Advanced maintenance operations

For the Delft Offshore Turbine

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For the Delft Offshore Turbine

By

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Summary

Offshore wind energy is one of the fastest growing markets in renewable energy and is an important future opportunity. Governments wish to diversify in their energy sources to keep up with climate goals and they see the need to move away from the uncertainty of fossil fuel prices and unreliable suppliers.
Cost of energy is one of the most important factors for a transition to a more renewable source of energy but offshore wind is currently characterised by high costs for operation and maintenance (O&M). These high costs are a consequence of the design of the wind turbines, the layout of the wind farm and the maintainability.

Delft Offshore Turbine (DOT) intents to reduce the costs for offshore wind energy through the use of a technical solution. By making the turbine less complex it aims to reduce failure of the components and improve the maintainability. However, failure can never be fully prevented and a proper maintenance strategy is needed to reduce downtime of the wind turbine.

This research aims to develop a maintenance strategy for large offshore DOT wind farms to reduce the costs for O&M. The strategy consists of a logistical solution in the form of a stock keeping scenario and a mechanism to exchange parts of the drive train. Requirements for the maintenance strategy is to be innovative, in order to stand out from conventional wind turbines and to reduce downtime to a maximum of 5%, in order to be competitive with conventional wind turbines.

The research was performed by simulating five stock keeping scenarios and six mechanisms to exchange the complete drive train, or parts of the drive train. Every combination between stock keeping scenario and exchange mechanism was simulated for a 700 MW DOT wind farm located at the proposed wind farm sites of both "Hollandse Kust: Noord-Holland" and "IJmuiden Ver", for 5.0 MW and 7.0 MW turbine configurations.
The simulations were carried out using the O&M Calculator developed by ECN.

The results of the simulations show that the conventional approach to maintaining offshore wind turbines is not the best approach. In terms of a logistical solution, making use of a dedicated maintenance island in the sea or a floating workshop in the form of a service operations vessel (SOV) gives a 2 to 3% higher availability compared to how stock keeping is currently performed.

Nowadays the exchange of components of the drive train is done by expensive and scarce installation vessels. Even though a large intervention like this is not often needed a decrease in downtime of up to 1% can be achieved if DOT wind farms make use of a better exchange mechanism. Best results are achieved for an integral exchange of the complete drive train, hub and blades, in case of component failure.

For a DOT wind farm to reach the industry's goals to reduce downtime to a maximum of 5% the maintenance strategy needs to be changed. The greatest downtime reduction is found in reducing the waiting time for a suitable weather window. Keeping resources closer to the wind farm or improving weather capabilities of your vessel can help in doing so. Conclusively an innovative component exchange, making use of the modular concept of the DOT can ensure a maximum downtime of 5%.

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Introduction

1.1 Wind energy background

Offshore wind energy is one of the fastest growing markets in renewable energy and promises to be an important future opportunity. Resources are stable and abundant and public acceptance is generally high[12]. Governments wish to diversify in their energy sources to increase national energy security[13] and offshore wind provides the opportunity to move away from the uncertainty of fossil fuel prices and unreliable suppliers.
The security of energy is paramount to human security and one of the most important goals of energy policies around the globe[14]. The availability of energy, and being able to provide a continuous supply of energy is dependent on the available energy sources but also on the affordability and sustainability of power generation. Cost of energy is one of the most important factors for any transition to a renewable source of energy.

Apart from energy security, offshore wind energy is also a crucial component in meeting European climate goals for 2020 and beyond. In 2016 the EU had a total installed capacity of 12,6 GW, accounting for 1,6% of the total power generation and 6,9% of Europe's renewable power generation[15]. About 1,6 GW was installed in 2016 and numbers are expected to rise over the coming years for both installed capacity and rated capacity per turbine.
All EU memberstates have set the goal to generate 14% of their energy in a sustainable way by 2020. The Netherlands has set the goal to generate 16% in a renewable way in 2020 and to install 4450 MW of wind power by then[16]. Currently the Netherlands only produces 5,8% of its energy in a renewable way and has a total installed capacity of offshore wind energy of 1118 MW[15].

The most recent addition to the Dutch offshore wind portfolio is the 600 MW wind farm Gemini, 55 kilometres north of the Frisian islands. Gemini wind farm produces electricity for €168/MWh, whereas future Dutch wind farms aim to produce electricity for prices between €72,7/MWh for Borssele I+II and €54,5/MWh for Borssele III+IV. Both are planned to be operational in 2019. The enormous reduction in costs that is required to meet these goals calls for innovative solutions for wind turbines and foundations but also a smart way to manage operation and maintenance (O&M).

1.2 Problem definition in relation to O&M costs

The current situation for offshore wind energy is characterised by high costs for operation and maintenance. Estimates of the share of O&M costs with respect to the total lifetime costs of a wind turbine vary between 18-23% according to P.J. Tavner[17] to over 30% according to Scheu et.al.[18]. These high costs for operation and maintenance are caused by the design of wind turbines and layout and accessibility of the wind farm.

Firstly, the actual repair costs of these complex offshore machines are high due to the sheer number of subsystems and complex components with risk of failure. But also due to the difficulties in performing maintenance activities in an offshore environment. High waves, wind and large distance to shore requires specialised equipment, complex access methods for the crew and innovative exchange strategies.

Secondly, complex systems and difficult access to broken wind turbines imply long downtime of the turbines and therefore large potential revenue losses. Whenever a wind turbine is not operational it is not producing electricity and will therefore not create revenue. Over 80% of total maintenance costs is caused by revenue losses[19]. Quick repair of a turbine is therefore favourable but often impeded by harsh weather conditions that make the turbine inaccessible. In order to mitigate total costs, a clear strategy has to be made to deal with failure of wind turbine components.

When we look deeper into operation and maintenance activities for large offshore wind farms a clear distinction can be made between preventing component failure and correcting a failed component. In order to reduce downtime a form of preventive maintenance is always favoured over ad-hoc approaches to fix turbines. Unfortunately the need for correcting a failure can never fully be eliminated.
Reduction of downtime losses is the main objective in this research to reduce total costs for offshore wind energy. This research will look into the reduction of downtime losses primarily caused by maintenance on the drive train, a concept explained in section 1.3.

1.3 Wind turbine configurations

A three-bladed upwind turbine is currently the most common configuration for wind turbines. A hub with three attached blades is positioned nose first in the current wind direction. These turbines are fitted with pitch regulation that adjusts the angle of the blades and yaw control that can rotate the nacelle in the horizontal plane to control the power output. The yaw control makes sure the wind turbine is always positioned nose first in the wind.

1.3.1 Drive train configurations

The drive train is a series of mechanical components that convert the kinetic energy from the rotation of the blades to electric energy. There are two primary drive train configurations, a gearbox system and a direct drive system. These two most common drive train configurations are represented in Figure 1.1.

A gearbox system converts the slow turning speeds of the hub and blades to a faster rotating drive shaft entering the generator. Typical speed conversions are from 15-20 RPM to around 1800 RPM.
A direct drive turbine offers a gearbox free design where the rotation of the blades is directly converted to electricity. This alternating current has a variable frequency, linked to wind speeds and thereby frequency of rotation of the blades. Power electronics convert this to 50Hz or 60Hz.

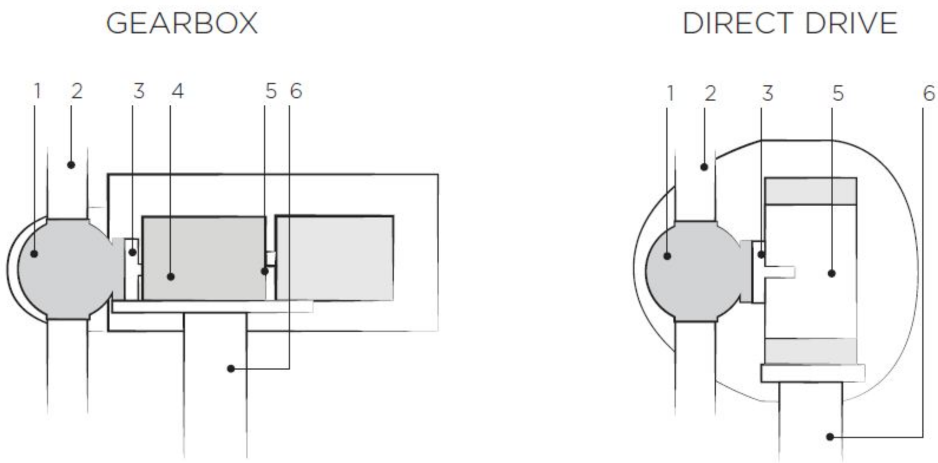

Figure 1.1: Conventional wind turbine configurations

1.Hub 2.Blades 3.Drive shaft 4.Gearbox 5.Generator 6.Tower

An advantage of a direct drive system is the absence of a complex high-speed gearbox that is sensitive to failure. If a single component of a gearbox fails the complete turbine experiences downtime. Gearbox components are often heavy, expensive and hard to replace. Direct drives are currently heavier and more expensive than gearbox systems but require less expenses for operation and maintenance[20]. Direct drive systems are expected to be largely represented in future offshore wind farms that are further away from shore and have a higher power rating. This is due to the fact that maintenance further away from shore is more expensive and downtime for high power turbines causes higher losses than for turbines with a lower power rating.

An alternative drive train configuration is currently being developed in the Netherlands. This drive train configuration will be explained in the next subsection.

1.3.2 DOT system

Started as a research project the Delft Offshore Turbine, or DOT in short, aims to reduce costs for offshore wind energy through the use of a technical solution. In case of the DOT system the gearbox and generator are replaced by a pump. Figure 1.2 shows the workings of this hydraulic drive train where sea water is pressurised by the hydraulic pump and transported to a pelton wheel to generate electricity. The hydraulic pump is powered by the kinetic energy of the rotating blades.
The DOT system can entail multiple turbines generating hydraulic pressure and transferring this to a single pelton turbine and generator. Figure 1.3 is a schematic representation of this concept.

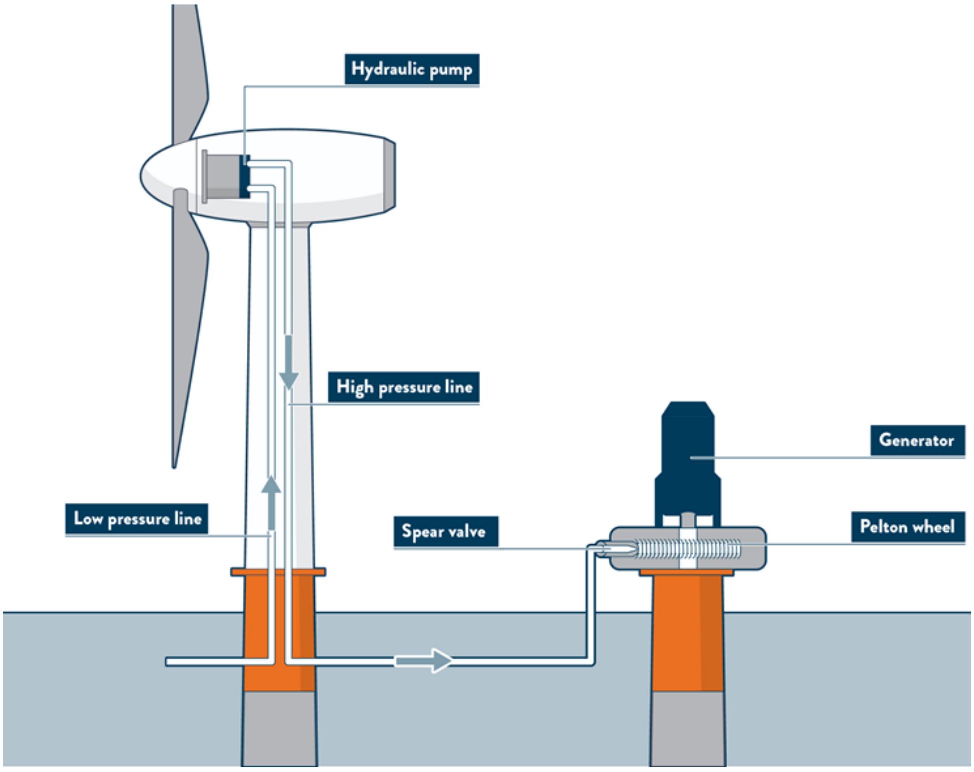

Figure 1.2: Introduction to the DOT system

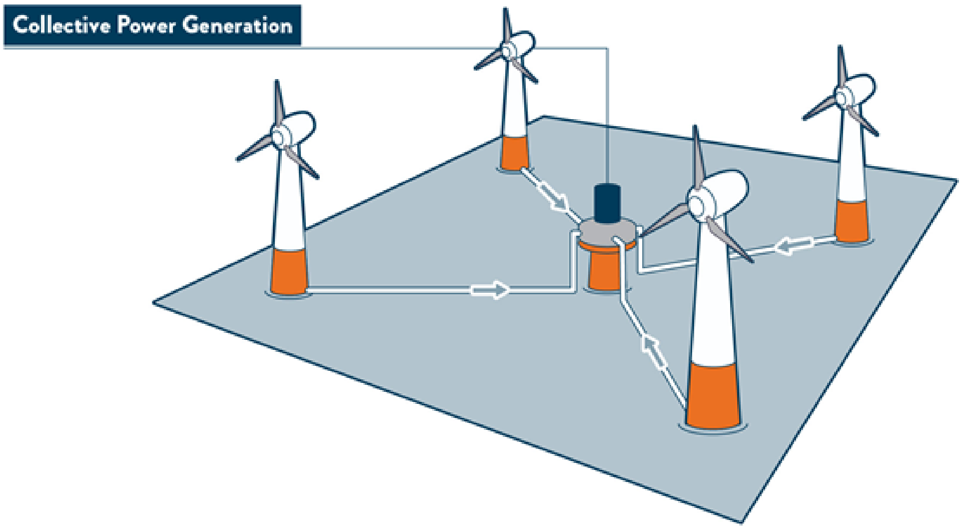

Figure 1.3: Schematic representation of the DOT system

The reduction of moving parts in the nacelle reduces the amount of wearing parts that are in need of maintenance at great height. Maintenance of these wind turbines will therefore become more straightforward as less components have to be inspected, repaired or even replaced. Maintenance will however never become obsolete. It is therefore essential to design a new approach for the maintenance of blades, hub and hydraulic pressure pump. This new maintenance strategy should include a **logistical solution** as well as an **exchange strategy**. These aspects will be included in the research question and described in section 1.4.

1.4 Objective and research question

This research aims to develop a maintenance strategy for a large offshore DOT wind farm to reduce the costs for operation and maintenance. The new maintenance strategy deals with failure as part of the operating phase, rather than an unexpected event. Whenever a failure occurs spare parts should become available and the broken component needs to be repaired or exchanged.
The strategy consists of a combination between a stock keeping scenario for all components of the wind turbine and a mechanism to exchange parts of the drive train of a wind turbine. For the DOT this means the exchange of the hydraulic pump.

1.4.1 Relevance of the research

To verify the relevance of the research the objective is placed into perspective. From an academic perspective an advanced O&M strategy and logistic operation is of vital importance when it comes to the implementation of a new technique. Preventing failure and increasing reliability can never fully solve downtime[11]. Also from a practical point of view it can be an advantage to develop an advanced O&M strategy:

As mentioned before the Delft Offshore Turbine is currently still in its developing phase and the development trajectory of the Delft Offshore Turbine includes several goals to serve as a horizon for the project. The most important goal is the development of two offshore sites in the North Sea within the next years.

- 2020: 2 wind turbines Borssele kavel V (Innovation Site Borssele)
- 2023: 100 wind turbines "Hollandse Kust: Noord-Holland"

The Innovation Site Borssele can be used as a pilot for a full-scale wind farm in 2023 and lessons can be learned during this small scale preliminary project. The two wind turbines at Borssele V have to demonstrate the concept of the DOT and also show innovation in other facets of the wind farm. The Innovation Site Borssele poses five main research & innovation areas that form the basis for award criteria. The award criteria for regular sites are mainly focused on costs.

Research and innovation areas

- Offshore foundation technology
- Wind turbines and wind farm optimisation
- Electrical network and grid connection
- Transport, installation and logistics
- Operation and maintenance

An advanced maintenance operation for the DOT is not only favourable in terms of fulfilling the award criteria for the Borssele V but is also essential in competing with conventional wind turbines and reducing costs in the offshore energy market. In order to do so the DOT aims for a maximum of 5% downtime for the entire wind farm, or 95% time-based availability.

Current offshore wind turbines have an availability of 93% for wind farms that are between 15 and 24 km from port and 95% for wind farms located less than 15 km from port[6]. The propsed site "Hollandse Kust: Noord-Holland" is approximately 23 km from port.

1.4.2 Research question

The aim of reducing downtime to a maximum of 5% has to be achieved by using a suitable maintenance strategy. Consisting of a logistical solution and an exchange strategy. The research question will therefore be:

What maintenance strategy should be used for a DOT wind farm with respect to component exchange strategies and allocation of materials?

The main research question will be answered using various sub-questions:

- What are the different ways of keeping stock for a large offshore wind farm and what scenario reduces downtime the most?
- What mechanisms to exchange large and heavy components are available and how do they affect downtime?
- What combinations between stock keeping scenarios and exchange mechanisms can be used to meet the aim of the DOT to have an availability of at least 95%?

1.4.3 Approach of the research

To answer the research question the following approach is used:
First a definition of component failure and an overview of common maintenance strategies is given. This is a reference for the maintenance strategy that is to be developed and simulated. This background can be found in chapter 2. Simulation of the new maintenance strategy is done with the use of the O&M Calculator by ECN. The simulations are carried out for a selection of stock keeping scenarios and exchange mechanisms that are defined in chapter 3.

The O&M calculator is a time-based simulation tool that calculates annual downtime losses for a wind farm. This downtime is affected by the different stock keeping scenarios and exchange mechanisms. First the impact of five different stock keeping scenarios is analysed, followed by five different exchange mechanisms and conclusively the results of the 30 combinations between stock keeping scenarios and exchange mechanisms.
All simulations are carried out in comparison to a base case where all components are stored on land, maintenance crew is deployed from the nearest port and exchange of main components in the drive train requires a large crane vessel.

Different implementation costs for the scenarios and mechanisms will not be taken into account because these costs cannot be estimated. According to the literature 80% of O&M expenses are considered with revenue losses due to downtime[19] so this research will focus on minimising downtime.

The effect of the different stock keeping scenarios and exchange mechanisms can be very specific for the location of a DOT wind farm and the capacity of the turbines. Besides an extensive analysis for the location of "Hollandse Kust: Noord-Holland" (23 km West of IJmuiden) a sensitivity check will be done for the location "IJmuiden Ver" (60 km West of IJmuiden) at the border of the Dutch Exclusive Economic Zone (EEZ).
Both locations are simulated with 5.0 MW turbines and 7.0 MW turbines, the input specifications for the model can be found in chapter 4 and their results in chapter 5.

The concluding chapter 6 gives a final analysis of the results and recommendations for future research as well as suggestions to improve the model.

Literature study

“Failure is the only opportunity to more intelligently begin again”

Henry Ford

A literature research is performed as an introduction to the field of system reliability and to gain knowledge on common practises and theories regarding the operation and maintenance of complex systems. This chapter provides information on failure rates and reliability of current wind turbines and their subsystems. System reliability theory is explained to give insight in how life expectancy of a component is calculated. Furthermore trends in failure rates and downtime losses are discussed together with O&M strategies and an overview of the playing field. Conclusively the ECN model that will be used for the quantitative analysis in chapter 4 is elaborated upon.

2.1 Maintenance theory and terminology

“All equipment is unreliable in the sense that it degrades with age and/or usage and fails when it is no longer capable of delivering the products and services. System failure can result in economic losses, hazardous situations or damage to the environment and is therefore an unwanted phenomenon in any situation.[21]”

The left column of Figure 2.1 shows the process and interrelation of failure. Underlying the cause of failure is a failure source, typically false operation or poor design. This can lead to a mechanical, physical or chemical process in the component that will imminently be a cause of failure. Whenever a component for example experiences excessive loads due to false operation, physical deformation of the component takes place. This deformation is the failure mechanism, leading up to the physical event that causes the system to lose its ability to perform its required function. This event is called the failure mode and can be anything from broken bearings to worn seals or burned connectors[1].

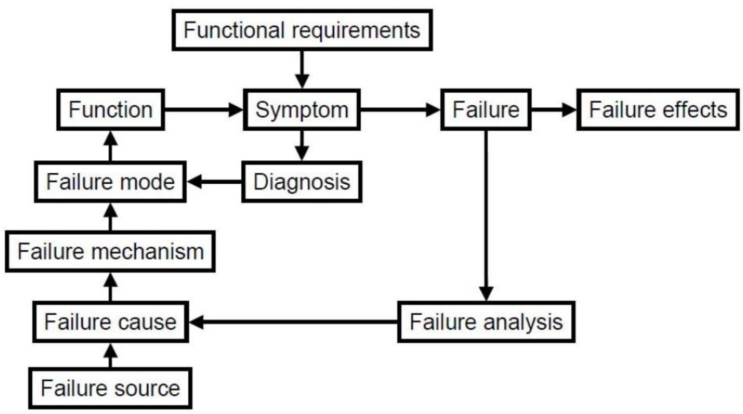

Figure 2.1: Terminology of failures[1]

Through proper corrective maintenance, a failed system can be restored to an operational state by repairing or replacing the components that failed. Failures can be limited through maintenance actions such as preventive maintenance, inspection or condition-monitoring but can never be fully eliminated[21]. There are basically two types of maintenance actions possible that will be explained in subsection 2.1.1 and subsection 2.1.2.

2.1.1 Corrective maintenance

Corrective maintenance is considered the most expensive way of maintaining and offshore wind farm. Maintenance is only carried out in case of a turbine malfunction or breakdown. The failing component is then fixed or replaced in a responsive way. Immediate availability of components, transport and crew is required and this is what makes corrective maintenance so expensive.

The main expenses are concerned with the downtime of the turbine[19]. Weather conditions may not allow immediate action as all vessels are limited by a significant wave height and other constraints to their window of operation. A weather window is a limited time interval where weather conditions can be expected to be suitable for an intervention[22]. The probability of finding a suitable weather window is highly correlated with weather conditions during the season as can be seen in Table 2.1. A smaller probability of a suitable weather window P_w means a higher average waiting time T_w to begin your intervention.

Table 2.1: Weather window probability and average waiting time per season[11]

Season	**Probability P_w**	**Waiting time T_w (day)**
Winter	0.30	60
Autumn	0.50	30
Spring	0.60	10
Summer	0.80	3

2.1.2 Preventive maintenance

Preventive maintenance can be defined as care and servicing of the equipment to prevent or reduce possible malfunctioning. Maintenance activities can be undertaken after a specified period of time or at predetermined levels of power generation. To proactively perform maintenance, sensors and signal processing equipment can diagnose system conditions so predictive maintenance activities can be started before failure of the equipment[23]. “Preventive maintenance involves additional costs and is worthwhile only if the benefits exceed the costs[21].”
Different intervals of preventive maintenance can be identified. These strategies or policies are discussed in section 2.2.

2.2 Operation & Maintenance policies

Based on corrective and preventive maintenance strategies several policies can be identified according to Andrawus et. al [24] and Pintelon et. al [25]. These maintenance strategies are depicted in Figure 2.2 and will be explained in the following section.

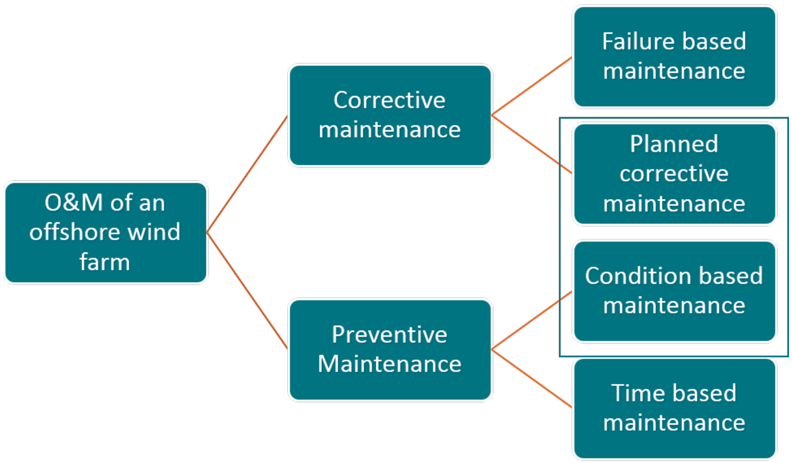

Figure 2.2: Maintenance strategies flowchart [2]

2.2.1 Failure based maintenance (FBM)

A wind turbine or a component is used until it fails. Failure of critical components can have severe operational and environmental consequences but FBM strategies can be implemented for components that have limited influence on revenue costs or negative externalities. An example of a negative externality is the possible pollution of sea water due to a component failure. (Non-monetary) costs suffered by a third party should always be avoided. Failure based maintenance is a good strategy for components with enough redundancy or a limited impact on the performance of the wind turbine.

2.2.2 Time based maintenance (TBM)

Time based maintenance is carried out at pre-determined intervals and is typically implemented for components that are still under Original Equipment Manufacturer (OEM) warranty, or if corrective maintenance costs of the component are higher than the preventive maintenance costs. The length of the maintenance interval has to be suited to the known failure pattern of the component, however problems due to interval frequencies are common. Too short intervals wastes production time and lifespan of the component, too long intervals can lead to failure of the component.

2.2.3 Condition based maintenance (CBM)

Condition based maintenance is based on the monitoring of performance and condition parameters of the system. The condition of a component can be monitored on request, continuously or scheduled. Monitoring can be done visually or with the use of a Condition Monitoring System (CMS) [3]. Whenever the deterioration in the condition of a component is detected, the component will be repaired shortly. The biggest advantage of condition based maintenance is the ability to schedule maintenance of a component in periods of low wind. This decreases downtime and ensures optimal use of the lifetimes of the components. "Condition based maintenance is defined as the most cost-effective means of maintaining critical equipment [24]."

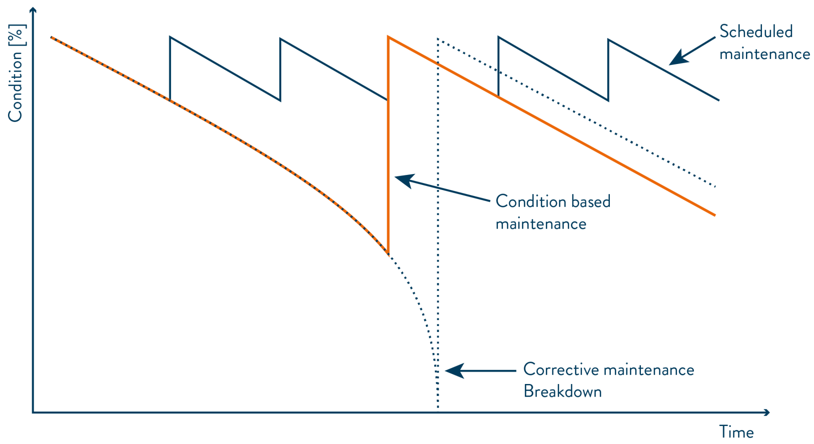

Figure 2.3: CBM compared to FBM and TBM[3]

Planned corrective maintenance can be regarded as a form of condition based maintenance. Failure rates are known and corrective maintenance is scheduled at the end of a components lifetime.

Figure 2.3 show the deterioration process of mechanical components and at what point the different maintenance strategies plan to intervene. Please note that a gradual deterioration of the condition of a component is an ideal situation for a mechanical component. For most electrical components there is no process of deterioration at all. Components are either fully functional or not.

2.3 Failure rates

In this section the concept of failure is explained. Elaborating on the distinctions made between different types of failures and the urgency to act. Furthermore an overview of recent reliability studies is given to provide in current failure data for onshore as well as offshore wind turbines.

2.3.1 Definition of failure

In the broadest sense of the word a failure is the state or action of not functioning [26]. In order to define failure for offshore wind farms three characteristic reliability parameters are appointed as the most trustworthy: Mean time to failure (MTTF), Mean time to repair (MTTR) and Mean time between failures (MTBF). These are indicators for the reliability of a component and its associated downtime after failure [7].

MTTF is the average period between unplanned turbine stoppages and is used as a statistical value for failure probability of a system. It is defined as the inverse of the failure rate λ, this is the amount of failures over a period of time [5]. This failure rate however is not constant over time but often described by a bathtub curve, which will be explained in section 2.4.

MTTR is the statistical value for downtime and is defined as the average time it takes for a component to be repaired or replaced. The MTTR is dependent on the severity of a failure and the level of difficulty to replace or repair the component.

MTBF is the combined value of MTTF, logistic delays and MTTR [4]. In Figure 2.4 the elements and chronological order of the MTBF are depicted. Whenever a component is installed the operability is 100% until failure occurs. This happens after MTTF (on average). When failure occurs, resources have to be mobilised and the component is repaired or replaced. The time this takes are the logistic delay time and the MTTR. Together they form the MTBF.

Logistic delays are all delays between failure of a component and the intervention. Organisation time, travel times and waiting for suitable weather is combined here.

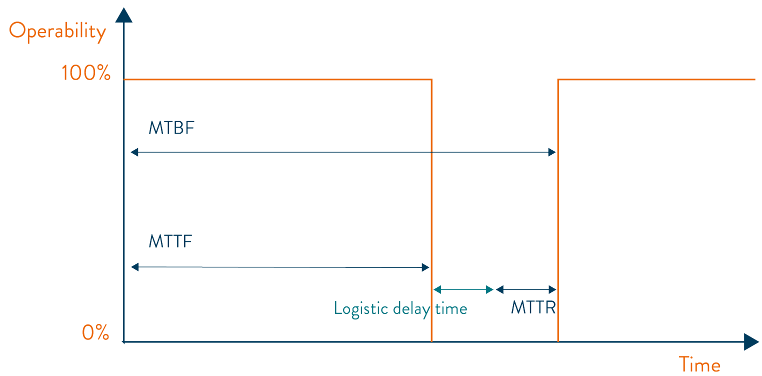

Figure 2.4: MTTF, MTTR and MTBF over time [4]

Limited information for failure rates, reliability and downtime is available for offshore wind farms. However, several recent surveys provide data on average failure rates and downtime. This data is often linked to the responsible component.

Figure 2.5 shows the annual stop frequency and downtime per stop for first three years of operation for OWEZ, the first Dutch offshore wind farm. The annual stop frequency is the multiplicative inverse of the MTTF. When a component fails 40 times a year the annual stop frequency is 40 and the MTTF is $\frac{1}{40}$ of a year. The related downtime per stop is a addition of the MTTR and logistic delays.

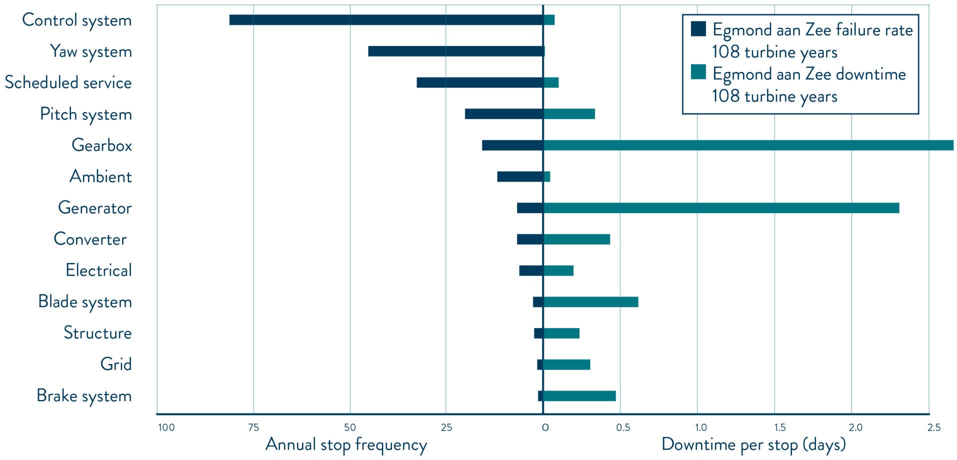

Figure 2.5: Offshore reliability of OWEZ wind farm [5]

The average number of monthly interventions per turbine has been thoroughly inspected by Sparta [6]. Sparta is the world's largest database for offshore wind farm performance and maintenance.Figure 2.6 puts into perspective how often failure occurs. It means that every offshore turbine currently needs a form of intervention between 1 and 1.7 times a month. This can be anything from a hard reset to a major component exchange.

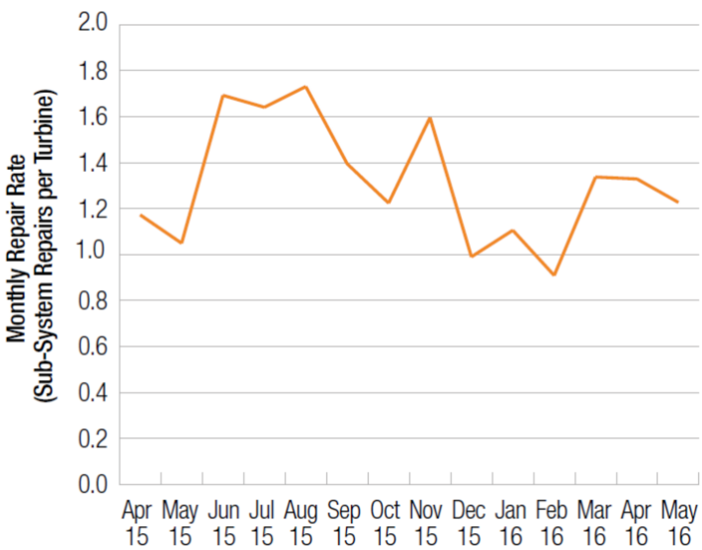

Figure 2.6: Average number of monthly interventions per wind turbine [6]

2.3.2 Major and minor failures

In case of a component failure a distinction can be made between failures with a downtime ≤1 day and failures causing downtime > 1 day.
Component failures with a downtime of ≤1 day are considered minor failures that only require small maintenance or a hard reset of a system. Minor failures are concerned with software errors and small replacements. Examples are the replacement of a fuse or resetting the communication software of a controller. A hard reset of controller software is usually done remotely but still causes downtime.
If downtime surpasses 1 day the failure is considered major. Major failures require large scale repairs or possibly exchange of components. Major failures require heavy maintenance equipment that is not always available or not always employable because of weather conditions. It is also possible that required components are not available due to limited stock or a suitable crew is not available on demand.

During a large scale monitoring survey for onshore wind turbines (WMEP) between 1989 and 2006 it was found that 25% of the failures were responsible for 95% of the downtime. The results can be seen in Figure 2.7. On the horizontal axis we see the annual failure rate on the left-hand side and the associated downtime per failure on the right-hand side. They are specified for the different subsystems on the vertical axis.

According to the survey 75% of failures were considered minor and were remedied within 5% of total downtime. To reduce downtime, condition monitoring and remote servicing is essential and the focus should be on the mitigation of the 25% failures causing most downtime[7].
This ratio is only valid for onshore turbines and is likely to be different for offshore turbines as *all* onsite repairs for offshore turbines imply considerable travel times and limited window of operation due to possible harsh weather conditions. Downtime caused by minor failures that cannot be fixed remotely is therefore expected to be higher for offshore wind turbines.

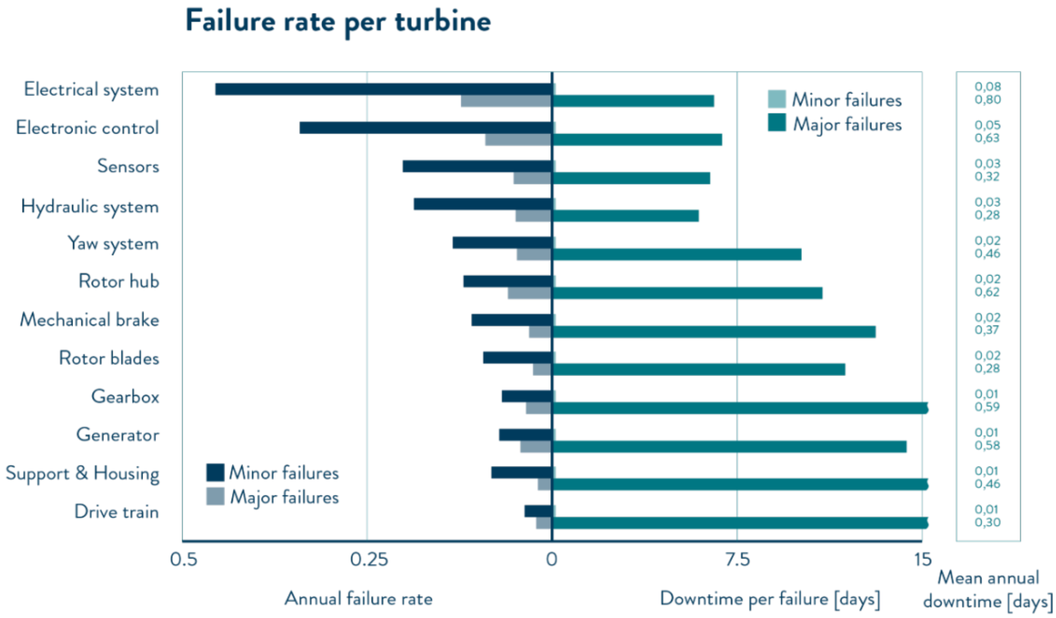

Figure 2.7: MTTF-MTTR according to failure[7]

2.4 Wind turbine reliability

Reliability is the quality of being trustworthy or of performing consistently well [27]. In order to determine the availability of a wind turbine and by extension the projected revenues of a wind turbine a reliability model has to be adopted. The availability of a wind turbine can be calculated, as in Equation 2.1:

$$Availability = \frac{MTTF}{MTTF + delays + MTTR} \tag{2.1}$$

The denominator of the equation is the summation of the Mean time to failure (MTTF), the delays and the Mean time to repair (MTTR). This is the Mean time between failures (MTBF) and is heavily dependent on accessibility of the wind farm and the availability of equipment, mechanics and components. The accessibility is a product of distance to port of the wind farm and the current weather conditions. MTBF is highly specific per wind farm and is therefore hard to generalise.

Mean time to failure (MTTF) is the numerator of the equation and is dependent on the failure rates of sub-assemblies and components. The failure rate λ of a component is described by the intensity function 2.2:

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t-\gamma}{\theta}\right)^{\beta-1} \tag{2.2}$$

Parameter β describes the shape of the intensity function so the slope of the probability plot. Parameter θ describes the scale of the function, an increase in θ with constant β and γ stretches the distribution to the right. A decrease in θ with constant β and γ pushes the distribution to the left. θ has the same dimension as time t and is expressed in hours, days, years etc.
Parameter γ is the location parameter and can shift the distribution over the horizontal axis. In most cases this parameter is set to zero. In the intensity function $\theta > 0$ for t ≥ 0 [28].

The reliability of a component is a product of the quality of the component. Using this reliability one can derive an estimate of the component's useful life. To find a useful general distribution to describe failure time of a component the Weibull distribution is often used.
The Weibull distribution is calculated according to Equation 2.3 [29]:

$$f(t) = \frac{\beta}{\theta}\left(\frac{t-\gamma}{\theta}\right)^{\beta-1} exp\left\{-\left(\frac{t-\gamma}{\theta}\right)^{\beta}\right\}; \theta \leq t; \theta > 0; \beta > 0 \tag{2.3}$$

For Equation 2.1 and Equation 2.2 the variables are defined as:
β = shape parameter of the distribution
γ = location parameter of the distribution
θ = scale parameter of the distribution
t = time

The intensity curve, describing the probability of failure. is often referred to as bathtub curve due to its characteristic shape. Figure 2.8 shows the three stages in the lifetime of a component using different values for β to shape the curve. During the early life of a component the probability of failure is relatively high due to so-called burn in or infant mortality failures. After all components settle, the rate of failure is relatively constant and low. These failures are probabilistic failure modes or random failures. After a certain period of operation the failure rate increases again due to wear-out of the components. The Weibull distribution can be used for all three stages of the intensity curve, with a different shape parameter β.

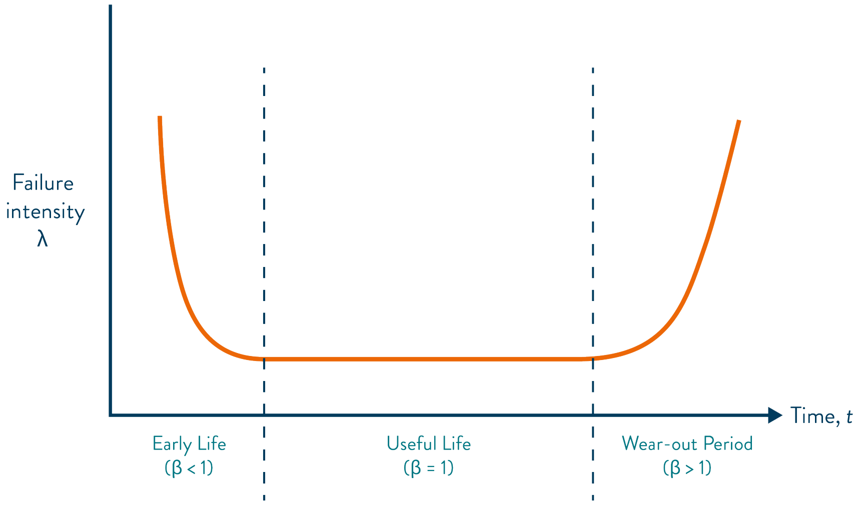

Figure 2.8: Bathtub curve for mechanical components [4]

In some cases the failure intensity in the early-life stage is very high. Wind turbines have been known to be deployed at a very early stage of development of its main components. This can be the cause of premature failure of its components due to design flaws. Higher stresses than anticipated during the design phase can cause premature and unanticipated wear-out of a component. These kind of failures have to be tackled by improving the product reliability from design point-of-view [30].

2.4.1 Relevance to the research

In the past sections it has become clear that an increased reliability of a component leads to a decrease in required maintenance actions. In the first place a reliable component can decrease the need for preventive maintenance as the component is more trustworthy. Secondly, a component that is able to perform consistently well has an extended mean time to failure (MTTF). This brings down the number of component failures and thereby the number of interventions needed.

For this research it should be clear that reliability of a component is prerequisite to achieve a minimum of 95% availability. The denominator in Equation 2.1 should be kept as small as possible. The MTTF of the DOT is currently unknown as many components are still in their developing phase.

The other two components of Equation 2.1 that have an impact on the availability are logistic delays and the mean time to repair (MTTR). Provided that failure of a component is inevitable, at some point an intervention has to take place. The vessels that are needed for these interventions are discussed in section 2.5. How the impact of the logistic delays and MTTR is modelled will be explained in section 2.6.

2.5 The playing field

A suitable maintenance strategy is to be selected to cope with failures. In the following section the large variety of vessels that are being used for the installation, operation and maintenance of offshore wind farms will be elaborated upon as they are a part of the different maintenance strategies.

2.5.1 O&M vessels

To keep any type of wind turbine generator operational there is a need for O&M vessels for the transportation of materials and access of the mechanics. These vessels can be used in a complementary way as each of them have different workability specifications. Some are cheaper, but slower and cannot be used in all weather conditions. It is a trade-off between their restrictions and potential losses due to downtime of the turbine and deployment costs.

Three main examples of access and transportation equipment for technicians can be identified. Their *relative* charter rates and window of operation is shown in Figure 2.9

- **Crew transfer vessel (CTV)**
  CTV's are deployed from port and can deliver crew to the boat landing on the transition piece of the offshore turbine. Transfer times are longer than for the other two modes of transport and the operating window is restricted by wave heights for 60% of the year.
- **Service operations vessel (SOV)**
  An SOV can stay near the offshore wind farm and crew is deployed via a gangway to the turbine. Because transfer times are shorter and operating windows are bigger the SOV is currently considered the most efficient way of performing operation and maintenance. Accessibility up to 78% of the year.
- **Helicopter**
  Helicopters are used very often in performing corrective maintenance. Due to very short transfer times and ad-hoc deployment combined with a large operating window the high costs for this transport mode are often taken for granted.

Currently, the helicopter outperforms the crew transfer vessels and service operations vessels because helicopters can work with significant wave heights up to 6 meters. Crew transfer vessels and service operations vessels are limited to respectively 1.5 and 2.5 meters of significant wave height. The additional costs are justifiable in some cases, if downtime of the wind turbine and thereby revenue losses of the turbine can be minimised in harsh weather conditions.

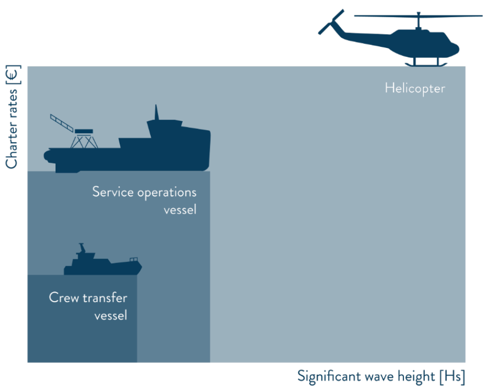

Figure 2.9: O&M vessel operationality

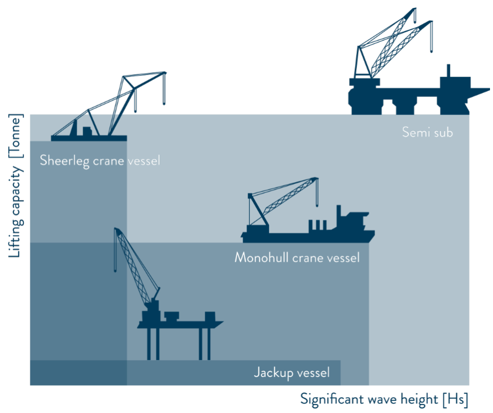

Figure 2.10: Service vessel operationality

2.5.2 Service and installation vessels

There is a large variety of vessels that can be used during the installation of a wind turbine. The overview of installation vessels can be found in Figure 2.10. The figure shows the *relative* differences in significant wave height restrictions and lifting capacities.

For replacement or servicing of large components like rotor blades, nacelle and parts of the gearbox or generator it is sometimes necessary to charter a large installation vessel. To perform maintenance on heavy components lifting capacity but also stability of the vessel is essential. Most common for these types of operations is the use of a **jackup vessel**.
Jackup vessels provide a stable lifting platform and can hold a crane with sufficient reach to install or maintain heavy components such as the nacelle. The large deck space on a jackup vessel can be used to store multiple spare parts and avoid the need to transit back and forth to collect parts from the port.

It is also possible to use a different installation vessel with sufficient lifting capacity such as:

- **Sheerleg crane vessel**
  Crane vessels that are able to lift very heavy loads, they can be regarded as shallow-draught flat-bottomed ships with a large crane.
- **Monohull crane vessel**
  Unlike the sheerleg crane vessels, the regular crane vessels (or pedestal crane vessels) are able to rotate the crane independent of the hull and provide a bigger window of operation due to lower sensitivity to waves.
- **Semi-submersible crane vessel**
  Slow moving crane ships with an enormous lifting capacity. Hardly ever used for wind farm installation.

These crane vessels provide plentiful lifting capacity but are much more expensive or do not provide a stable platform. The Dutch marine contractor 'van Oord' has built jackup vessels especially for wind farm installation. An example can be seen in Figure 2.11

Figure 2.11: Van Oord Aelous

2.6 Modelling the availability of a wind turbine

For a quantitative analysis of different stock keeping scenarios and exchange mechanisms a model is needed. The model should be able to simulate the availability of a wind turbine using failure rates of the different components, the logistic delay time and the time needed to inspect, repair or replace a component. These concepts were explained earlier in this chapter with the help of Figure 2.4 and are highly dependent on the reliability of the components, the weather delays and the way a maintenance activity is performed. In order to simulate this dependency a sophisticated model is needed that incorporates all.

The O&M calculator by ECN is a time-based simulation tool that simulates degradation of components and maintenance activities, under the conditions of actual weather data. In the next subsection the simulation steps of the O&M calculator are explained. First describing how a time to failure is calculated, followed by the logistic delays and the time to repair. The properties of the O&M calculator come from ECN[31].

2.6.1 ECN O&M calculator input

Component failure is based on the mean time to failure (MTTF), that is defined for each component, and dependent on operating time and load. The O&M calculator runs a simulation for a predetermined period of time and processes the meteo data for a specific location. The weather and wind conditions from the meteo data determine the load on the turbine. Higher wind speeds means higher loads and this causes more frequent failures.

For all failures over the defined period of time a repair class (RC) is selected. This repair class is dependent on the size of the component and the severity of the failure. The repair class can vary from inspection of a small component to a 40 hour replacement operation of a major component. How many interventions of a certain repair class are needed is derived from literature and is actually very specific per turbine model. This input is defined in the repair class library

For every repair class it takes some time to organise the intervention and gather crew, equipment and components. Due to varying weather conditions it is possible that the intervention has to wait for a suitable weather window to come up. The ECN O&M calculator defines these logistic delays as:

- **T_organisation** - Spare components, crew and equipment are arranged [h]
- **T_logistics** - Waiting for resources to arrive [h]
- **T_wait** - Awaiting suitable weather conditions to depart [h]
- **T_travel** - Travel time from port to broken wind turbine [h]

The repair time is defined as:

- **T_repair** - Actual repair time of the wind turbine [h]

T_organisation is defined manually in the model and is dependent on the complexity of and experience with the organisation procedures. **T_logistic** depends on suppliers and stock size. **T_travel** is a product of the distance between wind farm and service port and the speed of the vessel. **T_wait** is caused by weather delays and defined by the weather data. However, **T_travel + T_repair** together is the weather window for the operation at sea. When a smaller weather window is required the **T_wait** also becomes smaller.

How long these logistic delays are is dependent on the weather but also on stock size and capabilities of equipment. Availability and lead times of spare components can be managed with the use of the spare control input library. The equipment input library can be adjusted manually to manage characteristics or availability of your vessels.

T_repair is the actual repair time of the wind turbine and varies per component and repair class. For replacement of large components a subdivision is made for the following activities:

- **Preparation** - On site preparation of the intervention [h]
- **Positioning** - Bringing vessels and crew in place [h]
- **Hoisting** - Physical exchange of the component [h]
- **Finalisation** - Connecting the new component and finalising intervention [h]

2.6.2 ECN O&M calculator output

The O&M calculator simulates a total number of failures and their corresponding repair classes over a set period of time. The logistic delays and repair times that are linked to the repair classes make up the total time that the turbine is not operational. This is defined as downtime for unplanned corrective maintenance.
A subdivision of these delays is made:

- **Logistics** - Travel times and time spent awaiting components [h]
- **Weather** - Total weather delay time [h]
- **Lack of equipment** - Time spent waiting for available equipment [h]
- **Lack of technicians** - Time spent waiting for available technicians [h]
- **Repair** - Total length of the repair periods [h]
- **Balance of plant** - Downtime of supporting components and auxiliary systems [h]

The results that will be used during this research are the effects of downtime on the availability of the turbine. There are two types of availability that that the model generates: time-based and energy-based availability.

The time-based availability of one turbine is calculated by taking the total amount of hours in a year (8766 hours) and dividing it by the total amount of hours in a year *minus* the total time a turbine is not operational per year. This downtime per turbine is an average value for the complete wind farm over the simulated period of time.

Depending on how many turbines are installed and the capacity of the turbines, an energy-based availability is calculated. This is done by dividing the yearly theoretical yield of the wind turbines by the actual yield. The theoretical yield in MWh is calculated by multiplying the rated capacity of the wind turbines by the total amount of hours in a year.

The model also calculates annual costs for carrying out maintenance actions. These costs are based on material, labour, equipment and fixed costs. Given the annual costs of maintaining a wind farm and the energy production of the wind farm it is possible to calculate the maintenance cost per MWh. However, the costs are rough estimates and can be unfunded, especially for more conceptual scenarios. This is why the simulated results for maintenance costs will not be taken into account in this research.

O&M simulation cases

In the following chapter the selection process takes place for the stock keeping scenarios and exchange mechanisms that are to be simulated during the quantitative research in chapter 4. Before putting together the different scenarios a number of proven concepts for maintenance strategies are assessed. These reference projects will serve as inspiration for the maintenance strategy for the DOT offshore wind farm. For reference projects it is important to also look past maintenance strategies for the offshore industry as DOT is aiming to break with protocol strategies.

3.1 Reference projects

In this section different cases with uncommon practices concerning exchange mechanisms or stock-keeping strategies are elaborated upon. In the first place to search for an application in the maintenance strategy of the DOT wind farm. Secondly, to analyse the possible competitive advantage of having a strategy different that is different to standard practices.

3.1.1 The Google case

An example of an innovative and unusual maintenance strategy can be found in the Google data centres. When Larry Page and Sergey Brin founded Google in 1998, during their time as PhD students at Stanford, their funds and space were limited. Lego's were the main building blocks of their server racks and the servers were built up out of low-end, off-the-shelf components but with proven technology [32]. These standard components were linked using specialised, self-developed interfaces and software. The Google logo constructed in Lego blocks can be seen in Figure 3.1.

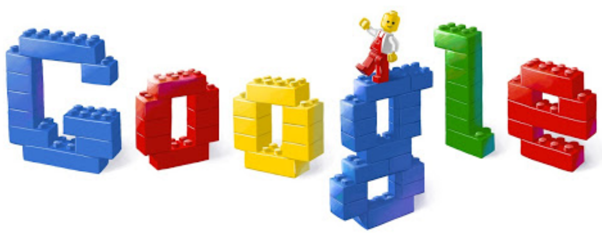

Figure 3.1: Google logo in Lego

The use of proven technology reduces the costs of the individual components and by extension the costs of the system as a whole. Apart from the significant cost reduction there are two other big advantages of using standard components.

The reliability of proven components opposed to new components that are still in their development phase is significant. Regular breakdown in early life, or burn-in failure rates will remain present in the intensity curve of the component. The bathtub curve describing the probability of failure is inevitable, however infant mortality due to premature failure can be eliminated because imminent failures have already been "ironed out" [29].

Google uses large numbers of the same generic components to build their data centres[32]. By doing so Google can easily create a stock of components that are all able to carry out the same task. In case of a failure a rapid exchange of the broken component can reduce downtime of a server. Thus limiting the impact on the system.

Figure 3.2: Exchange of a server

This strategy is in contrast with other large soft- and hardware companies of that time. Both software companies like Yahoo! and Microsoft as hardware companies such as AOL and IBM have made use of specialised hardware solutions for their servers[32]. In case of a failure or a malfunction the possibility of a fast exchange of components is limited because the component is often custom-made and not widely available. In-situ repair of the component can be time-consuming and expensive. Exchange with an off-the-shelf component can be done almost instantaneously, the action is shown in Figure 3.2. Once the component is replaced it can be repaired and serve as stock for a next failure.

3.1.2 Ro-Ro vessel

Siemens' wind power division will take into operation a roll-on-roll-off vessel for the transhipment of large, heavy components. The Rotra Vente will be used for offshore wind farms on the North Sea and can carry towers, nacelles and blades from shore to the installation site. An artist impression of the Rotra Vente is shown in Figure 3.3.

Figure 3.3: Roll-on-roll-off vessel Rotra Vente[8]

The Rotra Vente has a movable bow and a retractable ramp to allow heavy components to be rolled on board. Rolling, rather than hoisting the components will decrease loading time and minimise risk of damaging the component. At the installation site components will still need to be hoisted off the vessel.

“Siemens estimates cost savings of 15-20 percent compared to current transport procedures, depending on the location of the offshore wind power plant.[8]” The Ro-Ro vessel aims to reduce installation and commissioning times, reducing the required time window for installation but also for repairs. The vessel is an interesting development in the maintenance of offshore wind farms and can be seen as a movable warehouse, reducing travel times.

3.1.3 Amazon’s floating warehouse

In 2014, Amazon filed for a patent regarding an “airborne fulfillment center” (AFC). This AFC is essentially a flying airship, capable of flying at great altitudes (over 10km) and storing thousands of items that can be delivered to houses with the use of flying drones[33].
Drones will descend from the airborne warehouse, carrying the goods. Drones, unable to fly to extreme heights, will later return to a ground station.
Stocking the AFC with drones and items will be done with the help of an occasional logistic shuttle, much like local warehouses and distribution centres on land. The concept is depicted in Figure 3.4.

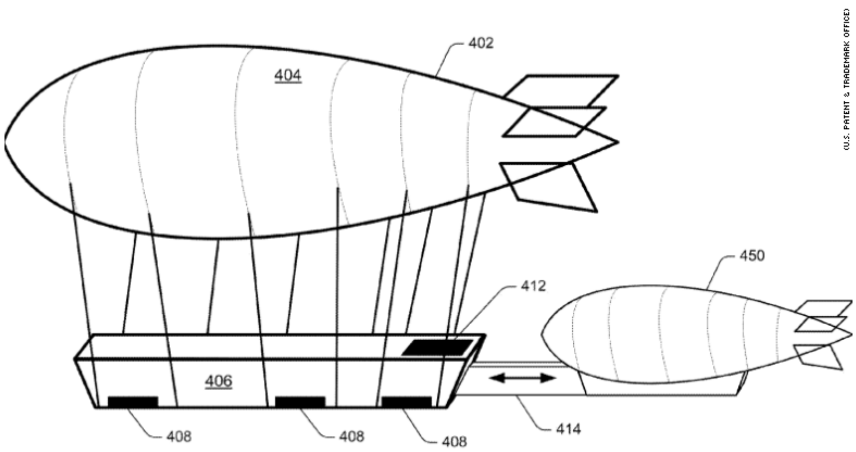

Figure 3.4: Amazon patent for an AFC[9]

According to Amazon one of the main benefits is the ability for the floating warehouse to move around. The warehouse is able to navigate to different areas depending on weather, expected demand and/or actual demand[9].

A centralised and easily accessible warehouse with frequently used articles is an outcome for fast logistics service provision. The organisation of articles as well as the travel times to the customer can be decreased when a suitable location is chosen.

3.1.4 Floating harbour transhipper

Researchers at the Australian Maritime College have developed an offshore transhipment terminal that functions as a transfer hub for cargo. An offshore hub enables forwarders to supply their goods to large, deep-draft ships rather than using multiple shallow-draft vessels to reach their destination. The results is a more economical and environmentally responsible logistic solution. The offshore hub will function as a large warehouse, reducing individual ship movements for small quantities. Transhipment is becoming more cost-effective, offering reduction in both operating and capital costs in comparison to direct call services[34]. An example of this concept is shown in Figure 3.5

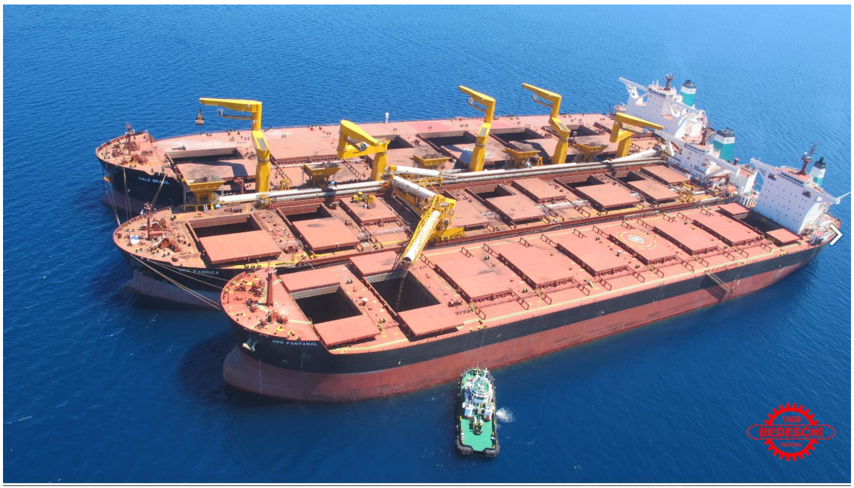

Figure 3.5: Floating harbour transhipper concept

"The FHT is a floating warehouse that can be moored in deep water with a roof to protect the cargo[35]." This concepts promises to be of great value for the environmental impact of for example the transportation of bulk products.

3.1.5 Artificial island solution

TenneT Netherlands, Energinet and TenneT Germany have agreed to develop a North Sea wind power hub. The plan is to construct power link islands in the middle of the North Sea to connect multiple wind farms to the surrounding countries. The current power infrastructure connects each individual wind farm to the main land of the owner of the wind farm.

An island at for instance Doggersbank will facilitate large wind farms that can be situated further offshore. The island will facilitate staff, components and workshops. A dedicated island for offshore wind simplifies offshore logistics and can create economies of scale when serving multiple wind farms at once. The first island is to be created at Doggersbank, satisfying some important requirements for offshore wind: shallow water, optimal wind conditions and a central location to all client countries[36].

Besides savings due to economies of scale, the integration of the energy market is put forward as a primary reason for the construction of Doggers island as a spider in an electricity web[37]. A provisional design is shown in Figure 3.6.

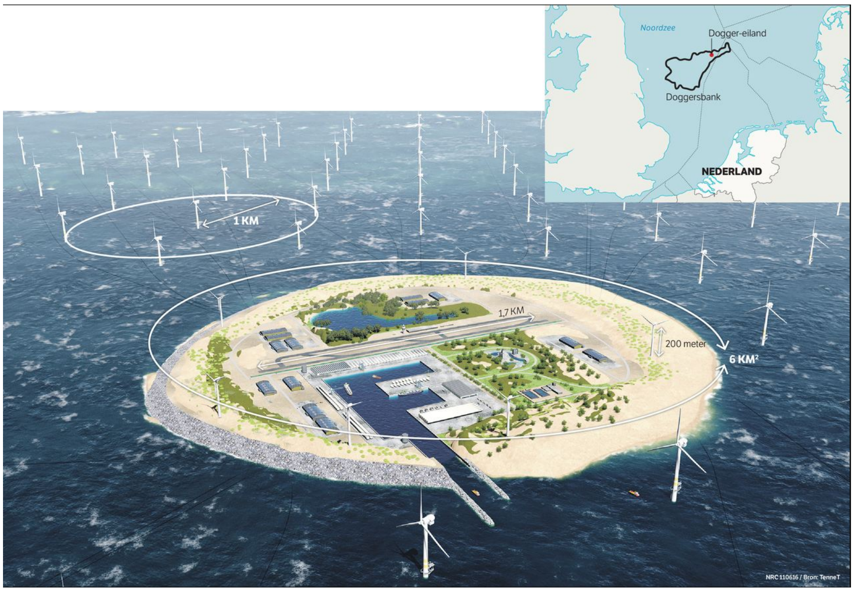

Figure 3.6: Tennet's artificial island concept [10]

3.1.6 Conclusion of the reference projects

The references projects discussed in this sections serve as inspiration for the stock keeping scenarios and exchange mechanisms that are described over the next two sections. The concepts of the Ro-Ro vessel, floating harbour transhipper and artificial island are good examples of grouped component storage near the place of use. Amazon's floating warehouse takes it one step further, decentralising storage and only keeping stock of frequently used products nearby.
These projects will be used in shaping the stock keeping scenarios in section 3.2.

The Google case is the main source of inspiration for the exchange mechanisms in section 3.3. The main recommendation is to promote quick exchange of modular components. The DOT is suitable for exchange of separate modules, but the optimal exchange mechanism is yet to be decided on.

3.2 Stock keeping scenarios

In this section multiple scenarios are described to find a suitable replacement strategy for unplanned corrective maintenance. The scenarios are concerned with the stock keeping location of spare components. The location of stock can be centralised, spread over multiple locations or even able to move around as sailing stock. Four scenarios are described with respect to their impact on the logistic delays and repair time.

The impact on logistic delays and repair time is broken town to the five different dependent variables we have seen in subsection 2.6.1.

- **T_organisation** - Spare components, crew and equipment are arranged [h]
- **T_logistics** - Waiting for resources to arrive [h]
- **T_wait** - Awaiting suitable weather conditions to depart [h]
- **T_travel** - Travel time from port to broken wind turbine [h]
- **T_repair** - Actual repair time of the wind turbine [h]

The four stock keeping scenarios all have a different effect on the dependent variables and will therefore have a different input in the ECN model. The input is relative to a base case. In the base case scenario all components are stored on land, inspection teams are deployed from the nearest port and exchange of main components in the drive train requires a standard installation vessel.

This section provides input for the quantitative analysis in chapter 4 and concludes with a short qualitative comparison between the different scenarios.

3.2.1 Scenario I - Internal stock

In this scenario there is a possibility to store spare parts or complete components of the drive train within the nacelle. Spares of crucial components that normally require specialised transportation, installation or lifting equipment will be stored next to the functioning components. Figure 3.7 shows the nacelle of a wind turbine with a set of working components on the right-hand side, near the rotor, and a supply of spare parts next to it. Mechanics can access the turbine and take parts from the internal stock to fix the wind turbine.
In case of an unforeseen event that causes the wind turbine to break down, and replacement of a component of the drive train is urgent, mechanics will be deployed from the nearest service port or SOV. Only carrying their tools.

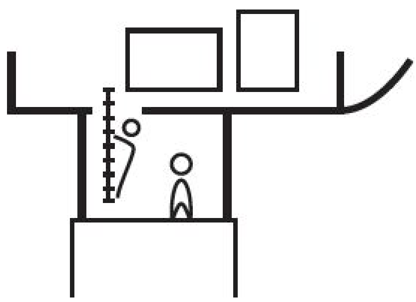

Figure 3.7: Internal stock of spare parts

Storing extra components within the nacelle makes it possible to exchange a broken part or component with an identical part very quickly. The internal stock is built in during the installation phase with the use of the installation vessel. The internal exchange of a component will take place within the nacelle, using one of the exchange mechanisms described in section 3.3.

For the model this means that the availability of resources significantly increases as the spare components are already present in the nacelle and heavy equipment is not required. This reduces the **T_organisation** and **T_logistics** within the logistic delays.
Secondly the **T_repair** can be brought down due to the limited movements the mechanics have to make to replace components within the nacelle. In comparison to removal, and lifting procedures in the base case.

3.2.2 Scenario II - Central warehouse

This scenario describes a situation where all vessels used for general or major interventions are deployed from land, just as in the base case. The spare parts and components however can be found on a centralised storage unit within the wind farm. This central warehouse is either a dedicated storage unit as can be seen in Figure 3.8 or part of the foundation of one or more of the turbines. The central warehousing unit will hold a large variety of components that are prone to failure.

Advantages of scenario II over the base case are mainly concerned with the reduction of **T_organisation** and **T_logistics**. In case of a failure the complex logistical project of bringing components to the quay and shipping them to the wind farm can be skipped and O&M vessels can be deployed immediately, if weather conditions allow it.

The main difference between scenario I and scenario II is the necessity for the component to travel to the nacelle. The component travels from the central storage area to the broken wind turbine. The exchange mechanism of the wind turbine will lift the component to the nacelle.

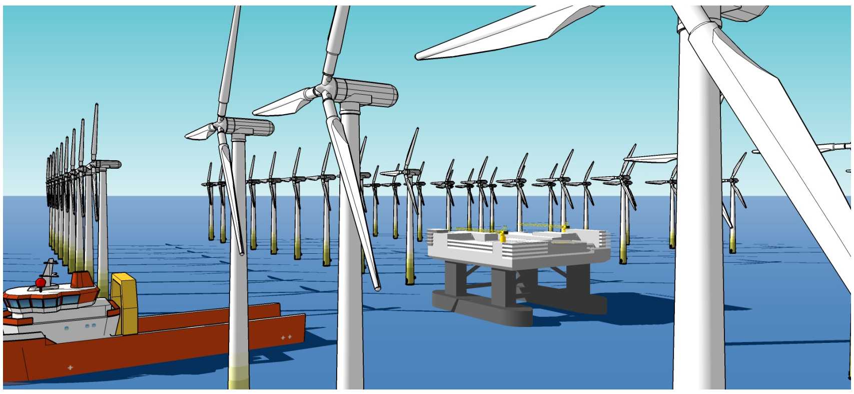

Figure 3.8: Central storage of components

There will be no reduction in **T_repair** or **T_wait** compared to the base case. The reduction in **T_logistics** will be smaller than for scenario I but the quantitative analysis will expose the advantages of scenario II over scenario I.
Because equipment and personnel is still deployed from land **T_travel** is hardly reduced. Therefore time slots are rather long and sufficient weather windows for the combined **T_travel** and **T_repair** are limited.

3.2.3 Scenario III - Maintenance island

Maintenance island is based on the reference case in subsection 3.1.5 where TenneT wishes to construct an island that functions as an offshore electricity hub. Constructing an offshore island to host all maintenance and stock keeping activities combines the logistical advantages of a near shore wind farm with the wind conditions and visual absence of a farshore wind farm.
In scenario III an island is created with accommodation, warehousing and port facilities to harbour installation- or O&M vessels, an impression can be found in Figure 3.9. Deployment of equipment and personnel will no longer be done from shore but is all located on maintenance island.

Whenever a crucial component fails, the **T_logistics** and **T_organisation** require minimal effort because all assets are locally present. **T_travel** is also limited to the travel time between the island marina and the turbine in question.

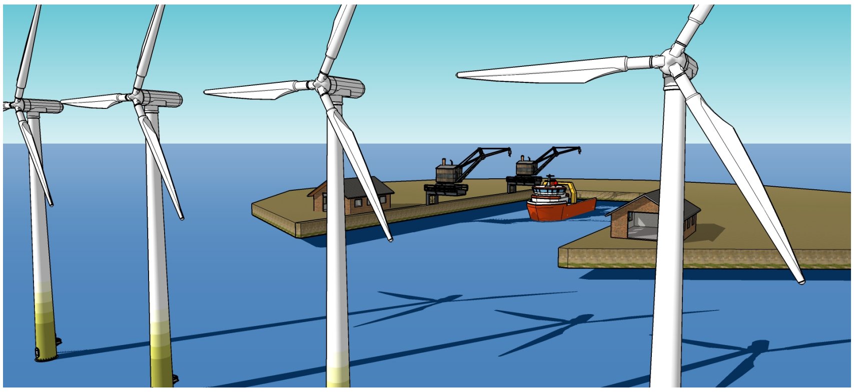

Figure 3.9: Maintenance island

Because all assets are deployed from the dedicated island marina **T_wait**, waiting time for a suitable time window is significantly reduced because the required time window (**T_travel** + **T_repair** is smaller than in for example scenario I and II. This is due to the convenient location of port, vessels and assets.

3.2.4 Scenario IV - Sailing workshop

In scenario IV a specialised vessel will perform maintenance activities on the wind turbine but is also in charge of repairs and revision of the components. The spare components available on the vessel ensure quick replacement of a component to minimise downtime. After the component is replaced the malfunctioning part will be refurbished and used as stock. Figure 3.10 is an artist impression of the sailing workshop.

The specialised vessel is comparable to a Service Operations Vessel (SOV), explained in subsection 2.5.1, and will stay in the vicinity of the wind farm at all times. In case of a failure of the wind turbine, the sailing workshop will be in charge of a rapid exchange of the component using one of the exchange mechanisms explained in section 3.3.

Figure 3.10: Sailing workshop

There is a large variety of advantages when using the sailing workshop concept. Having a supply- *and* maintenance vessel in the vicinity of the wind farm at all times decrease the **T_logistics** as components and crew are immediately available. This is a big advantage compared to the complex logistical operations from shore that is the base case.

In terms of the quantitative analysis this means the logistic delays and repair time for a broken wind turbine can significantly be brought down on several fronts. **T_organisation**, **T_logistics**, and **T_travel** can be reduced when using an SOV-like sailing workshop. Like for Scenario III, the required time window is reduced due to a limited **T_travel**, also indirectly reducing **T_wait**.

3.2.5 Qualitative comparison

The four scenarios described above have different characteristics with respect to the base case. There are practical implications in terms of the need for different equipment and perhaps higher capital investments. Also their influence on the dependent variables is different for the quantitative model. Table 3.1 shows the relative advantages of the different stock keeping scenarios on the dependent variables of the model.

Table 3.1: Comparison of the scenarios

	T_ organisation	**T_ logistics**	**T_ wait**	**T_ travel**	**T_ repair**	**Total**
Base case	0	0	0	0	0	0
Internal stock	+1	+1	0	0	+1	+3
Central warehouse	+1	+1	0	0	0	+2
Maintenance island	+1	+1	+1	+1	0	+4
Sailing workshop	+1	+1	+1	+1	0	+4

No conclusions can be drawn from this qualitative comparison because the objectives of the different scenarios are always the same: a quicker and more efficient way of allocating components and personnel. This is done by improving the five different dependent variables. It is more important to find out how much improvement there is. This is done by performing the quantitative analysis in chapter 4.

3.3 Exchange mechanisms

There will always be the need for a mechanism to exchange the heaviest of components. In the case of a DOT wind turbine this means the pump in particular. For conventional wind turbines, an internal crane is used to exchange small components and a large crane vessel is needed to exchange large heavy components. In future operation it may be desirable to use a different exchange mechanism. Various examples and their practical implications will be discussed in this section. The first three mechanisms are proven concepts, the last four are undeveloped concepts for the exchange of a DOT hydraulic pump.

3.3.1 Internal knuckle boom crane

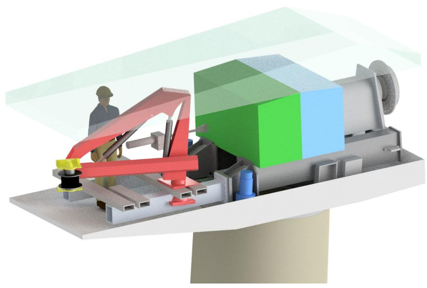

Figure 3.11: Knuckle boom crane

In Figure 3.11 an example of a small knuckle boom crane installed within the nacelle is shown. This internal crane does not need to be transported and is designed to fit within the nacelle. The specifications for the crane are determined by the heaviest component in the nacelle and is therefore always suitable for the job, and as small as possible.

The main disadvantage of an internal crane is the need for extra nacelle space and extra capital expenditures. It is very costly to have a dedicated crane for every individual turbine that needs to be operational at all times but is not used very frequently.

3.3.2 Internal overhead crane

A different example of an internal crane is the overhead crane as shown in Figure 3.12. Integrated in the design of the nacelle and with limited requirements for extra space. The nacelle can stay relatively small despite a small increase in height. Another advantage of the overhead crane over the knuckle boom crane is the possibility of having a closed roof.

A nacelle with an integrated overhead crane does require extra design challenges in terms of a hatch to lower the components. Also, the operational disadvantages of an individual crane per wind turbine also apply to this type of internal crane.

Figure 3.12: Integrated overhead crane

3.3.3 Self-hoisting crane

Figure 3.13: Liftra self-hoisting crane

Self-hoisting cranes have the ability to hoist themselves to the top of the wind turbine. The cranes are deployed from ship and are either fitted with grabbers to climb along the turbine tower or are hoisted up by a winch on top of the nacelle as can be seen in Figure 3.13 and Figure 3.14. Self-hoisting cranes reduce mobilisation costs significantly[38] for onshore purposes, reducing crane movements on the ground. For offshore purposes the self-hoisting crane can also reduce overhead costs, taking away the need for individual cranes per turbine. The equipment costs are reduced to purchase or renting costs of a limited number of general-purpose self-hoisting cranes.

In terms of a slim and efficient design of the nacelle the self-hoisting crane is probably the most favourable option. The only design prerequisite is the presence of a stable mounting place and the ability of opening the roof of the nacelle. Internally the nacelle can be designed in the most efficient way, needing no extra place for crane storage and movements.

Figure 3.14: Vestas tower crane

The downside of a self-hoisting crane is the long installation and de-installation time. Self-climbing or self-hoisting cranes need to be mobilised, transported to the offshore wind turbine and brought up to the nacelle. After the exchange operation the crane also has to be de-installed. Typically taking at least one full day[38].

3.3.4 Supported pulley concept

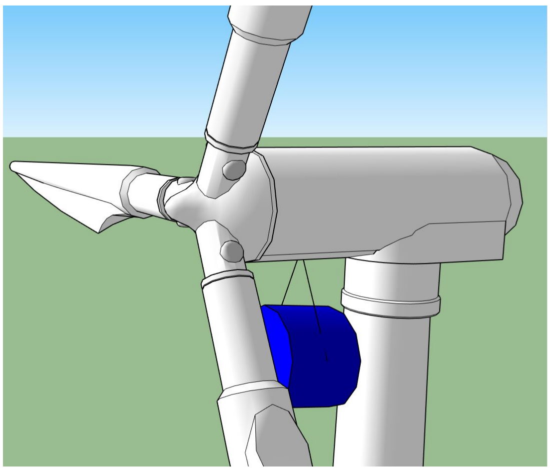

Figure 3.15: Supported pulley hoist

In this concept the pump is hoisted out of the nacelle using a pulley located on the inside of the roof of the nacelle. The pump is placed directly behind the rotor and can be hoisted out with limited horizontal movements if the hatch is directly located beneath the pump as can be seen in Figure 3.15. There will be no need for motorised lifting equipment within the nacelle, unlike for the internal cranes described above. A hook supported by an A-frame within the nacelle can easily be fitted with a chain hoist or regular pulley to lower the pump. The simplicity of the concept will reduce costs and mobilisation time. However, structural design difficulties may be hard to overcome.

3.3.5 Revolver exchange concept

Ideally, the exchange of a pump requires no boat movements and mobilisation of equipment and material at all. A revolving concept where the broken pump is rotated to make place for a functional pump requires very limited movements. Whenever a pump breaks down the hoses are to be disconnected and the cylinder will rotate to bring a new pump into place. The hoses are reconnected to the new pump and the turbine is operational again. The concept is pictured in Figure 3.16 and Figure 3.17.

Service and maintenance vessels are completely left out of the equation as mechanics can use the internal stock of components in the wind turbine. O&M vessels are needed to transport the mechanics to and from the wind farm.

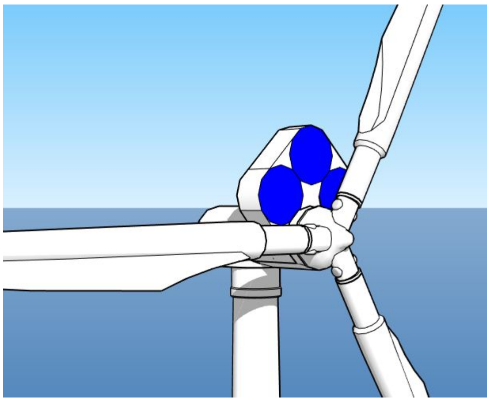

Figure 3.16: Revolver

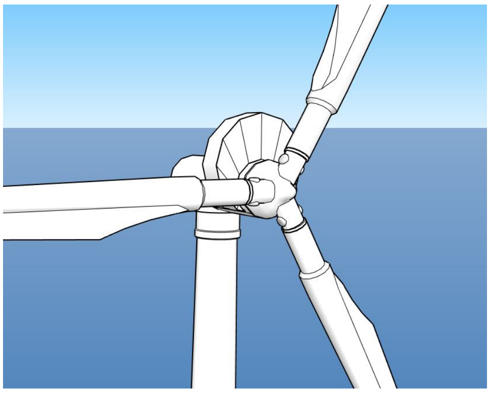

Figure 3.17: Revolver

This concept is very interesting for modelling purposes as mobilisation costs of equipment and material is very low and downtime can be limited to a few hours. However, the feasibility of the concept is questionable regarding the high costs that come along with this design. Let alone structural and aerodynamic complications.

3.3.6 Rotor integrated pump concept

Pump, rotor and hub are exchangeable as a whole using two winches, integrated in the design of the nacelle, to lower the assembly. Exchange of this large assembly gives the opportunity to revise not only the pump but *all* moving components of the wind turbine generator. The nacelle and tower remain as the immovable structural components of the turbine and the moving components (more sensitive to failure) can be exchanged as a whole.

In practice this means that in case of a failing moving component a complete assembly that is new or revised has to be available for exchange. And large offshore supply vessels have to be mobilised for the operation whenever weather conditions are suitable.

Figure 3.18: Exchange RIP

3.3.7 Fixed pump

In the concept of a fixed pump, the pump is an inseparable part of the nacelle. In other words, the nacelle is the pump and the rotor is directly attached to the pump. Practical implications of this design are that the pump cannot be exchanged and in case of failure individual components of the pump need to be removed.

Prerequisite for this design is that the pump is modular and exchange of pistons, valves and camshaft of the radial piston pump can be done on site. The main advantage is the elimination of lifting heavy components during the operational phase. All spare components can be taken on Service Operation Vessels (SOV's) and brought to the nacelle by the mechanic.

3.3.8 Qualitative comparison

Not all exchange mechanisms will be analysed in the simulation. Some concepts will have too similar results or do not have properties suitable for modular exchange. Table 3.2 provides a quick overview of the different exchange mechanisms and their pros and cons. For the quantitative analysis it is most illustrative to pick the mechanisms that lie furthest apart to get a broad range of results.

Table 3.2: Exchange mechanisms

Exchange mechanism	Advantages	Disadvantages	Suitable for exchange
Internal crane	Proven concept	Space consuming	yes
Overhead crane	Proven concept	Individual cranes	yes
Self-hoisting crane	Fewer resources needed	Time consuming operation	yes
Supported pulley	No motorised crane in nacelle	Design difficulties	yes
Revolver exchange	Few movements	Design difficulties	yes
Rotor integrated pump	Complete exchange and overhaul	Large logistic operation	yes
Fixed pump	Robust design	No room for serial failure	no

The concepts of the internal crane(1), the overhead crane(2) and the supported pulley(4) concept may be different in terms of design but in terms of logistic operation and time consumption for the exchange these mechanisms are very similar. These mechanisms will be **combined** in the quantitative analysis and multi-criteria analysis (MCA) as internal crane mechanisms. Furthermore, the fixed pump will not be analysed because a complete exchange is not possible. This is a prerequisite for the exchange mechanisms. The following four mechanisms plus the base case will be analysed in chapter 4 and in the MCA in the next section.

- Internal crane
- Self-hoisting crane
- Revolver exchange
- Rotor integrated pump (RIP)

3.3.9 Multi-criteria analysis

To qualitatively assess the performance of the different exchange mechanisms a multi-criteria analysis is performed. The assessment criteria can be found in Table 3.3 and are divided in 3 categories: Time, design and costs. The criteria are assigned certain weights, resembling their relative importance.

The method used to determine the weights is according to "Gids voor beoordelingskaders" by de Boer et al.[39] and his tree structure. Weighting of the criteria and scoring of the different exchange mechanisms is further elaborated upon in Appendix B.

Table 3.3: Scoring of the MCA criteria

Criterion	**Final weight**	**Rank**
Mobilisation time	0.163	2
Exchange time	0.327	1
Construction time	0.082	4
Simplicity crane	0.041	6
Simplicity structure	0.163	2
Maintainability	0.082	4
Capital cost	0.092	3
Mobilisation cost	0.048	5

The assigned weights are a product of an internal survey at DOT on the relative importance of the criteria. Every exchange mechanism has been scored and weighed. A short overview of the results can be found in Table 3.4. Full results can be found in Appendix B

Table 3.4: Results of the MCA for exchange mechanisms

Exchange mechanism	**Unweighted score**	**Weighted score**
Internal crane	29	3.245
Self-hoisting crane	27	3.007
Revolver exchange	23	3.395
Rotor integrated pump	29	3.429

Resulting from the MCA, with weights based on the internal survey, the rotor integrated pump is the most favourable option for exchange. It shares the same unweighted score as the internal crane but on account of the weights the RIP is ranked higher. Most remarkable is the weighted score of the Revolver exchance in relation to its unweighted score. We have seen that mobilisation time and exchange time have been given the highest weight and the revolver exchange scores very high on these criteria.

Model for quantitative analysis

The model that is used for the quantitative analysis and comparison between the scenarios and exchange mechanisms is the O&M Calculator by ECN. This simulation program is a time-based calculator to determine optimal O&M strategy for wind farm operators. The calculator uses actual wind farm and weather data. Output values are estimates of O&M costs as well as quantification of uncertainties in costs and downtime[31]. The model is more thoroughly explained in section 2.6

The biggest advantage of the ECN O&M calculator is the possibility to adjust almost all input parameters. This creates the possibility to simulate the different stock-keeping scenarios and mimic the different exchange mechanisms and their effect on the exchange time.

In the following chapters the input parameters for a DOT wind farm are explained and the adjustments in parameters for the different stock keeping scenarios and exchange mechanisms are discussed.

4.1 Model input

The O&M calculator specifies 5 input libraries where input data is imported by the user. The input libraries are specified as follows:

- General input
- Wind Turbine input
- Spare control input (SCS)
- Repair class input (RC)
- Equipment input (EQP)

The input data for all libraries is specified for a certain base case where maintenance for a wind farm is performed in a conventional way. In this base case a small stock is being kept in the nearest port and in case of failure of a component the intervention is organised on land. Crew and equipment are deployed from the nearest port. Specific input data for the base case can be found in Appendix C.
In order to simulate the influence of the different stock keeping scenarios and exchange mechanisms adjustments to the input libraries have to be made.

4.2 General input and wind turbine input

The general input and wind turbine input is the same for all stock keeping scenarios and exchange mechanisms. The parameters for the general input are specified for a DOT wind farm, located at "Hollandse kust: Noord-Holland". This is 23 kilometres west of IJmuiden, coordinates 52°3524N 4°1312E. A sketch of the location can be found in Appendix A. Please note that the location of the DOT wind farm is only relevant for the weather data. Distance to port is never specified but is expressed in different travel times, dependent on distance and the vessel.

The general input in Table 4.1 is the standard input from the ECN model with a fixed energy price and a simulation period of 5 years. According to ECN the model already converges after 5 years and a longer period of time would have to many uncertainties regarding energy prices and charter rates. In Table 4.2 the parameters for a 7.0 MW DOT are specified.

Table 4.1: General input

General input	
Meteo data	North Sea K13
Length of shifts	11 hours
No. of available technicians	36
Price of energy	€130/MWh
Simulation period	5 yr
No. of simulations	100

Table 4.2: Wind turbine input

Wind turbine specifications	
Type of turbine	DOT 7MW
No. of turbines in wind farm	100
Rated power [MW]	7
Hub height [m]	85
Cut-in velocity [m/s]	4
Cut-out velocity [m/s]	25

4.3 Scenario specific input

In section 3.2 several stock keeping scenarios have been specified as a possible strategy for quick replacement of components. To simulate the different stock keeping scenarios adjustments to the input libraries for spare control, repair classes and equipment have to be made. All adjustments are adjustments to the base case as described in Appendix C
The following scenarios are analysed:

- Internal stock
- Central warehouse
- Maintenance island
- Service operation vessel

4.3.1 Internal stock

For internal stock the logistic time of small parts below 2 metric tonnes is set to zero as small parts will be kept as stock within the nacelle. This is an adjustment to the base case in the spare control input library.
Because components are being stored in the nacelle itself the organisation time is reduced as well as the actual repair time. This is the case because components do not have to be ordered from the onshore warehouse and taken to the nacelle by the mechanic.

4.3.2 Central warehouse

For the central warehouse a large central stock is being kept for all components that are normally stored or ordered on land. This means that for the spare control input library the logistic time for all components is set to zero and a stock size of 15 pieces is kept centrally. The stock size is derived from regular stock sizes for the small components as determined in the base case.

The repair class input library is changed in the way that the organisation time for small components under 2 metric tonnes is reduced from 12 to 8 hours. This saved time is due to easier procedures at a dedicated storage facility and the possibility to finalise procedures for giving out components while travelling to the wind farm. For large components this time advantage is negligible because the replacement of components heavier than 2 metric tonnes is not as common and require special procedures and attention every time.

Thirdly, a small adjustment to the equipment input is be made. The jack-up barge, responsible for 24h and 40h replacement of parts no longer needs to travel from service port to the wind farm as components weighing over 2 metric tonnes are also stored in the wind farm. Jack-up barges are seldom deployed from the regular service ports or warehouse location. This means that the 8 hour travel time as depicted in the base case can be regarded as travel time between pick-up location of the component and wind farm and thus be disregarded in the case of a centralised storage facility.

4.3.3 Maintenance island

Maintenance island holds a centralised stock that is equal to the central warehouse scenario. This means all turbine related components regardless of value and weight are stored on the island, 15 items per stock category.

The organisation time for all inspections and repairs is decreased by $\frac{1}{3}$ in the repair class input library. This decrease is due to the dedicated storage facility but rather the dedicated crew that is available 24/7 at the island.
The organisation time for replacement of small components under 2 metric tonnes is also decrease by $\frac{1}{3}$ because of the same reason. The organisation time for the replacement of large components weighing over 2 metric tonnes however is not decreased. This is similar to what we saw for the central warehouse and a consequence of the complex operation of replacing a large component.

As for the equipment input library; the travel times of the workboat, jack-up barge and mothervessel with Ampelmann is set to 0 hours as all vessels are deployed from the maintenance island, next to the wind farm.

4.3.4 Sailing workshop (SOV)

The last scenario makes use of a service operation vessel. This SOV has the ability to store small components up to 2 metric tonnes and limit travel times because the vessel stays in the vicinity of the wind farm at all times. Up to 36 technicians can stay on board of the SOV versus 12 technicians on a regular workboat. Equal to the maintenance island it is assumed that a dedicated crew will help to reduce organisation time for all activities except replacement of large components.
In library input terms this means that the stock keeping library holds 15 items of all components under 2 metric tonnes, with no logistic delay time.
The repair class library is the same as for the maintenance island and the difference with the base

case in terms of the equipment input is an adjustment to the workboat specifications. Instead of 12 technicians, the SOV holds a maximum of 36 technicians. Three workboats are therefore replaced by one SOV and costs are fixed per year instead of linked to the amount of trips. The SOV can sail with significant wave heights of 2.5 metres instead of 1.5 metres and travel times are always reduced to zero hours.

4.3.5 Input variables

An overview of the changes to the model per stock keeping scenario can be found in Table 4.3. This is a summarising table of what is described in the subsections above.

Table 4.3: Input variables for stock keeping scenarios

	Base Case	Internal stock	Central warehouse	Maintenance island	SOV
SCS			SCS3 - SCS7 Stock size 15 i/o 0	SCS3 - SCS7 Stock size 15 i/o 0	SCS2 - SCS4 (<2MT) Stock size 15 i/o 0
RC		RC2 - small repairs T_org 4h i/o 6h T_work 3h i/o 4h	RC4 - RC 6 (<2 MT) T_org 8h i/o 12h	RC2 - RC6 (<2MT) T_org to 66.7%	RC2 - RC6 (<2MT) T_org to 66.7%
EQP			EQP3 - Jack-up barge Travel time 0h i/o 8h	EQP1, EQP3, EQP7 Travel time to 0h	EQP1 - Workboat SOV i/o Workboat 36 technicians i/o 12 Traveltime 0h i/o 1h

4.4 Exchange mechanism specific input

The workings of the different exchange mechanisms have been explained in section 3.3. The influence the different exchange mechanisms have on the model will be explained in this section. A base mechanism and 4 variations to that regular exchange will be tested in the model. The variations on the base case are only concerned with the repair class input library. The different exchange mechanisms beside the regular exchange are:

- Internal crane
- Self-hoisting crane
- Revolving exchange
- Rotor integrated pump

The biggest change to the model is the introduction of two new repair classes. Repair class 18 and 19 are introduced to replace repair classes 7 and 8 and thereby the need for a jack-up barge. Repair class 7 and 8 are 24h and 40h replacement of heavy components (<100MT) respectively.

The new repair classes trade in the expensive and scarce jack-up barges for a strong internal or external crane and a support vessel that carries the spare component. The required time for replacement of a large component by the internal crane is set equal to the replacement time of the component by a jack-up barge for simulation purposes. Being 24 hours for repair class 18 and 40 hours for repair class 19. The advantage of the internal crane over the jack-up barge is therefore limited to the reduced logistic delays and saved charter costs.
As mentioned in section 2.6 the time the replacement of a heavy component takes is defined by the following activities:

- Preparation
- Positioning
- Hoisting
- Finalisation

4.4.1 Internal crane

The internal crane has the advantage of being able to lift components that weigh more than 2 metric tonnes. The internal crane works similar to the existing nacelle crane in the base case but is suitable for all drive train components. A regular nacelle crane is only capable of hoisting components up to 2 metric tonnes.
Replacement time of a large component by the internal crane is set equal to the replacement time by a jack-up barge, as explained above.

4.4.2 Self-hoisting crane

The self-hoisting crane has the same properties as the internal crane but the preparation takes 4 hours longer because the crane needs to be installed before becoming operational.

4.4.3 Revolver exchange

The revolver exchange holds the same properties as the internal crane but due to limited hoisting activities the time to repair is lowered by 7 hours. Hoisting time is lowered from 8 to 1 hour to be exact. There is no actual lifting operation, only the rotation of the chambers.

4.4.4 Rotor integrated pump (RIP)

Where the internal crane, the self-hoisting crane and the revolving concept are quite similar and relatively easy to integrate into the O&M calculator, the rotor integrated pump is different and a little more complex.
The rotor systems, blade adjustment system, drive train and generator are grouped together and whenever one of these components is to be replaced; repair class 19 is used to do so. Repair class 18 is the 24h replacement class for components weighing more than 2 metric tonnes (up to 100MT) and is in this case used to change the complete assembly as described above.

The main difficulty is to integrate a reset function for the operating time of all grouped components whenever the assembly is replaced due to the failure of one single component within the assembly. It is possible that a component within the assembly, approaching the end of its useful life is in fact replaced during the complete exchange but, according to the model, still breaks down shortly after.

A second difficulty is to whether or not replace the whole assembly whenever a small component within the assembly fails. That is why a fifth mechanism with extra nacelle crane will be tested. The rotor integrated pump with extra nacelle crane will be explained in the next section.

4.4.5 Rotor integrated pump + nacelle crane (RIP+crane)

To avoid having to replace the complete assembly whenever a small component within the assembly fails the rotor integrated pump can be complemented with a second crane that can lift out components up to 2 metric tonnes. This means that in situ repairs to the wind turbine are also made possible instead of immediate exchange of the assembly whenever there is failure.

Results and discussion

In section 1.4 the overall aims for a full scale DOT wind farm are set. A limit to downtime losses is marked as one of the most important aims in order to get a higher availability. First of all the influence of different stock keeping scenarios on the availability is analysed in section 5.1. To answer the first subquestion of the research question all stock keeping scenarios are simulated using the same exchange mechanism.

Secondly the exchange mechanism are varied, using the base stock keeping scenario. This should give the answers for the second subquestion. In section 5.2 the impact of the different exchange mechanisms on the availability is explained.
In order to find results for all the subquestions of the research question a final analysis is performed on *all* 30 combinations between stock keeping scenarios and exchange mechanisms. The result of simulating all 30 combinations is a filled-in cross-table like in Table 5.1.

The simulation results are always analysed for statistical significance so exclude the possibility that there is an effect on downtime that is caused by the uncertainty of the model.

Table 5.1: Example availability cross-table

	Regular exchange	Internal crane	Self-hoisting crane	Revolver	RIP	RIP+crane
Base case						
Internal stock						
Central warehouse						
Maintenance island						
SOV						

Please note that many other factors influence the availability besides a stock keeping scenario or exchange mechanisms. Distance to shore, wind farm configuration, availability of technicians or even operational windows of vessels also influence the downtime. A sensitivity analysis is performed for two locations and two wind farm configurations but the depicted availabilities are not an absolute truth. Their differences do indicate relative (dis)advantages.

5.1 Scenario specific output

The simulation summary in Table 5.2 contains information on average simulation availability and costs per MWh for the different stock keeping scenario. These key simulation results provide quick insight in the relative advantage of the different scenarios. The most important indicator is the availability. The origin of the relative differences between the different stock keeping scenarios as depicted in Figure 5.1 will be discussed in this section.

Table 5.2: Scenario specific key simulation results

Key simulation results	Base case	Internal stock	Central warehouse	Maintenance island	SOV
Availability [time/yield]	91.4 / 90.3%	91.9 / 90.9%	91.6 / 90.6%	93.4 / 92.5%	94.9 / 94.6%
Costs [c€/MWh]	22.8	21.8	22.5	20.4	22.5

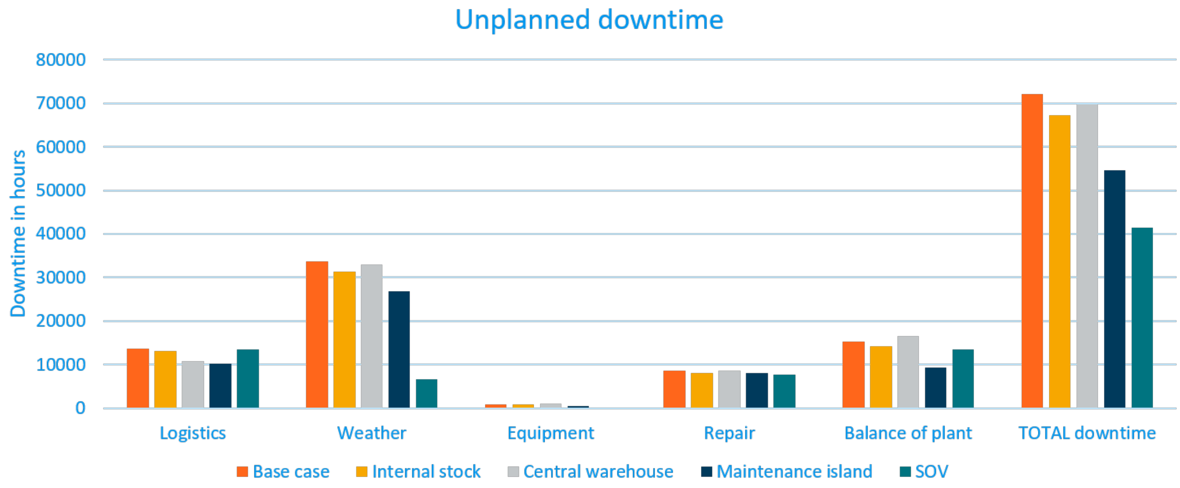

Figure 5.1: Downtime specification per scenario

The total downtime over the different scenarios shows an overall decrease in unplanned downtime of the wind turbine as stock keeping becomes more sophisticated. The total downtime of a central warehouse is lower than the base case, however, it is higher than for the internal stock. This higher total downtime is a product of several individual sources of downtime that vary per stock keeping scenario. It is important to check the validity of the contribution of the individual sources to the total downtime.

The individual sources of downtime are identified as:

- Logistic delays
- Weather delays
- Lack of equipment
- Repair time
- Balance of Plant (BoP)

The downtime caused by these individual sources vary according to the different stock keeping scenarios applied because the scenarios have influence on for example travel times and repair times. It is possible that the variance in downtime is not caused by the the stock keeping scenario but by a large deviation in outcome results due to uncertainty of the model. It is necessary to perform a test to determine if the different stock keeping scenarios actually have an impact on the downtime or if this impact is coincidental.

In the following subsection a statistical analysis is performed to see whether the impact of the individual sources of downtime is significant or due to uncertainty of the model.

5.1.1 Statistical analysis of the scenario specific results

To determine whether different stock keeping scenarios have a different impact the one-way ANOVA test is used, an analysis of variance between multiple groups, to determine if the simulated mean values (μ) of the different scenarios are significantly different. The null hypothesis would be that all scenarios are the same for a particular downtime source. A rejection of the null hypothesis means that the different scenarios actually have different impacts. In formal notation we can write the null hypothesis as:

$$H_0 : \mu_{\text{Base case}} = \mu_{\text{Internal stock}} = \mu_{\text{Central warehouse}} = \mu_{\text{Maintenance island}} = \mu_{\text{SOV}} \tag{5.1}$$

The full results of this analysis can be found in Table D.1 in the appendix, the most important results can be found in Table 5.3.

Table 5.3: ANOVA: p-values scenarios

Source	p-value
Logistics	<0.01
Weather	<0.01
Equipment	<0.01
Repair	<0.01
BoP	0.744
Total downtime	<0.01

Most individual downtime sources display a p-value below 0.01 which means H_0 can be rejected on a 99% confidence interval. Variance downtime related to the balance of plant however cannot be considered significant as the p-value exceeds a 0.01 and even a 0.05 level of significance.

This means that the influence of the different stock keeping scenarios on the downtime caused by logistics, weather, equipment and repairs is in fact different per stock keeping scenario. The influence of the different scenarios on the downtime caused by the balance of plant is indifferent. The results are therefore not statistically significant and ought to be removed. The significant results can be found in Figure 5.2.

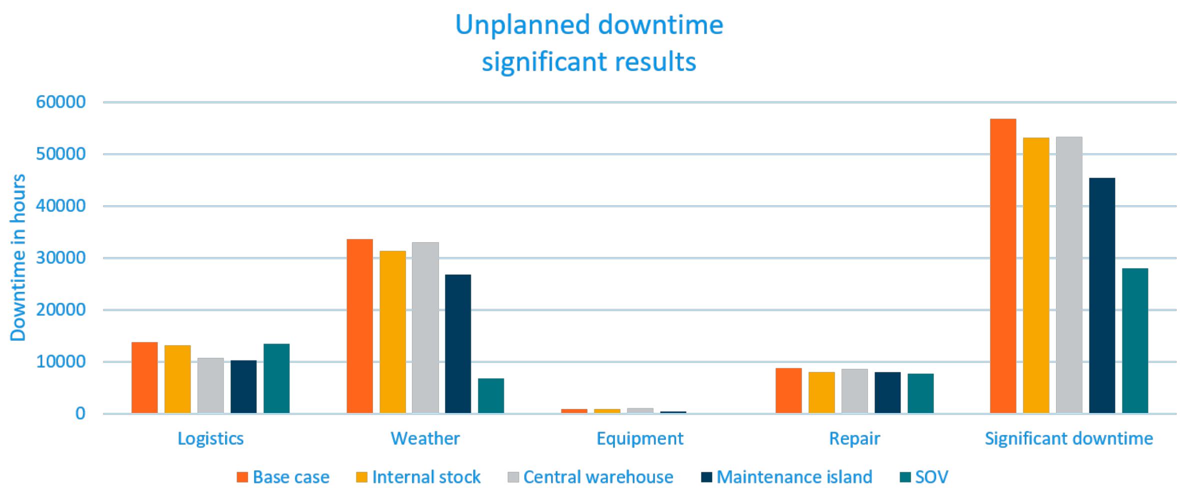

Figure 5.2: Significant downtime specification per scenario

Time-based availability also has to be adjusted for insignificant individual downtime sources. For the time-based availability this means the downtime caused by the BoP is not taken into consideration. What is depicted in Table 5.4 is the time-based availability of the wind turbines only, a valuable indicator to test our overall aim.

Table 5.4: Time-based availabilities for significant downtime

	Base case	Internal stock	Central warehouse	Maintenance island	SOV
Availability [time]	93.1%	93.5%	93.5%	94.4%	96.4%

5.1.2 Scenario specific conclusions

Breaking down the individual sources of downtime we can explain several effects of the different stock keeping scenarios. The effects of the different scenarios are discussed in this subsection, in the same order as they are displayed in Figure 5.2.

Logistic delays are caused by the distance travelled between stock and wind farm. The more stock is kept on location, more logistic delays are averted. The SOV only holds small stock so logistic delays are expected to be similar to the internal stock scenario. However, the logistic delays for the SOV are higher than for internal stock. This can be explained by the amount of vessels available. All scenarios except the SOV have three workboats available for crew transfer. The SOV can make one crew transfer at the time whereas regular workboats could in theory drop off three crews simultaneously. Logistic delays for the SOV are therefore higher.

The difference between the different scenarios for the *weather delay* time is remarkable. Despite availability of all spare components, the central warehouse scenario has higher weather delays than the scenario with internal stock. The only advantage of the internal stock scenario over the central warehouse scenario is the reduced T_organisation and T_work for repair class 2 (RC2), i.e. small repairs inside the nacelle, for the internal stock scenario. Apparently the advantage of the smaller weather window that is required for RC2 is bigger than the advantage of a large stock, reduced T_organisation for other repair classes and the reduced travel time for the jack-up barge.
Weather delays for the SOV are extremely low due to the extended weather window the SOV can operate in as explained in subsection 4.3.4.

The delays caused by a *lack of equipment* are quite low for all scenarios and lowest for maintenance island and the SOV. This is to be expected as these scenarios have dedicated equipment and this equipment is always available.

Repair times are higher for the stock keeping scenarios that do not have a positive impact on the T_organisation or T_work of repair classes 2 and 3 such as the base case and the central warehouse These repair classes are concerned with 4h and 8h small repairs and inspections.

Overall it can be concluded that vessels with the ability to cope with adverse weather and high waves have a substantial advantage over workboats with limited weather windows.
Secondly the reduction of T_organisation and T_work for repair classes 2 and 3 have a big impact on the total repair time and thereby on the weather window required to do 4h or 8h small repairs and inspections. When the required weather window is smaller, more opportunities for actual repair open up and weather delays also go down.

5.2 Exchange mechanism specific output

Similar to the last section, the simulation summary in Table 5.5 contains average availability and efforts, only now for the exchange mechanisms. The simulation means (μ) can be very similar for the different exchange mechanisms because the number of interventions where an exchange mechanism is needed is small in relation to the total amount of interventions. Small differences in the results that can be seen in Table 5.5 and in Figure 5.3 should be carefully analysed and explained. This will be done in the following section.

Table 5.5: Exchange mechanism specific key simulation results

Key simulation results	Base exchange	Internal crane	Self-hoisting crane	Revolver	RIP	RIP+crane
Availability [time/yield]	91.4 / 90.3%	92.0 / 90.3%	92.0 / 91.0%	91.9 / 91.1%	91.4 / 90.3%	92.5 / 91.7%
Costs [c€/MWh]	22.8	20.2	20.3	20.2	18.6	18.2

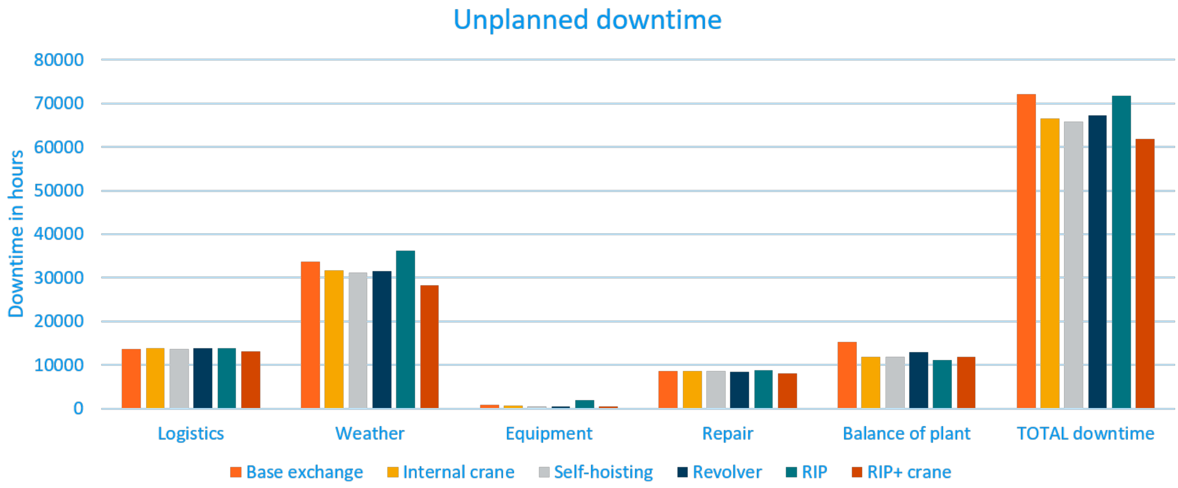

Figure 5.3: Downtime specification per exchange mechanism

5.2.1 Statistical analysis of the exchange mechanism specific results

The total downtime over the different exchange mechanisms is again influenced by the different downtime sources.. To determine whether or not the different exchange mechanisms actually have a significant effect on the downtime a one-way ANOVA test is performed. This time the null hypothesis is:

$$H_0 : \mu_{\text{Base exchange}} = \mu_{\text{Internal crane}} = \mu_{\text{Self-hosting crane}} = \mu_{\text{Revolver}} = \mu_{\text{RIP+crane}} = \mu_{\text{RIP}} \quad (5.2)$$

Table 5.6: ANOVA: p-values exchange mechanisms

Source	**p-value**
Logistics	0.203
Weather	<0.01
Equipment	<0.01
Repair	<0.01
BoP	0.984
Total downtime	0.445

As we can see in Table 5.6 the difference in downtime for logistics and for the balance of plant cannot be assigned to the different exchange mechanisms. Both p-values are outside the 99% confidence interval and therefore H_0 is not rejected. The statistic insignificance of the different mechanisms for the balance of plant and the logistics even influences the significance of the total downtime. In Figure 5.4 this is adjusted for.

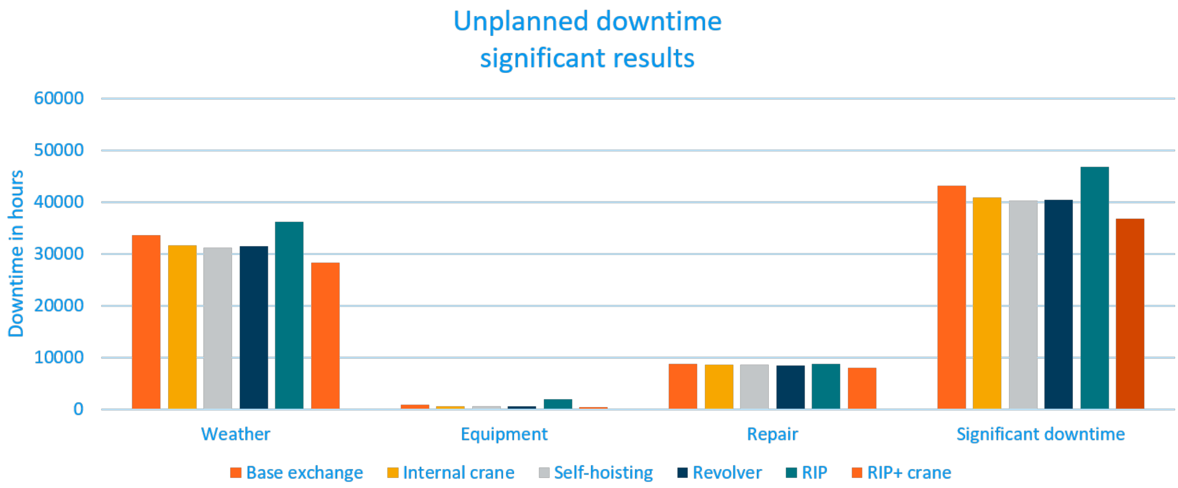

Figure 5.4: Significant downtime specification per exchange mechanism

The time-based availability is adjusted for the influences of the BoP and logistic delays. The difference in influence of these sources of downtime is statistically insignificant if we look at the different exchange mechanisms. The influence of the other sources is processed in the new time-based availability depicted in Table 5.7.

Table 5.7: Time-based availabilities for significant downtime

	Base exchange	Internal crane	Self-hoisting crane	Revolver exchange	RIP	RIP + crane
Availability [time]	94.7 %	94.9 %	95.0 %	95.0 %	94.3 %	95.4 %

Before we start to look into the individual sources of downtime in subsection 5.2.2 we must note that the results for the internal crane, the self-hoisting crane and the revolver exchange seem very similar. The input in the model for these three exchange mechanisms are only marginally different so it is possible that their results are actually indifferent from one another.
Once more a one-way ANOVA test is performed with null hyphothesis:

$$H_0 : \mu_{\text{Internal crane}} = \mu_{\text{Self-hosting crane}} = \mu_{\text{Revolver}} \tag{5.3}$$

Table 5.8: ANOVA: p-values internal, self-hoisting and revolver

Source	**p-value**
Logistics	0.013
Weather	0.543
Equipment	0.270
Repair	$<$0.01
BoP	0.802
Total downtime	0.738

What we see in Table 5.8 is that the null hypothesis can only be rejected for the repair time. The effect of the three exchange mechanisms is indifferent for all individual sources of downtime except for repair time on a 0.01 level of significance. Logistic delays would be significant on a 0.05 level of significance but we saw in Table 5.6 that logistic delays for the different exchange mechanisms are indifferent to the base case. Full results can be found in Appendix D in Table D.3.

It makes sense that the effect of the repair time is significantly different per exchange mechanism as this parameter is varied in the model but apparently this effect is not big enough to make the effect on the total downtime significantly different. That is why the internal crane, the self-hoisting crane and the revolver will be regarded as the same in the analysis in the next subsection. For convenience we shall call them crane-based mechanisms.

5.2.2 Exchange mechanism specific conclusions

In this subsection the results of the different exchange mechanism on the individual sources of downtime are discussed. Keep in mind that all mechanisms other than the base case have traded in the jack-up barge for a different exchange mechanism to replace components over 2 metric tonnes.

For *weather delays* the three crane-based mechanisms have an advantage over the base case as the slow and expensive jack-up barge is replaced by different (crane-based) exchange mechanism. The slow moving jack-up barge needs a bigger weather window to operate than the crane-based exchange mechanisms.
We do see that the rotor integrated pump + nacelle crane has an even bigger advantage because the exchange operation is standardised and both 24h and 40h replacement of components between 2 and 100 metric tonnes (RC7 and RC8) are taken over by a 24h replacement by the nacelle crane (RC18). Because the exchange time of the complete assembly is always 24h instead of occasionally 40h the average required weather window is smaller and logistics delays go down. The big elephant in the room is the rotor integrated pump without nacelle crane. Because there is a need for a 24h replacement (RC18) each and every time a component in the assembly breaks down, a suitable weather window has to be found. Also for the replacement of components up to 2 metric tonnes.

For delays due to a *lack of equipment* or actual *repair time* we see similar results. It is remarkable to see that the extra *repair time* that is concerned with the rotor integrated pump is lower than the extra *weather delays* and delays due to the *lack of equipment*. This means that the advantages of a quicker repair or replacement has consequences that are amplified by other sources throughout the total downtime. A similar conclusion can be drawn from subsection 5.1.2.

5.3 Combined results

In the previous sections the impact of different stock keeping scenarios with the use of a regular exchange mechanism was analysed first. Later on the different exchange mechanisms, while using a base stock keeping scenario, were elaborated upon. This analysis gives insight in the specific effect of either stock keeping or exchange mechanism. The two different input parameters can be combined, perhaps forming a better combination. These combinations are discussed in the following section.

Combining five different stock keeping scenarios with the six different exchange mechanisms a total of 30 simulations was carried out. A complete overview of all the possible combinations between stock keeping scenarios and exchange mechanisms is shown in Table 5.9.

Table 5.9: Key simulation results of all combinations

	Regular exchange	Internal crane	Self-hoisting crane	Revolver exchange	RIP	RIP + crane
Base case						
Availability [time/yield]	91.4 / 90.3%	92 / 91%	92.1 / 90.9%	91.9 / 91.1%	91.4 / 90.3%	92.5 / 91.7%
Costs [€/MWh]	22,8	20,2	20,3	20,2	18,6	18,2
Internal Stock						
Availability [time/yield]	91.9 / 90.9%	92 / 90.9%	92 / 91.1%	92.4 / 91.3%	89.5 / 88.4%	92.7 / 91.5%
Costs [€/MWh]	21,8	20,5	20,7	19,9	19,0	17,6
Central Warehouse						
Availability [time/yield]	91.6 / 90.6%	92.9 / 91.9%	92.9 / 92%	91.9 / 90.8%	89.6 / 88.3%	92.7 / 91.7%
Costs [€/MWh]	22,5	20,1	20,2	20,4	18,4	18,0
Maintenance Island						
Availability [time/yield]	93.4 / 92.5%	92.2 / 91.3%	93.5 / 92.5%	93.9 / 92.9%	92.4 / 91.2%	94.3 / 93.4%
Costs [€/MWh]	20,4	19,4	19,5	19,0	16,8	17,0
SOV						
Availability [time/yield]	94.9 / 94.6%	95.5 / 95.1%	95.7 / 95.6%	95.8 / 95.5%	94.2 / 93.8%	95.7 / 95.6%
Costs [€/MWh]	22,5	21,4	21,1	21,3	20,0	19,3

The most important indicator is the time-based availability. This indicator is wide-spread across the industry and is a way to compare performance of your wind turbine but, more importantly in this case, also the effectiveness of your maintenance strategy. The time-based availability per combination can be found in Table 5.10 and is depicted in Figure 5.5 and Figure 5.6.

Table 5.10: Normal time-based availability

	Regular exchange	Internal crane	Self-hoisting crane	Revolver	RIP	RIP + crane
Base case	91.4%	92.0%	92.1%	91.9%	91.4%	92.5%
Internal stock	91.9%	92.0%	92.0%	92.4%	89.5%	92.7%
Central warehouse	91.6%	92.9%	92.9%	91.9%	89.5%	92.7%
Maintenance island	93.4%	92.2%	93.5%	93.9%	92.4%	94.3%
SOV	94.9%	95.5%	95.7%	95.8%	94.2%	95.7%

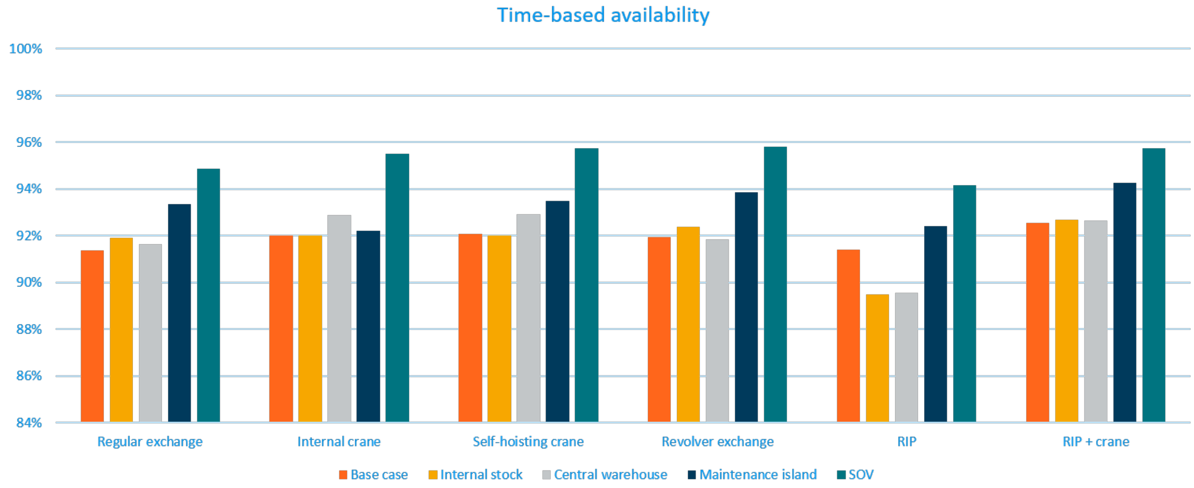

Figure 5.5: Time-based availability per scenario

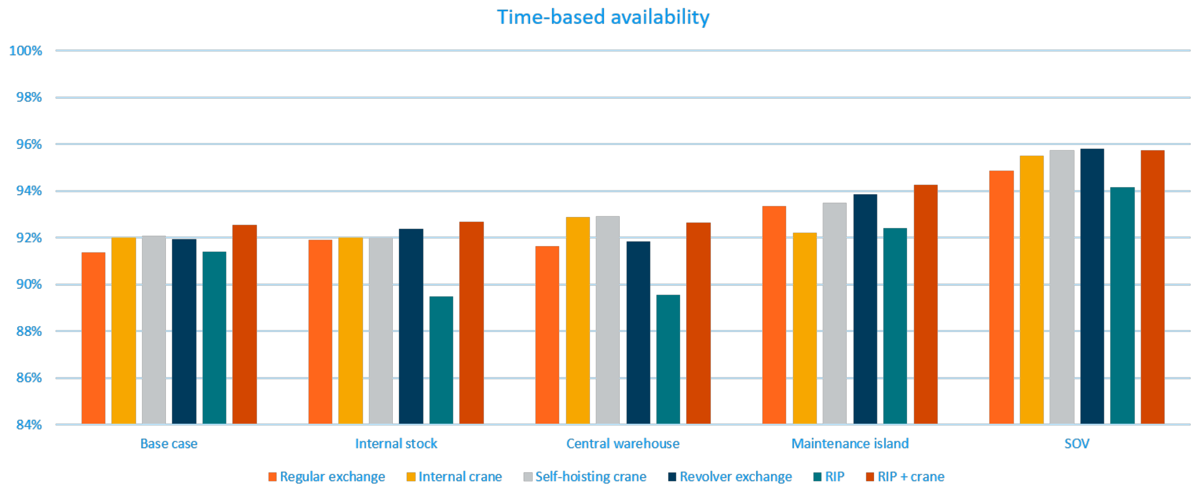

Figure 5.6: Time-based availability per exchange mechanism

5.3.1 Statistical analysis of the combined results

In the scenario specific and exchange specific output several downtime sources were discarded because of their insignificance. Downtime sources that were found to be insignificant for the stock keeping scenarios were concerned with the BoP. The influence of both BoP *and* logistic delays was deemed indifferent for the exchange mechanisms.

It is impossible to take a specific downtime source into consideration for the scenario but not for the exchange mechanism whenever a combination of the two is made. That is why logistic delays *will* be considered significant in calculating the availability of the wind farm. The influence of the BoP on downtime will not be taken into consideration. Please find the time-based availabilites for all the combinations, adjusted for significant results, in Table 5.11, Figure 5.7 and Figure 5.8.

Table 5.11: Significant time-based availability

	Regular exchange	Internal crane	Self-hoisting crane	Revolver	RIP	RIP + crane
Base case	93.1%	93.4%	93.4%	93.4%	92.7%	93.9%
Internal stock	93.5%	93.5%	93.6%	93.7%	90.6%	94.1%
Central warehouse	93.5%	93.6%	93.7%	93.6%	91.5%	94.2%
Maintenance island	94.4%	94.5%	94.4%	94.5%	93.5%	94.9%
SOV	96.4%	96.4%	96.4%	96.4%	96.0%	96.7%

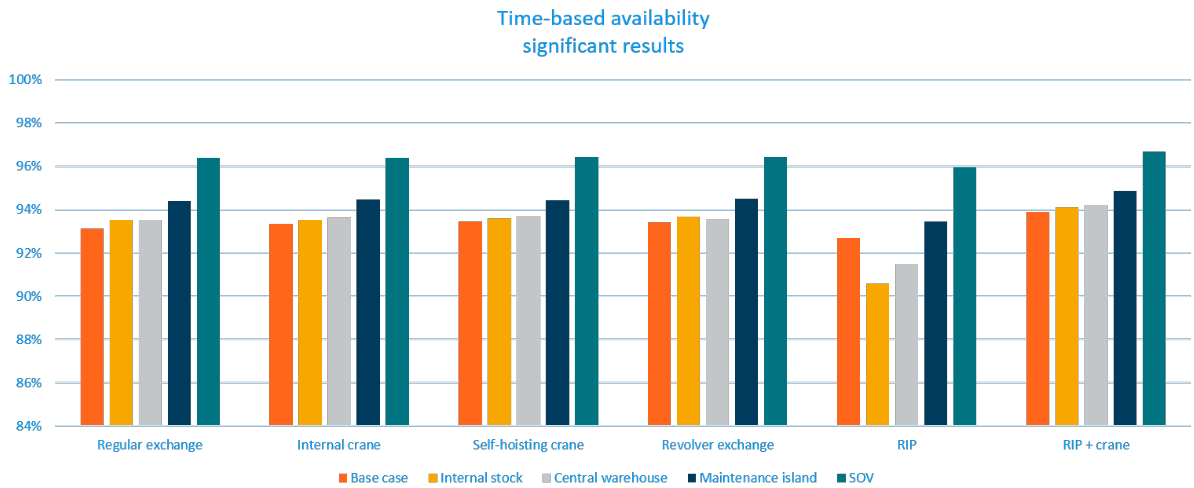

Figure 5.7: Significant time-based availability per scenario

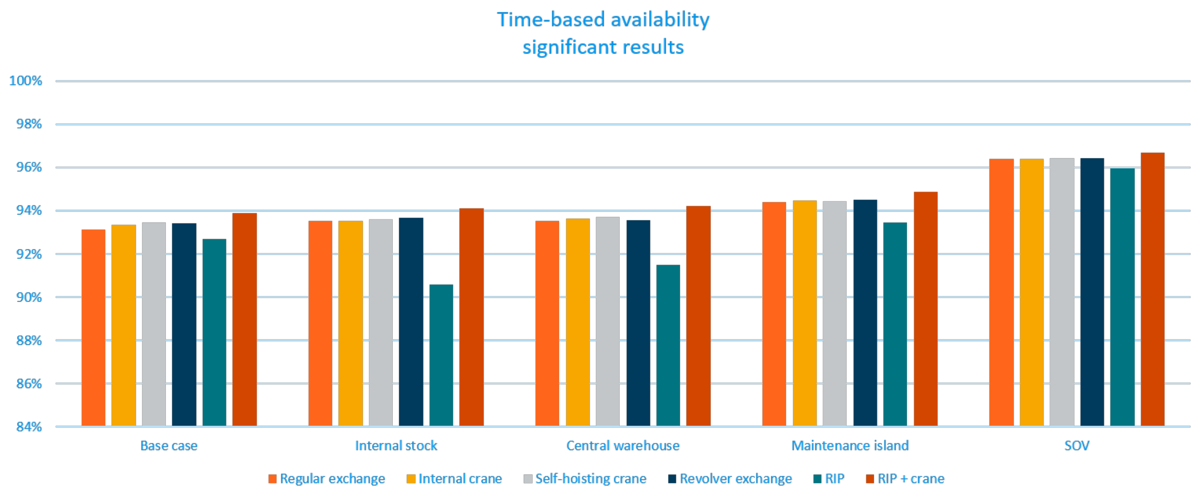

Figure 5.8: Significant time-based availability per exchange mechanism

5.3.2 Combined conclusions

Looking into the results in Table 5.11 we can conclude that there is a difference in time-based availability between the conservative combinations in the top left corner and the more sophisticated combinations in the bottom right corner. The lowest availability in fact is the stock keeping scenario base case with regular exchange of components and the highest availability is reached with the SOV combined with the RIP + crane. The results for the RIP column will be discussed separately.

The table shows an upward trend on the *horizontal axis*, this trend is depicted in Figure 5.7. For every stock keeping scenario the overall availability increases when we move towards more sophisticated exchange mechanisms. It is important to note that for the crane-based mechanisms (internal crane, self-hoisting crane and revolver exchange) the availability varies slightly. In the previous section we have demonstrated that this difference is to be disregarded.

A second point of remark is the availability of the different stock keeping scenarios for the rotor integrated pump. In section 5.2 we had already concluded that this exchange mechanism was inferior to the other exchange mechanisms but Figure 5.7 shows that the RIP without nacelle crane is in fact performing worse than the regular exchange. Especially for more advanced stock keeping mechanisms the logistic advantage of large stocks in the vicinity of the wind farm is completely done away with.

On the *vertical axis* of the table the general trend is also upward, considering the time-based availability over the different stock keeping scenarios. A small discrepancy to the trend can be found in the revolver exchange column. The other crane-based mechanisms do however show the upward trend. This discrepancy will be disregarded on account of the similarity between the crane-based mechanisms.

Conclusively the results for the RIP without nacelle crane are discussed. The base case availability for the RIP is higher than for the internal stock and central warehouse scenarios. This means that these stock keeping mechanisms have an adverse effect on the availability. Especially when parts are available near the wind farm but travel times are long (i.e. internal stock & central warehouse scenarios) the availability drops dramatically. Workboats *and* support vessels have to be deployed from shore for every replacement operation and parts have to be gathered elsewhere. This causes extra weather delays and a lack of equipment.

5.4 Sensitivity analysis

The results stated in the previous sections are specific for the location "Hollandse Kust: Noord-Holland". It is possible that the different stock keeping scenarios and exchange mechanisms have a different impact on the time-based availability when the wind farm is located further away from shore. An example of a farshore wind farm that is to be developed is "IJmuiden Ver", located 60 km west of IJmuiden. A analysis for this location is performed as a comparison to the base location.

The results are also very specific for the configuration of the wind farm. The previously used configuration was 100 wind turbines with a rated capacity of 7.0 MW. It is likely that a different configuration with more turbines of a lower rated capacity has an impact on the availability. In this section the impact of a different wind farm configuration is also analysed.

5.4.1 Location of the wind farm

A simulation for a DOT wind farm at the location of "IJmuiden Ver" has been conducted in the same way as for the location "Hollandse Kust: Noord-Holland". Specific results for the stock keeping scenarios and exchange mechanism can be found in Appendix E, the most important results on time-based availability can be found in Table 5.12, Table 5.13 and Table 5.14. These tables show the time-based availability associated with the different combinations between stock keeping scenarios and exchange mechanisms.

Table 5.12: Significant time-based availability per scenario "IJmuiden Ver"

	Base case	Internal stock	Central warehouse	Maintenance island	SOV
Availability [time]	91.7%	91.2%	91.7%	94.4%	96.4%

Table 5.13: Significant time-based availability per mechanism "IJmuiden Ver"

	Base exchange	Internal crane	Self-hoisting crane	Revolver exchange	RIP	RIP + crane
Availability [time]	91.7 %	91.7 %	91.8 %	91.7 %	90.7 %	92.1 %

Table 5.14: Significant time-based availability "IJmuiden Ver"

	Regular exchange	Internal crane	Self-hoisting crane	Revolver	RIP	RIP+crane
Base case	91.7%	91.7%	91.8%	91.7%	90.7%	92.1%
Internal stock	91.2%	91.4%	91.6%	91.5%	90.6%	91.9%
Central warehouse	91.7%	91.7%	91.8%	91.8%	91.3%	92.2%
Maintenance island	94.4%	94.5%	94.5%	94.5%	93.5%	94.9%
SOV	96.4%	96.4%	96.4%	96.4%	96.0%	96.7%

When comparing Table 5.11 and Table 5.14 it becomes clear that, regardless of the exchange mechanism that is used, the disadvantage of a the stock keeping scenarios where crew and components are deployed from land becomes even bigger.

5.4.2 Configuration of the wind farm

The planned 700 MW wind farm at "Hollandse Kust: Noord-Holland" can have many configurations. There are only a few 7.0 MW turbines available at this moment and there is no 7.0 MW hydraulic pump for the DOT available yet. It is possible that a configuration with 140 wind turbines with a rated capacity of 5.0 MW is the configuration of choice.
Effects of this configuration on the time-based availability are shown in Table 5.15. This analysis is only done for the most important exchange mechanisms. Full results can be found in Appendix E.

Table 5.15: Significant time-based availability "Hollandse Kust"

	Regular exchange	Internal crane	RIP + crane
Base case	93.5%	93.4%	93.9%
Internal stock	93.3%	93.0%	93.7%
Central warehouse	93.4%	93.7%	94.1%
Maintenance island	94.4%	94.5%	94.8%
SOV	94.1%	94.1%	94.4%

Table 5.16 shows the most important results for a wind farm located at "IJmuiden Ver" with a 140 wind turbines with a rated capacity of 5.0 MW configuration.

Table 5.16: Significant time-based availability "IJmuiden Ver"

	Regular exchange	Internal crane	RIP+crane
Base case	91.2%	91.1%	91.6%
Internal stock	91.0%	91.1%	91.6%
Central warehouse	91.0%	91.3%	91.7%
Maintenance island	94.4%	94.5%	94.8%
SOV	94.1%	94.1%	94.4%

When comparing Table 5.15 and Table 5.16 it becomes clear that the advantage of keeping stock, equipment and crew in the vicinity of your wind farm becomes essential whenever you move further away from shore. The time-based availability is higher for maintenance island and the SOV than for the base case, internal stock or central warehouse for both distances.

The most interesting result from changing the configuration of the wind farm is that a maintenance island becomes more favourable option than the use of an SOV. For every exchange mechanism and location the time-based availability is higher when a maintenance island is used instead of an SOV.

Conclusions and recommendations

The aim of this report is to develop a new maintenance strategy for large offshore DOT wind farms. This new strategy consists of a logistical solution in the form of a stock keeping scenario and a mechanism to replace the drive train.
Developing a strategy for maintaining your offshore wind farm helps dealing with failure as part of the operating phase, rather than an unexpected event. Despite all good efforts, failure of wind turbine components can never be fully prevented. A suitable way of maintaining your components is therefore of vital importance to remain operational.

6.1 Conclusions

The requirement for a maintenance strategy is to be innovative, in order to stand out from conventional wind turbines and to reduce downtime to a maximum of 5%, in order to be competitive with conventional wind turbines.

This research is performed by simulating five stock keeping scenarios and six mechanisms to exchange the complete drivetrain, or parts of the drivetrain. Every combination between stock keeping scenario and exchange mechanism is simulated for a DOT wind farm located at the proposed site for Hollandse Kust: Noord-Holland. This DOT wind farm consists of 100 turbines with a rated capacity of 7.0 MW per turbine.

Additionally, a sensitivity analysis is performed. First to show the effect of distance to shore on the availability of a wind farm and how it may affect the desired maintenance strategy. Secondly to show the effect of a different wind farm configuration, varying the number of turbines and rated capacity.

6.1.1 Stock keeping scenarios

A variety of stock keeping scenarios have been simulated with the use of the ECN O&M Calculator. The simulations show that a stock keeping scenario where crew and equipment are located near the wind farm is always favoured over deployment from land. Downtime percentages for stock keeping scenarios combined with a regular exchange mechanism are 5.6% for a maintenance island and 3.6% for an SOV. For the other stock keeping scenarios this percentage lies between 6.9% and 6.5%, according to the model.

This means that regardless of the location of the spare components, a maintenance island or SOV is more effective in reducing downtime than a scenario where workboats come from the nearest port. This effect is even stronger when the wind farm is located further away from shore, as is shown in the sensitivity analysis. The results for a maintenance island and SOV stay the same for a wind farm located further away from shore but downtime losses for the other stock keeping scenarios drop to values between 8.8% and 8.3%.

The reason for this can be found in the detailed results of the simulations. Waiting for a suitable weather window to perform maintenance is the cause for most downtime losses. By reducing travel times or choosing a vessel with higher weather limits this can be averted.

A maintenance island reduces the distance that needs to be travelled to the wind farm, thus reducing travel times. An SOV both has higher weather limits as well as a reduced travel time compared to workboats coming from shore because the SOV can stay in the vicinity of the wind farm. This is why they are favoured over workboats deployed from land.

Despite the fact that an SOV has no storage capacity for large and heavy components (unlike for example a maintenance island) it still is the stock keeping scenario with the largest downtime reduction. This can be explained by the small number of large component exchanges compared to small repairs or replacements. Replacement of large components is so uncommon that focusing on small repairs or replacements has a bigger effect.

A limitation of the SOV is the capacity. As seen in the sensitivity analysis, a large number of wind turbines means a larger number of failures and a single SOV is limited in the amount of transfers per hour it can make. A maintenance island is an option for very large wind farms as multiple workboats can be deployed simultaneously. For the location of "IJmuiden Ver" the downtime for the SOV dropped below 5% while downtime for a maintenance island remains the same according to the model.

6.1.2 Exchange mechanisms

The different exchange mechanisms that are analysed focus on the modular design of a DOT drive train. Replacement of individual components of the drive train can be performed with the use of crane mechanisms situated in the nacelle and doing so reduces downtime losses compared to a regular exchange. The reduction in downtime losses is primarily because large crane vessels can be taken out of the equation for replacement operations. Whenever an internal crane is strong enough to lower modules of the drive train to a supporting vessel the long waiting times caused by crane vessels can be avoided.

The results vary between 5.3% downtime for a regular exchange with a basic stock keeping scenario to 4.6% downtime for the exchange of the rotor integrated pump with additional crane.

One important lesson when replacing individual components of the drive train is that the results are indifferent from the exchange mechanism that is being used. The effect on downtime is statistically the same for a large internal crane as for a self-hoisting crane and even a concept with redundancy of components. This is interesting considering the fact that dedicated cranes or redundancy of components requires large structural changes to the wind turbine.

The real advantage is found in the possibility to replace multiple components of the drive train at the same time. The concept of the rotor integrated pump defines a sub-assembly where multiple components of the drive train are grouped together and exchanged simultaneously. If the exchange of a complete drive train can be done in a standardised way multiple components can quickly be exchanged at the same time.

The simulation results show that the complete exchange of a rotor integrated pump is the best option to reduce downtime losses but only if there still is the possibility to perform small maintenance inside the nacelle. There is still a need for a nacelle crane to hoist small spare components. This avoids that exchange of the whole sub-assembly for every small failure.

6.1.3 Combinations

The combined simulations of both stock keeping scenarios and exchange mechanisms show that the best practices for the separate simulation groups can be combined to form an optimal maintenance strategy. This means that a maintenance island or SOV combined with a rotor integrated pump with extra nacelle crane has the highest time-based availability according to the simulations.

The most important conclusion that can be drawn from this research is the need for stock in the vicinity of the wind farm in order to get downtime under 5%. This can be done by using an island close to the wind farm with dedicated equipment, crew and stock or by using an SOV. Most important stock and maintenance activities are concerned with small, in-situ repairs. This contradicts practises used by for example Google in their service centres and also contradicts the expectations of DOT previous to the research. This research demonstrates that exchanging a complete drivetrain assembly is only a favourable option if small components of the drive train can still be repaired or exchanged seperately.

6.2 Recommendations

The recommendations concluding this research will come in two-fold. First the method of analysis and possible next steps will be presented. In this subsection the possibility of extending the research and how to validate the results even more is discussed. After that the limitations of the ECN model and possible additions to it will be discussed.

6.2.1 Recommendations for further research

The simulations carried out during this research concern a non-existent wind farm and are solely based on reference data from other wind farms and assumptions. For example the components and corresponding failure rates from regular 5.0 MW offshore wind turbines are used. The components and failure rates of a DOT turbine will be different due to a different technical layout. Currently, a complete inventory of components for a 7.0 MW DOT turbine is not available, let alone accurate data on mean time to failure of these components. More accurate data on the amount of turbines and the distance to shore can also change the relative effect of the stock keeping scenarios or the exchange mechanisms.

Whenever more data is available the simulations should be carried out again for more accurate results. The approach of this research makes it easy to implement more accurate data whenever this is available. General input and wind turbine input can easily be adjusted in the model and dividing the simulations up in 30 combinations enables cross-using of the input for the different scenarios and mechanisms. This makes it very easy to form combinations again for the new input data.

Secondly the stock keeping scenarios could be taken one step further. In the current model a division for decentralised storage of components is picked according to their weight. For example all components up to 2 metric tonnes are stored on the SOV in multiples. Perhaps it is more beneficial to keep smaller stocks on board, or keep stocks based on frequently used articles such as in the Amazon approach in subsection 3.1.3.
The overall concepts of the different stock keeping scenarios have been analysed but possible variations within the scenarios could be investigated further.

Furthermore, a thorough costs-benefit analysis has to point out whether the downtime advantages of certain stock keeping scenarios or exchange mechanisms weigh up to the extra capital expenditures. It is the goal of this research to identify the relative advantages of different scenarios and mechanisms on the time-based downtime. However, these results only take into account the extra operational costs for the different scenarios and exchange mechanisms. Extra expenditures on physical modifications to the wind turbine or to the playing field such as the construction of extra warehouses or a complete island are not taken into account.
A cost-benefit analysis could help further improve the validity and reliability of the results on a financial level.

6.2.2 Recommendations for the ECN model

The O&M Calculator by ECN is focused on simulating the interventions needed to maintain an offshore wind farm and, according sea states and availability of parts, crew and equipment, calculate the downtime and operational costs.

The model does not give the opportunity to group certain components together for simultaneous replacement. It does allow for components to be assigned the same repair class but the total operation time of a component will only be reset for the faulty component. Because the failure rates are normally distributed in the model the impact on this research is small. When the model makes use of more realistic way of simulating the failure, for example by using the bathtub curve, a reset of operation time is essential.
Allowing the model to group components together and perform simultaneous replacement will simulate a complete revision of the assembly of grouped components. This is a form of preventive maintenance carried out during an act of corrective maintenance and could be very beneficial to reduce the total amount of interventions.

An extension to this is the exchange of components for multiple wind turbines during a single intervention. It can be an economic trade-off to postpone repairing a single turbine and wait for grouped maintenance. This trade-off should be made available in the model.

Conclusively a more holistic approach for the inshore supply chain of spare components could be very beneficial for the model. For now it is unclear what the limitations are on the supply side of spare components or what the limitations are for the ports they are dispatched from. If we are looking to improve stock keeping of spare components for large offshore wind farms the model should also be able to make decisions on where the spare parts are located best and how large stocks should be. Decentralised stock keeping would in that case not just be a black box with dead capital.

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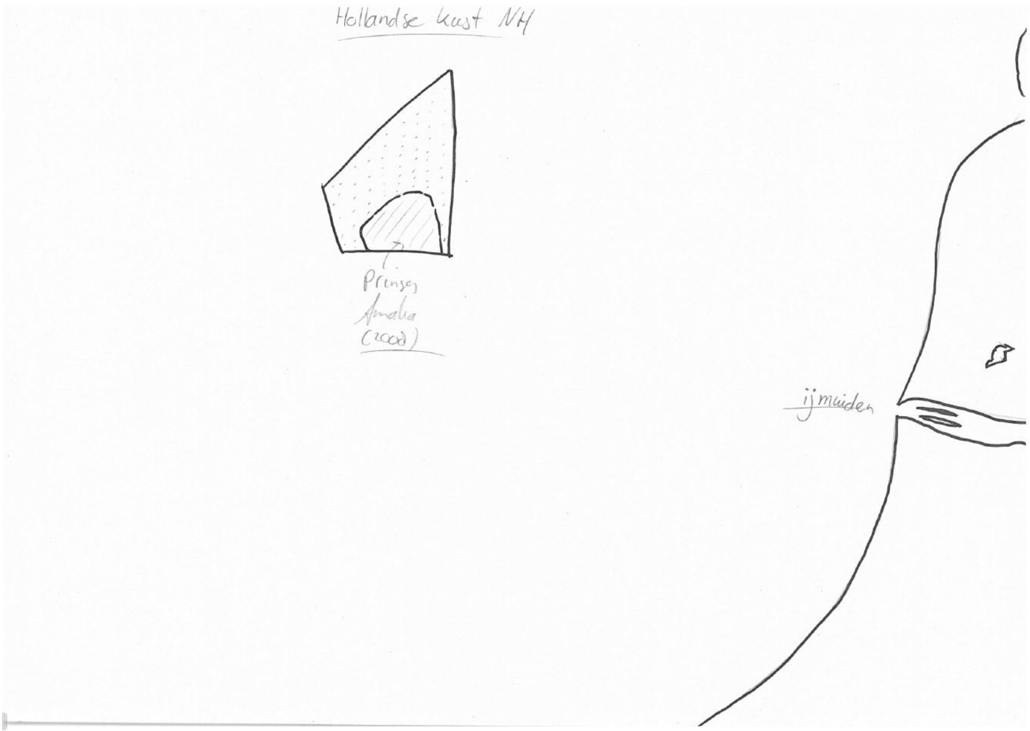
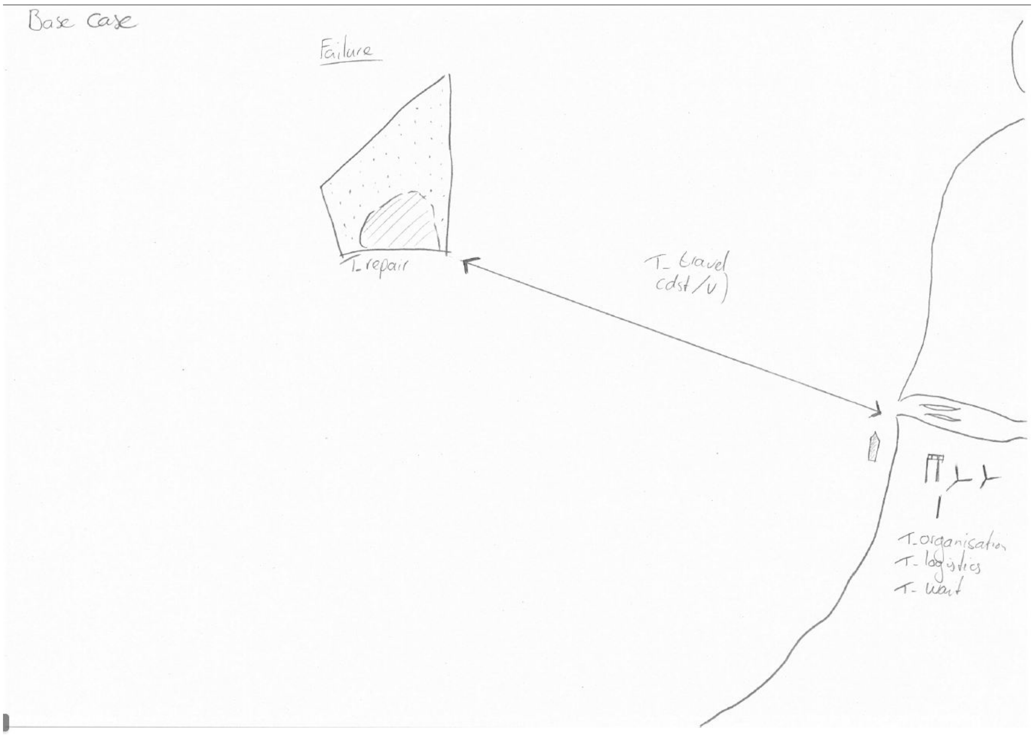
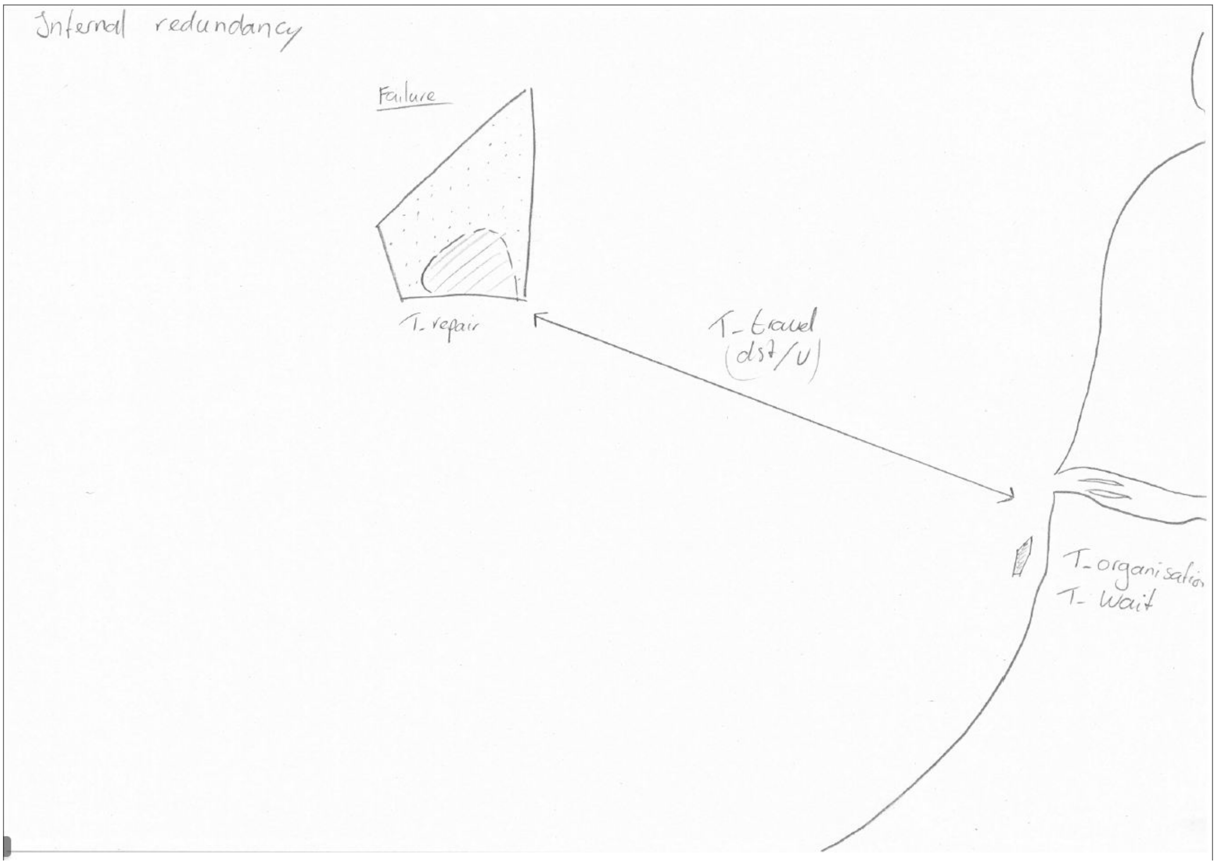
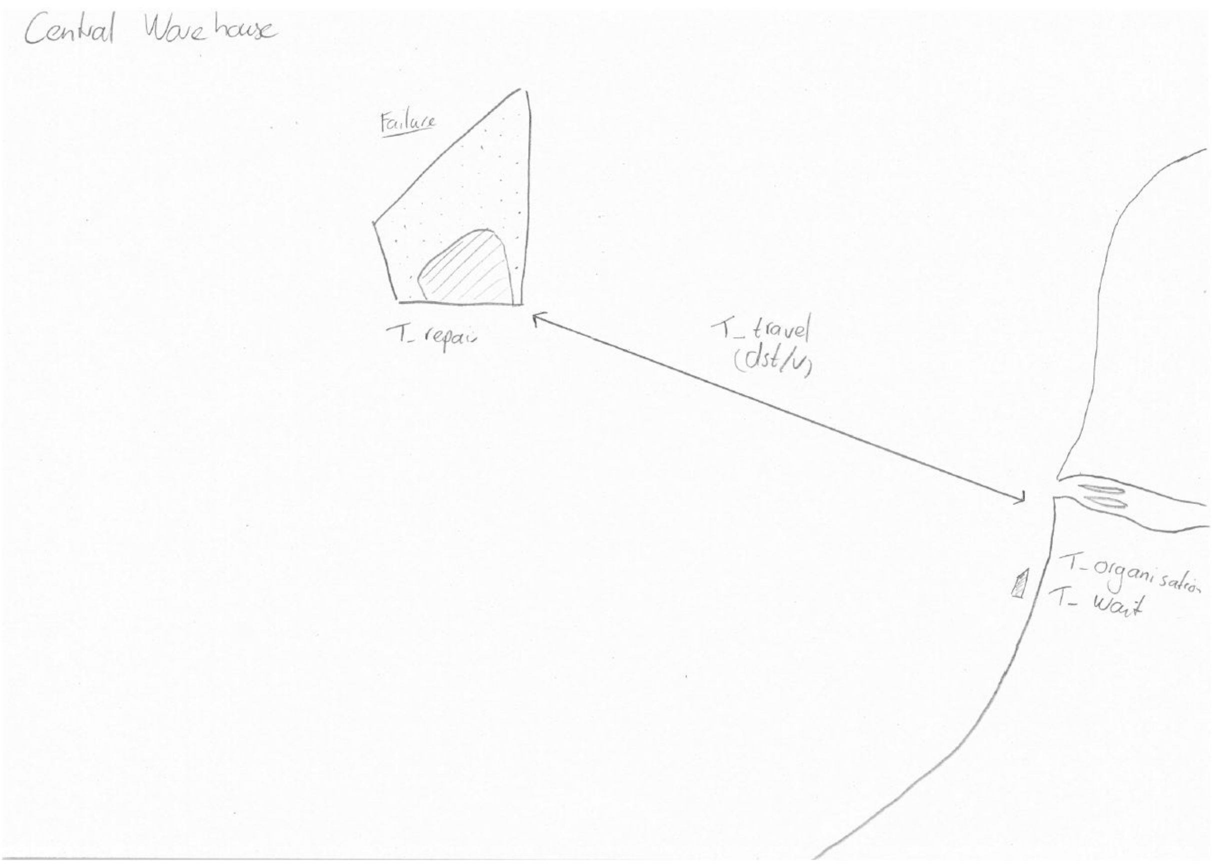
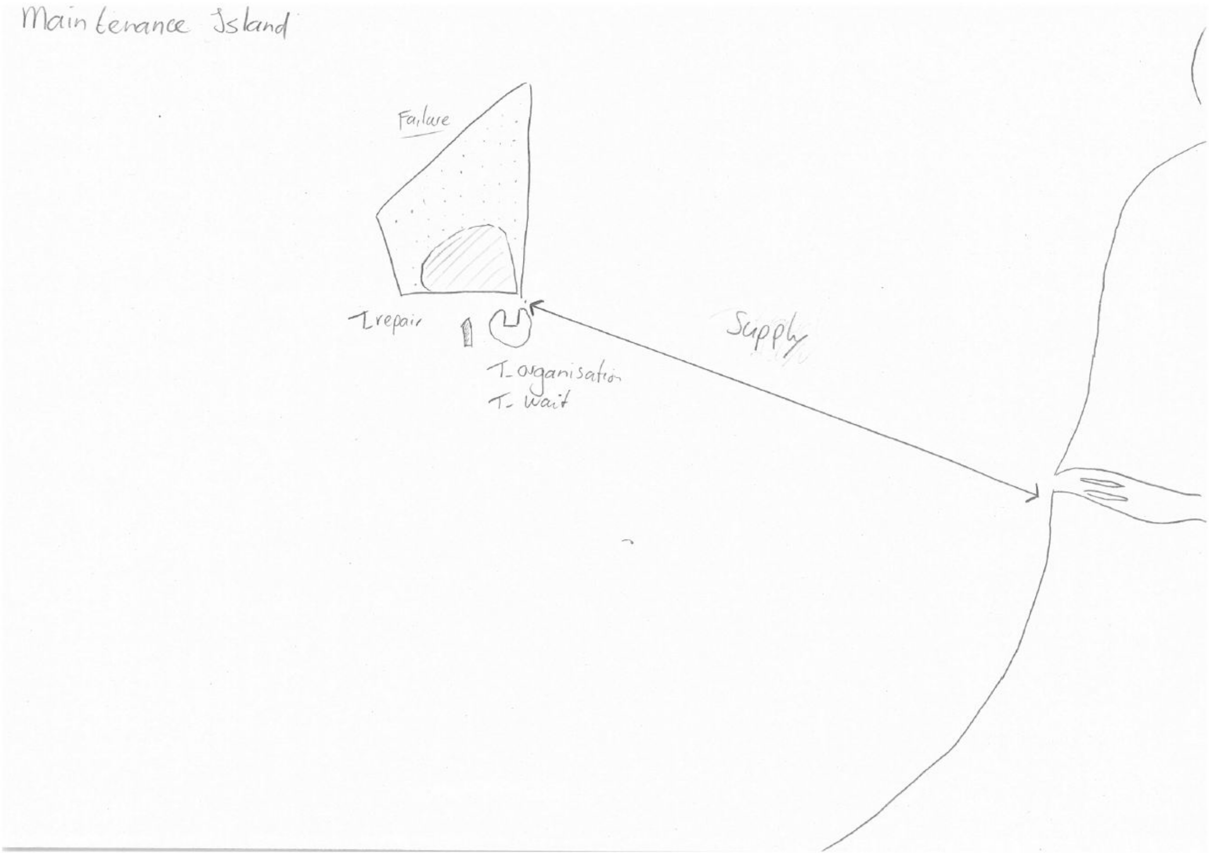
Appendix A - Sketches

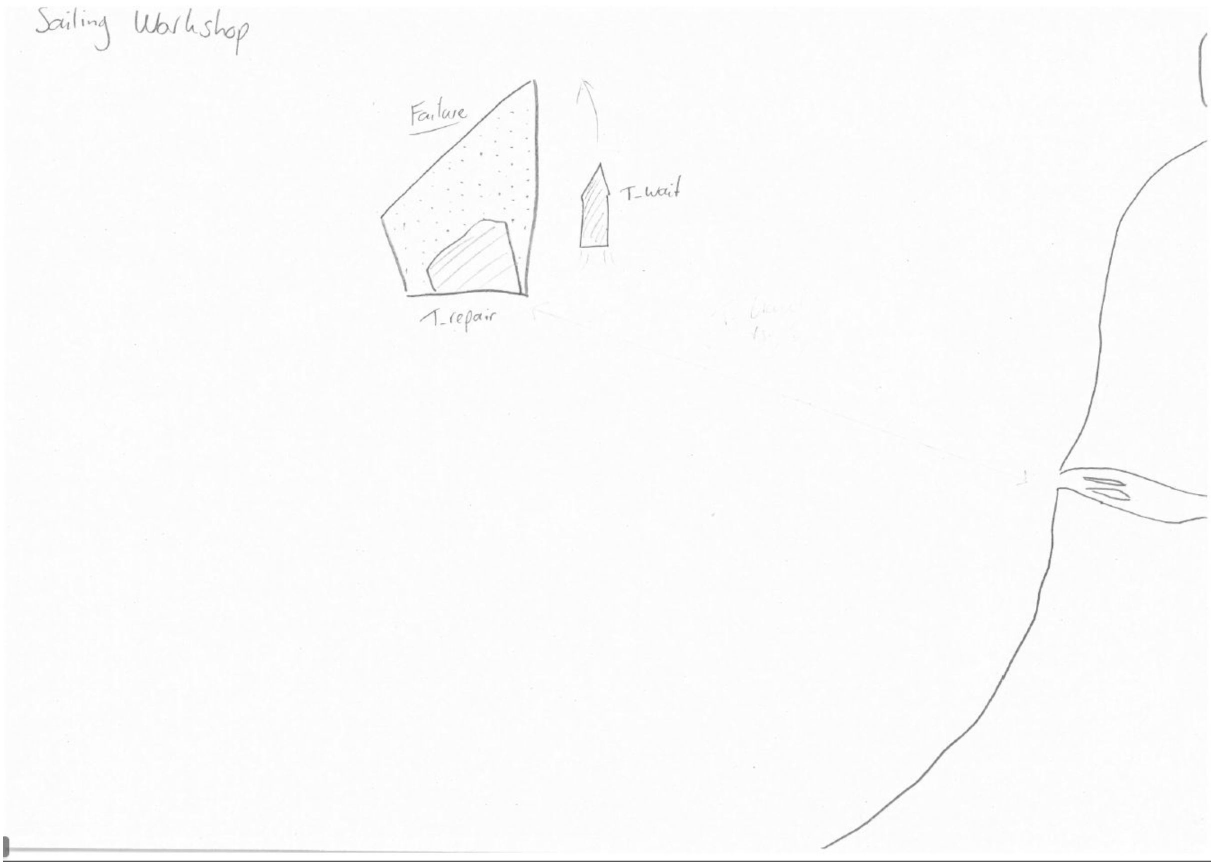





Internal redundancy
Failure
T_repair
T_travel
(dst/v)
T_organisation
T_wait


Central Warehouse
Failure
T_repair
T_travel
(dst/v)
T_organisation
T_wait


Maintenance Island
Failure
T_repair
T_organisation
T_wait
Supply


Sailing Workshop
Failure
T_wait
T_repair

Appendix B - Multi-criteria analysis

In compliance with "Gids voor beoordelingskaders" by de Boer et al.[39] a tree structure is used to determine the weights for the MCA.
In Table B.1 the different categories are ranked and scored. In Table B.2 the different criteria are ranked and scored. The scoring is done as follows:

Categories and criteria within categories are ranked. If a criterion is equally or more important than the other the criterion will score a 1, less important criteria score 0. Scores are added to form the *Total*. Total scores are doubled and scores of 0 are converted to a score of 1. This is the *Adjusted total*. All criteria must have an adjusted total greater than 0 at the end. The *Weight factor* is determined by dividing the adjusted total by the sum of the adjusted totals within the category. In Table B.2 a *Final weight* is specified. The weight factor of the criterion is multiplied by the weight factor of the category it belongs to.

Table B.1: MCA scoring of the categories

	Time	Design	Costs	Total	Adjusted total	Weight factor
Time	X	1	1	2	4	0.571
Design	0	X	1	1	2	0.286
Costs	0	0	X	0	1	0.143

Table B.2: MCA scoring of the criteria

	Mobilisation time	Exchange time	Construction time	Total	Adjusted total	Weight factor	Final weight
Mobilisation time	X	0	1	1	2	0.286	0.163
Exchange time	1	X	1	2	4	0.571	0.327
Construction time	0	0	X	0	1	0.143	0.082

	Simplicity Crane	Simplicity Structure	Maintainability	Total	Adjusted total	Weight factor	Final weight
Simplicity Crane	X	0	0	0	1	0.143	0.041
Simplicity Structure	1	X	1	2	4	0.571	0.163
Maintainability	1	0	X	1	2	0.286	0.082

	Capital costs	Mobilisation costs	Total	Adjusted total	Weight factor	Final weight
Capital costs	X	1	1	2	0.667	0.095
Mobilisation costs	0	X	0	1	0.333	0.048

The different exchange mechanisms are then scored on how they perform on each of the criteria. Results can be found in Table B.3

Table B.3: MCA scoring of the mechanisms

	Internal crane	Weighted	Self-hoisting crane	Weighted	Revolver	Weighted	Rotor integrated pump	Weighted
Mobilisation time	5	0.816	3	0.490	5	0.816	2	0.327
Exchange time	2	0.653	1	0.327	5	1.633	3	0.980
Construction time	4	0.327	5	0.408	2	0.163	5	0.408
Simplicity Crane	5	0.204	2	0.082	1	0.041	5	0.204
Simplicity Structure	4	0.653	5	0.816	1	0.163	5	0.816
Maintainability	2	0.163	5	0.408	3	0.245	5	0.408
Capital costs	2	0.190	4	0.381	1	0.095	2	0.190
Mobilisation costs	5	0.238	2	0.095	5	0.238	2	0.095
	29	**3.245**	**27**	**3.007**	**23**	**3.395**	**29**	**3.429**

Appendix C - Base case

C.1 General input

General input	
Meteo data	North Sea K13
Length of shifts	11 hours
No. of available technicians	36
Price of energy	€130/MWh
Simulation period	5 yr
No. of simulations	100

C.2 Turbine input

Wind turbine specifications	
Type of turbine	DOT 7MW
No. of turbines in wind farm	100
Rated power [MW]	7
Hub height [m]	85
Cut-in velocity [m/s]	4
Cut-out velocity [m/s]	25

C.3 Spare control input library

Table C.1: Spare control input library

SCS no.	Name	Logistic time [h]	Material costs [€]	In stock [y/n]	Reordering time [h]	Stock size
1	Consumables 0.5k	0	500			
2	Small parts 5k in stock (<2 MT)	0	5000	yes	48	15
3	Small parts 50k 48h (<2 MT)	0	50000			
4	Small parts 250k 48h (<2 MT)	0	250000			
5	Large parts 100k 168h (<100 MT)	168	100000			
6	Large parts 100k 336h (<100 MT)	336	100000			
7	Large parts 500k 336h (<100 MT)	336	500000			
8	Transformer 250k 1440h (<25 MT)	1440	250000			
9	Small parts found./scour 5k 48h	48	5000			
10	Cable 350k 240h	240	350000			
11	No costs	0	0			

C.4 Repair class input library

In this section the base case with regular exchange mechanism is depicted.

Table C.2: Repair class input library part 1

RC no.	Name	Maint. phase	T_org [h]	EQP1	EQP2	EQP3	T_work [h]	N_tech
1	Remote reset							
		Remote reset	-	-	-	-	2	-
2	4h Inspection/small repair inside							
		Repair	6	1	-	-	4	3
3	8h Inspection/small repair outside							
		Replacement	6					
		Preparation	-	1	6	-	1	3
		Hoisting	-	1	8	-	6	3
		Finalisation	-	1	6	-	1	3
4	8h Replacement parts (<2MT)							
		Inspection	6	1	-	-	4	3
		Replacement	12					
		Preparation	-	1	-	-	2	3
		Hoisting	-	1	6	-	3	3
		Finalisation	-	1	-	-	3	3
5	16h Replacement parts (<2MT)							
		Inspection	6	1	-	-	4	3
		Replacement	12					
		Preparation	-	1	-	-	6	3
		Hoisting	-	1	6	-	3	3
		Finalisation	-	1	-	-	7	3
6	24h Replacement parts (<2 MT)							
		Inspection	6	1	-	-	4	3
		Replacement	12					
		Preparation	-	1	-	-	10	4
		Hoisting	-	1	6	-	3	4
		Finalisation	-	1	-	-	11	4
7	24h Replacement parts (<100 MT)							
		Inspection	6	1	-	-	4	3
		Replacement	16					
		Preparation	-	1	-	-	4	6
		Positioning	-	1	3	-	2	6
		Hoisting	-	1	3	-	8	6
		Finalisation	-	1	-	-	10	6
		Repair	6	1	-	-	8	3
8	40h Replacement parts (<100 MT)							
		Inspection	6	1	-	-	4	3
		Replacement	16					
		Preparation	-	1	-	-	10	6
		Positioning	-	1	3	-	2	6
		Hoisting	-	1	3	-	8	6
		Finalisation	-	1	-	-	20	6
		Repair	6	1	-	-	12	3

Table C.3: Repair class input library part 2

RC no.	Name	Maint. phase	T_org [h]	EQP1	EQP2	EQP3	T_work [h]	N_tech
9	8h BOP transformer repair							
		Repair	6	1	-	-	8	3
10	48h BOP transformer repair							
		Inspection	6	1	-	-	4	3
		Repair	12	2	-	-	2	4
		Repair	0	7	-	-	44	4
11	8h BOP Foundation/scour protection							
		Replacement	6					
		Hoisting	-	9	4	-	8	0
12	32h BOP cable replacement							
		Replacement	24					
		Preparation	-	9	5	-	8	0
		Positioning	-	9	5	-	4	0
		Hoisting	-	9	5	-	12	0
		Finalisation	-	9	5	-	8	0
18	24h Large replacements by Crane (<100 MT)							
		Replacement	16					
		Preparation	-	1	6	-	4	6
		Positioning	-	1	6	7	2	6
		Hoisting	-	1	6	7	1	6
		Finalisation	-	1	-	-	10	6
		Inspection	6	1	-	-	4	3
		Repair	6	1	-	-	8	3
19	40h Large replacements by Crane (<100 MT)							
		Inspection	6	1	-	-	4	3
		Replacement	16					
		Preparation	-	1	6	-	10	6
		Positioning	-	1	6	7	2	6
		Hoisting	-	1	6	7	1	6
		Finalisation	-	1	-	-	20	6
		Repair	6	1	-	-	12	3

C.5 Equipment input library

In this chapter the equipment input library is discussed.

Table C.4: Equipment input library part 1

Eqp no.	Type	Name	
1	Access vessel	Workboat	
	Logistics & availability	Unit	Input
	Mobilisation time	h	0
	Demobilisation time	h	0
	Travel time	h	1
	Max. technicians	-	12
	Transfer category	-	multiple crews
	Travel category	-	daily
	no. of eqp corrective	-	3
	no. of eqp condition	(# per period)	3
	no. of eqp calendar	(# per period)	0
2	Helicopter	Helicopter BOP	
	Logistics & availability	Unit	Input
	Mobilisation time	h	8
	Demobilisation time	h	4
	Travel time	h	0
	Max. technicians	-	6
	Transfer category	-	single crew
	Travel category	-	daily
	no. of eqp corrective	-	1
	no. of eqp condition	(# per period)	0
	no. of eqp calendar	(# per period)	0
3	Vessel for replacement	Jack-up barge (100 MT)	
	Logistics & availability	Unit	Input
	Mobilisation time	h	720
	Demobilisation time	h	48
	Travel time	h	8
	Max. technicians	-	0
	Transfer category	-	single crew
	Travel category	-	stay
	no. of eqp corrective	-	1
	no. of eqp condition	(# per period)	0
	no. of eqp calendar	(# per period)	0

Table C.5: Equipment input library part 2

Eqp no.	Type	Name	
4	Vessel for replacement	Diving support vessel	
	Logistics & availability	Unit	Input
	Mobilisation time	h	360
	Demobilisation time	h	0
	Travel time	h	4
	Max. technicians	-	0
	Transfer category	-	single crew
	Travel category	-	stay
	no. of eqp corrective	-	1
	no. of eqp condition	(# per period)	1
	no. of eqp calendar	(# per period)	0
5	Vessel for replacement	Cable laying vessel	
	Logistics & availability	Unit	Input
	Mobilisation time	h	720
	Demobilisation time	h	0
	Travel time	h	6
	Max. technicians	-	0
	Transfer category	-	single crew
	Travel category	-	stay
	no. of eqp corrective	-	1
	no. of eqp condition	(# per period)	0
	no. of eqp calendar	(# per period)	0
6	Internal crane	Nacelle crane	
	Logistics & availability	Unit	Input
	Mobilisation time	h	0
	Demobilisation time	h	0
	Travel time	h	0
	Max. technicians	-	0
	Transfer category	-	single crew
	Travel category	-	daily

Table C.6: Equipment input library part 3

Eqp no.	Type	Name	
7	Support vessel	Mother vessel - Ampelmann	
	Logistics & availability	Unit	Input
	Mobilisation time	h	0
	Demobilisation time	h	0
	Travel time	h	1
	Max. technicians	-	36
	Transfer category	-	single crew
	Travel category	-	daily
	no. of eqp corrective	-	1
	no. of eqp condition	(# per period)	0
	no. of eqp calendar	(# per period)	0
8	Internal crane	Blade inspection	
	Logistics & availability	Unit	Input
	Mobilisation time	h	0
	Demobilisation time	h	0
	Travel time	h	0
	Max. technicians	-	0
	Transfer category	-	single crew
	Travel category	-	daily
9	Support vessel	Dummy access	
	Logistics & availability	Unit	Input
	Mobilisation time	h	0
	Demobilisation time	h	0
	Travel time	h	0
	Max. technicians	-	12
	Transfer category	-	single crew
	Travel category	-	daily

Appendix D - Statistial analysis

Table D.1: One-way Anova for all scenarios

Scenarios					
Logistics					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	9,029,714,339,960.000	4	2,257,428,584,990.000	8,144,821.804	0.000
Within groups	12,472,254.000	45	277,161.200		
Total	9,029,726,812,214.000	49			
Weather					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	5,092,106,720.000	4	1,273,026,680.000	139.368	0.000
Within groups	411,043,914.000	45	9,134,309.200		
Total	5,503,150,634.000	49			
Equipment					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	4,670,260.000	4	1,167,565.000	44.640	0.000
Within groups	1,176,975.000	45	26,155.000		
Total	5,847,235.000	49			
Repair					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	6,762,452.000	4	1,690,613.000	42.282	0.000
Within groups	1,799,307.000	45	39,984.600		
Total	8,561,759.000	49			
Balance of plant					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	302,088,652.000	4	75,522,163.000	0.489	0.744
Within groups	6,946,795,062.000	45	154,373,223.600		
Total	7,248,883,714.000	49			
Total downtime					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	6,604,039,300.000	4	1,651,009,825.000	10.336	0.000
Within groups	7,188,226,551.000	45	159,738,367.800		
Total	13,792,265,851.000	49			

Table D.2: One-way Anova for all exchange mechanisms

Exchange mechanisms					
Logistics					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	3,043,513.333	5	608,702.667	1.507	0.203
Within groups	21,815,523.000	54	403,991.167		
Total	24,859,036.333	59			
Weather					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	343,986,893.333	5	68,797,378.667	5.826	0.000
Within groups	637,667,829.000	54	11,808,663.500		
Total	981,654,722.333	59			
Equipment					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	14,952,073.333	5	2,990,414.667	35.272	0.000
Within groups	4,578,237.000	54	84,782.167		
Total	19,530,310.333	59			
Repair					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	3,324,288.333	5	664,857.667	11.057	0.000
Within groups	3,247,047.000	54	60,130.500		
Total	6,571,335.333	59			
Balance of plant					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	105,722,393.333	5	21,144,478.667	0.133	0.984
Within groups	8,583,752,502.000	54	158,958,379.667		
Total	8,689,474,895.333	59			
Total downtime					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	749,439,388.333	5	149,887,877.667	0.969	0.445
Within groups	8,349,066,963.000	54	154,612,351.167		
Total	9,098,506,351.333	59			

Table D.3: One-way ANOVA on Internal, Self-hoisting and Revolver crane

Logistics					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	3,322,066.667	2	1,661,033.333	4.433	0.013
Within groups	111,273,624.000	27	374,658.667		
Total	114,595,690.6672	29			
Weather					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	9,151,800.000	2	4,575,900.000	0.611	0.543
Within groups	2,223,214,191.000	27	7,485,569.667		
Total	2,232,365,991.000	29			
Equipment					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	54,866.667	2	27,433.333	1.314	0.270
Within groups	6,203,043.000	27	20,885.667		
Total	6,257,909.667	29			
Repair					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	1,329,800.000	2	664,900.000	8.214	0.000
Within groups	24,042,546.000	27	80,951.333		
Total	25,372,346.000	29			
Balance of plant					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	75,473,266.667	2	37,736,633.333	0.220	0.802
Within groups	50,854,744,215.000	27	171,228,095.000		
Total	50,930,217,481.667	29			
Total downtime					
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Between groups	96,950,600.000	2	48,475,300.000	0.303	0.738
Within groups	47,443,152,834.000	27	159,741,255.333		
Total	47,540,103,434.000	29			

Appendix E - Sensitivity analysis

E.1 Sensitivity analysis for 7.0 MW "IJmuiden Ver"

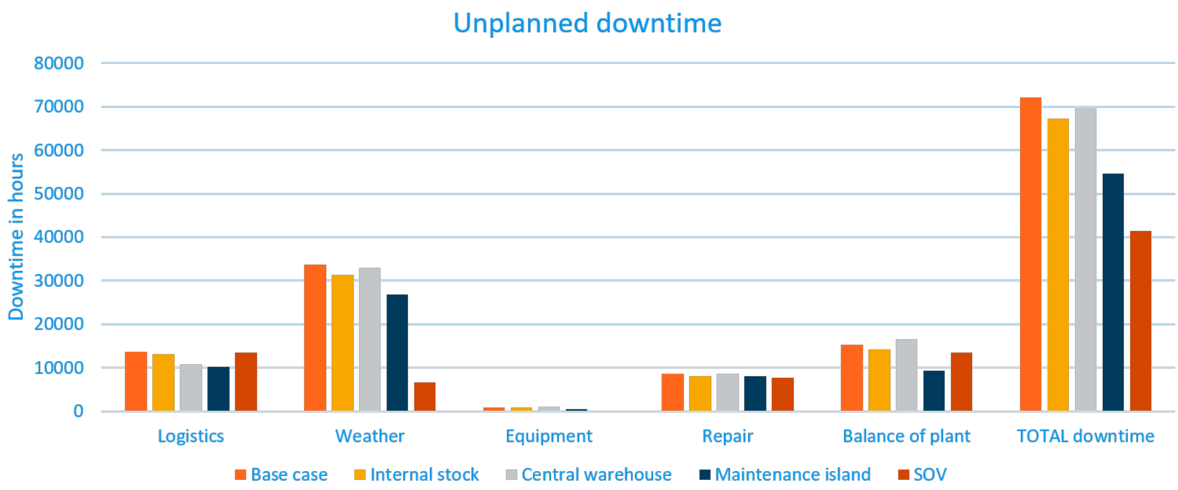


Figure E.1: Significant downtime per scenario for 7.0 MW "IJmuiden Ver"

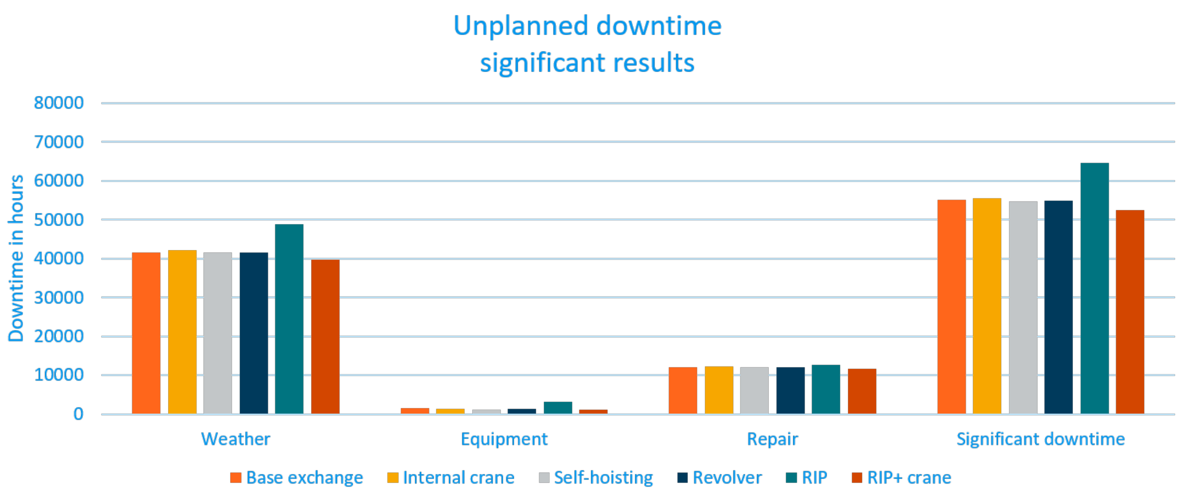


Figure E.2: Significant downtime per mechanism for 7.0 MW "IJmuiden Ver"

E.2 Sensitivity analysis for 5.0 MW "Hollandse Kust: Noord-Holland"

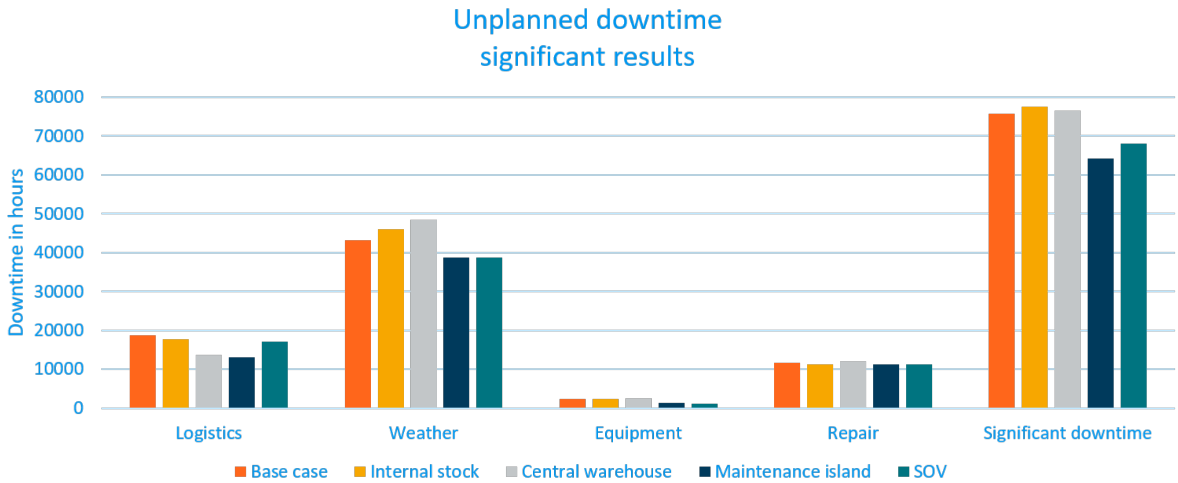


Figure E.3: Significant downtime per scenario for 5.0 MW "Hollandse Kust: Noord-Holland"

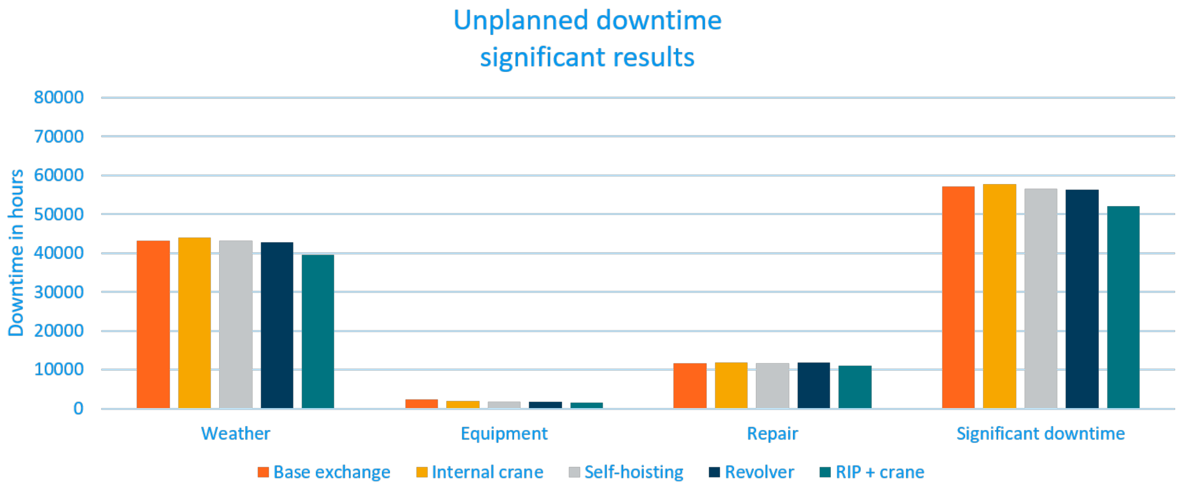


Figure E.4: Significant downtime per mechanism for 5.0 MW "Hollandse Kust: Noord-Holland"

E.3 Sensitivity analysis for 5.0 MW "IJmuiden Ver"

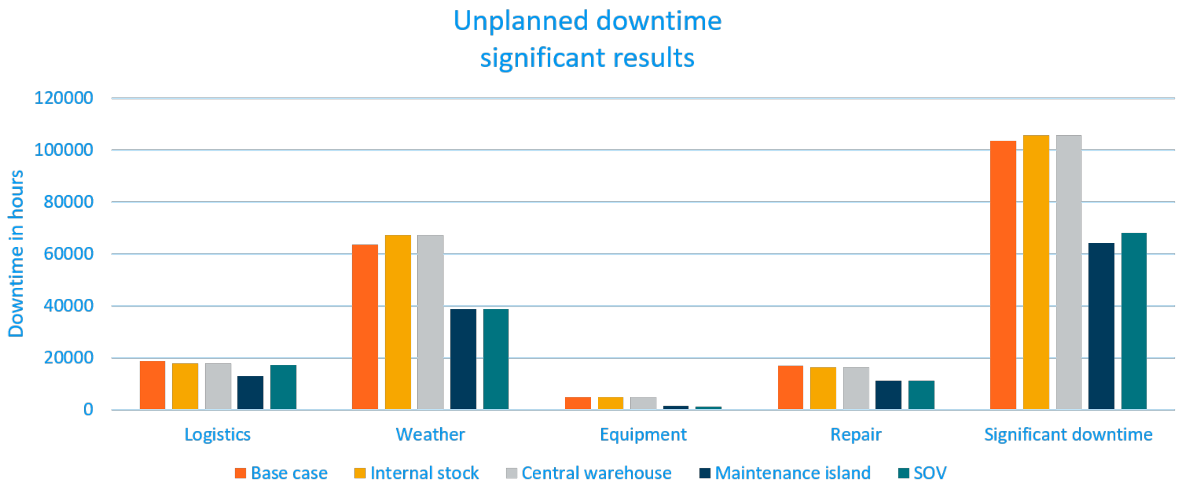


Figure E.5: Significant downtime per scenario for 5.0 MW "IJmuiden Ver"

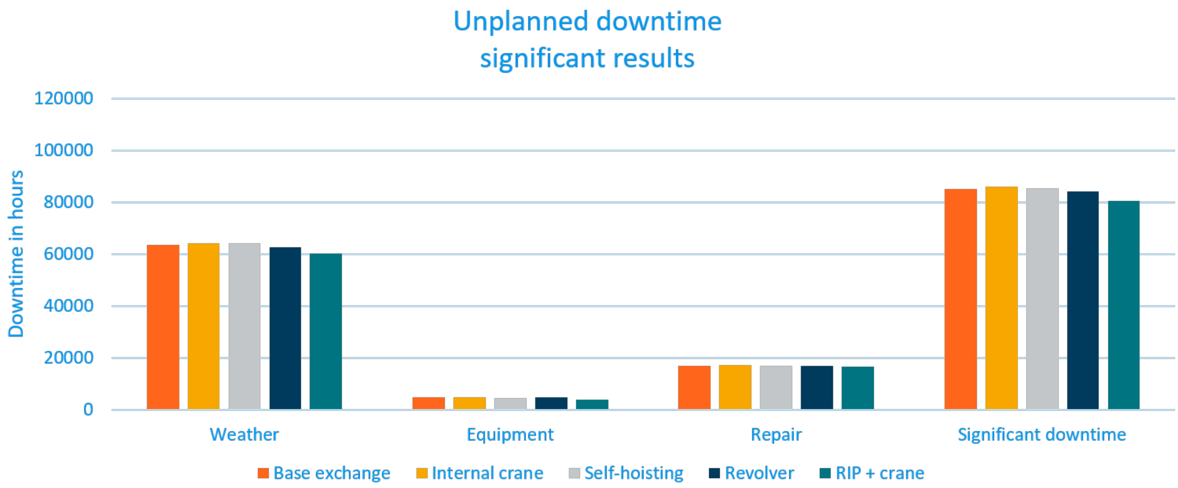


Figure E.6: Significant downtime per mechanism for 5.0 MW "IJmuiden Ver"