. Insurance costs include public liability insurance, technical risks and statutory inspection costs. Administration fee is the cost for management of wind farms. If an onshore base for operating the wind farm is necessary, then the land rent has to be considered. Some countries subsidize offshore wind as well, such as Dutch MEP tariff, but it has expired after 2006 (Anonymous, 2010b). Due to the uncertainty, it is not considered in this report.

Maintenance costs consist of component and material costs, personnel costs, access costs as well as maintenance down time costs. Material and component costs include costs for the purchase of new components and costs of stock keeping as well. Access costs include vessel rent and transportation costs of material and components. Personnel costs contain costs of labors (on working) and stand-by costs. This is because the crews are notified when a failure is occurred rather than working all the time on the wind farms. The maintenance down time cost is not the direct cost that caused by maintenance activity but rather an implicit cost caused by production loss. Details can be seen in figure 2-2 and figure 2-3.

Having a close look at these costs, one can find some costs are dependent on the strategy, others are more or less fixed. Taxes, insurance and land rent are almost fixed and thus independent of the strategy. Personnel costs, access costs and material and components are variable, thus, become the focus of optimization. The production loss costs is an implicit cost, which should be considered in the levelised production costs (LPC) rather than maintenance cost.

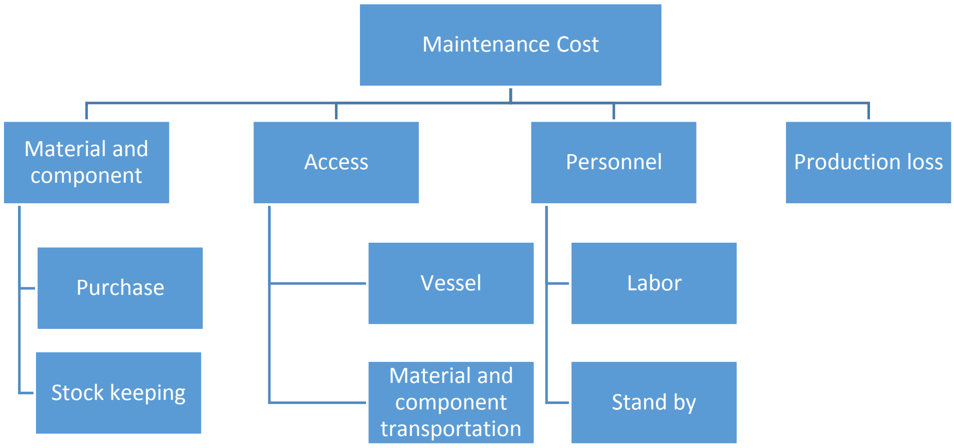


Figure 2-2 Contribution to maintenance costs

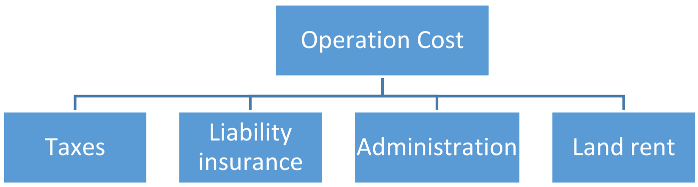


Figure 2-3 Contribution to operation costs

2.4.1 Material and component

When some failures take place, the technical crew need to prepare material and components for repair work. If some components are not available in time, the downtime will increase. In general, the material and components can be divided into three types: risk type items, repairable item and consumable item.

Risk type items have a low probability of failure. They are expensive and the lead times of reorder is usually long, such as blades and generators. Keeping such spare parts in stock is costly, while without stock, the downtime will lead to much loss of production. Thus, keeping them in stock or reordering need careful assessment.

Repairable items can be repaired when maintenance is carried out. Their status can be recorded, and operators can reorder components in advance according to their lead times to reduce stock cost. These components are, e.g. gearbox and inverter.

Consumable items should always be kept in stock, their demands are easily predictable, and they are frequently used and inexpensive, such as lubrication oil.

2.4.2 Access approach

Offshore wind farms are built far from the coast and access is not convenient. Ships or helicopters are needed to transport technical crews and maintenance spare parts to wind farms. Currently, helicopter, gol boat, tender vessel, twin hull, flexible gangway and Ampelmann are being used (van Bussel G.J.W., 2013). Future tends may be offshore O&M basis.

Helicopter is the fastest access approach and the most expensive as well, and it has a large operating window. Experience from real maintenance of Horns Rev, a North Sea wind farm, shows it is able to reach sites 6 out of 7 days in winter. While the accessibility with a boat is 5 out of 7 days, in some worse cases, even 1 out of 7 days (van Bussel G.J.W., 2013). Besides the high cost of helicopters, another drawback is its low load capacity, they usually have a load capacity less than one ton, which leads to their applications only in repairing some failures with small and light components.

A tender vessel is slow but cheap, the operating window is smaller than that of a helicopter. This is because transportations via ships largely dependent on the weather conditions. The wind speed and wave height criteria for different access approaches is shown below in Table 2-1 (Bierbooms W.A.A.M, 2002). Boats have more restrictions on weather than helicopters.

Table 2-1 Preliminary wind speed and wave height criteria for different access systems

Access approach	Significant wave height (m)	Mean(1-hour) wind speed(m/s)
Fictitious	0.75	NA
Rubber boat, jump on ladder	1.5	10
Offshore access system	2	12
Offshore access system + optimistic assumption	3	15
Helicopter	NA	20

Flexible gangway and Ampelmann belong to the category of offshore access system. Ampelmann eliminates any relative motion by taking instant measurements of the ship's motions and then compensates them by using hydraulic cylinders. This makes the top of the Ampelmann remain completely stationary compared to the structure. Then, the offshore gangway can be extended towards the structure so all personnel can access offshore structure safely, even in high wave conditions.

2.4.3 Personnel

Maintenance crews consists of technicians, who are responsible for preventive and corrective maintenance tasks, as well as some administrative tasks. The size of the staff is determined by the installed wind turbines and the work that has to be carried out under own supervision. This is because some work, like blades overhaul can be done at maintenance base or by manufacturer, which decreases the required number of technical crews. Most of the preventive maintenance tasks can be done by one person, such as add lubrication oil, change of oil filters etc., but in real cases, for safety reasons, a 'team' consists of at least two persons is required, usually a mechanic and an electrician.

The operating personnel of transportation devices depends on whether the transportation devices are rented or bought, usually supplier of transportation devices will provide operating personnel. But personnel has to be taken into consideration when boats are self-owned.

According to the maintenance tasks, three employing strategies can be developed. First, if maintenance work load is high, then one can form a permanent maintenance team. Second, one can employ a maintenance team on demand to cover the peak work load that occur seasonally, e.g. maintain several wind turbines after seasonally storm. Third, the complete maintenance work can be rent out to a maintenance company.

2.4.4 Lifting equipment

Wind turbines are composed of many large and heavy components, such as blades, nacelle and generators. These components need to be overhauled and replaced after a period of time. In a five year cycle, these components will be brought to the maintenance base for thorough inspections. In this case, heavy lifting equipment is required since thorough inspections cannot be made when turbines are operating. There are five main lifting equipment available, jack-up barge, crane vessel, liftboat, helicopter and built-in lifting system. When choosing the lifting equipment, one should pay attention to the following factors. The lifting operation should have a large working range of wind speed and wave height. When the lifting equipment is rented from suppliers, it should have a high availability and offer a short lifting operation. Moreover, the water depth of wind farms may also affect the choice of lifting equipment.

Jack-up Barge

Jack-up barge is a platform with 3 or 4 hydraulically actuated legs. A land based crane then can easily be used on this platform, details can be seen in Appendix A. Jack-up barge is used in lifting large components, like rotor hub or the entire nacelle. When lifting work is operating, the wave will not affect the crane. But jack-up barge itself has a wave height limit, thus the wave condition should under the threshold of the selected jack-up barge. The platform should be positioned at a safe distance from wind turbines to ensure that the platforms legs do not damage the foundation of the turbines and the power cables. This require an increased cranage.

Crane vessel

Crane vessel is a ship with a crane specialized in lifting heavy loads. They are widely used in offshore construction and maintenance work. Conventional monohulls are used, but the largest crane vessels are often catamaran or semi-submersible types as they have increased stability. In offshore wind industries, crane vessels are used in lifting heavy components, like generator, gearbox, a single blade, etc.

2.5 Levelised production cost (LPC)

In order to have a comparison between different operation and maintenance strategies as well as a more comprehensive overview of the cost of production, one should apply an economic analysis method. Hereby, levelised production cost (LPC) is chosen. The calculation equation of LPC is shown below:

$$LPC = \frac{C_{Invest}}{aE_y} + \frac{C_{O\&M}}{E_y} + \frac{C_{Decom}(1+\mathrm{r})^{-T}}{aE_y} \quad (2\text{-}1)$$

Where:

LPC	is the levelised production cost.[Euro/kWh]
C_{Invest}	is the cost of investment.[Euro]
$C_{O\&M}$	is the cost of operation and maintenance. [Euro]
C_{Decom}	is the cost of decommissioning. [Euro]
a	is the annuity factor.[-]
E_y	is the annual energy output.[kWh]
r	is the discount rate.[-]
T	is the total life.[-]

The annuity factor can be calculated with the following equation:

$$a = \frac{1}{r}[1-(\frac{1}{1+r})^{T}] \quad (2\text{-}2)$$

The total life of offshore wind farms, T is now mostly designed to be 20 years. The discount rate, r, is chosen as 2.5%. Note that the selection of discount rate should be very careful. For example, in year 5, a 10% discount rate will have a net present value (NPV) of 62.1%, compared to 78.4% with a 5% discount rate. This can be calculated with equation 2-3.

$$NPV = \frac{Income}{(1+\mathrm{r})^{N}} \quad (2\text{-}3)$$

Where N is the year that income is generated.

Chapter 3 Maintenance Theory and Model Description

In this chapter, TeamPlay will be described, the ideas of the model come from M.B. Zaaijer (Zaaijer M.B., 2013b), and descriptions are based on the ideas of how the model express the expected value of downtime and failures. Therefore, maintenance theories will be discussed in details, while other data (turbine data, site data etc.) that needed for running the model are described in details in Appendix C. Further details of derivation are provided in the memo of TeamPlay (Zaaijer M.B., 2013c).

3.1 Model description

To estimate the overall availability and maintenance cost, researchers have modelled many strategies. For instance, In Rademakers's model (Rademakers. L, 2002), waiting time for reordering of spare parts, travel time and repair time are taken into consideration. But he missed some other parameters, like shift length, number of shifts and number of crews. These parameters will affect the final availability. Number of shifts and crews determine whether failures after a storm can be repaired before the coming of next storm. Therefore, TeamPlay takes these parameters into consideration, and these parameters are represented as a function of time. Therefore, TeamPlay provides a more gradual response for downtime and availability, and the response includes the effect of shift duration, number of crews and number of shifts. The idea of the model Figure 3-1 shows a schematic drawing of the number of failed turbines due to storm and normal operation.

From this schematic drawing, one can see turbines are repaired immediately in the period before storms. When a storm comes, turbines begin to fail, and due to the inaccessibility of storm period, the number of failed turbines begin to increase until the end of that storm. Moreover, the failure rate of turbines in a storm decreases with time, which is represented as $p_{fail}(\mathrm{t})_{storm} = h \times e^{-ht}$, where h is the constant hazard rate and p is the probability density of failure.

During a storm, turbines begin to fail and the number of failed turbines begin to accumulate. If the storm period t goes to infinity, all turbines will fail eventually, and the probability of failure will decrease to zero in the end.

When the storm ends, the catch-up period begins. Technical crews begin to repair failures that only happened in storm period, and the number of failed turbines decreases, but failures may also happen in the catch-up period, so the number of failed turbines can increase or decrease.

When all failures happened in storm period and catch up period are repaired, a steady state period begins. Technical crews will repair failures until the next storm comes. These three periods, storm, catch-up and steady state, constitute a storm cycle.

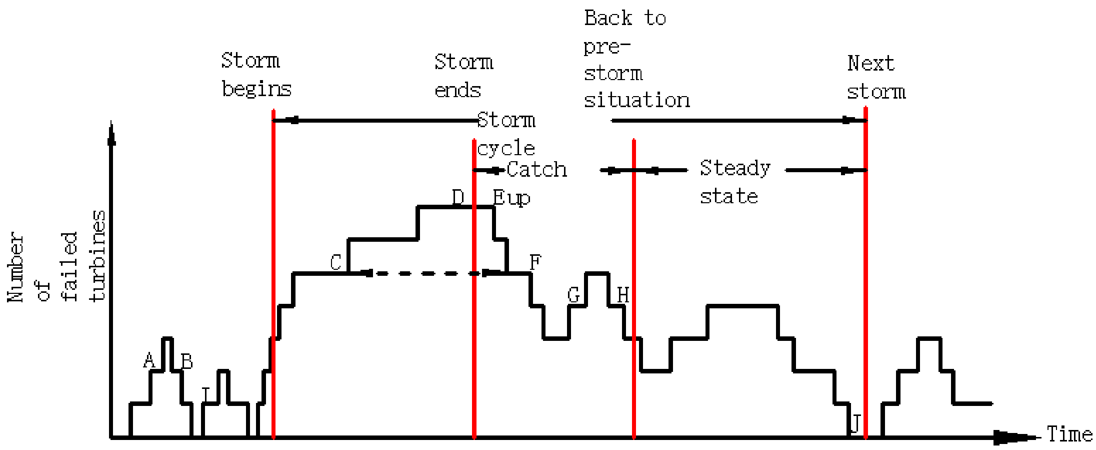


Figure 3-1 Number of turbines down over time (Zaaijer M.B., 2013b, with adaptions)

3.2 General expression of availability

The overall availability represents the average number of turbines that are in operational state, and it can be expressed as below:

$$\eta = 1 - \int \frac{N_f(t)}{N_t \cdot T_{life}} dt = 1 - \frac{T_{down,total}}{N_t \cdot T_{life}} \quad (3\text{-}1)$$

Where:

η is the overall availability, N_t is the number of turbines in the wind farm, T_{life} is the total life of turbines, usually take 20 years. $T_{down,total}$ is the total downtime of all turbines over its entire lifetime. For $T_{down,total}$, it can be further divided into all kind of failures (different failure types and failures) of all turbines. For instance, gearbox, generator and blade are belong to the same failure type, which needs lifting equipment during the repair period. Some failures may not need lifting equipment but need diagnosis, and others may neither need lifting equipment nor diagnosis. Thus the equation becomes:

$$T_{down,total} = \sum_{all\ failures} \left(t_{repair} - t_{fail}\right) = \sum_{turbine\ i} \sum_{failure\ type\ j} \sum_{failure\ k} \left(t_{repair\ i,j,k} - t_{fail\ i,j,k}\right) + \sum t_{service} \quad (3\text{-}2)$$

From the schematic drawing, one can see different mechanism of failure and repair during the whole period. Failures can take place in storm, catch up period and normal calm weather. Repairs can be made in normal calm weather and catch up period, due to the storm here is defined as inaccessible period.

3.3 Downtime of failures and its expected value during storms

3.3.1 Downtime of failures during storms

From figure 3-1, for failures that happen in storm periods, for instance, C point, the downtime during storms is t_{CD}. D is the end of the storm. Then the total downtime during storm for all kinds of situations can be expressed as:

$$T_{down,st} = \sum_{turbine\ i} \sum_{failure\ type\ j} \sum_{storm\ cycle\ s} \sum_{failure\ k} \left(\left(t_{e,st,s} - t_{fail\ i,j,k} \right) \Big|_{t_{b,st,s} \le t_{fail\ i,j,k} < t_{e,st,s}} \right) \tag{3-3}$$

$t_{b,st,s}$ represents the beginning of storm, $t_{e,st,s}$ represents the end of storm.

3.3.2 Expected value of downtime during storms

To model the expected value, one can consider the downtime during storm as a sum of $\left(t_{e,st,s} - t_{fail\ i,j,k} \right)$ for all turbines that failed during the storm. The expected value becomes:

$$\begin{aligned} E_{down,s} &= E\Big(\sum_{turbine\ i} \sum_{failure\ type\ j} (t_{e,st,s} - t_{fail,i,j,k}) \Big) \\ &= \int_{t_{s(tart)}}^{t_{e(nd)}} \sum_{turbine\ i} \sum_{failure\ type\ j} (t_{e,st,s} - t_{fail,i,j,k}) P_{fail,i,j,k}(t)\, dt \end{aligned} \tag{3-4}$$

Then if one substitute the probability density function of failure during storm, the value becomes:

$$\begin{aligned}
E_{down,s} &= N_{t,s} \sum_{failure\ type\ j} \int_{t_s}^{t_e} (t_e - t) h_j e^{-(t-t_s)\sum_k h_k} dt \\
&= N_{t,s} \sum_{failure\ type\ j} \int_{0}^{t_e - t_s} (t_e - t_s - t^{'}) h_j e^{-t^{'}\sum_k h_k} dt \\
&= N_{t,s} \sum_{failure\ type\ j} h_j \left(\int_{0}^{t_e - t_s} T_{storm} \cdot e^{-t^{'}\sum_k h_k} dt - \int_{0}^{t_e - t_s} t^{'} e^{-t^{'}\sum_k h_k} dt \right) \\
&= N_{t,s} \sum_{failure\ type\ j} h_j \left(\frac{T_{storm}}{\sum_k h_k} + \frac{e^{-T_{storm}\sum_k h_k} - 1}{(\sum_k h_k)^2} \right) \\
&= N_{t,s} \left(T_{storm} + \frac{e^{-T_{storm}\sum_k h_k} - 1}{\sum_k h_k} \right)
\end{aligned} \tag{3-5}$$

Summation of all turbines is replaced by multiplying with the number of operational turbine $N_{t,s}$, T_{storm} is defined as $T_{storm} = t_e - t_s$. $t^{'} = t - t_s$ is used during integration. In TeamPlay, equation 3-5 is used to determine the expected value of downtime during storm.

3.4 Downtime of failures and its expected value during catch up maintenance

3.4.1 Downtime of failures during catch up maintenance

The catch up period is a period after storm, during which, only failures that happened in the last storm and in this catch up period will be repaired. Once failures that happened in the last storm and in this catch up period have been repaired, the steady state (calm weather) begins. For failures that happened during the last storm, besides downtime t_{CD}, their downtime during catch up maintenance is t_{DE}. The assumption here is that the catch up period begins at once at the end of the storm. All kinds of t_{DE} can be expressed as:

$$T_{down,r} = \sum_{turbine\ i} \sum_{failure\ type\ j} \sum_{storm\ cycle\ s} \sum_{failure\ k} \left(\left(t_{repair\ i,j,k} - t_{b,r,s} \right) \Big|_{\substack{t_{b,st,s} \le t_{fail\ i,j,k} < t_{e,st,s} \\ t_{b,r,s} \le t_{repair\ i,j,k} < t_{e,r,s}}} \right) \tag{3-6}$$

$t_{b,r,s}$ represents the beginning of catch up, $t_{e,r,s}$ represents the end of catch up.

For failures that happen during the catch up period and are repaired also in this period, the downtime is t_{GH} . All kinds of t_{GH} can be expressed as:

$$T_{down,r} = \sum_{turbine\ i} \sum_{failure\ type\ j} \sum_{storm\ cycle\ s} \sum_{failure\ k} \left(\left(t_{repair\ i,j,k} - t_{fail\ i,j,k} \right) \Big|_{\substack{t_{b,r,s} \le t_{fail\ i,j,k} < t_{e,r,s} \\ t_{b,r,s} \le t_{repair\ i,j,k} < t_{e,r,s}}} \right) \quad (3\text{-}7)$$

3.4.2 Expected value of downtime of catch up maintenance

In the model, the downtime during the catch up period can be divided into different failure types, each failure of the same type has the same repair time. And for one failure type j, the downtime without waiting for spare parts and equipment can be expressed as:

$$T_{down,r} = \sum_{i=1}^{N_{f,j}} \left(t_{repair\ i} - t_{s,r} \right) \quad (3\text{-}8)$$

$t_{s,r}$ represents the start of repair batch, $t_{repair\ i}$ represents the time of repair of turbine i.

If the crew number is N_{crew} and the number of failed turbine is $N_{f,j}$, then for one repair sub-batch, the crew can work only on N_{crew} turbines for one time. Only after the first batch of repair work is finished, the crews can start to repair another batch of failed turbines, and the number is up to N_{crew}. This process will continue until there is no failed turbine left. N_b is used to express the number of full sub-batches:

$$N_b = ROUNDDOWN\left(\frac{N_{f,j}}{N_{crew}} \right) \quad (3\text{-}9)$$

The number of remaining repairs, N_r represents the number in the last (incomplete) sub-batch, which can be expressed as:

$$N_r = N_{f,j} - N_{crew} N_b \quad (3\text{-}10)$$

So the downtime of failure type j can be expressed as:

$$\begin{aligned} T_{down,r} &= \sum_{i=1}^{N_{f,j}} \left(t_{repair\ i} - t_{s,r} \right) \\ &= T_{wip,j} \cdot (N_r + (N_r + N_{crew}) + (N_r + 2N_{crew}) ... + (N_{f,j})) \\ &= T_{wip,j} \cdot (\frac{1}{2}(N_r + N_{f,j})(N_b + 1)) \\ &= T_{wip,j} \cdot (N_{f,j} - N_{crew} \frac{N_b}{2})(N_b + 1) \end{aligned} \quad (3\text{-}11)$$

3.5 Downtime of failures and its expected value in normal calm weather

3.5.1 Downtime of failures in normal calm weather

Failures and repairs that happen in calm weather can be divided into two types. One is repair before the next storm. For instance, point A and point B, the downtime is thus t_{AB}. The downtime of all kinds of failures like AB can be expressed as:

$$T_{down,normal} = \sum_{turbine\ i} \sum_{failure\ type\ j} \sum_{failure\ k} \left(\left(t_{repair\ i,j,k} - t_{fail\ i,j,k} \right) \Big|_{\substack{t_{b,n,s} \le t_{fail\ i,j,k} < t_{e,n,s} \\ t_{b,n,s} \le t_{repair\ i,j,k} < t_{e,n,s}}} \right) \tag{3-12}$$

The other type is failure that happens in the normal calm weather, but repair happens after a storm period, for example, point I and point J. The downtime t_{IJ} can be expressed as downtime in storm period and downtime in catch up period plus downtime between failures happen point I to storm beginning point. T_{st} represents storm period and T_r represents time in catch up period. The first term of equation 3-13 represents the downtime between the beginning of a storm and the end of a catch up period. The second term represents the downtime between point I and the beginning of the storm plus downtime between the end of the catch up period and the end of repair work.

$$T_{down,normal} = \sum_{turbine\ i} \sum_{failure\ type\ j} \sum_{failure\ k} \left(\begin{array}{l} \displaystyle\sum_{storm\ cycle\ s} \left(T_{st} + T_r \right) \Big|_{\substack{t_{b,n,s'} \le t_{fail\ i,j,k} < t_{e,n,s'}|_{s'<s} \\ t_{repair\ i,j,k} > t_{e,r,s}}} \\ + \left(t_{repair\ i,j,k} - t_{fail\ i,j,k} - \left(\displaystyle\sum_{storm\ cycle\ s} \left(T_{st} + T_r \right) \Big|_{\substack{t_{b,n,s'} \le t_{fail\ i,j,k} < t_{e,n,s'}|_{s'<s} \\ t_{repair\ i,j,k} > t_{e,r,s}}} \right) \right) \end{array} \right) \tag{3-13}$$

Equation 3-12 and 3-13 together represent two kinds of failures and repairs happen in calm weather, and the summation of these two are the total downtime in calm weather (steady state).

3.5.2 Excepted value of downtime in normal calm weather

From figure 3-1, one can see the steady state periods are interrupted by storms and catch up periods with failures happen during these periods. To determine the number of failures and downtime due to failures in steady state, one can take the storms and catch up periods out as if there are no storms and catch up periods during the wind farm lifetime. The expected value of downtime can be expressed as:

$$E\left(T_{down}\right)=\sum_j N_{f,j}\cdot\left(T_{prepare}+T_{wait,crew}+T_{wip}\right)_j$$
$$=\sum_j E\left(T_{up}\right)h_j\left(T_{prepare}+T_{wait,crew}+T_{wip}\right)_j$$
$$=E\left(T_{up}\right)\cdot\sum_j h_j\left(T_{prepare}+T_{crew}+T_{wip}\right)_j$$
$$\Rightarrow \tag{3-14}$$
$$\frac{E\left(T_{up}\right)}{T}=\frac{1}{1+\sum_j h_j\left(T_{prepare}+T_{crew}+T_{wip}\right)_j}$$
$$\frac{E\left(T_{down}\right)}{T}=1-\frac{1}{1+\sum_j h_j\left(T_{prepare}+T_{crew}+T_{wip}\right)_j}$$

From equation 3-14, the expected value of steady state downtime, without waiting for crew can be expressed as:

$$E\left(T_{down,wip+prepare}\right)=\sum_j p_{f,j}\cdot\left(T_{wip}+T_{prepare}\right)_j$$
$$=\frac{T\sum_j h_j\left(T_{wip}+T_{prepare}\right)_j}{1+\sum_j h_j\left(T_{prepare}+T_{wait,crew}+T_{wip}\right)_j} \tag{3-15}$$
$$\overset{\sum_j h_j\left(T_{wait,crew}\right)_j\ll 1}{\approx}\frac{T\sum_j h_j\left(T_{wip}+T_{prepare}\right)_j}{1+\sum_j h_j\left(T_{prepare}+T_{wip}\right)_j}$$

Here, $N_{f,j}$ represents the number of failure of type j, h_j is the hazard rate of failure type j. T_{wip} represents time that work in progress, $T_{prepare}$ represents time for preparing, $T_{wait,crew}$ represents time waiting for crews.

The expected value of downtime per turbine times the number of operating turbines gets the total downtime during steady state without waiting for crew:

$$E\left(T_{down,wip+prepare}\right)\approx\frac{N_t\cdot T_{life}\sum_j h_j\left(T_{wip}+T_{prepare}\right)_j}{1+\sum_j h_j\left(T_{wip}+T_{prepare}\right)_j} \tag{3-16}$$

3.6 Downtime waiting for crews in calm weather

The probability $P_{d,j}$ of one turbine that is down due to failure type j and ready to be repaired equals the fraction of time that the turbine is down due to this failure and is not waiting for spare parts or equipment. This fraction of time can be expressed with the waiting time for crew included, and the derivation of equation 3-17 has the similar process as derived in equation 3-14.

$$\begin{aligned} p_{d,j} &= \frac{T_{down,wip+wait,crew}}{T} \\ &= \frac{T_{up}}{T} \cdot h_j \left(T_{wait,crew} + T_{wip}\right)_j \\ &= \frac{h_j \left(T_{wait,crew} + T_{wip}\right)_j}{1 + \sum_j h_j \left(T_{prepare} + T_{wait,crew} + T_{wip}\right)_j} \end{aligned} \tag{3-17}$$

The probability p_d of one turbine being down is the summation of $p_{d,j}$ of all different failure types. This can be expressed as:

$$\begin{aligned} p_d &= \frac{\sum_j h_j \left(T_{wait,crew} + T_{wip}\right)_j}{1 + \sum_j h_j \left(T_{prepare} + T_{wait,crew} + T_{wip}\right)_j} \quad \overset{\sum_j h_j T_{wait,crew,j} \ll 1,\ T_{wait,crew,j} \ll T_{wip,j}}{\Rightarrow} \\ &\approx \frac{\sum_j h_j T_{wip,j}}{1 + \sum_j h_j \left(T_{prepare} + T_{wip}\right)_j} \end{aligned} \tag{3-18}$$

The simplification made here is that the downtime due to waiting will not significantly affected the failure probabilities (MTTR does not include waiting). This simplification can avoid an iterative computation, otherwise the expected value of waiting times will be a function of waiting times. Therefore, $p_{d,n}$, the probability of n turbines are down can be expressed by the binomial distribution:

$$\begin{aligned} p_{d,n} &= C(N_t, n) \cdot p_d^n \cdot \left(1 - p_d\right)^{N_t - n} \\ &= \frac{N_t!}{\left(N_t - n\right)!n!} p_d^n \cdot \left(1 - p_d\right)^{N_t - n} \end{aligned} \tag{3-19}$$

The expected value of duration, $T_{d,n}$, of having n failures over the lifetime is:

$$\begin{aligned} E\left(T_{d,n}\right) &= \int_0^{T_{life}} p_{d,n} dt \\ &= p_{d,n} \cdot T_{life} \\ &= \frac{N_t!}{\left(N_t - n\right)!n!} \left(p_d\right)^n \cdot \left(1 - p_d\right)^{N_t - n} \cdot T_{life} \end{aligned} \tag{3-20}$$

If the number of failures is $n = N_{crew} + 1$, then only one turbine is put on the waiting list. Then the duration of existence of this waiting list with one turbine on is

$$E(T_{down,N_{crew}+1}) = T_{life} \cdot \frac{N_t!}{\left(N_t - (N_{crew}+1)\right)!(N_{crew}+1)!}(p_d)^{N_{crew}+1} \cdot \left(1 - p_d\right)^{N_t - (N_{crew}+1)} \quad (3\text{-}21)$$

When $n = N_{crew} + 2$, which means there are two turbines on the waiting list. Then the duration corresponds with the downtime due to waiting for two turbines has to be multiplied with 2.

$$E(T_{down,N_{crew}+2}) = T_{life} \cdot (n - N_{crew}) \cdot \frac{N_t!}{\left(N_t - (N_{crew}+2)\right)!(N_{crew}+2)!}(p_d)^{N_{crew}+2} \cdot \left(1 - p_d\right)^{N_t - (N_{crew}+2)}$$

(3-22)

For other greater value of n, $E(T_{down,n})$ has the similar derivation. So, the total downtime due to waiting for crew equals the summation of the probability of any number of simultaneous failures larger than the number of crews, multiplied by the difference between the number of failures and the number of crews:

$$E\left(T_{down,wait-crew}\right) = T_{life} \cdot \sum_{n=N_{crew}+1}^{N_t} \left(n - N_{crew}\right) \frac{N_t!}{\left(N_t - n\right)!n!} p_d^n \cdot \left(1 - p_d\right)^{N_t - n} \quad (3\text{-}23)$$

3.7 Downtime due to waiting for lifting equipment

The downtime due to waiting for lifting equipment is modelled by assuming that the first failed turbine has to wait the full mobilization time. The next turbines have to wait half the mobilization time plus half the time needed to repair previously failed turbines. This leads to a downtime, $T_{d,lift}(n)$ can be expressed as:

$$\begin{aligned} T_{d,lift}(n) &= \left(T_{mc} + T_m\right) + \frac{1}{2}\sum_{i=2}^{n}(T_{mc} + T_m + (i-1) \cdot T_{wip}) \\ &= \left(T_{mc} + T_m\right) + \frac{1}{2}(T_{mc} + T_m)\sum_{i=2}^{n}1 + \frac{1}{2}T_{wip}(\sum_{i=2}^{n} i - \sum_{i=2}^{n}1) \\ &= \left(T_{mc} + T_m\right) + \frac{1}{2}(T_{mc} + T_m - T_{wip})\sum_{i=2}^{n}1 + \frac{1}{2}T_{wip}\sum_{i=2}^{n}1 \\ &= \left(T_{mc} + T_m\right) + \frac{1}{2}\left(T_{mc} + T_m - T_{wip}\right)\left(n-1\right) + \frac{1}{2}T_{wip}\left(\frac{n\left(n+1\right)}{2} - 1\right) \end{aligned} \quad (3\text{-}24)$$

T_{mc} represents waiting time before ordering and mobilizing (hoisting) equipment to collect more failures that need lifting equipment, T_m represents time for ordering and mobilizing (hoisting) equipment. T_{wip} represents time that work in progress.

$T_{d,lift}$ is expressed as:

$$T_{d,lift} = \sum_{n=1}^{\infty} T_{d,lift}(n) \cdot N_n \tag{3-25}$$

Here, the summations should be taken up to the number of wind turbines in the farm rather than infinity.

3.8 Downtime due to preventive maintenance

The downtime due to preventive maintenance is the number of visits multiplied by the working hours per preventive maintenance.

$$T_{d,pm} = N_{pm} \cdot T_{pm} = N_t \frac{T_{life}}{T_{si}} \cdot T_{pm} . \tag{3-26}$$

T_{si} is the maintenance service interval, T_{pm} is the working hours per preventive maintenance, they are inputs of the model.

3.9 Other intermediate result

As mentioned above, TeamPlay is a statistic model. Therefore, all intermediate results are determined by expected value rather than simulation. For the expected value of number of failures during storm, after storm and in steady state, the equations are given below. Detailed derivations can be found in the memo of TeamPlay (Zaaijer M.B., 2013c).

The expected value of number of failures during storm is expressed as:

$$E_{f,s,j} = N_{t,s} h_j \frac{1 - e^{-T_{storm} \sum_k h_k}}{\sum_k h_k} \tag{3-27}$$

The expected value of number of failures during catch-up period is expressed as:

$$E_{f,j,p} = \frac{\left(N_{t,s} - N_f\right) h_j}{\sum_k h_k} \left(1 - e^{-T_{repair,i} \sum_k h_k}\right) \tag{3-28}$$

The expected value of number of failures during steady state is expressed as:

$$E\left(N_{f,j}\right)=N_t\,\frac{h_j\left(T_{life}\left(1-f_s\right)-T_{catch\,up,total}\right)}{1+\sum_i h_i\left(T_{prepare}+T_{wip}\right)_i} \qquad (3\text{-}29)$$

$T_{catch\,up,total}$ is determined by multiplying the N_{storms} with $T_{catch\,up}$. f_s is the storm fraction for the site with a specific access method.

Chapter 4 Model Validation and Comparison

The validation of the model will focus on the comparison of the availability and detailed downtime in each category. Some differences are expected. Possible reasons will be pointed out for the differences. To compare the model result and the real availability data, one first needs to get failure and repair data of an offshore wind farm. Data of Offshore Wind park Egmone aan Zee (OWEZ) of year 2009 is chosen as an example year for validation. Failure data of some components are given in the table below. Further data processing will also be made in the following part of the text. Once the input data are ready, availability and downtime can be determined, and these will be used in comparison with reported data. Some differences are expected since the initial data are very limited, and some of the input data are estimated. Analysis of the result and verification from logical aspects will add further confidence. Moreover, the output of TeamPlay will be compared with another wind farm maintenance simulation model Contofax, which is created by Christian Schöntag and Gerard van Bussel from Delft University of Technology, to further validate it.

4.1 Data collection of Windpark Egmond aan Zee

To run the model, besides failure and repair data, one also needs site data, power and thrust data for turbines and data for the rotor-nacelle assemblies, etc. these data are given in Appendix C (C-1, C-2, C-3). Operation data of 2009 of Offshore Windpark Egmond aan Zee (OWEZ) is chosen for validation. From the Noordzee wind operational report, one knows the reported availability determined from downtime data was 82.9% (Anonymous, 2010a). A schematic figure is given in Appendix B. Below is the detailed stops and downtime data of OWEZ 2009. Here stops are not failures, and these stops also contain small faults that only need remote restart, which means they cannot be used to determine the mean time between failures of each components.

Table 4-1 Failure data of OWEZ 2009 (Anonymous, 2010a)

	Lost MWh	%Lost MWh	# stops	% stops	downtime hrs
Available time 82.90%	0	0	0	0	0
Gearbox 9.64%	36713	55.6	567	7.4	30400.5
Generator3.56%	14920	22.6	101	1.3	11226.0
Control system 1.24%	4537	6.9	2523	33	3918.5
Pitch system 0.84%	4382	6.6	1599	20.9	2633.5
Scheduled service 0.54%	919	1.4	858	11.2	1706.5
Converter 0.37%	890	1.3	228	3	1173.5
Blade system 0.3%	774	1.2	88	1.2	952.5
Electrical 0.19%	882	1.3	69	0.9	605.0
Grid 0.17%	0	0	31	0.4	521.0
Ambient 0.15%	1335	2	419	5.5	474.5
Yaw system 0.06%	502	0.8	1127	14.7	204.0
Brake system 0.02%	107	0.2	25	0.3	74.0
Structure 0.01%	44	0.1	15	0.2	49.0
Total	**66005**	**100**	**7650**	**100**	**53938.5**

4.2 Input data processing

To determine the mean time between failures (MTBF) from other information, one first needs to classify the components and make different categories. Here, three basic categories are classified. Category one is components that need lifting equipment. Generator, gearbox and blade system are heavy and expensive components, thus they need lifting equipment during the repair work (Zaaijer M.B., 2013b). Moreover, these repair work need lifting usually take a long time. For instance, failures of gearbox will result in average downtime in excess of 14 days (Anonymous, 2014b). So the MTBF and repair time of this categories become the dominant factors. Category two is components that do not need lifting equipment but need diagnosis. Category three is components that neither need lifting equipment nor diagnosis.

According to the operational report, the failure frequency of some components of V90 are given below, in Table 4-5. (Crabtree. C J, 2012). The MTBF then can be determined by equation 4-1

$$MTBF = \frac{8760}{f_{failure}} \tag{4-1}$$

Table 4-5 Failure and repair data of V90

Components need lifting	Failure frequency [per year]	MTBF [Hours]	MTTR [Hours]
Gearbox	0.18[a]	48670[b]	144[c]
Generator	0.18[a]	48670[b]	72[c]
Blade system	0.24[a]	36500[b]	72[c]

a Reported data (Crabtree C J, 2012)
b Determined from equation 4-1.
c Failure and repair data of V90 (Zaaijer M.B., 2013b)

The average MTBF of category one that needs lifting is determined by equation 4-2,

$$\frac{1}{MTBF_{average}} = \sum \frac{1}{MTBF_{lifting}} \quad (4\text{-}2)$$

Considering the weight of three components, the average repair time of category one that needs lifting can be determined by equation 4-3,

$$t_r = \frac{\sum (MTTR \times f_{failure})}{\sum f_{failure}} \quad (4\text{-}3)$$

Where t_r is the average repair time of a certain category, $f_{failure}$ is the failure frequency of each components that belong to this category.

From equations and data above, one can determine the MTBF and repair time. For components that need lifting equipment, the MTBF is 14600 hours and the average repair time is 95 hours.

One exception for OWEZ is that in 2009 the operator made a pro-active replacement of gearboxes and generators during its operation, and the replacement started at 2007 and finished at 2009. Therefore, in these three years there was a lower overall availability, and reported data for these three years ranged from 76%-83% (Elke Delnooz, 2011). After the replacement was finished, the availability was 91.0% in 2010 (Elke Delnooz, 2011).

The model does not contain such special replacement. In order to make a closer validation, a pro-active category should be added to the model. This pro-active replacement was taken due to potential problems of gearboxes and generators rather than failures. In 2009, 8 generators and 34 gearboxes were replaced (Anonymous, 2010a). Thus for this exception, the annual failure frequency was 0.22 for generator and 0.94 for gearbox. Then, the MTBF of this category is 7500 hours. Repair time was not reported, therefore, a same repair time as category one is used for pro-active replacement as an estimation.

With the same method, one can determine the data of other categories. While due to very limited data available, categories two and three are determined from reported failure rates of all failures of Horns Rev (Lindqvist M, 2010). Table 4-6 shows the failure and repair input data for the model.

Table 4-6 Failure and repair data of OWEZ in 2009

Category	MTBF(h)	Diagnose time(h)	Repair time(h)	Waiting time for spare parts(h)	Lifting equipment
Needs lifting	14600[a]	8[c]	95[a]	0	Yes
Needs diagnosis	6100[b]	1[c]	5[b]	0	No
No diagnosis	13000[b]	0	5[b]	0	No
Pro-active replacement	7500[d]	0	95[e]	0	Yes

a Determined from operation data of OWEZ in 2009.
b Determined from reported failure rates of all failures of Horns Rev.
c Not reported data, this is an estimation.
d Determined from reported pro-active replacement data of gearbox and generator.
e Not reported data, set the same repair time as category one.

4.3 Model result analysis

The model output shows the availability is 84.6%, 1.7% higher than the reported data of 2009. When only use the first three categories, so without pro-active replacements, the availability is 94.4%, 3.4% higher than reported data of 2010. The reported availability after replacement of gearbox and generator was 91.0% in 2010 (Elke Delnooz, 2011). The detailed data of downtime are given in Table 4-7, and the uptime increment can be determined by equation 4-4 and 4-5. Comparing the difference of results with and without category four, one can find the downtime caused by pro-active replacement are 858 hours in the model and 709 hours in the real situation for each turbine. The downtime caused by pro-active replacement is determined by the availability increment.

$$T_{increment}^{TeamPlay} = (\eta_{2010}^{TeamPlay} - \eta_{2009}^{TeamPlay}) \times 8760 \tag{4-4}$$

$$T_{increment}^{reported} = (\eta_{2010}^{reported} - \eta_{2009}^{reported}) \times 8760 \tag{4-5}$$

Where T is the uptime increment and η is the availability, and other superscripts and subscripts gives more information to distinguish.

It is realized that there are some differences between two cases. Official report shows that repair work on 33 piles started in 2010, because more settlement in the vertical direction is occurring between the foundation pile and the transitional section than had been expected (Anonymous, 2010a). However, in TeamPlay, this kind of repair work cannot be modelled. How much downtime the repair work on piles would cause is unknown, while an availability lower than 94.4% is expected. The difference between 709.6 hours and 858.5 hours is 6.2 days, which is also estimated to be in a reasonable range for repairing piles.

The preventive maintenance time also match well. They are 46 hours in the model and 47.4 hours in the real situation for each turbine, which is determined from data in table 4-1. The preventive maintenance is somewhat an input rather than an output. However, it shows that TeamPlay models a close preventive maintenance strategy.

Moreover, comparing the downtime of each turbine caused by failures that need lifting, from table 4-1, one can determine that it is 1182.7 hours. In TeamPlay, the downtime caused by failures that need lifting are composed of downtime of category one, category four and downtime waiting for equipment and crews. The downtime waiting for crew is allocated evenly according to the failure rates of those four categories. Then, the downtime caused by failures that need lifting is 1165.0 hours.

From the analyses above, one can summarize that the scheduled maintenance time, the downtime caused by category one and category four, and the uptime increment after pro-active replacement was finished are more or less identical.

Table 4-7 detailed downtime (uptime) in specific category for each turbine

	TeamPlay result [hours/(turbine*year)]	Reported data [hours/(turbine*year)]
Uptime increment after pro-active replacement	858.5	709.6
Scheduled maintenance	46.0	47.4
Downtime caused by category one and four	1165.0	1182.7
Downtime caused by category two and three	136.4	268.1

There are also some differences between the model result and reported data. Comparing the downtime caused by category two and category three, one can find that they are 136.4 hours in the model and 268.1 hours in real situation respectively.

One reason for the difference may come from the MTBF of category two and category three. Since there is no failure and repair data available for OWEZ, the reported failure rates of all failures of Horns Rev are used as inputs. However, Horns Rev had a 95.3%-97.3% availability during its operation (Zaaijer M.B., 2013b), comparing the 82.9% availability, the MTBF data are much more optimistic for OWEZ. The MTBF of category one is 73000 hours for Horns Rev, but for OWEZ, it is 14600 hours. The failure rate of turbines is much higher in OWEZ, therefore, the failure rate of category two and category three used in the model emulation are expected to be lower than real situation, which results in a higher availability.

Another reason for the availability difference comes from spare parts delay. In TeamPlay, it is modeled that there is no spare parts delay during the corrective maintenance, as shown in Table 4-6, however, there might be some delay in real situations. The time for ordering of spare parts will not directly affect the downtime, because ordering and mobilizing hoisting equipment, processing diagnosis information etc., these work can be done at the same time. Time for ordering of spare parts will become the dominant element only when it is the longest. The influence caused by spare parts delay are given in equation 4-6.

$$T_0 = \max(T_{sp}, T_{mc} + T_m, T_{pd}) \quad (4\text{-}6)$$

Where T_{sp} represents time for ordering of spare parts;

T_{mc} represents waiting time before ordering and mobilizing(hoisting) equipment to collect more failures that need lifting equipment;

T_m represents time for ordering and mobilizing(hoisting) equipment;

T_{pd} represents time to process diagnosis information.

A possible scenario that may happen in real situation is that the time for ordering of spare parts exceeds the time for ordering and mobilizing hoisting equipment or any other time of work, while it is not considered in the model, which may lead to the difference in final result.

There are also some other possible factor that may cause differences between reported data and model result. For example, there might be some delay in the normal repair work. When failures that belong to category two or category three happen during the pro-active replacement, technical crews need to finish the replacement work first and then begin to repair other failures, because pro-active replacement should have the priority due to the high daily rate of lifting equipment and vessel.

4.4 Model result verification

To further validate the model, one can also validate from logical points of view. The following aspects show the reliability of this model from logical aspects:

1. When a storm begins, more and more turbines begin to fail until all turbines failed, so the probability density function of failure during storm is expected to start at the failure rate and decrease to zero. This means the failure rate is a function of time.

The PDF of failure used in the model is $P_{fail}(\mathrm{t})_{storm} = h \times e^{-(t-ts)\mathrm{h}}$, where P goes to zero when storm duration goes to infinity.

2. Since the probability of failure decreases with time, the total number of failures from the model should be less than the number of failures calculated from a constant failure rate. The results in Table 4-8 show that the number of modeled failures match the logical expectation.

Table 4-8 Failure frequency and number of failures per turbine

Category	Model results [times/year/turbine]	Number of failures over 20 years(modelled) [times/turbine]	Calculated from constant failure rate [times/year/turbine]	Number of failures over 20 years(calculated) [times/turbine]
Need Lifting	0.567	11.33	0.600	12.00
Need diagnosis	1.357	27.14	1.436	28.72
No diagnosis	0.636	12.72	0.674	13.48
Pro-active replacement	1.102	22.04	1.168	23.36
Total	3.66	73.23	3.88	77.56

3. The total downtime (only caused by four categories, without time waiting for lifting equipment and time for preventive maintenance) calculated with a constant failure rate and mean time to repair is 184.7 hours per turbine per year, which should be lower than that from the model as expected. The total downtime only caused by four categories can be determined by equation 4-7. In the model, it is 933.9 hours per turbine per year.

$$T_{4\ categories}^{down} = \sum h \times (t_d + t_r) \quad (4\text{-}7)$$

Where $\mathrm{T}_{4\ \mathrm{categories}}^{\mathrm{down}}$ is the total downtime that only caused by four categories, h is the failure rate of each category, t_d and t_r are the diagnose time and repair time of each category respectively.

If one increases the crews per shift or decreases the storm fraction, the differences of downtime will become smaller. Tests results show that for a larger number of crews, taking 20 crews per shift and storm fraction 0.6 as inputs, one can get the total downtime is 783.9 hours per turbine per year. If a small storm fraction 0.001 and 6 crews per shift are used as inputs, the total downtime is 483.6 hours per turbine per year.

4. For a small MTBF, the downtime during one storm should be close to the storm

length, which means the turbine will fail soon after the storm starts. With a 30-hours MTBF of category two as inputs, test result show the downtime during one storm is 23.8 hours, and the average storm length is 26.6 hours.

5. For a larger distance to shore, taking 30 km as input, a lower availability is expected. The downtime during inaccessibility is almost the same, with a difference only up to 10 minutes, which matches the logical estimation. The downtime differences are mainly in catch-up periods and steady state periods as expected, because travel time gets longer. The difference increases with an increasing distance to shore.

6. For a small storm fraction, the expected number of failures after the storm determined from the probability density function of the number of failures is close to the value obtained from a constant failure rate. Test data shows the following results:

Table 4-9 failures after storm periods of 36 turbines over 20 years

	Storm fraction 0.6	Storm fraction 0.05	Calculated from constant failure rate
Need Lifting	162	388	432
Need diagnosis	389	927	1034
No diagnosis	183	435	485
Pro-active replacement	317	754	841

4.5 Comparison with another model

The result of TeamPlay is going to be compared with that of Contofax, which is mentioned in the beginning of this chapter. To test whether TeamPlay and Contofax have the similar results, the inputs of Contofax should be the same as that of TeamPlay. Some important inputs of Contofax are the storm fraction, possible faults, time of mobilizing and hoisting lifting equipment and the store information of spare parts. In TeamPlay, it is assumed that there is no spare parts delay during repair work, so the number of stock in Contofax are set big enough to avoid spare parts delay. In TeamPlay, the time of mobilizing and hoisting lifting equipment is integrated into repair time. However, in Contofax, the time of moor, lifting and demoor are necessarily required as inputs. Therefore, to avoid error, in Contofax, a small number (one hour) is used as inputs for the time of moor, lifting and demoor. Certainly, a smaller repair time, 92 hours instead of 95 hours, is used in Contofax to ensure that the overall failure and repair data are close to each other as much as possible. The storm fraction in TeamPlay is calculated with equation 4-8:

$$f_s = \frac{1}{1+\left(\frac{H_s}{H_{s,ref}}\right)^b \times \left(\frac{1}{f_{s,ref}}-1\right)} \tag{4-8}$$

f_s is the storm fraction of a specific site. H_s is the significant wave height limit for a specific kind of vessel(access method). $f_{s,ref}$ and $H_{s,ref}$ are data of a reference site, b equals 2.3 (Zaaijer M.B., 2013b). In TeamPlay, $f_{s,ref}$ =0.6, $H_{s,ref}$ =1.5 are used as a reference site data. And H_s is 1.5 m for selected vessel. Therefore, the storm fraction can be determined as 0.6 in Contofax.

The simulated availability from Contofax is 84.4%, the availability from TeamPlay is 84.6%, and the reported availability was 82.9%. Moreover, if one only considers the first three categories, which represents the situation after pro-active replacements were finished, the simulated availability from Contofax is 86.0%, the availability from TeamPlay is 94.4%, and the reported availability is 91.0%.

To further compare the result, one can look at the detailed number of failures of different categories. TeamPlay is designed for 20 years lifetime, so results from TeamPlay can be read directly. However, the simulation periods of Contofax is free to set. During the simulation of Contofax, it is found that the longer the simulation period is, the closer number of failures to that calculated from MTBF one can get. The result of a twenty-year simulation is more accurate than that of a one-year simulation. The data in the table below resulted from a twenty-year simulation.

Table 4-10 Number of failures per year for 36 turbines and availability

NO. of failures Categories	Calculated from MTBF[failures/year]	TeamPlay [failures/year] 2009	Contofax [failures/year] 2009
Needs lifting	0.600	0.567	0.556
Needs diagnosis	1.436	1.357	1.194
No diagnosis	0.674	0.636	0.567
Pro-active replacement	1.168	1.102	1.028
	Reported data[%]	**TeamPlay[%]**	**Contofax[%]**
Availability of 2009	82.9	84.6	84.4
Availability of 2010	91.0	94.4	86.0

From the data above, the overall availability from TeamPlay and Contofax can somewhat match with each other. From table 4-10, one can determine the annual failure rate from both two models and calculated from MTBF as well. From Contofax, it is

3.34 times per turbine per year, which is a little bit lower than that from TeamPlay (3.66) and determined from MTBF (3.88). With a longer simulation period, Contofax will has less uncertainties in generating the storm periods, the number of failures from Contofax will show a closer value to that calculated from MTBF, and availability as well. Other possible reasons caused difference are analyzed in section 4.3

From table 4-1, one can determine the downtime caused by failures that need lifting is 1182.7 hours. In TeamPlay, the downtime caused by failures that need lifting is composed of downtime of category one, category four and downtime waiting for equipment and crews. The downtime waiting for crew is allocated evenly according to the failure rates of those four categories. Then, the downtime caused by failures that need lifting is 1165.0 hours. In Contofax, it is 458.0 hours. Therefore, when one only considers the first three categories, the availability increment is only 2% in Contofax. Comparison shows TeamPlay has a closer value than Contofax in both availability and number of failures.

Due to very limited operational details, the validation of TeamPlay is far from perfect, but discussions and analysis provide some confidence. With further detailed data, especially failure rate, downtime, and average repair time of each components, a more comprehensive investigation and a more accurate result would be expected.

Chapter 5 Model Expansion Combined Access

In the current model, TeamPlay only has one vessel access method. Due to the low accessibility of vessel (only 40% of the lifetime), there are a lot of failures happened in the storm periods without being repaired. Employing helicopter access could repair failures in time and reduce the downtime happen in storm periods. This chapter will introduce the combined access ideas and remodel the combined access maintenance strategy. Afterwards, the cost model will be changed due to different cost of helicopters and vessels.

5.1 Helicopter access

Helicopter access has less weather and wave restriction than vessel access. For access by helicopters, there is no significant wave height limit, and the wind speed limit is generally 20 m/s (van Bussel G.J.W., 2003). Generally, the accessibility of helicopter can be considered as 100% (van Bussel G.J.W., 2013). For the specific location OWEZ, it has a Weibull scale factor 9.6 and a Weibull shape factor 2.31 (Zaaijer M.B., 2013b). One can get the wind speed Weibull distribution in Egmond aan Zee with these two factors, and the curve is shown in Appendix D. From the calculation of Weibull distribution, one can find the probability of wind speed that over 20 m/s is 0.0043. This means the theoretical accessibility of helicopter is 99.57%. However, the weather and wave condition should be under the threshold during the whole transport mission. Other researchers investigated weather and wave data of several locations in the North Sea, and results show that when wind speed limit equals 15 m/s and no wave limit, the fraction of accessible period is 94.6% (Rademakers L et al, 2002). When the wind speed limit is 15 m/s, the theoretical accessibility from Weibull distribution shows a result of 94.0%. Based on these comparisons, one can make an estimation that when the wind speed limit is 20 m/s and no wave limit, the fraction of accessible periods is in the range of 94.6% and 99.57%. Hereby, considering some foggy days, 98% is estimated to be the accessibility of helicopters.

5.2 Other access information of helicopters

Helicopter access also has some drawbacks. Generally, the maximum load capacity of a helicopter is below 1000 kg. The limited load capacity means failures that need lifting equipment still need vessel access, because only crew transportation is not enough for repair work. Therefore, helicopters can only be used in repairing failures call for small components that do not need lifting. Moreover, due to the smaller capacity of passengers, helicopter access needs more crew transportation when passenger number exceeds its limit. For the discussion below, a specific helicopter, Bell 505, is selected, whose maximum load is 700 kg and maximum passenger is 6 persons (Anonymous, 2014c).

The speed of helicopters is usually more than 200 km/hour, considering the take-off and landing stage, the average speed of helicopters is estimated to be 50 m/s during its maintenance work. The maximum crew depends on the size of helicopters, Bell 430 has 9 seats (Rademakers L et al, 2002). Maximum passengers for Bell 505 is 6 with 1 pilot.

5.3 Helicopter and vessel combined access method

In TeamPlay, the storm fraction is taken as same as Horns Rev 60%, therefore, the accessibility is 40% for vessel access. As mentioned above, the helicopter accessibility for the specific location OWEZ is 99.57%. Since helicopters have a much higher accessible limit than vessels, and weather is changing gradually, one can conclude that all accessible periods for vessels are also accessible periods for helicopters, and when helicopters are inaccessible, it must be the storm periods for vessels. The storm periods and accessible periods for each access methods are determined by their storm fraction respectively.

Then, one can conclude the combined access method is determined by the access method whose accessibility is higher. During the accessible periods, there are some periods that both vessels and helicopters can access. For these periods, the combined access method would choose vessel as access tools, because vessels are relatively cheaper and has larger capacity. From the discussion above, one can get the schematic drawing of combined access method from combining vessel access and helicopter access, the schematic drawing is given in Figure 5-1. Red dash line parts are periods that vessel can also access, so in combined access method, vessels are chosen instead of helicopters.

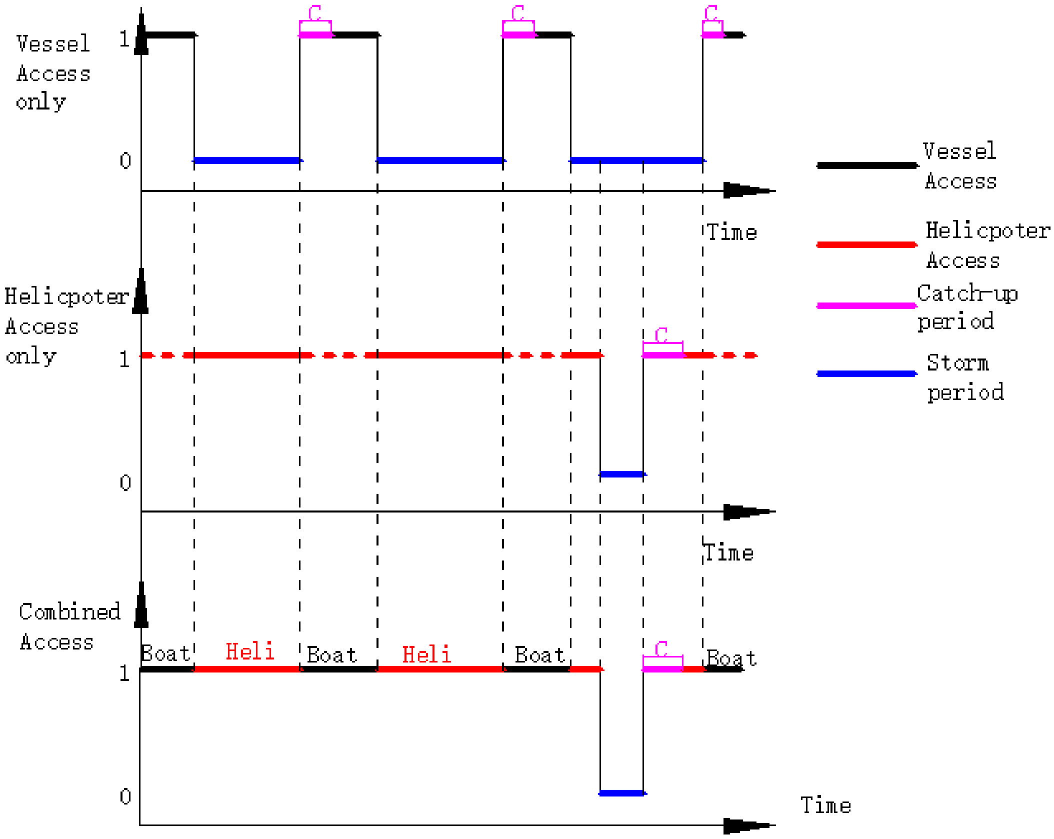


Figure 5-1 Schematic drawing of O&M models for different access methods

From the current model, one can get the number of failures that happen in storm periods, catch-up periods, and steady state periods and their corresponding downtime. The ideas and equations of how to get these values are discussed in Chapter 3. To express in a clear way, one can use Table 5-1 and Table 5-2 to define identifiers for the relevant equations of vessel access model and helicopter access model. A, B, C, D, E and F associate with equation 3-5, 3-11, 3-16, 3-27, 3-28 and 3-29 respectively, and MTBF, repair time and diagnose time should be used correspondingly for each category.

If one input the access limitation of helicopter and other initial variables, they follow the same ideas and equations, one can get Table 5-2 as below. But the values for category that need lifting are not used, since helicopter cannot transport lifting equipment and only access of technical crews is not helpful.

Comparing with the difference between two access methods, one can find the difference are mainly in travel speed, maximum passenger capacity, load capacity and access limitation (wind speed and significant wave height).

The model for combined access is derived from models for vessel access only and helicopter access only, using the ideas and equations of the original model as a starting point. Identifiers in Table 5-1 and Table 5-2 will be used to clarify the combined access model.

Table 5-1 Downtime and number of failures for vessel access

	Downtime of category 1 [hours]	Downtime of category 2 [hours]	Downtime of category 3 [hours]	Number of failures of category 1	Number of failures of category 2	Number of failures of category 3
Storm period	A_1	A_2	A_3	D_1	D_2	D_3
Catch-up period	B_1	B_2	B_3	E_1	E_2	E_3
Steady state period	C_1	C_2	C_3	F_1	F_2	F_3

Table 5-2 Downtime and number of failures for helicopter access

	Downtime of category 1 [hours]	Downtime of category 2 [hours]	Downtime of category 3 [hours]	Number of failures of category 1	Number of failures of category 2	Number of failures of category 3
Storm period	A_1'	A_2'	A_3'	D_1'	D_2'	D_3'
Catch-up period	B_1'	B_2'	B_3'	E_1'	E_2'	E_3'
Steady state period	C_1'	C_2'	C_3'	F_1'	F_2'	F_3'

From the schematic drawing of combined access window, one can determine the downtime and number of failures for each category according to discussions below respectively. For discussions below, a specific helicopter, Bell 505, is selected to get representative results.

1. The downtime and number of failures of categories that need lifting equipment will follow the same equations and have the same values as that of vessel access. This is because the maximum capacity of helicopter is around 700kg (Anonymous, 2014c). For categories that need lifting equipment, repair work can only be finished by lifting vessel. In another word, helicopters are not helpful in repairing failures of categories that need lifting equipment. Categories that need lifting still have the same storm window as vessel access. Therefore, the downtime and the number of failures of category one will follow the same equations and have the same value as in vessel access only, which means A_1, B_1, C_1, D_1, E_1 and F_1 will apply to the combined access model.

2. From figure 5-1, the combined access window depends on one which has higher accessibility. Moreover, whether turbines have failures or not is independent of access methods once two methods have the same accessibility. There is an important assumption behind this conclusion. That is the number of operational turbines of helicopter access only and combined access should be the same. Test result shows for different access methods, the access method with higher accessibility can repair failures relatively in shorter time and thus cause new failures a little bit more. But the number of failures can still be regarded as constant, since failure rate is the dominant factor that affects the number of failures. Detailed numbers are given in Table 5-3.

Table 5-3 number of failures for different access method

	Vessel access only	Helicopter access only	Combined access
Number of failures [-]	1897	1907	1905

So the number of failures of category two and category three (categories that do not need lifting equipment) will follow the same equations and have the same values as helicopter access only, which means D_2', D_3', E_2', E_3', F_2' and F_3' will apply to the combined access model.

3. During storm periods, neither vessel nor helicopter can access, since combined access method has the same storm window as helicopter access. The downtime of category two and category three (categories that do not need lifting equipment) should follow the same equations and have the same values as helicopter access only, which means A_2' and A_3' will apply to the combined access model.

4. For combined access, the catch up periods account for a very small fraction of the total lifetime. From the intermediate results of TeamPlay, it is only 117 hours over the total lifetime. Therefore, during catch-up periods, it is decided that all accesses are executed by helicopters, which means B_2' and B_3' will apply to the combined access model.

5. During steady state periods for combined access, the maintenance activities can be finished by helicopters and vessels, whether helicopters are used will follow the access window. The total statistical value of downtime in steady state periods for combined access is affected by the following factors, they are the downtime in steady state for vessel access only, the downtime in steady state for helicopter access only, the storm fraction of vessel access, the storm fraction of helicopter access, the catch-up time for vessel access only and the catch-up time for helicopter access. Taking downtime of category two for combined access as an example, a clearer expression is given below. For the other categories that do not need lifting, one can follow the similar derivation process.

$$C_2^{''} = f(C_2,\ C_2^{'},\ f_s^{vessel},\ f_s^{heli},\ t_{catchup}^{vessel},\ t_{catchup}^{heli}) \tag{5-1}$$

Where C_2 is the downtime of category two when apply vessel access only, C_2' is the downtime of category two when apply helicopter access only, f_s^{vessel} and f_s^{heli} are the storm fraction of vessel access and helicopter access, $t_{catchup}^{vessel}$ and $t_{catchup}^{heli}$ are the time of catch up periods of vessel access and helicopter access.

Based on the assumption that the number of operational turbines are almost the same for three different access methods, the downtime is determined by repairing data, access speed, and time of waiting for crews. Then, for combined access, in helicopter access part (red lines), the downtime in a unit time should have the same value as helicopter access only. In vessel access part (black lines), the downtime in a unit time should have the same value as vessel access only. The downtime for vessel access parts and helicopter access parts in combined access model can be expressed as below:

$$T_{down,\ steady\ state}^{heli\ part\ combined\ access} = T_{down,\ steady\ state}^{heli\ access\ only} \times \frac{L_{red\ line\ parts}^{combined\ access}}{L_{red\ line\ (solid+dash)}^{heli\ access\ only}} \tag{5-2}$$

Where $T_{down,\ steady\ state}^{heli\ part\ combined\ access}$ is the downtime in steady state of helicopter access part in the combined access model, $T_{down,\ steady\ state}^{heli\ access\ only}$ is the downtime in steady state in the helicopter access only model. $\frac{L_{red\ line\ parts}^{combined\ access}}{L_{red\ line\ (solid+dash)}^{heli\ access\ only}}$ is defined as helicopter weight factor, f_{heli} .

$$T_{down,\ steady\ state}^{vessel\ part\ combined\ access} = T_{down,\ steady\ state}^{vessel\ access\ only} \times \frac{L_{black\ line\ parts}^{combined\ access}}{L_{black\ line\ parts}^{vessel\ access\ only}} \tag{5-3}$$

Where $T_{down,\ steady\ state}^{vessel\ part\ combined\ access}$ is the downtime in steady state of vessel access part in the combined access model, $T_{down,\ steady\ state}^{vessel\ access\ only}$ is the downtime in steady state in the vessel access only model. $\frac{L_{black\ line\ parts}^{combined\ access}}{L_{black\ line\ parts}^{vessel\ access\ only}}$ is defined as vessel weight factor, f_{vessel} .

According to the analyses above, helicopter weight factor and vessel weight factor can be determined by equations 5-4 and 5-5 respectively:

$$f_{heli}=\left(\frac{(1-f_s^{heli})-(1-f_s^{vessel})-\frac{t_{catchup}^{heli}}{8760}}{(1-f_s^{heli})-\frac{t_{catchup}^{heli}}{8760}}\right)=\left(1-\frac{1-f_s^{vessel}}{(1-f_s^{heli})-\frac{t_{catchup}^{heli}}{8760}}\right) \quad (5\text{-}4)$$

$$f_{vessel}=\left(\frac{(1-f_s^{vessel})}{(1-f_s^{vessel})-\frac{t_{catchup}^{vessel}}{8760}}\right) \quad (5\text{-}5)$$

Then, knowing the total downtime in steady state periods of helicopter access only, one can determine the downtime of helicopter access parts for combined access with equation 5-6.

$$T_{down,\ steady\ state}^{heli\ part\ combined\ access}=\left(\frac{(1-f_s^{heli})-(1-f_s^{vessel})-\frac{t_{catchup}^{heli}}{8760}}{(1-f_s^{heli})-\frac{t_{catchup}^{heli}}{8760}}\right)\times C_2^{'}=\left(1-\frac{1-f_s^{vessel}}{(1-f_s^{heli})-\frac{t_{catchup}^{heli}}{8760}}\right)\times C_2^{'}=f_{heli}\times C_2^{'} \quad (5\text{-}6)$$

The downtime of vessel access part for combined access can be determined by the similar methods with equation 5-7.

$$T_{down,\ steady\ state}^{vessel\ part\ combined\ access} = \left(\frac{(1-f_s^{vessel})}{(1-f_s^{vessel}) - \frac{t_{catchup}^{vessel}}{8760}} \right) \times C_2 \quad (5\text{-}7)$$

$$= f_{vessel} \times C_2$$

The downtime in steady state periods of combined access will be the summation of these two parts, which can be calculated by equation 5-8:

$$C_2^{"} = T_{down,\ steady\ state}^{vessel\ part\ combined\ access} + T_{down,\ steady\ state}^{vessel\ part\ combined\ access}$$

$$= \left(\frac{1-f_s^{vessel}}{(1-f_s^{vessel}) - \frac{t_{catchup}^{vessel}}{8760}} \right) \times C_2 + \left(1 - \frac{1-f_s^{vessel}}{(1-f_s^{heli}) - \frac{t_{catchup}^{heli}}{8760}} \right) \times C_2^{'} \quad (5\text{-}8)$$

$$= f_{vessel} \times C_2 + f_{heli} \times C_2^{'}$$

The number of failures and downtime in each periods are determined and expressed in Table 5-4.

Table 5-4 Downtime and number of failures for combined access

	Downtime of category 1 [hours]	Downtime of category 2 [hours]	Downtime of category 3 [hours]	Number of failures of category 1	Number of failures of category 2	Number of failures of category 3
Storm period	A_1	$A_2^{'}$	$A_3^{'}$	D_1	$D_2^{'}$	$D_3^{'}$
Catch-up period	B_1	$B_2^{'}$	$B_3^{'}$	E_1	$E_2^{'}$	$E_3^{'}$
Steady state period	C_1	$C_2^{''}$	$C_3^{''}$	F_1	$F_2^{'}$	$F_3^{'}$

6. For combined access, during steady state periods, the number of failures of category that do not need lifting are analyzed, they should have the same value as helicopter access only. However, some of these failures need helicopter access, and for the other, vessel access is enough. In order to model the cost of combined access and LPC of electricity, the exact number of failures that need helicopter access and vessel access should be figured out. Taking category two as an example, the number of failures in total lifetime that need helicopter access and vessel access are derived and shown in equation 5-11 and 5-12 respectively.

The catch-up period is defined as a period during which all failures that happened in previous storm period were repaired, and all failures happened in this catch-up period were repaired as well. With the assumption that during catch-up periods all accesses are executed by helicopters, the number of failures of category two that need helicopter access during non-steady state periods can be determined by equation 5-9:

$$N_{failure-non-steady}^{heli} = D_2^{'} + E_2^{'} \tag{5-9}$$

During steady state periods, the red solid line parts in combined access represent helicopter access. During steady state periods, in a unit time, the number of failures of category two that need helicopter access should have the same value as helicopter access only.

The number of failures that need helicopter access then is determined as below:

$$\begin{aligned} N_{failure-steady}^{heli} &= \left(\frac{(1-f_s^{heli})-(1-f_s^{vessel})-\frac{t_{catchup}^{heli}}{8760}}{(1-f_s^{heli})-\frac{t_{catchup}^{heli}}{8760}} \right) \times F_2^{'} \\ &= \left(1-\frac{1-f_s^{vessel}}{(1-f_s^{heli})-\frac{t_{catchup}^{heli}}{8760}} \right) \times F_2^{'} \\ &= f_{heli} \times F_2^{'} \end{aligned} \tag{5-10}$$

The total number of failures that need helicopter access of category 2 can be expressed as below:

$$N_{total}^{heli} = N_{failure-non-steady}^{heli} + N_{failure-steady}^{heli} \tag{5-11}$$

The black solid line in combined access represent vessel access, the number of failures that need vessel access can be expressed as below:

$$\begin{aligned} N_{failure-steady}^{vessel} &= \left(\frac{(1-f_s^{vessel})}{(1-f_s^{vessel})-\frac{t_{catchup}^{vessel}}{8760}} \right) \times F_2 \\ &= f_{vessel} \times F_2 \end{aligned} \tag{5-12}$$

Since all the failures of category that need lifting equipment will be accessed by vessel, the total number of failures that need vessel access is expressed as all the failures of categories that need lifting plus all failures (without lifting) happened in steady state multiply by the weight factor of vessel. The total number of failures that need vessel access can be determined by equation 5-13:

$$N_{total}^{vessel} = N_{failure\text{-}all}^{lifting\ categories} + N_{failure\text{-}steady}^{no\text{-}lifting\ categories} \times f_{vessel} \tag{5-13}$$

Where $N_{failure\text{-}all}^{lifting\ categories}$ is the total number of failures in three periods of lifting categories, and $N_{failure\text{-}steady}^{no\text{-}lifting\ categories}$ is the total number of failures of no lifting categories in steady state.

The total number of failures that need helicopter access is expressed as all the failures happened in storms and catch-up periods of categories that do not need lifting plus all the failures happened in steady state of categories that do not need lifting multiply by the weight factor of helicopter. The total number of failures that need helicopter access can be determined by equation 5-14:

$$N_{total}^{heli} = N_{failure-storm\&catch}^{no-lifting\ \text{categories}} + N_{failure-steady}^{no-lifting\ \text{categories}} \times f_{heli} \tag{5-14}$$

Where $N_{failure-storm\&catch}^{no-lifting\ \text{categories}}$ is the total number of failures in storm and catch up periods of no lifting categories, and $N_{failure-steady}^{no-lifting\ \text{categories}}$ is the total number of failures in steady state periods of no lifting categories.

5.4 Cost model

The cost of combined access should also be changed since vessels are used less and helicopter are rented. Note that helicopters rent policy are different with that of vessels. Vessels are assumed to be ready all the time, while helicopters are hired on demand bases. Therefore, the number of crew transportation by vessels depends on the number of repair batch. In a repair batch, crews can repair several failed turbines and the vessel will wait there until they finish the repair work. And the cost of hiring vessels depends on the total mission time of the vessel. Helicopters are hired hourly, the helicopter will send crews to failed turbines and go back, and they will be picked up when they finish the repair work. Therefore, the cost of hiring helicopters depends on the total time needed for transporting crews, and the repair time periods are not included in the helicopters hiring time. The time needed for transporting crews depends on the number of failures that need helicopter access.

To determine the number of helicopter transportation, one should first figure out the distribution of number of failures. Because having one failure at one time and having several failures at one time will lead to different number of helicopter transportation. Figure 5-3 shows a schematic route of helicopter transportation. The red dot represents the failed turbines. For cases of having only one failure, the helicopter will transport a crew to the failed turbine and goes back. When the crew finish the repair work, the helicopter will go to the crew again to pick them up. In the cases of having only one failure, the total number of crew transportation is two. A round trip will be accounted as one time of helicopter transportation.

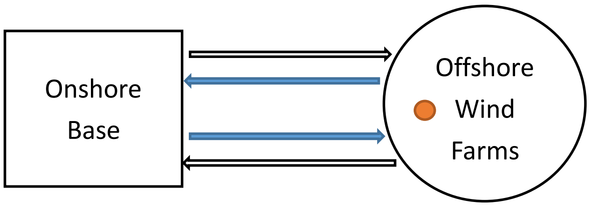


Figure 5-3 Helicopter maintenance schematic route of one failure

The chosen helicopter have a maximum passenger of six, the number of person in each crew in TeamPlay is set as three. So, the chosen helicopter can transport two crews one time at most. For cases of having two failures at the same time, the helicopter will carry two crews and send them to failed turbines respectively, then it will go back. After repair work is finished, two crews will be picked up together. The total number of crew transportation is still two in such cases.

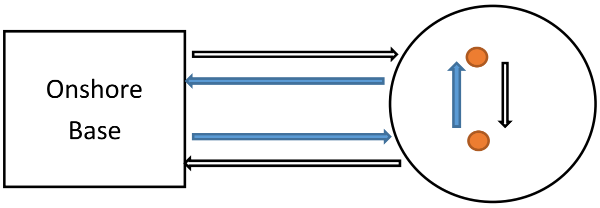


Figure 5-4 Helicopter maintenance schematic route of two failures

For cases of having three failures, helicopter will transport two crews then go back to transport another crew again. The total number of crew transportation will be four in these cases.

With similar analysis, one can get the relationship between number of crew transportation and distribution of number of failures. They can be expressed as below:

$$N_{n\ failures}^{crew\ transport} = \begin{cases} n+1 & \text{n is an odd number} \\ n & \text{n is an even number} \end{cases} \tag{5-15}$$

Where n is the number of failures having at the same time. The total number of crew transportation by helicopter can be expressed as the summation of the number of failures at one time multiply by the number of crew transportation under these cases, when more than one failures happen at a time, these failures are considered as a group, therefore, n is divided to calculate the number of groups of n failures happen together. For example, the number of failures that having two failures simultaneously is $N_{2\ \text{failures}}$, and every two failures as a group need two times of crew transportation, so the total number of crew transportation of cases that having two failures will be $\frac{N_{2\ \text{failures}}}{2} * 2$. For the other cases, one can follow the similar analysis, the total number of crew transportation by helicopter can be derived as below:

$$N_{total}^{crew\ transport} = \sum_{n=1}^{N_{turbines}} \left(\frac{N_{n\ failures}}{n} \times N_{n\ failures}^{crew\ transport} \right) \tag{5-16}$$

The total number of failures that need helicopter access is already determined by equation 5-14. With the distribution of failures, one can determine the number of failures of having n failures at the same time. The probability of failure after a time period t can be expressed as below:

$$P_{fail,heli} = 1 - \mathrm{e}^{-t \cdot \sum h_{heli}} \tag{5-17}$$

$P_{fail,heli}$ is the probability of failures that need helicopter access, $\sum h_{heli}$ is the failure rate of categories that do not need lifting. t is the time interval of helicopter access, t can be determined from the shift duration interval.

During the steady state periods, the distribution of failures follows the binomial distribution, then the probability of having n failures that need helicopter access can be expressed as below:

$$P_{n\ \text{failures}}^{need\ heli} = \frac{N_t!}{(N_t - n)! \times \text{n}!} \times \left(P_{fail,heli}\right)^n \times (1 - P_{fail,heli})^{N_t - n} \tag{5-18}$$

N_t is the number of operational turbines. However, one should get rid of the cases that there is no failure happens, because helicopters will only access the wind farm when failures are detected. Without considering the probability of having zero failure, one can get the conditional probability of failure distribution. Figure in Appendix E shows the conditional probability of failure distribution.

For the case of OWEZ of year 2010, by multiplying the conditional probability $P_{n\ \text{failures}}^{need\ heli}$ by N_{total}^{heli}, one can get the total number of failures of having n failures, $N_{n\ failures}$ respectively. Substituting $N_{n\ failures}$ into equation 5-16, the total number of crew transport by helicopter can be calculated. Table 5-5 below shows the details. The probability of having four failures at one time is $5.4*10^{-5}$, so details of having five failures and above are omitted in Table 5-5.

The maintenance cost of helicopter access per year then can be expressed as below:

$$C_{opex}^{heli} = t_{mission}^{heli} \times R^{heli} \times N_{total}^{crew\ transport} / T_{total\ lifetime} \tag{5-18}$$

R^{heli} is the rent value of helicopters, the hourly rate of helicopters varies in 3400 and 4100 Euros (Rademakers L et al,2002). 4000 Euros is chosen for helicopter rent value. Wind farm Egmond aan Zee is 15 km far away from the shore, so each crew transport mission can be finished within one hour, $t_{mission}^{heli}$ is one in this case.

From the calculation of failures distribution, one can conclude that more than 99% cases are having one or two failures during the steady state periods. During the catch-up periods, failures have been accumulated after the previous storm period. Therefore, cases that having more than two failures may happen more frequently. When the catch up periods account for a large part, the calculation of crew transport of helicopters should still follow the general method discussed above. However, modelled results reveal that the number of failures accumulated after storm periods in the total lifetime are 20 and 10 for category two and category three respectively, which means they only account for a very small fraction in the total failures. When calculating the crew transport, one can more or less neglect the failure distribution and use a simpler method.

The general method of determining the crew transport by helicopters discussed above can be used in accurate calculations. Operators can also choose a simpler way that considering all failures are taking place one by one, since over 90% of the failures are distributed in the region that n equals one, and the crew transport by helicopters can be simply determined by just multiplying by 2 with the number of failures that need helicopter access. The results are given in Table 5-5, the simplified methods also gives a 95% accuracy.

Table 5-5 Calculation details of failure probabilities and helicopter access

Having n failures at one time	Binomial distribution	Probability of having n failures at one time	Conditional Probability	Total number of failures of having n failures at one time	Total Number of crew transport by helicopter
0	1	0.812	-	-	-
1	36	0.170	0.902	825.44	1650.87
2	630	0.017	0.092	83.78	83.78
3	7140	0.001	0.006	5.51	7.34
4	58905	5.413E-05	0.0002	0.26	0.26
Summation				915	1742
Results of the simplified method				915	1830

5.5 Result of combined access model

With the expanded access model, for the case of OWEZ of year 2010, one can compare the results from vessel access only and combined access. From results of the new model, one can find that the availability of the wind farm increases due to higher accessibility. The LPC also increases due to higher operational cost, which is presented in Table 5-6.

Table 5-6 Details of availability and LPC of initial model and improved model

	Initial guess (vessel access only)	Optimization (vessel access only)	Initial guess (combined access)	Optimization (combined access)
LPC[euro/kWh]	0.1576	0.1530	0.1622	0.1540
Energy yield[kWh/year]	$3.226*10^8$	$3.320*10^8$	$3.229*10^8$	$3.382*10^8$
Availability[-]	94.40%	92.74%	94.76%	95.18%

The optimization process is based on lowest LPC, therefore, it looks for the lowest LPC rather than highest availability. Comparing the optimized LPC of vessel access model and combined access model, one can find that if the operator apply a cost based policy, vessel access will be selected. However, if the operators' policy is based on maximum revenue, considering that the electricity price of the Netherlands is 23 euro cents per kWh (Zeman M, 2013), the difference of revenue of two access methods will be 140,000 euros per year. In such cases, combined access would be more attractive.

Combined access will largely decrease the downtime in storm and catch-up, because, most of the time will be steady state periods for combined access. Further investigating the downtime of different categories, one can find if failures that do not need lifting equipment happen easily, which means the MTBF of categories that do not need lifting equipment is small, helicopter access will be effective to decrease the downtime. If the downtime due to failures that need lifting equipment is the dominant, helicopter access may not be helpful enough. The total downtime due to failures that do not need lifting equipment are 96436 hours in the vessel access model and 73764 hours in the combined access model respectively. Results of two models show the total downtime of categories that do not need lifting equipment decrease 23.5% after applying combined access.

Chapter 6 Stock Model

Teamplay does not contain stock model parts currently, it is assumed that there are enough spare parts in stock, and there is no downtime due to spare parts delay. However, in real operation, stock problems have to be considered. Since every components in wind turbines cannot be replaced by each other, the stock policy has to be determined in terms of each specific component separately rather than in terms of category together. The MTBF of each component is necessary to determine the corresponding stock policy. The MTBF of gearboxes, generators and blades are known, stock policy of these three components will be determined. Other components in category two and three are unknown, but two of them will be selected to discuss as an example of how to determine the stock policy of components in different categories. One can follow the similar process of analysis to determine the corresponding stock policy of other components.

6.1 Spare parts information

The spare parts of wind turbines can be classified as repairable components and unrepairable components. Line Replaceable Units (LRU) are spares that can be replaced and repaired, when a LRU component fails, it will be replaced by another new component, and it will be sent to a workshop to repair then stored for next use. Discardable Units (DU) are spares that cannot be repaired, and they will be replaced by new components and be discarded directly.

Lead time is the latency between the initiation and execution of a process. In wind industries, it is a time period that between making the order of spare parts and getting spare parts. For some important and expensive components, like gearboxes and generators, usually the lead time will be long. Other less important components are cheaper and easier to get. In terms of LRU, there is a repair turn-around-time (TAT), TAT is the time that it takes for an item to be repaired in a workshop and ready to be sent back to a depot (Lindqvist M, 2010). The detailed information is given in Table 6-1.

Table 6-1 Spare parts information

Spare Code	Spare Name	MTBF [hours]	Spare Price[euro](2013)	Lead time [weeks]	TAT [weeks]	Type [-]
1	Gearbox***	48670	$2*10^5$[a]	10	10	LRU
2	Generator***	48670	10^5[a]	10	10	LRU
3	Rotor blades***	36500	10^5[a]	15	0	DU
4	EMC filter*	182000	1800[b]	1	0	DU
5	Ultra Sonic Anemometer*	57000	1800[b]	0	8	LRU

a Spare parts data (Dewan A, 2013)
b Spare parts data (Lindqvist M, 2010)
* Components with low cost and high criticality
*** Components with high cost and high criticality

According to Sheikh A K et al, spare parts need to be evaluated in terms of cost and criticality (Sheikh A.K et al, 1991). They can be classified as low, moderate and high respectively. Since the failures of components we discussed now are failures would cause downtime and crew-access repair in operation, therefore, they can be all regarded as components with high criticality. Cost classification are based on the relative price of components shown in the table above.

6.2 Stock balance calculation

With the MTBF of specific components, one can determine the number of spares needed during a certain period of time with a probability of without shortage equals P, the equation for calculating the number of spare parts is given as below (Sheikh A K et al, 1991):

$$N = \frac{t}{\overline{T}} + \frac{1}{2} \times (K^2 - 1) + K\sqrt{\frac{t}{\overline{T}}} \times \Phi^{-1}(P) \tag{6-1}$$

Where N is the number needed, t is the time period, $\overline{T}$ is the average MTBF of the whole system, P is the probability of without shortage, $\Phi^{-1}(P)$ is the coefficient corresponding to P. Values of $\Phi^{-1}(P)$ are given in Appendix F. Taking gearbox as an example:

$$\frac{1}{\overline{T}_{gearbox}} = \frac{1}{MTBF_{gearbox}} \times N_{operational\ turbines}$$

$$\overline{T}_{gearbox} = \frac{MTBF_{gearbox}}{N_{operational\ turbines}} \tag{6-2}$$

K is the coefficient of variation of time between failures. K represents the scatter of life, K varies from 0 to 1, when K equals 0, it means there is no scatter in the life of the parts, whereas K equals 1 means a significant amount of scatter. K can either be calculated from historical time between failure data of the part, or in case of absence of time between failure data, initial estimation of K can be determined by Weibull reliability shape factor β (Bloch H P et al, 1983). According to the research of Bloch H P, the approximate relation between K and β is $K \approx 1/\beta$. For failures of mechanical parts, researchers have given K values for different failure modes (Bloch H.P et al, 1983). Detailed information are shown in Table F-2 in the Appendix. The possible failure mode in wind industries would be aging or wear, therefore, K equals 0.33 is selected in the later discussion.

6.3 Influence on cost, downtime and energy loss

When take stock into consideration, there are some extra cost, downtime and energy loss. The holding cost and energy loss have opposing effects on LPC, therefore, they need to be balanced to find a point with maximum profit or lowest LPC.

6.3.1 Holding cost

By keeping components in the stock, one needs to consider the holding cost, which is proportional to the number of components in stock, in the discussion below, the holding and management cost per year is assumed to be 10% of the price of each component. To be consistent with TeamPlay, the interest rate q is selected as 10% and inflation rate v is selected as 2.5% (Zaaijer M.B., 2013b). Then the real interest rate r can be determined by equation 6-3:

$$r = \frac{1+q}{1+v} - 1 \qquad (6\text{-}3)$$

With a certain time interval t, one can calculate the number of components needed, $N_i^{in\ stock}$, according to different spare parts availability requirement with equation 6-1. For every batch of component, the holding cost depends on time interval t, a smaller t leads to a lower holding cost per batch but a larger number of batch in the whole lifetime. Once failure mode and MTBF of a component is given, $N_i^{in\ stock}$ is a variable that depends on time interval t and spares availability P.

In year one, the holding cost of component i can be determined by equation 6-4:

$$C_{i\ year\ 1}^{holding\ costs} = 10\% \times P_i^{component} \times N_i^{in\ stock} \times N_y \times N_B$$
$$= 10\% \times P_i^{component} \times N_i^{in\ stock} \times \frac{t}{8760} \times \frac{8760}{t}$$
$$= 10\% \times P_i^{component} \times N_i^{in\ stock} \quad (6\text{-}4)$$

Where N_y represents the number of years that each batch stay in the stock, and N_y equals $\frac{t}{8760}$. N_B represents the number of re-ordering batches per year, and N_B equals $\frac{8760}{t}$.

In the whole lifetime, the holding cost in later years will have less net present value than that in earlier years. With a real interest rate r, one can get the net present value of holding cost in year n of component i will be $C_{i\ \text{year 1}}^{holding\ costs} \times \frac{1}{(1+r)^{n-1}}$. The total holding cost of component i in 20 years will be the summation of such a geometric sequence, and summation is shown in equation 6-5:

$$C_{i\ \text{20 years}}^{holding\ costs} = C_{i\ \text{year 1}}^{holding\ costs} \times \left(\frac{1-\left(\frac{1}{1+r}\right)^{20}}{1-\left(\frac{1}{1+r}\right)} \right) \quad (6\text{-}5)$$

The total holding cost due to stock is calculated by equation 6-6:

$$C_{total}^{holding\ costs} = \sum_i C_{i\ \text{20 years}}^{holding\ costs} \quad (6\text{-}6)$$

6.3.2 Downtime due to spares shortage

In a time interval t, if one spare part shortage of component i happens, the extra downtime caused by stock shortage will be the lead time of component i. In the next time interval, similar analysis can be made. With the probability of without shortage P, the expected value of extra downtime caused by stock shortage will be the lead time of component i multiplies the probability of shortage, multiply the expected value of number of failures in time interval t, multiply the number of time interval in the total lifetime.

Here, it is assumed that there are enough components in the workshop so that the TAT of LRU components will not affect the date of delivery. The downtime due to stock shortage of component i can be calculated with equation 6-7. $\frac{T_{total\ lifetime}}{MTBF_i}$ represents the expected value of number of failures of component i that would happen in the total life time.

$$
\begin{aligned}
T_i^{downtime\ stock\ shortage} &= T_i^{Lead} \times (1-P) \times \frac{t}{MTBF_i} \times \frac{T_{total\ lifetime}}{t} \\
&= T_i^{Lead} \times (1-P) \times \frac{T_{total\ lifetime}}{MTBF_i}
\end{aligned} \tag{6-7}
$$

The total extra downtime caused by stock shortage will be:

$$T_{total}^{downtime\ stock\ shortage} = \sum_i T_i^{downtime\ stock\ shortage} \tag{6-8}$$

When calculate the availability of wind farm, the downtime caused by spare part shortage should also be considered.

6.3.3 Energy loss and new LPC

The extra downtime caused by spare parts shortage will lead to a lower availability and less energy production as well. The spare parts shortage can happen in any weather condition, so the expected value of energy production is proportional to the uptime of turbines. Then the expected energy loss can be derived as equation 6-9:

$$\frac{T_{total}^{downtime\ stock\ shortage}}{E_{loss}} = \frac{\eta \times N_{operational\ turbines} \times T_{total\ lifetime}}{E_{initial\ production}} \tag{6-9}$$

η is the overall availability of the wind farm, $E_{initial\ production}$ is already calculated from the initial model. Therefore, the LPC with stock influence can be determined by equation 6-10:

$$LPC_{with\ stock} = \frac{C_{invest} + C_{O\&M} + C_{decom} + C_{total}^{holding\ costs}}{E_{initial\ production} - E_{loss}} \tag{6-10}$$

Where C_{invest} is the cost of investment in year 0, $C_{O\&M}$ is the total cost of operation and maintenance in 20 years and C_{decom} is the cost of decommissioning in the 20th year.

6.4 Stock policy determination

From the analysis above, one can find that the LPC will be affected by $C_{total}^{holding\ costs}$ and E_{loss}. Equation 6-1 and 6-7 show that $C_{total}^{holding\ costs}$ and E_{loss} are all affected by time interval t and spare parts availability P. A smaller t leads to lower stock number and lower holding cost but more energy loss, and a larger P leads to less energy loss but higher holding cost. Therefore, one can find the new LPC with equation 6-10. A test result for case OWEZ 2010 with combined access and stock management is shown in Figure 6-1, and detailed values are shown in Appendix G. Table H-1 to Table H-5 in Appendix H show the number in stock of each component with different spares availability. From Figure 6-1 and Table H-1 to Table H-5, one can find that with a certain spares availability, a larger t leads to higher LPC, because more spare parts in stock means higher holding cost. And in this case, holding costs are more dominant than saved energy loss. In terms of a certain time interval t, a too low spares availability means too much energy loss, a too high spares availability means too much holding cost. There is an optimal point of spares availability, and this needs to be determined with detailed wind farms information.

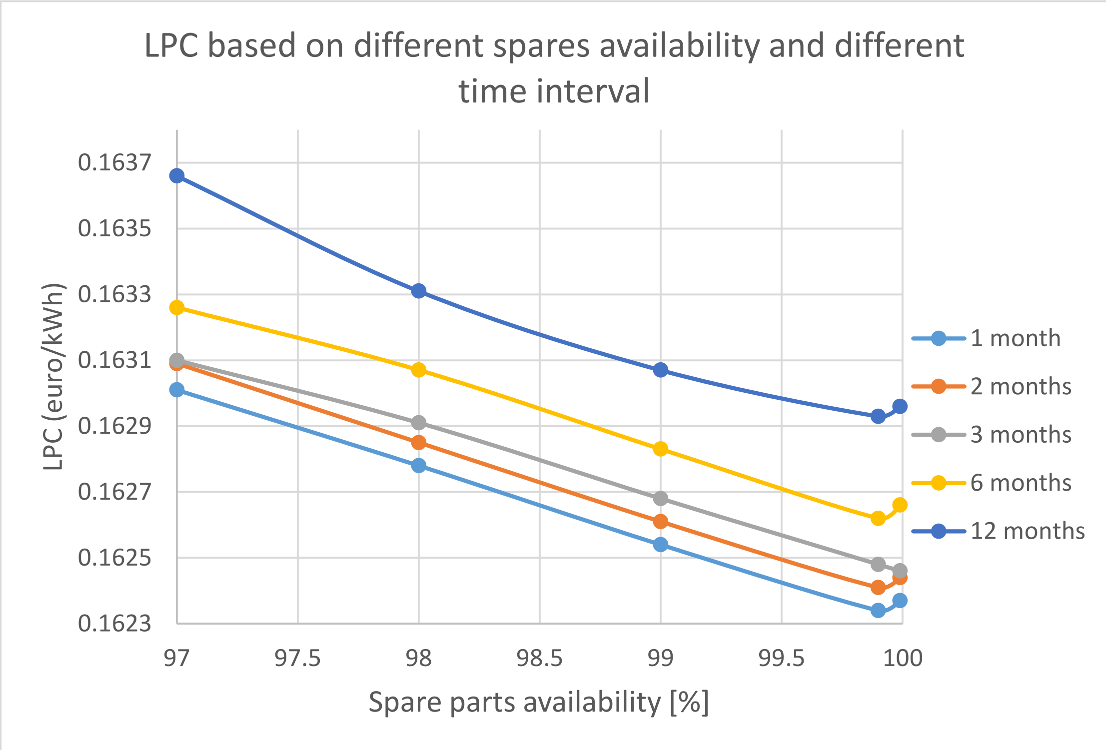


Figure 6-1 LPC based on different spares availability and different time interval

The number of spare parts in stock must be integral, so the values in Table H-1 to Table H-5 are rounded up from initial calculated results. This makes different spares availability have the same value of number in stock.

From the calculation, in the case of OWEZ, an appropriate stock number corresponds to the point with lowest LPC in Figure 6-1. This point means in a time interval equals 730 hours, the number of spare parts in the stock shown in Table H-1 can guarantee 99.9% of spare parts demands. And orders are placed on one by one basis when failures occur.

In the current stock point selection, there is no zero stock occurs in components with high lead time. Other smaller time interval would cause zero stock of components with much higher lead time, like blades and gearbox, which makes the downtime due to spares shortage increase sharply. Moreover, based on calculation, one can find energy loss is the dominant factor in calculating the LPC. Although the holding costs may decrease a little, the energy production would decrease much more. If operators are total profit based, they should avoid zero stock of components with high lead time.

The ordering cost are not considered in the analysis, because comparing to the holding costs, they are much smaller and can be neglected. The chosen components, EMC filter and ultra-sonic anemometer have a good reliability and a short lead time, hence, one or zero stock is acceptable.

When ordering cost of some components becomes the dominant factor or analysis with higher accuracy are required, the ordering cost should be considered. The components discussed above are all critical to operation. Other frequently used, predictable and less expensive items can always kept in stock, such as lubrication oil, they will not affect the total holding costs too much.

Chapter 7 Conclusion and Recommendation

7.1 Conclusion

In this report, an overview of wind energy development and basic offshore maintenance theory are given in the first two chapters. The statistical model, TeamPlay, is explained and validated.

The validation is completed through comparison of modelled results versus reported data for two specific years of the OWEZ wind farm. Results show that in 2009, the availability of wind farm is 84.1%, which is 1.7% higher than reported data. For 2010, it is 94.4%, which is 3.4% higher than reported data. Further analyses show that these difference might result from too optimistic MTBF data used in model input of category that only needs diagnosis and category that neither needs lifting equipment nor diagnosis. Because the uptime increment after pro-active replacement (unusual replacement taken by operators to avoid reliability problems), downtime of schedule maintenance and downtime of other categories are more or less the same. Only downtime of category that needs diagnosis and category that neither needs lifting equipment nor diagnosis has a much smaller value in model results. Another reason may come from spare parts delay, which is not considered in the initial model. Moreover, validations are also done from logical aspects. For instance, the failure probability during storms and the influence on downtime during a storm of MTBF are evaluated in this way. In terms of failure probability during storms, it goes to zero when storm duration goes to infinity, as expected. In terms of MTBF, when a certain component is quite easily to fail, the downtime caused by this kind of component during one storm would be close to the storm length. Results are closely monitored and they are logical as expected. The model is evaluated from logical point of view to guarantee its validity. Comparison with another simulation model Contofax also show that TeamPlay yield a more accurate result both in number of failures and availability.

A combined access with helicopter and vessel provides operators with more options to access wind farms, and higher accessibility leads to higher availability. For the combined access model, there are some assumptions and simplifications. First, the combined model does not take into account cases where wind farms can be accessed by vessels, while not accessible for helicopters. This occurs, for instance, during extreme foggy days. Moreover, it is assumed all repair works in catch up periods are executed by helicopter access. Afterwards, the number of total failures is still determined by MTBF. Higher accessibility has little effect on the number of total failures. The effect of combined access will only be noticeable when categories that do not need lifting equipment have a small MTBF. If these categories prove to be reliable, the chance of utilizing helicopters becomes much smaller. Failures of components in categories that need lifting equipment cannot be repaired by helicopter access, which weakens the effect of high accessibility of helicopters. In general, the LPC after applying combined access will increase, however, higher energy production is expected as well. Whether operators choose combined access or solely vessel access largely depends on the company strategy. For the case of OWEZ in 2010, if a total revenue based strategy is selected, combined access would be economically favorable.

Stock management takes the lead time of components, holding costs and extra downtime into consideration, which makes the model more realistic. Holding costs, extra downtime and energy production losses are evaluated based on some assumptions. The selection of appropriate stock strategy varies from case to case. For OWEZ, the appropriate stock strategy is to keep one month stock with 99.9% spare parts availability. This would avoid having no stock and large downtime caused by excessive lead time, and minimize the holding costs as well. By applying combined access and stock management in OWEZ, the new LPC with stock has a 0.068% increase compared to the initial LPC without stock. The overall availability of wind farm now has a 0.014% decrease after considering the stock problem. Although there is only a small difference between new LPC and original LPC, and wind farm availability as well, the stock management provides operators with a more precise number of components that should be kept in stock. This is more reasonable than the initial assumption that there are enough spare parts in stock but without extra holding costs.

7.2 Recommendation

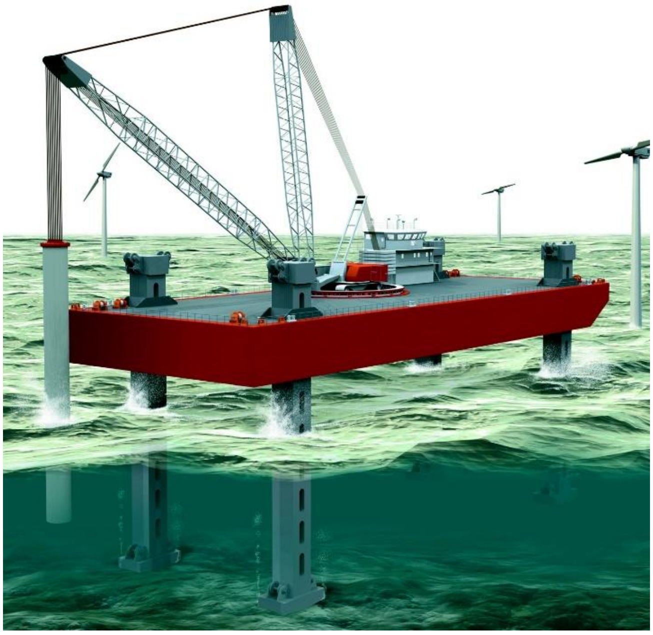
In this report, the initial input data of TeamPlay are somewhat estimated from incomplete information. Furthermore, some data is extracted from only looking at Horns Rev, which could not be the same for a different wind farm. Detailed downtime and failures of each component are also retained from official operation reports. For the future, if more accurate component properties and real operation data would become available, like MTBF and repair time of each component, a clearer comparison and a more precise validation is expected.

When discussing the combined access window, situations where wind farms can only be accessed using vessel rather than a helicopter are neglected. This occurs, for instance, during some foggy days. Although these situations account for only a small percentage, further improvements can be made when these aspects are incorporated.

Finally, the stock parts analyses do not consider the ordering costs, it only balances the holding costs with energy losses. When ordering costs were to be considered, the model would be more accurate.

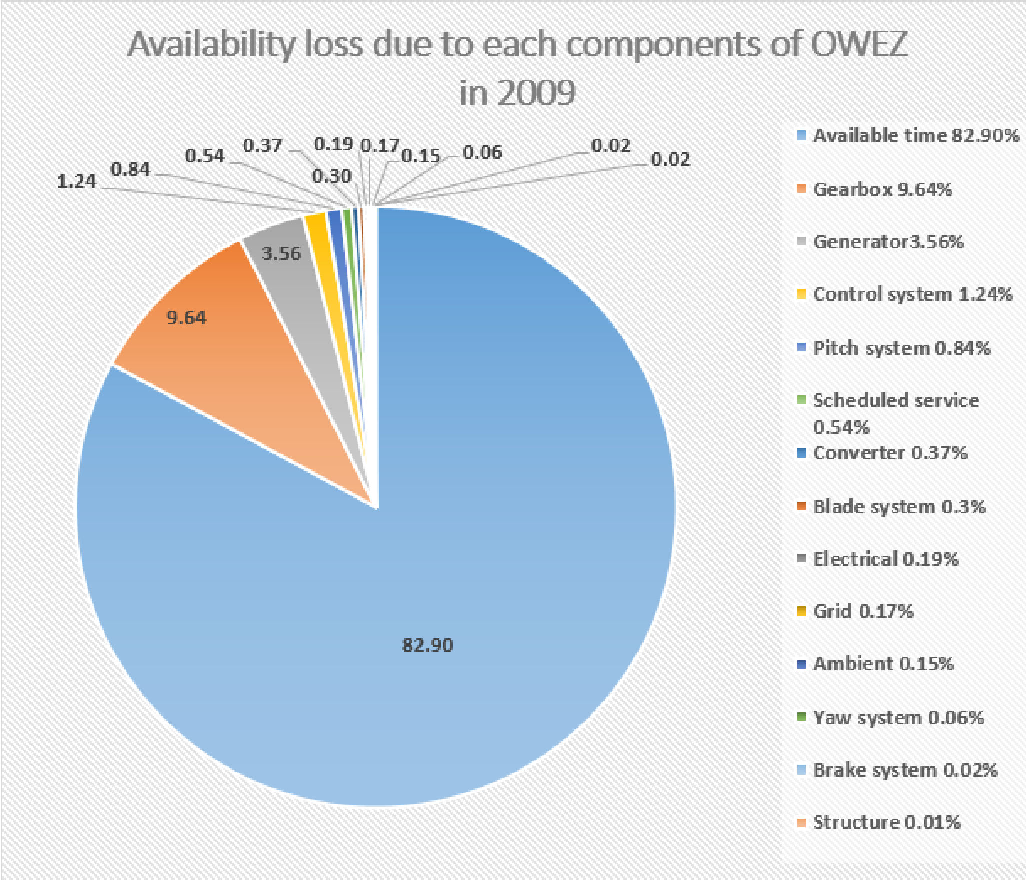
Appendix

Appendix A



Jack-up barge

Appendix B



Availability loss of OWEZ in 2009 (operation reports, 2010, with adaptations)

Appendix C

C-1 Input data for the rotor-nacelle assemblies (Zaaijer M.B., 2013b)

Input data for the rotor-nacelle assemblies	
Geometric properties	
Rotor radius[m]	45
Rotor solidity[-]	0.052
Front area nacelle[m^2]	15.4
Height from yaw to hub[m]	2
Yaw bearing diameter[m]	2.26
Mass properties	
Mass of rotor and nacelle[kg]	130800
Eccentricity (downwind is positive)[m]	-2
Aerodynamic load properties	
Cd rotor idling in vane[-]	0.4
Cd nacelle[-]	1.2
Maximum operational thrust[N]	485000
Wind speed at maximum thrust[m/s]	13
Electrical properties	
Generator voltage[V]	1000
Operational properties	
Preventive maintenance interval[h]	4380
Preventive maintenance duration[h/turbine]	23
Preventive maintenance consumables costs[€/service]	1800
People per maintenance crew[-]	3
Financial data	
Purchase price[€]	2200000
One-off warranty premium (percentage of purchase price)[%]	15

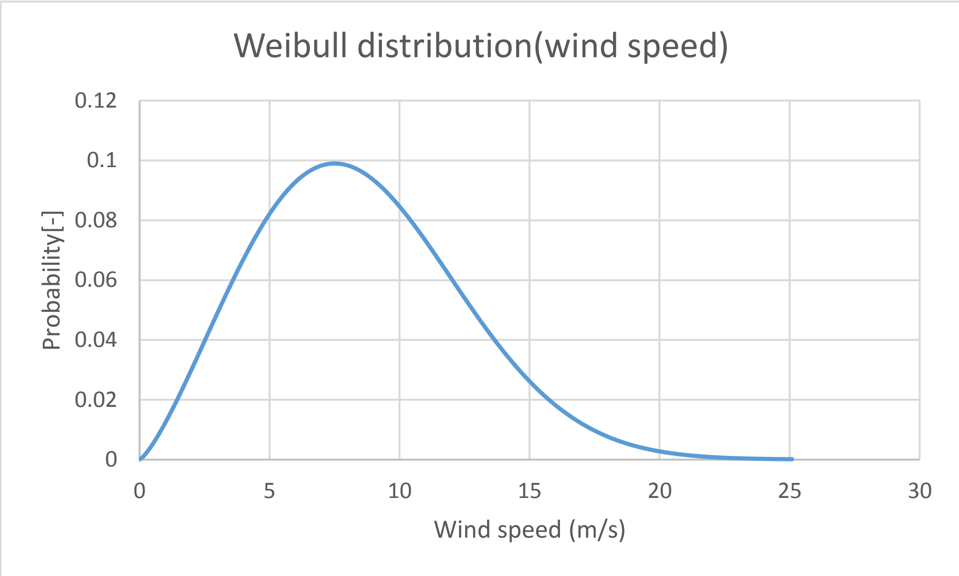
C-2 Input site data for OWEZ (Zaaijer M.B., 2013b)

Site data for OWEZ		
Wind climate		
Weibull scale factor	[m/s]	9.6
Weibull shape factor	[-]	2.31
Reference height above MSL	[m]	70
Wind shear power exponent (alpha)	[-]	0.1
Water levels		
Water depth (deepest in site)	[m]	18
Highest astronomical tide above MSL	[m]	0.8
Lowest astronomical tide (negative value)	[m]	-0.8
Positive storm surge	[m]	2.5
Negative storm surge (negative value)	[m]	-0.5
Wave and current climate		
Significant wave height (1 year extreme)	[m]	5.65
Significant wave height (50 year extreme)	[m]	6.29
Depth average current (50 year extreme)	[m/s]	0.8
Angle between wave and current (50 year extreme)	[degrees]	20
Water properties		
Average density	[kg/m^3]	1025
Maximum temperature at seabed level	[° Celsius]	15
Geophysical properties		
Seabed grain size (d50)	[m]	0.0002
Seabed grain size (d90)	[m]	0.0005
Typical soil friction angle	[degrees]	35
Typical submerged unit weight	[N/m^3]	10000
Accessibility information		
Distance to harbor (for maintenance)	[m]	15000
Reference significant wave height limit	[m]	1.5
Fraction of time with no access for reference wave height	[-]	0.6
Weibull scale factor for no access windows	[h]	19.5
Weibull shape factor for no access windows	[-]	0.65
Grid coupling point		
Distance to grid coupling point	[m]	15000
Frequency	[Hz]	50
Voltage	[V]	150000

C-3 Thrust coefficient and power data of V90 (V90-3.0MW brochure)

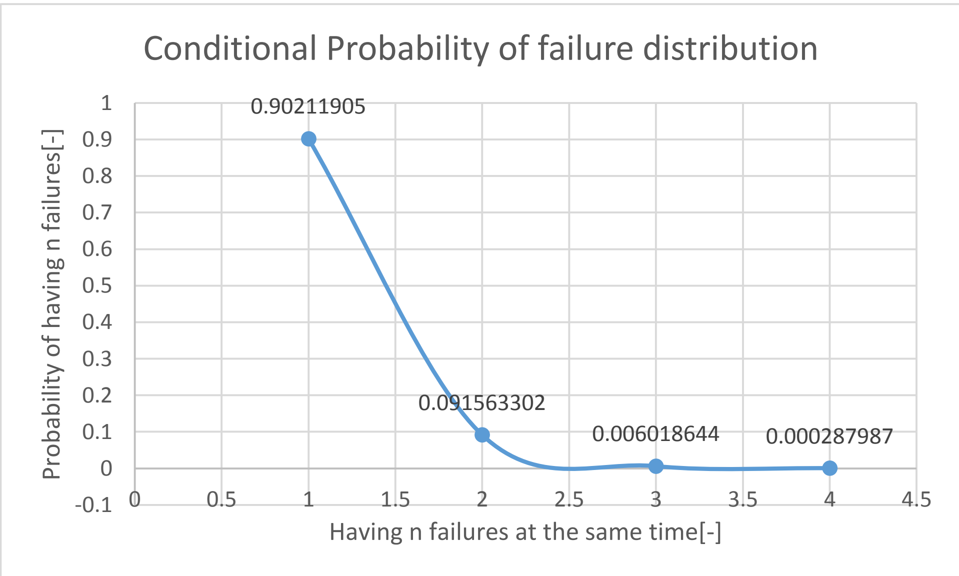
Wind speed	Thrust coefficient	Power	Wind speed	Thrust coefficient	Power
[m/s]	[-]	[KW]	[m/s]	[-]	[KW]
3.999	0	0	**15**	0.304	2995
4	0.815	77	**16**	0.246	3000
5	0.818	190	**17**	0.203	3000
6	0.823	353	**18**	0.17	3000
7	0.823	581	**19**	0.144	3000
8	0.824	886	**20**	0.124	3000
9	0.802	1273	**21**	0.107	3000
10	0.73	1710	**22**	0.094	3000
11	0.648	2145	**23**	0.082	3000
12	0.564	2544	**24**	0.073	3000
13	0.49	2837	**25**	0.065	3000
14	0.39	2965	**25.0001**	0	0

Appendix D



Wind speed Weibull distribution of OWEZ

Appendix E



Condition probability of failure distribution

Appendix F

F-1 Φ-1 (P) for various values of P (Lipson C et al, 1973, with adaptions)

P(%)	Φ^{-1}(P)	P(%)	Φ^{-1}(P)	P(%)	Φ^{-1}(P)	P(%)	Φ^{-1}(P)
50.00	0.00	93.32	1.50	98.00	2.05	99.70	2.75
75.00	0.67	94.00	1.56	98.61	2.20	99.80	2.88
80.00	0.84	94.54	1.60	99.00	2.33	99.86	3.00
84.13	1.00	95.00	1.65	99.18	2.40	99.90	3.09
85.00	1.04	96.00	1.75	99.38	2.50	99.93	3.20
89.44	1.25	97.00	1.88	99.50	2.57	99.99	4.00
90.00	1.28	97.72	2.00	99.60	2.65		

F-2 Coefficient of variation K for different failure modes (Bloch H.P et al, 1983)

	Failure mode	Coefficient of variation K
1	Deformation	1.0
2	Fracture	1.0
3	Change of material quality	
3(a)	Aging	0.33
3(b)	Degradation	0.5
3(c)	Burning	1.0
3(d)	Embrittlement	1.0
4	Corrosion	0.5
5	Wear	0.33
6	Leakage	0.67

Appendix G

LPC based on different spare parts availability and different time interval

	Spares availability 97%	Spares availability 98%	Spares availability 99%	Spares availability 99.9%	Spares availability 99.99%
t (730 h)	0.16301	0.16278	0.16254	0.16234	0.16237
t (1460 h)	0.16309	0.16285	0.16261	0.16241	0.16244
t (2190 h)	0.16310	0.16291	0.16268	0.16248	0.16246
t (4380 h)	0.16326	0.16307	0.16283	0.16262	0.16266
t (8760 h)	0.16355	0.16331	0.16307	0.16293	0.16296

Appendix H

H-1 Stock number of each component (730 hours, different spares availability)

	Number in stock (97%)	Number in stock (98%)	Number in stock (99%)	Number in stock (99.9%)	Number in stock (99.99%)
Gearbox	1	1	1	1	2
Generator	1	1	1	1	2
Rotor blades	1	1	1	2	2
EMC filter	0	0	0	1	1
Ultra Sonic Anemometer	1	1	1	1	1

H-2 Stock number of each component (1460 hours, different spares availability)

	Number in stock (97%)	Number in stock (98%)	Number in stock (99%)	Number in stock (99.9%)	Number in stock (99.99%)
Gearbox	2	2	2	2	3
Generator	2	2	2	2	3
Rotor blades	2	2	2	3	3
EMC filter	1	1	1	1	1
Ultra Sonic Anemometer	2	2	2	2	2

H-3 Stock number of each component (2190 hours, different spares availability)

	Number in stock (97%)	Number in stock (98%)	Number in stock (99%)	Number in stock (99.9%)	Number in stock (99.99%)
Gearbox	2	3	3	3	3
Generator	2	3	3	3	3
Rotor blades	3	3	3	4	4
EMC filter	1	1	1	1	1
Ultra Sonic Anemometer	2	2	2	3	3

H-4 Stock number of each component (4380 hours, different spares availability)

	Number in stock (97%)	Number in stock (98%)	Number in stock (99%)	Number in stock (99.9%)	Number in stock (99.99%)
Gearbox	4	5	5	5	6
Generator	4	5	5	5	6
Rotor blades	6	6	6	6	7
EMC filter	1	2	2	2	2
Ultra Sonic Anemometer	4	4	4	5	5

H-5 Stock number of each component (8760 hours, different spares availability)

	Number in stock (97%)	Number in stock (98%)	Number in stock (99%)	Number in stock (99.9%)	Number in stock (99.99%)
Gearbox	8	8	8	9	10
Generator	8	8	8	9	10
Rotor blades	11	11	11	12	13
EMC filter	3	3	3	3	4
Ultra Sonic Anemometer	7	7	7	8	9

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