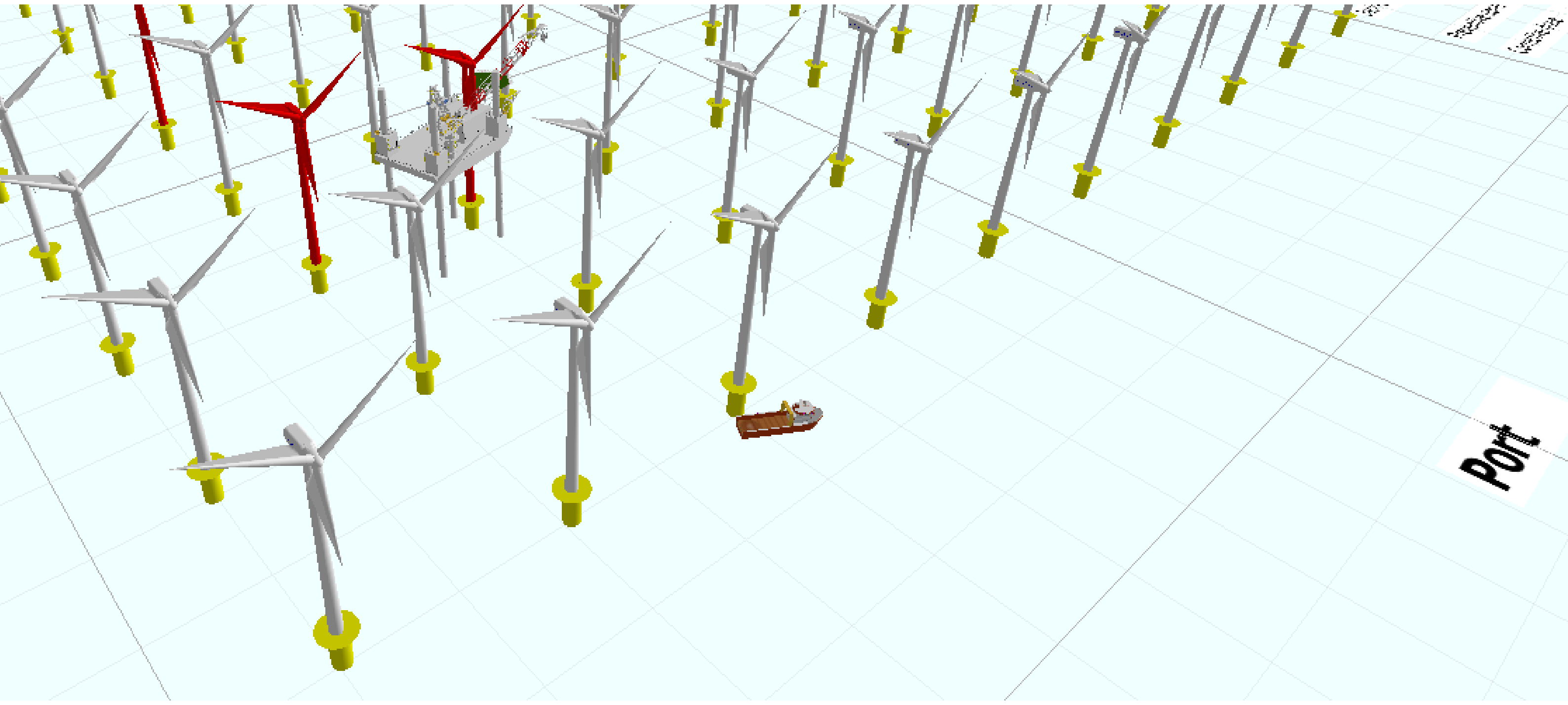
An Integrated and Generic Approach for Effective Offshore Wind Farm Operations & Maintenance

A design-oriented approach to ensure effective Operations & Maintenance planning and process by developing a decision support tool



Master Thesis
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Abstract

Due to renewable energy regulations, wind energy becomes more attractive and the offshore wind sector is growing significantly the recent years. Operations and Maintenance (O&M) of offshore wind farms facing more challenges and is more expensive, compared to the O&M of onshore wind farms. O&M costs of offshore wind farms are on average double as high compared to onshore wind farms. This is mainly caused by the cost intensive maritime resources required for O&M and uncertainty of offshore weather conditions, while latest research indicates that the O&M of offshore wind farms can be more effective.

Weather conditions have a substantial impact on the production, cost, and planning of offshore wind farms which require O&M strategies that minimize production losses and O&M costs, while making sure scheduled maintenance tasks are completed in time. Previous research show a lack of an approach that is 1) integrated: including all the stakeholders' requirements that are necessary to assess the effectiveness of the O&M in terms of production, cost, and planning and 2) generic: applicable for all wind farms.

This master thesis identified first all the requirements for an integrated and generic O&M decision support tool. By means of literature research and interviews with stakeholders in the offshore wind sector, all the requirements for modelling an integrated and generic O&M tool are gathered and verified, supporting the offshore wind O&M plan and process.

35 model requirements are identified covering wind farm parameters, O&M strategies, external factors, O&M effectiveness indicators and tool capabilities. Of these requirements, 9 are not or partly fulfilled by the examined studies or tools. The main gaps in the current research are related to the option to perform only maintenance during low wind speeds, the planning aspect covering the feasibility and robustness of maintenance plans, the insight in the O&M process (e.g. visualization or process animation) and to the optimization capability.

The second part of this thesis focused on the conceptualization and implementation of all the identified requirements into one O&M tool. The developed tool, based on discrete event simulation covered all the identified gaps in the current research besides all the other stakeholders' requirements, apart from some spare parts logistics requirements which are simplified included with assumptions. The developed tool enable users to compare optimize different O&M strategies (covering the resource configuration and deployment options) on all the KPIs of the O&M plan and process, to optimize the O&M strategies and to gain insight in the maintenance process in order to find the optimum in the production, cost, and planning trade-off triangle, taking into account all the requirements.

After the implementation in the discrete event simulation software the tool is verified and validated by means of a model comparison with the validated ECN O&M tool and an expert validation with an actor from the offshore wind sector. The results is a verified and validated tool that is demonstrated with a fictitious cases study in the last part of this thesis.

The tool can be improved on several aspects, most notably by performing a real validation project for a maintenance campaign of an existing wind farm. Other recommended improvements implying further research are extending the scope regarding the inventory aspect, including the option to incorporate historical data for condition based maintenance, including more transporters, extending the model with a user-friendly interface around the actual tool and integrating forecast weather data to enable day-to-day planning.

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List of Abbreviations

CTV	Crew Transfer Vessel
DE(V)S	Discrete EVent Simulation
ISP	Independent Service (maintenance) Provider
KPI	Key Performance Indicator
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
O&M	Operations & Maintenance
OWEZ	Offshore Wind farm Egmond aan Zee (NL)
P&S	Planning & Scheduling
RPS	Risk-based Planning and Scheduling.
TRIA(a,b,c)	Triangular distribution with *a* min, *b* mode and *c* max
UML	Unified Modeling Language

Introduction

1. Problem Introduction

The last decades, there is an increased attention to climate change, renewable energy and sustainability. Currently, the world is still relying on conventional energy supply, with a 4.7% share for renewable energy sources in the total global power generation (BP, 2013). The developed countries, as such specified in the Kyoto Protocol, realized that a shift in the energy sector is desired to secure the energy supply and to maintain the environment. In the legally binding Kyoto protocol the concerned countries agreed to a Green House Gasses (GHG) reduction of around five percent, compared to the baseline in 1998 for European Union countries. This agreement differs per country and is agreed for the first commitment period from 2008 till 2012 (United Nations, 2010). In 2007, the European Union even agreed to a GHG reduction of twenty percent and to a twenty percent (also differs per country) share for renewable energy sources, e.g. wind or solar energy, by 2020 (European Commission, 2007). On the long term the EU proposed an emission reduction target of 40% by 2030 and set an objective of 80-95% GHG reduction by 2050, compared to 1990 levels (European Commission, 2014). Due to these regulations, wind energy becomes more attractive and the offshore wind sector has grown significantly the recent years, making it an interesting upcoming sector (European Wind Energy Association, 2013).

Due to the offshore location and the uncertain weather conditions, wind farms at sea have different requirements, challenges and costs compared to onshore wind farms. This also holds for the Operations & Maintenance (O&M). Weather conditions have a substantial impact on the production, cost, and planning of the O&M and require O&M strategies that minimize production losses and O&M costs, while making sure scheduled maintenance tasks are completed in time.

These differences and challenges results in substantially higher O&M costs compared to onshore wind farms; approximately twice as high (Rademakers, Braam, Zaaijer, & Bussel, 2003). According to The German Offshore Wind Energy Foundation (2013), these O&M costs of offshore wind farms could be reduced by five till eight percentage points, due to technological potentials and increased efficiency.

So there can be concluded that there is demand for an approach to make the O&M more effective. Previous research show a lack of an approach that is 1) integrated: including all the stakeholders' requirements that are necessary to assess the effectiveness of the O&M and 2) generic: applicable for all wind farms. Therefore the goal of this thesis is to develop an integrated and generic approach that enable users to find the optimal strategy in the production, costs and planning trade-off triangle.

This thesis will use a structured approach to contribute to a more effective offshore wind by developing a decision support tool. This model based approach, to make the offshore wind O&M more effective, will consist of first a top-down approach to investigate who could be interested in such a tool, what their requirements are for the O&M process and the O&M model, which aspects are already researched and what are the strengths and weaknesses of the current approaches or tools. This part will be concluded with research gaps between the requirements of the sector and the current studies. Then, a bottom-up approach will be used to examine what the integration challenges are. Based on the shortcoming of the current studies and the integration challenges, a suitable approach will be identified to integrate these challenges and thereby improve the O&M of offshore wind farms. To look forward, this thesis will argue that a discrete event simulation (DES) model is the most suitable approach and could offer more than the current analytical models. The next step in this thesis is the development of a DES model. The focus of the model will be on the shortcomings and the integration challenges found. The main challenge will be to integrate the Planning & Scheduling (P&S) of preventive scheduled maintenance, the weather influence and the impact on the energy-based availability. This thesis further presents a (fictitious) case study with the developed DES model to verify the model and to demonstrate the capabilities of the model and O&M improvement possibilities.

To identify and structure the problem, the subjects depicted in the figure below will be discussed in this chapter. The numbers in the grey boxes correspond with the paragraph numbers of this chapter. At the end of this chapter the problem and objective are set, the research questions are presented and the approach that will guide the research is discussed. Finally, the outline of this thesis is disclosed.

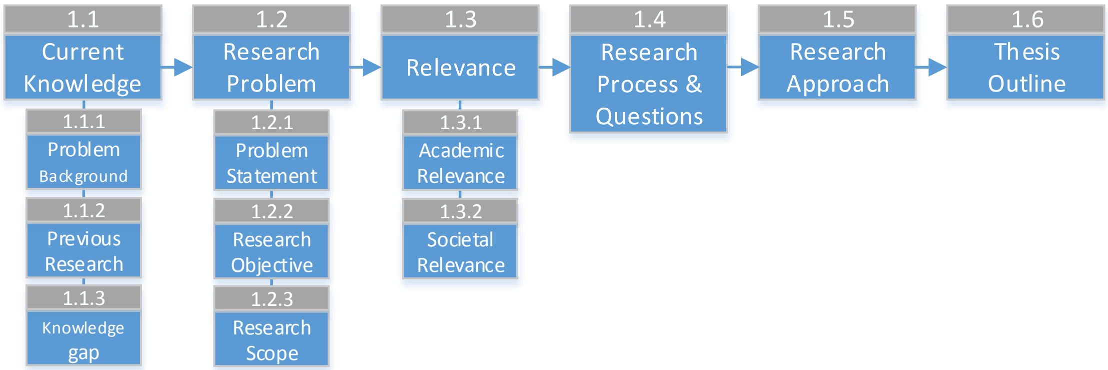


Figure 1: Problem structure

1.1. Current Knowledge

In this paragraph a short overview of the current knowledge will be presented. First the problem background will be described before the previous research will be assessed. This will result in the knowledge gap of the current knowledge.

1.1.1. Problem Background

Since and possible due to the regulations mentioned in the introduction the installed capacity of wind farms in Europe has grown from 0.8GW in 2006 till 3.8GW in 2011 (Besnard, Fischer, & Tjernberg, 2013). The European Wind Energy Association (2013) expects a continuing growth, to an installed capacity of 40GW by 2020. As depicted in Figure 2, the expected total expenses in only the United Kingdom on offshore wind O&M show a growth and are expected to increase enormously in the next 10 years. Also in the Netherlands a significant investment is agreed to increase the wind power share. In the Energy Agreement, more than 40 parties in the energy sector agreed to invest in renewable energy. They agreed to establish 4450MW installed wind power offshore and 6000MW installed wind power onshore before 2020 (Sociaal-Economische Raad, 2013).

In Figure 3 another recent development affecting the O&M is presented. The current (2013) online wind farms are relatively close to the shore in quite shallow water. Looking at the future plans, the trend is more towards deeper water further from the coast. This will have an impact on the O&M aspect, more specific the O&M equipment. For wind farms further than ~75km (40 nautical miles) an offshore base (platform) is economically beneficial, while for facilities closer to the coast it is more beneficial to maintain those facilities by workboats possibly assisted by helicopters (based on UK offshore wind projects (GL Garrad Hassan, 2013)). This development makes the O&M more complex, new and different O&M strategies will arise and a decision support tool could assist for these innovations.

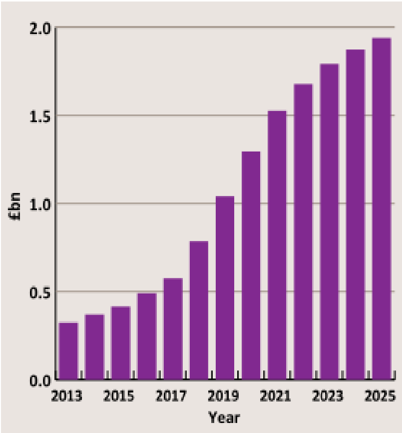


Figure 2: Expected UK offshore wind O&M spend (GL Garrad Hassan, 2013)

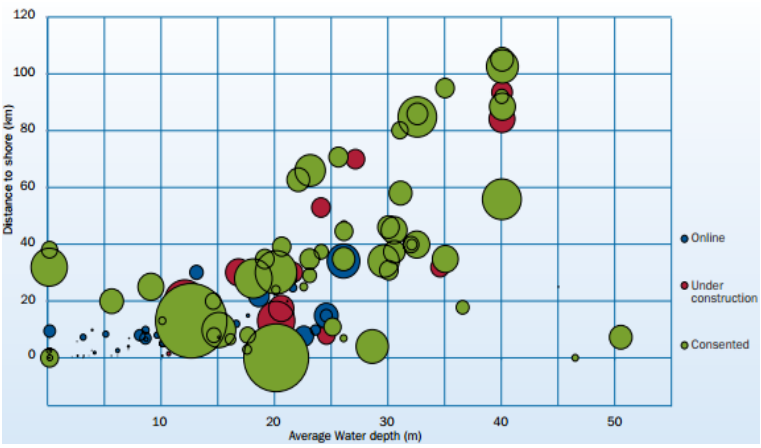


Figure 3: Distance and water depth offshore wind farms (European Wind Energy Association, 2013)

To identify the possibilities in the offshore wind O&M field, an overview of the costs is useful. The German Offshore Wind Energy Foundation (2013) sets the current production costs of offshore wind energy on 12.8 to 14.2 €cent/kWh, still significantly higher than onshore production. According to several research (Blanco (2009), Rademakers, Braam, Zaaijer, & Bussel (2003) and Greenacre, Gross, & Heptonstall (2010)) the O&M costs could even contribute up to 30% of the total costs, varying significantly depending on the properties of the wind farm. These O&M costs are approximately twice as high as for onshore facilities (Rademakers et al., 2003).

These facts show that the O&M costs are quite substantial, and more important they could be reduced. The total generation costs could be reduced by 32% till 39% in the next ten years, whereby a reduction of five till eight percentage points on the O&M costs could be achieved, mainly due technological developments and by increasing efficiency (The German Offshore Wind Energy Foundation, 2013). If this reduction can be achieved offshore wind energy, although it is not yet profitable without subsidies, is expected to be economically viable without subsidies in the coming twenty years (PwC, 2011).

1.1.2. Previous Research

The developments mentioned in the previous paragraph provide space for an approach to achieve a (more) effective O&M for offshore wind farms, for current and future wind farms. Such an approach could give insight in the current O&M process and in the possibilities to improve the O&M.

In chapter 5 a detailed overview of the most comparable studies found so far in the literature is presented. That chapter will give a clear overview on the aspects that are already or not researched while chapter 6 will elaborate on the shortcoming of these current studies.

The main conclusion of these previous studies is that most aspects of the offshore wind O&M are already researched and optimized. However, this concerns mostly isolated optimization of single (or not all) aspects or integrated tools that do not cover all the stakeholders' requirements. Other studies oversimplify the system, e.g. testing strategies for a few components of a single turbine. The implication of isolated optimization and oversimplifying is that not all the relations and dependencies of the system are included and will lead to inaccurate results.

Aspects that are (hardly) not examined within the offshore wind O&M, are the P&S of the scheduled maintenance and the energy-based availability or lost production during the maintenance, especially in combination with the (actual) weather conditions. Furthermore, the integrated tools developed so far are mostly analytical. This makes them more static; only averages and the variability is often ignored. Another shortcoming of the current integrated tools, still not covering all the requirements, is that they are 'black boxes' that allows input and calculates the results on the KPIs without providing insight in the (time) process and bottlenecks. A more dynamic tool with all output criteria, wherein every relation and process is visible and adjustable is desired (Van Dongen, 2014).

Section 1 elaborates further on what are the requirements for the O&M process and an integrated decision support tool. There will be identified what is already researched and what are the gaps that could be filled by this thesis.

1.1.3. Knowledge Gap

Previous research show a lack of an approach that is both:

1. Integrated
   Including all the requirements of the O&M actors, which will be further examined in section 1.
2. Generic
   On multiple types of wind farms applicable.

With an integrated and generic approach it is possible to get an overview of the whole O&M, including the relations between the aspects. An integrated and generic approach should enable the stakeholder(s) to make the O&M process and planning more effective by testing different O&M strategies per wind farm.

A specific aspect that is not included or just treated solely in the current literature or tools hereby, is the P&S aspect of operational strategies. For this aspect the variability or entire bandwidth is desired. With the variability included it is for example possible to examine what the probability is a maintenance campaign is performed before a specified target or what the maximum wait time is before a turbine is repaired. Most current literature or tools approached these (single) aspects with analytical models and are not able to answer these questions due to a lack of variability. This thesis will argue that analytical models are not sufficient to develop an integrated and generic tool and will focus on the use of a simulation model.

Other main gaps, besides the planning aspects, in the current research related to the different O&M strategies and the possibility to compare and optimize different strategies. Another shortcoming in the current literature is the visualization aspect in order to gain insight in the O&M process.

In section 1 all the requirements for an integrated tool will be identified and the gaps in the current literature will be discussed more elaborate.

1.2. Research Problem

This paragraph will elaborate on the problem statement and will set the research objective and scope of this thesis.

1.2.1. Problem Statement

To summarize the previous paragraphs: The O&M of offshore wind farms could be more effective. So far the current developed approaches or tools contain and optimize just different single aspects of the O&M and are not capable to get full picture of the O&M. However, the question is whether the optimization of all these single O&M aspects can be combined and lead to an improvement of the whole O&M. Furthermore, there is a big difference between different wind farms, regarding to the O&M. For a wind farm far from the coast other maintenance or transportation strategies could be more beneficial, e.g. the use of an offshore base or combine the maintenance of different turbines as much as possible, while other strategies are more beneficial for closer wind farms. So an integrated and generic approach to improve the O&M is lacking in the literature. This could be captured by the next problem statement:

> *There is no integrated and generic approach that could contribute to an effective Operations and Maintenance planning and process for offshore wind farms.*

Note that both the O&M planning and process are included in the problem statement. The O&M planning concerns the planning and scheduling of scheduled maintenance while the O&M process concerns the actual operations and processes required for the maintenance.

1.2.2. Research Objective

Based on the problem statement in the previous paragraph the next research objective is formulated for this design-oriented thesis:

> *This project should contribute to an effective Operations and Maintenance planning and process for offshore wind farms by developing an integrated and generic model that could serve as a decision support tool.*

First, in section 1 the requirements of an integrated tool and the shortcoming of current studies, will be identified. In section 2 the actual decision support tool will be developed, based on the identified requirements.

The objective of this thesis is to fill the identified gaps (paragraph 1.1.2 and more elaborate chapter 5 and 6). By filling these gaps, an integrated model will be developed that should meet the requirements identified in section 1 and that could serve as a decision support tool in the form of a model. According to Hewitt (2002), a model represents a system and the relationships that influence that system. So the model could give insight in the O&M process, help identify bottlenecks in the process and test different strategies. Furthermore, by developing a model time and money will be saved by using a representation (the model) without adjusting the real system (Hewitt, 2002). This model should be applicable for different wind farms and should therefore also be generic.

Additionally, an approach will be used that is not used yet in the current literature. Analytical models become too complex when there are multiple aspects/subsystems, are not able to include the Variability and do not show the behavior or process. To look forward, a simulation model is therefore considered the most suitable tool to contribute to a more effective O&M. The use of a simulation model will be further substantiated in the research method and chapter 8.

1.2.3. Research Scope

To set the boundaries for the project, a clear delineation is desired. In this thesis the focus will mainly be on the maintenance, since maintenance accounts for the largest portion of O&M effort, cost and risk (GL Garrad Hassan, 2013). To delimit the project further, a clear demarcation of the included O&M activities is useful. GL Garrad Hassan (2013) distinguish seven categories of offshore O&M activities (with short description):

1) **Onshore logistics** (including port facilities and inventory management)

2) **Offshore logistics** (equipment and planning)
3) **Turbine maintenance** (repair of turbines)
4) Export cable and grid connection (connection of the offshore power plant to the onshore power transmission system, including onshore and offshore electrical substations and export cables)
5) Array cable maintenance (sub-sea cables that connect the turbines to create a unified power plant)
6) Foundation maintenance (turbine foundations and sub-sea structures)
7) Back office, administration and operations (monitoring and sales)

The focus of this thesis will be on the first three categories. For these related categories, simulation is a suitable approach with enough (failure) data available (see more chapter 4). Categories 4, 5 and 6 are cable and foundation related and thus concerns significantly different activities. For these activities less data are available and will fall outside the scope. Category 7 concerns the back office, which is not suitable or desired for simulation. Therefore the demarcation is defined around the first three aspects.

The next demarcation component is related to the time aspect of the system. The integrated model will be developed for the O&M of offshore wind farms. O&M already implies that this concerns the operational phase. So the thesis and model will have the **operational phase** as subject. This will not limit the use of the model to only operational wind farms. Despite the fact that the operational phase is the subject, it is also possible to use the model in the construction phase the model to test different construction considerations and to optimize the O&M in advance.

1.3. Relevance

The relevance of this thesis exists on both the academic as the societal aspect.

1.3.1. Academic Relevance

The scientific relevance of this project will have four components. The third and fourth component will look forward on the actual model development. For the modelling part, this thesis argue a simulation model is suitable for this problem.

1. Integrated and generic O&M approach
   As stated in paragraph 1.1.2, this the main gap in the current research. The academic relevance of this component is to examine which aspects are already researched, what is (re)usable, and what and how could be combined into an integrated model.
2. The extent to which a wind farm is to parameterize
   This will be a validation to what extent it is possible to parameterize and simulate (any) wind farm(s) with a generic simulation model
3. The extent to which simulation and Planning & Scheduling can be combined
   With this part there will be researched to what extent it is possible to implement the P&S aspect of different strategies into a simulation model. These two parts are often approached solely while a combination of both is underexposed in the current literature. Therefore a relatively new P&S plug-in in the simulation software Simio will be used to test to what extent simulation and Planning & Scheduling can be combined.
4. Simulation approach for the O&M of offshore wind farms
   As stated in paragraph 2.2 most studies so far are approached with an analytical model while simulation is more suitable for an integrated model. This study will use the simulation software

Simio. This software is not used before to simulate the offshore wind O&M. This study will argue that Simio is (most) suitable and could offer more advantage than previous studies.

1.3.2. Societal Relevance

The societal relevance of this project consists of three components:

1. Getting insight in the offshore wind O&M field
   With this project there will be investigated what factors play a role in the field and how the O&M could be more effective.
2. Consultancy tool for offshore wind sector stakeholders
   The integrated and generic model should be usable for relevant stakeholders in the offshore wind energy sector to simulate and improve the O&M.
3. Contribution to a (more) effective O&M
   With the model insight in the O&M planning and process could be obtained that can contribute to a (more) effective O&M for the offshore wind sector.

1.4. Research Process and Questions

Deriving from the research problem, presented in paragraph 1.2, the next main research question is drafted:

> *What are the requirements for an integrated and generic offshore wind O&M decision support model and how could such an approach contribute to an effective O&M planning and process for offshore wind farms?*

In this design-oriented thesis the method that will be used to make the O&M more effective, is simulation. In the next paragraph there will be elaborated more on the type of modelling.

To answer this research question, a structured research process is designed in this paragraph. This is roughly based on two design models: 1) The five stage prescriptive model of the design process adopted from Dym, Little, Orwin, & Spjut (2004). This model prescribes to sequence of problem definition (this chapter), conceptual design with the requirements and alternatives, preliminary design and after testing the detailed design. 2) The ‘V-model’, used for software development in different appearances. According to Mattews (2002), the V(ee)-Model prescribes a top-down development process with a bottom-up implementation approach. Note that the research process for this thesis is derived from these two models, but is not a direct implementation of these models. This research approach covers as well the first five steps of the simulation project steps as listed by Musselman (1998); problem formulation (this chapter), model conceptualization, data collection, model building and verification & validation. The research process for this thesis is visualized in figure 4.

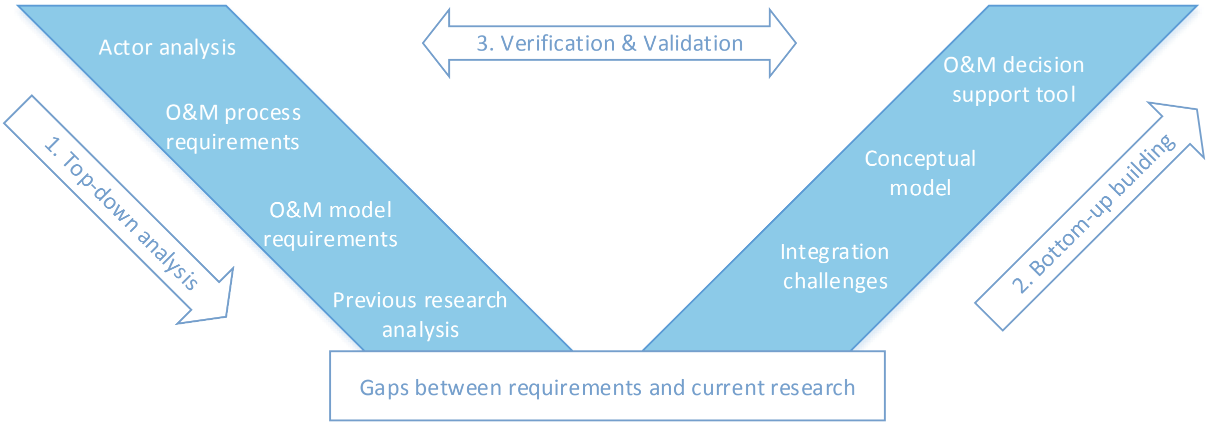


Figure 4: Research process

This figure shows that first a top-down approach will be used for section 1. This objective-directed approach will be performed to identify the stakeholders, their requirements, usable previous research and the shortcomings of those studies. In section 1 first the relevant actors in the offshore wind sector will be identified. These actors will all have requirements for the O&M process. The process requirements are high level input for the more detailed model requirements; the requirements the design (decision support tool) should meet. After all the requirements are set, there will be analyzed which requirements are already researched. Section 1 will be concluded by the gaps between the requirements and the current studies. These gaps could be requirements that are not included in any research yet or multiple requirements that are not integrated in current models and studies.

Then, a bottom-up approach will be used to examine what the integration challenges are. Based on these integration challenges, a suitable approach will be identified to integrate all the aspects. The next step is the development of the tool, first by means of a conceptual model and thereafter the specification of the conceptual model into the actual simulation software.

Section 3 elaborates on the verification and validation of the developed tool. There will be analyzed whether all the requirements are implemented well, whether the model produces the same results as existing tools and whether the tool is representative for the real O&M plan and process.

This research process and main research question are translated into the next sections and sub questions:

Section 1: Requirements for an integrated O&M model

These four sub questions will define the requirements for an integrated and generic decision support tool. Also an overview of the (re)usable components found in previous studies and the shortcomings of these studies will be presented.

1. *What are the interest of the stakeholders in the offshore wind sector and how could they benefit from a decision support tool?*
2. *What are the requirements of the stakeholders for the O&M process?*
3. *What are the requirements that should be included in an integrated O&M decision support tool?*
4. *Which requirements are already included in current studies and tools?*
5. *What are the shortcomings of the current studies and tools?*

<u>Section 2: Integration into an integrated O&M model</u>

After this section the requirements for an integrated model are clear as are the useable aspects from others. These could serve as components to build up the integrated model in section 2. The next question will guide the development of the conceptual model and the decision support tool, integrating all the requirements and integration challenges.

6. *What are the challenges when integrating the different requirements?*
7. *How could the requirements and integration challenges be integrated into an O&M decision support model and how will such a model look like?*
8. *How will the (conceptual) model be specified into the decision support tool and how will the tool look like?*

<u>Section 3: Validating the integrated O&M model and testing the model</u>

The next question is stated to test how correct and valid the actual simulation model is for the offshore wind sector.

9. *To what extent is the developed integrated model correct and can it be validated for different wind farms?*

Question 9 will elaborate on the capabilities of the decision support tool and will be answered with a case study with the developed model

10. *What is the added value of the developed decision support tool and how can the tool serve the O&M planning and process?*

<u>Section 4: Improving the O&M process</u>

The last section will focus on the conclusions, recommendations and future research.

11. *How can the offshore wind O&M process be improved and what future research is recommended?*

1.5. Research Method

The first section will be performed by means of a literature study to obtain all the relevant aspects and requirements for the model. This will be supplemented with interviews with experts in the field as much as possible. Possible experts are people working in the offshore wind energy sector, for this thesis from NUON/Vattenfall and Vestas. For the interview the techniques listed in Baarda, De Goede, Meer-Middelburg, & Van Der Meer (2007) will be used.

Section 2 will integrate all the requirements into an integrated tool that will represent the real offshore wind O&M process and can improve the O&M process and plan. To improve the O&M of offshore wind farms, a model of the real system is useful. According to Hewitt (2002), a model represents a system and the relationships that influence that system. So with a model it is e.g. possible to gain insight in the system and to test different O&M strategies and plans. Furthermore, by developing a model, time and money will be saved by using a representation without adjusting the real system (Hewitt, 2002).

On the highest level, two types of models could be distinguished: 1) physical and analogue models (globes or clay models) and 2) schematic and mathematical model (by using equations, also possible in computer models) (Blanchard & Fabrycky, 1990). For modeling the O&M of offshore wind farms and to calculate and to improve the performance a physical model is considered less suitable since physical models are not capable to measure the performance. Due to the complexity of the system a computer model, expressing the schematic and mathematical type of model, is recommended to model the O&M system. Still there are two different types of non-physical models found in the literature (Hewitt, 2002), see also picture 5; analytical models and simulation models. To make a well substantiated decision, first the definitions as used by Hewitt (2002) will be stated:

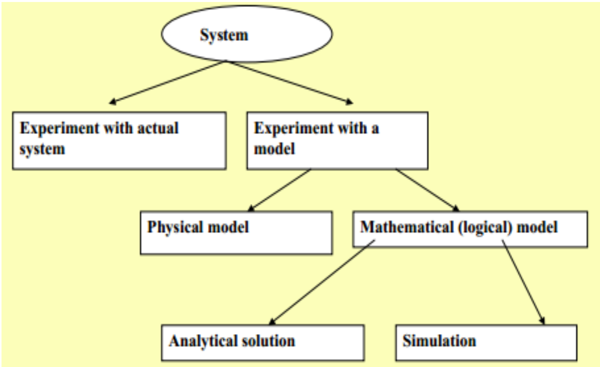


Figure 5: From system towards simulation (Ayani, 2003)

- "**Analytical models** are a collection of mathematical equations whose equations yield numerical answers only for specific components of the system. The mathematical nature of analytical models means it is easier for people to understand analytical models."
- "**Simulation models** are often only understood by those familiar with simulation programs. In contrast, discrete event simulation produces results for all components of the system (e.g., process time for each step, utilization of each machine, etc.)."

One important disadvantage of analytical models is that they become very complex when using multiple aspects. Simulation does not have this disadvantage, since it is possible to specify the relations easier in the simulation program, instead of specifying all the mathematical equations. Furthermore, analytical models will have one numerical expected solution (for each equation, unless multiple seeds from a distribution are included in the model), while with simulation it is possible to have results with variability, confidence interval, maximum values and graphs for every process, criteria or other model property. The last major disadvantage of analytical models is that it is hard to include the time aspect in the model. So there can be concluded that a simulation approach can be considered as a useful approach to design an integrated decision support tool that is able to make to offshore wind O&M plan and process more effective. The end of section 2 will elaborate on the implementation of this simulation approach in the discrete event simulation software Simio.

The research method of section 3, the verification and validation, will consist of a requirement verification to check whether all the requirements of the stakeholders are implemented. Furthermore, a model walk-through with animation will be performed to check the behavior of all the sub models. The decision support tool will be validated by means of a comparison with a validated model and an expert validation (based on the Dutch wind farm OWEZ). At last, section 3 will use a case study to demonstrate the capabilities of the tool.

1.6. Thesis Outline

The thesis is built up with four sections. Section 1 will identify the requirements for an integrated decision support tool. Section 2 will elaborate on the actual integration of these requirements into an integrated decision support tool. The tool will be tested on correctness and validity, complemented with a case study to demonstrate the capabilities, in section 3. At last, section 4 will be the concluding section. Each section has a more detailed outline at the start of each section.

Section 1: Requirements for an Integrated O&M Model

To gain more insight in the O&M plan and process of offshore wind farms, the first section of this thesis will discuss what is necessary for an integrated O&M decision support tool. Therefore, the requirements from the offshore wind field sector for an integrated approach will be identified, following the outline depicted in figure 6. This section will discuss what the requirements are from the field, which aspects are already researched in previous studies, what is usable from those studies and what the shortcomings of those studies are.

1. *What are the interest of the stakeholders in the offshore wind sector and how could they benefit from a decision support tool?*
2. *What are the requirements of the stakeholders for the O&M process?*
3. *What are the requirements that should be included in an integrated O&M model?*
4. *Which requirements are already included in current studies and tools?*
5. *What are the shortcomings of the current studies and tools?*

To answers the questions of this section a literature research is used, complemented and verified with interviews held with experts in the offshore wind field.

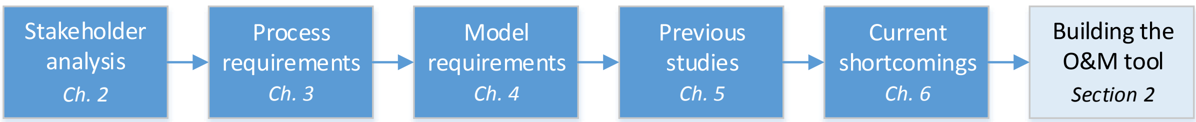


Figure 6: Outline section 1

2. Actors in the Offshore Wind Sector

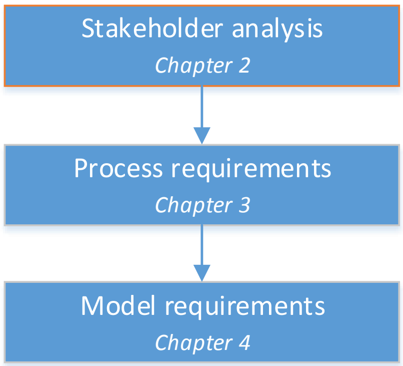


Figure 7: Identifying the requirements

To identity which actors are involved in the offshore wind sector and what are their interests are, a stakeholder identification and analysis is performed in paragraph 2.1 and more elaborate in Appendix A. For the term stakeholder the following definition of Freeman (1984) is used: *"Any group or individual who can affect or is affected by the achievement of the organization's objectives"*

There are many actors involved with the O&M aspect of an offshore wind farm. The actors responsible for the O&M are sometimes the same as during the construction phase, or sometimes different. This depends on the contract type agreed for the wind farm O&M. To examine who could be responsible for the O&M of the offshore wind farms, in paragraph 2.2 there will be described what type of contracts are most common in the field. To examine the relevant actors in different phases of a wind farm and the relations between those, the scope of the actor analysis in this paragraph will be broader in this chapter. In this chapter an overview of the key actors that are directly involved in the O&M is presented, in order to get insight in the relevant stakeholders who could benefit from the model. In Appendix A, a more elaborate analysis around those key actors can be found.

1. *What are the interest of the stakeholders in the offshore wind sector and how could they benefit from a decision support tool?*

2.1. Actor Analysis

To perform a structured and substantiated actor analysis this paragraph will follow the stakeholder analysis method proposed by Reed et al. (2009). They used three steps: 1) identifying the stakeholders, 2) categorize the stakeholders and 3) investigating the relations between the stakeholders. A schematic overview of this method could be found in Appendix A: Stakeholder Analysis.

The first step is to identify the stakeholder in the offshore wind sector. A literature review, complemented with some interviews with experts in the field, is used to identify the different stakeholders. Since this thesis is focused on a generic approach and this actor analysis gets insight in the types of actors and their (contractual) relation, there will be looked at the *types* of actors, which can be fulfilled by different parties per wind farm.

In the table below, the primary actors that play a role in the offshore wind sector are identified, based on GL Garrad Hassan (2013) and Markard & Petersen (2009). Note that actors possible against the construction of wind farms, e.g. coastal residents and environmental organizations, are not included since the subject of this is the operational phase wherein the farms are already built.

Table 1: Main offshore wind actors

Actor	Role
Turbine manufacturer	Design and fabrication of the turbine. Maintain the wind turbines during the warranty period.
Wind farm constructor	Design and build the wind farms
Wind farm owner	Own and operate the wind farms, depending on contract. Typically energy companies.
Operation & Maintenance (operator)	Operate and maintain (could also be separated) the wind turbines.
Power grid owner	Own and operate transmission infrastructure

The second step of Reed et al. (2009) is to categorize the stakeholders. All the actors in the table above have positive attitude towards offshore wind farms, the O&M and a decision support tool. The actors above can all be classified as 'Savior' or 'Acquaintance' according to the classification of Murray-Webster & Simon (2006). The turbine manufacturer, wind farm owner and operator are classified as 'Savior' and have to be considered as important actor. Regarding to the decision support tool (the model), the tool have to be developed with consultation of these actors and their needs should be taken into account when developing the model.

Step 3 of Reed et al. (2009) is to investigate the relations between the different stakeholders. Reed et al. describe several techniques to map the relations between the actors. For this thesis it is important to get insight in the relations between the actors to examine which actor is responsible for what and when. This will determine who could benefit from an O&M model and whose requirements must be included in the model. So the third step will investigate the O&M contracting types that exist in the offshore wind sector. These contracting structures will be discussed in the next paragraph.

2.2. Contracting Types in the Offshore Wind Sector

To determine who could benefit from an O&M model, in this paragraph the different types of contracts will be investigated. There will be described which contracting structures exist to divide the O&M responsibility.

To save O&M costs it is crucial to consider an O&M contract structure that ensure a good fit between owner and operator. Especially after the warranty period, which is shorter than the lifespan of a turbine (Wind Energy Update, 2008). During the warranty period the turbine manufacturer is responsible for the maintenance of the turbines. The warranty period will typically be 2 years (Van Dongen, 2014) or 5 years (The Crown Estate, 2010), but could also be longer. So during the warranty period only one player will perform the O&M; the turbine manufacture. Interesting is to examine who could be responsible for the O&M after the warranty period.

Based on an interview held by Windpower Monthly (2010) with some key players in the offshore wind sector there are 3 common options identified, depicted in figure 8. Mostly, the turbine manufacturer continues with the O&M after the warranty period (dashed line). More and more Independent Service Providers (ISPs) offer O&M services, option 2. In that case a third, specialized party will perform the maintenance of the turbines. The third option, only used by one wind farm so far, is the 'hands-on' approach of the wind farm owner being responsible for the O&M.

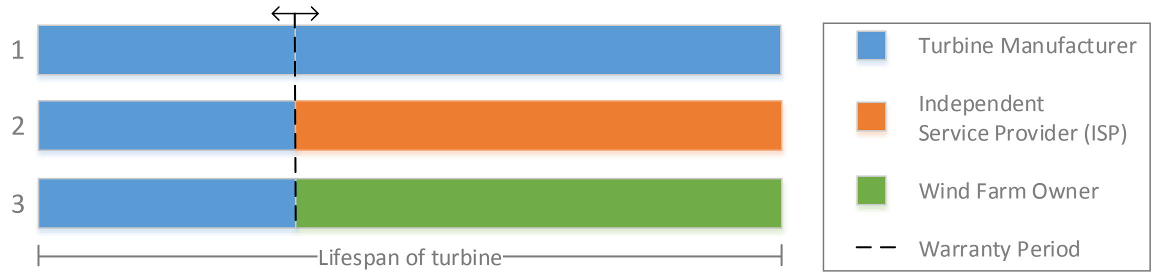


Figure 8: O&M contractual options

The (simulation) tool developed during this thesis could thus be valuable for three (types of) parties: turbine manufacturers, ISPs and wind farm owners. For the owners the model could not only be valuable in case they perform the O&M by themselves, but also in case of the other two options since they contract the O&M partner.

During the warranty period and after the warranty period, in case the O&M is outsourced by the wind farm owner, the contracts between the owner and the maintenance partner (either turbine manufacturer or ISP) could be closed on two different types of availability (Van Dongen, 2014):

1. Time-based availability
   The maintenance partner guarantees a certain percentage uptime of the total time
2. Energy-based availability
   The maintenance partner guarantees a certain percentage actual production of the potential generation (depending on the actual wind speeds)

In both cases the maintenance partner usually pays a penalty if the percentage is not met and receives a bonus if they performed better than agreed. Currently, there is a shift from time-based availability towards energy-based availability in the wind sector. The *energy-based* availability could be considered as the actual production (in kWh) as a share of maximum production that could be achieved without downtime. The energy-based availability provides insight in the lost production and in the planning of the maintenance. If maintenance is performed during a profitable windy day the energy-based availability will be affected significantly while maintenance during a non-profitable day will hardly affect the energy-based availability. So the focus is more on how much of the potential generation (based on wind speeds) is actually generated than on how much time the turbines are online. The next step will be a demand based availability; produce exactly as much as demanded. Since power is hard to store, this option reflects the performance of the O&M the best, but currently such a contract structure is not used yet (Van Dongen, 2014; Van Buchem, 2014a).

To conclude there are three actors that could be responsible for the O&M: turbine manufacturers, ISPs and wind farm owners. When the owner does not perform the O&M itself, the manufacturer or an ISP is contracted based on time-based availability or energy-based availability. In all options the maintenance party's goal is to increase the availability and decrease the costs in order to increase their profit. The next chapter will elaborate more on the requirements of the maintenance party.

3. Requirements for the O&M Process

The actors described in the previous paragraph are the main actors in the O&M process. These players all have requirements regarding the O&M process. This chapter will result in a requirement list for the O&M process based on literature and interviews held with people from the sector. This requirements list should incorporate the decisions the stakeholders could make in the O&M process.

2. *What are the requirements of the stakeholders for the O&M process?*

First a literature review will be presented to identify what are the important aspects of the O&M process. This literature review will give an overview what effective O&M is and which factors influence the process i.e. factors that influence the effectiveness of the O&M. This literature review will be supplemented with interviews held with Willem van Dongen (Director Operation UK at Vattenfall), Robin van Buchem (Service Manager Offshore at MHI Vestas Offshore Wind) and Systems Navigator (consultancy company in i.a. offshore wind sector) to ensure the requirements of the most important actors according to the analysis in chapter 2 (The turbine manufacturer, wind farm owner and operator) are taken into account. The process requirements, as listed in appendix B, are verified and completed by Van Buchem (2014b).

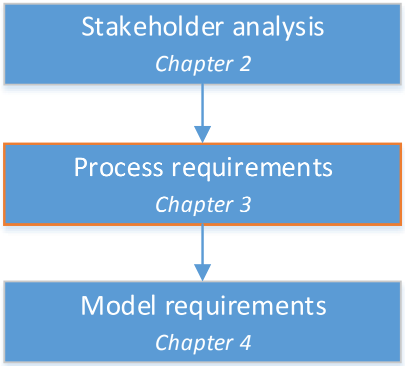


Figure 9: Identifying the requirements

Both methods will be summarized in the form of a requirements list. This list will be formatted freely based on to the NASA guideline *How to Write a Good Requirement* (NASA, 2007, pp. 279 – 281). These requirements should answer the stakeholders' demands.

To determine the requirements, or the included aspects for an integrated model, a structured approach is applied. A top-down, or reverse engineering, approach is used to start in paragraph 3.1 what effective maintenance is for a system, in this case an offshore wind farm. Thereafter, factors that influence this effectiveness will be identified in paragraph 3.2. These influential factors will be categorized in operating strategies and external factors in paragraph 3.3 and 3.4 respectively. In paragraph 3.5 requirements regarding the use of a decision support model within the O&M process will be presented. Paragraph 3.5 will present an overview of the high level requirements while a detailed list can be found in appendix B.

3.1. Effective Operations & Maintenance

The first step of the top-down approach is to determine what an effective O&M is and what the components are of effective O&M.

According to Van Dongen (2014), the most important goal for the wind farm owner (mostly an energy company) is to make as much profit as possible by generating as much power as possible. This could be achieved by having the turbines as much as available. For the maintenance actor (mostly the turbine manufacturer), Van Buchem (2014) stated that for them it is important to reach the availability level as specified in the contract for the lowest costs.

Most maintenance and offshore wind literature, including Nakagawa (2006) and Van Bussel & Zaaijer (2001), also considers the availability as one of the most important aspects of the O&M process. Regarding the availability, two types of availability in the offshore wind sector are identified during interviews (Van Dongen, 2014; Van Buchem, 2014); time-based and energy-based availability. The *time-based* availability represents a percentage uptime of the total time. The *energy-based* availability could be considered as the actual production (in kWh) as a share of maximum production that could be achieved without downtime. The energy-based availability provides insight in the lost production and in the planning of the maintenance. If maintenance is performed during a profitable windy day the energy-based availability will be affected significantly while maintenance during a non-profitable day will hardly affect the energy-based availability. For the O&M process both availabilities are desired since both are used. So on the one hand the maintenance party want to increase the availability and the production revenues, on the other hand the O&M costs has to be minimized and the maintenance plan should enable the responsible actor to finish the (preventive) maintenance campaign on time (Van Buchem, 2014a).

Above mentioned is translated into the first four requirements. The main goal of the maintenance party is to maximize their profit. This goal is divided into four sub goals, as depicted in the objective tree in Appendix C, with the related next four requirements:

Table 2: Effectiveness of O&M requirements

Nr	Requirement
	For the O&M process it shall be possible for the stakeholders, in order to maximize the profit, to make decisions to…
P1	Maximize the time- or energy-based availability of the wind farm
P2	Maximize the production revenues
P3	Minimize the O&M costs
P4	Maximize the robustness of the maintenance plan

Note that there can be some overlap between the requirements. In case the total production is measured in terms of MWh (to measure the energy-based availability) the production revenues are directly correlated. This is not the case if the production is expressed in terms of time, therefore both production and the production revenues are included.

First, some additional insights in the time-based availability will be discussed, before the next paragraph elaborates on the factors that influence an effective O&M.

Regarding the (time-based) availability the next literature could provide some insights. Rhee & Ishii (2003) calculated the availability by dividing the uptime or Mean Time To Failure (MTTF) by the total time: MTTF plus the Mean Time To Repair (MTTR) or the Mean Time Between Failure (MTBF). These relations are also depicted in figure 10, obtained from (Papenbrock, 2008).

Equation 1: Time-based availability (Rhee & Ishii, 2003)

$$Availability = \frac{MTTF}{MTTF + MTTR\ (= MTBF)}$$

Equation 2: MTTR (Based on Rademakers, Braam, Obdam, Frohböse, & Kruse (2008)

$$MTTR = wait\ time + travel\ time + repair\ time$$

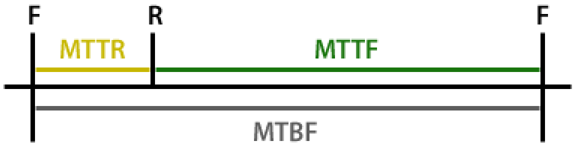


Figure 10: Failure definitions (Papenbrock, 2008)

For developing an O&M model with the operational phase as subject (as described in paragraph 1.2.3. Research Scope), the MTBF or failure rate is less interesting. In the operational phase, the components of the turbines are already in use and the reliability of these components can hardly be influenced anymore; failures occur randomly. The reliability of the components, or the failure rate could therefore be seen as an external factor in the operational phase, see more in paragraph 3.4. For decomposing the availability, the MTTR is a more interesting element of equation 1. The MTTR could be divided in three time elements, according to equation 2. The MTTR is the sum of 1) the wait time before a maintenance crew and material is deployed for the actual repair mission, 2) the time needed to travel to the wind turbine and 3) the time that is needed for the actual repair. One note that should be taken into account, is that this only holds for maintenance after failures; corrective maintenance. In case of preventive scheduled maintenance, more in next paragraph 3.3, the only time aspect that affects the availability is the actual maintenance time, not the wait or transfer time.

3.2. Factors that Influence the Availability

Availability, included as first requirement for the O&M tool, could be considered as one of the most important aspects in the literature. To examine what influences the availability, Van Bussel & Zaaijer (2001) decomposed the availability into several elements, depicted in Figure 11. This schematic overview is also in accordance with the RAMS terms and definitions (Echavarría, 2009; Van Bussel & Zaaijer, 2001):

- **R**eliability
  Probability or percentage of the systems perform its task; produce electricity.
- **A**vailability
  Probability or percentage of time that the system is operating satisfactory.
- **M**aintainability
  Qualitative or quantitative terms that describes how much effort is needed to repair failures.
- **S**erviceability
  The ease of performing regular service.

And an additional important term also presented by Van Bussel & Zaaijer (2001) and other literature:

- Accessibility
  Percentage of time the construction can be approached.

The decomposition of Van Bussel & Zaaijer (Figure 11) and the RAMS terms could be summarized by Figure 12, with availability (requirement P1) considered as the most important factor and the other four elements considered as the most important elements that influence the availability based on literature.

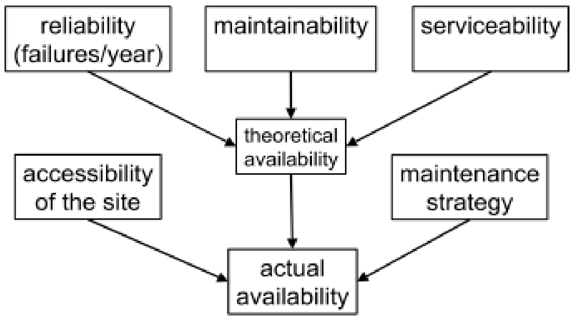


Figure 11: Elements of availability (Van Bussel & Zaaijer, 2001)

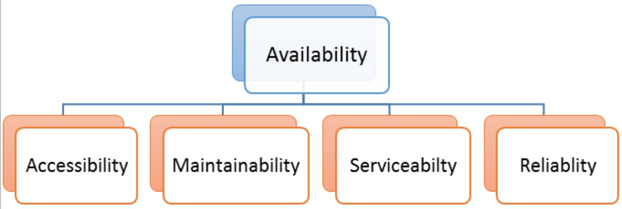


Figure 12: Important offshore wind O&M terms

To make the O&M more effective, it necessary to investigate how the effectiveness could be increased. For each of the orange terms in the figure above the will be examined which factors could influence them. These will be factors that indirectly influence the availability, either positively or negatively.

3.2.1. Accessibility

A main influential factor that affects the accessibility of offshore wind farms are the <u>weather conditions</u>. According to (Scholz-Reiter, Lütjen, Heger, & Schweizer, 2010) are the bad weather conditions, especially wave height and tide, the main cause for delays in transport, and thus also the entire O&M process and the availability of the wind turbines.

Each wind farm has different <u>site properties</u>. These properties are different for different farms and will determine how accessible a wind farm is. Site properties that have an influence on the accessibility could be the distance from the shore, number of turbines and type of turbines. As already mentioned will the future wind farms be located further from the coast. For these further located wind farms other equipment could be more beneficial for an effective maintenance, e.g. an offshore base (GL Garrad Hassan, 2013).

This type and amount of resources, or <u>resource management</u> is identified as last factor that has an influence on the accessibility. For further farms it could be more cost effective to use different equipment. Different equipment could also resist bad weather condition better than others, resulting in an improved accessibility. Paragraph 3.3 elaborates more on the resource management together with the other mechanisms.

3.2.2. Maintainability

The type and amount of <u>resources</u> is also important for the maintainability; how much effort is needed to repair failures. Some failures will require different equipment than other failures. Furthermore, different equipment could result in different travel times towards the wind turbines.

The second factor that influences the maintainability is the <u>inventory management</u>; the inventory number of spare parts and the location of these spare parts. To calculate how much inventory is needed, it could be useful to determine a safety stock; the inventory level to have a spare part for e.g. 95% (service level) of the time in stock.

One of the most important factors that influence the maintainability is how the maintenance is performed; the overall maintenance & transportation strategy. The maintenance and transportation strategy is defined in this thesis as the way the O&M resources are deployed; which resources, how many and when. This includes different types of maintenance, from only corrective till only preventive. It also covers the number of visits, e.g. perform only one (July) or two (May and October) planned visits per year (Karyotakis, 2011). Another consideration is how the planned visits are performed; by a regular vessel or, for further farms, also helicopter support or even an offshore maintenance base (GL Garrad Hassan, 2013). For the deployment of those resources also thresholds could apply. Preventive maintenance could be performed only during low wind speed, as suggested by Besnard, Patrikssont, Strombergt, Wojciechowski, & Bertling (2009) or helicopters will be deployed only during high waves (no access for vessels) in case of failures.

The maintenance & transportation strategies will be discussed more elaborate in the next paragraph.

3.2.3. Serviceability

The serviceability, the ease of performing a maintenance, could be specified best by how long a repair takes and how the maintenance is performed; the repair times and the maintenance & transportation strategy. The repair times are already discussed in paragraph 3.1, the maintenance & transportation strategy already above.

3.2.4. Reliability

The reliability, the probability or percentage of the systems (not) perform its task, could be represent by the failure rates of the different part of a wind turbine.

3.2.5. Overview

To summarize the influential factors, the (orange) terms in figure 12 could be extended with the identified (grey) influential factors in this paragraph to the next figure (Figure 13). These factors are found as the most important in the literature, still it is arguable which factors are a specification of which terms.

This overview is verified during the interviews (Van Dongen, 2014; Van Buchem, 2014) and should give a representative specification of the O&M, and the availability, of offshore wind farms.

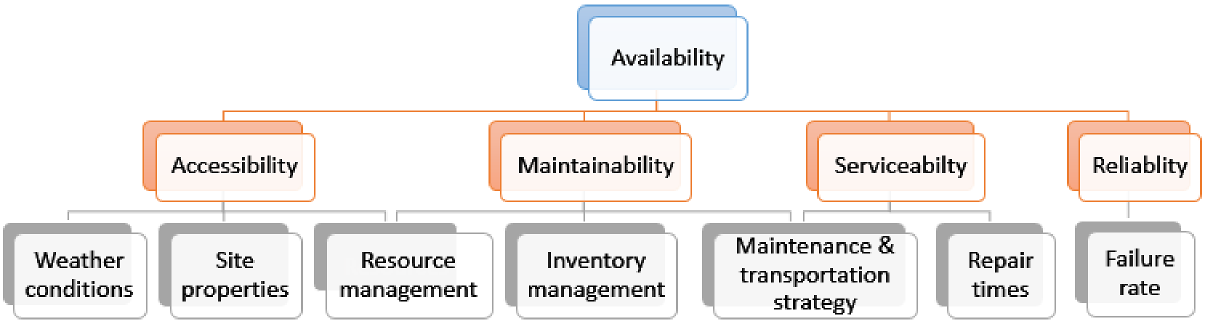


Figure 13: Influential factors of offshore maintenance

Of the influential factor in the figure above, a couple of factors could be considered as internal variables; mechanisms within the O&M process that could result in a more effective O&M. These factors will be grouped under *O&M strategies*. These O&M strategies are interesting for the actors to achieve an effective O&M and will therefore translated into requirements in the next paragraph.

3.3. O&M Strategies for an Effective O&M

Of the factors of figure 13 three could be classified as 'O&M strategies'; mechanisms within the O&M process that could be varied. For the stakeholders in the O&M process, as identified in chapter 2, it is important to be able to make decisions regarding the O&M strategies in order to achieve an effective O&M.

The three factors classified under the encompassing term 'O&M strategies', *inventory management, resource management*, and *maintenance & transportation strategy*, will be discussed in this paragraph. Furthermore, for each O&M strategy there will identified what the options are.

Inventory Management

The first O&M strategy is considered as the inventory strategy. This covers the (size of the) safety stock or the service level for the spare parts and the location of the stock. The location of the safety is considered as a strategy before the operational phase, in the operational phase it is considered as a wind farm property.

Resource Management

The second O&M strategy concerns the resource management; the amount and type of resources. For an effective O&M, it is interesting for the stakeholder to decrease or increase for example the number and the type of vessels in the O&M process. For the concerning maintenance partner a requirement for the O&M process is that it should be possible to determine the optimal deployment of resources by varying:

- Type of transporters
  E.g. type of vessel or helicopter, including their speed, weather thresholds, capacity and cost.
- Number of transporters
- Number of personnel
  Including the number during the weekends and costs

Maintenance & Transportation Strategy

The maintenance & transportation strategy determines how the resources will be deployed; which resources, how many and when.

To determine *which resources* will be deployed the distance and the costs are considered the most important factors. Nielsen & Sørensen (2011) identified three transportation option: 1) always by boat, 2) As soon as possible (ASAP) and 3) a risk-based option depending on the weather conditions to minimize the costs. This study will be discussed more elaborate in chapter 5. Looking at the Guide to UK Offshore Wind Operations and Maintenance (GL Garrad Hassan, 2013), three types of transportation could be distinguished. These options, depicted in Figure 14, depends mostly on the distance to the shore. For (future) farms far from the shore an offshore based accommodation is the most effective while for others a regular workboat operating form a port is cheaper. An offshore-based accommodation serves as a base for preventive maintenance and stores minor components for corrective maintenance. In case of major failures a jack-up barge will be required.

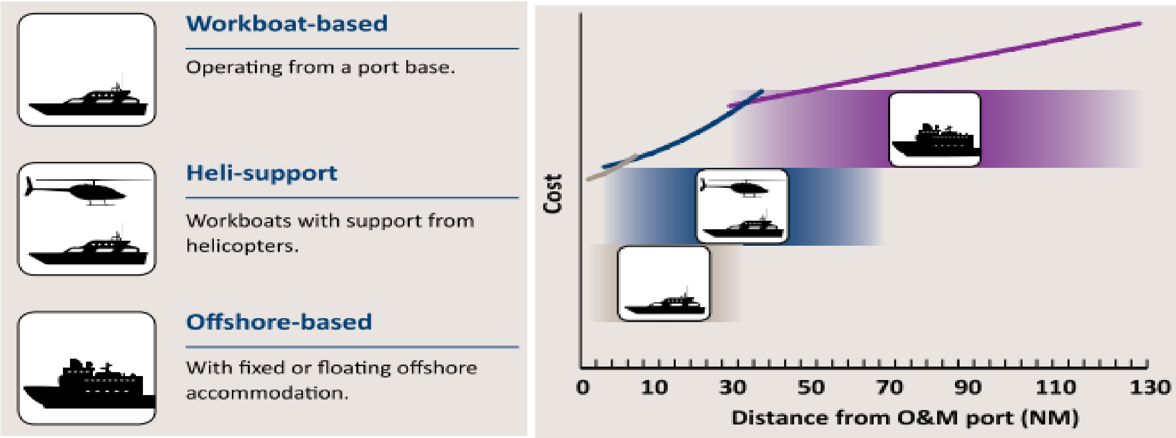


Figure 14: Transportation options & costs (GL Garrad Hassan, 2013)

Regarding the amount of personnel that will be used and how they will be deployed, the number of personnel per turbine and the number of service days per turbine (both elements are correlated) are part of the strategy and have influence on the speed of the maintenance and on the (robustness of the) plan. Other aspect of the maintenance & transportation strategy are considered the number of preventive maintenance visits per turbines per year.

The last important aspect of the maintenance & transportation strategy is when the resource will be deployed. The responsible maintenance party can play around with the threshold for different transporters. For example, a strategy could be to deploy only helicopter in case of a failure and during bad weather conditions for vessels. Another strategy is to only perform preventive maintenance during less productive days.

The overall maintenance strategy, including all the elements of this paragraph, determine the performance on the (lost) production, O&M costs and planning feasibility. Some strategies are cheaper in terms of resource costs but involves higher lost production costs, other strategies results in less lost production but also less feasible. This thesis and the developed model should provide the user insight in these trade-offs in order to determine an optimal strategy.

Types of Maintenance

Literature provides different types of maintenance. This paragraph will examine which types has to be incorporated in an O&M tool and what types of maintenance are common in the offshore wind sector and other sectors. Figure 15, obtained from the technology standard EN 13306 (European Committee for Standardization, 2001) and similar used in by ECN in their (leading) tool (Braam, Obdam, Van de Pieterman, & Rademakers, 2011), decomposes maintenance into three different maintenance types.

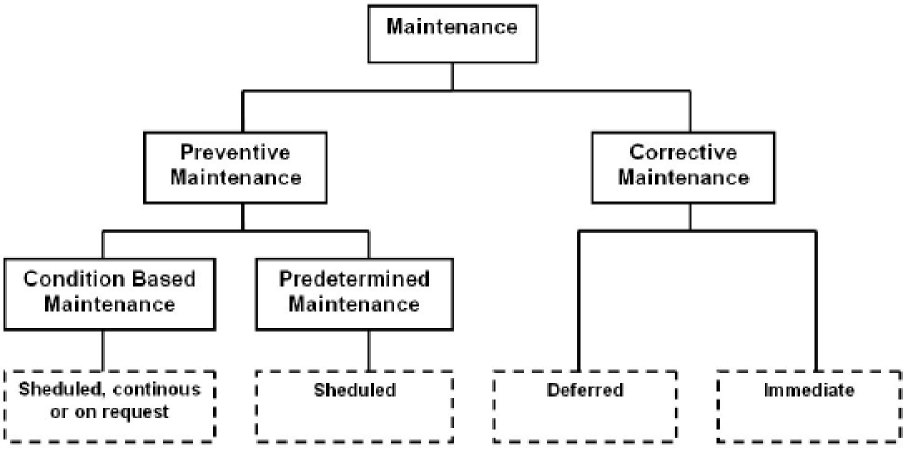


Figure 15: Types of maintenance (European Committee for Standardization, 2001)

According to this figure, maintenance could be divided in three types of maintenance: condition based and predetermined (scheduled) maintenance as part of preventive maintenance and corrective maintenance. To get the terminology clear, the definition used in the EN 13306 standard will be presented.

Condition based maintenance is defined as (European Committee for Standardization, 2001):

> *"Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions."*

Predetermined maintenance is defined as (European Committee for Standardization, 2001):

> *"Preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation."*

Corrective maintenance is defined as (European Committee for Standardization, 2001):

> *"Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function."*

These three types of maintenance are the three basic maintenance strategies. They could also be slightly adjusted or combined into more innovative strategies, as proposed in previous studies, e.g. Ding & Tian (2011), more in chapter 5.

To summarize this chapter, with the factors classified under the encompassing term 'O&M strategies' and some theoretical background with respect to different maintenance types, the next requirements for an O&M tool are identified. These requirements should enable the responsible actor(s) to make decisions regarding the O&M strategies, including *resource management*, *inventory management* and *maintenance & transportation strategy*.

Table 3: O&M strategies process requirements

Nr	Requirement *For the stakeholders in the O&M process, in order to achieve an effective O&M, it shall be possible to*
P5	Make decisions to adjust the resources (type and number of personnel and transport)
P6	Make decisions to adjust the service level regarding spare parts inventory
P7	Perform different types of maintenance (preventive and corrective)

3.4. External Factors for the O&M

The, controllable, operating strategies are not the only factors that influence the effectiveness of offshore wind farms, there are also external factors that affect the effectiveness of the O&M. The main difference is that operating strategies are controllable, while external factor are not, at least within the scope. Despite that external factors are not controllable, it is necessary to take them into account when making decisions. So for the stakeholders it is necessary to take the external factor, e.g. weather, into account when defining an O&M strategy to achieve an effective maintenance.

Of all the factors identified in figure 13 there could be two external factors be identified which should be taken into account in the O&M process and will therefore be translated into requirements.

The first and most uncontrollable factor is the weather. The weather conditions, both wind speed and wave height, have significant influence on the efficiency of the wind farms. To a smaller extent is the swell important (Van Buchem, 2014a).

The failure rate of the different components of a turbine is considered as the other external factor. It is arguable whether failures are uncontrollable. Preventive maintenance should result in less failures. On the other hand, even with preventive maintenance failures will still occur on uncertain moments. Therefore the failures rates are considered as an external factor, which should be dealt with by the O&M planner.

Besides the weather conditions and the failure rates, also the lead time between spare parts location and the port for the different components should be taken into account. It is assumed that the location of the spare parts production or spare parts stock location (not the port), and thus the lead time, will not change during the operational phase. Therefore the lead time of the components should be taken into account as an external factor.

3.4.1. Safety Regulations

Besides the above listed external factors, there are some other external safety regulations. These safety regulations constrain the O&M of the wind farms, in order to guarantee the safety of the maintenance personnel. According to Willem van Dongen (2014) there could be three safety regulations identified:

1. During maintenance on a turbine, at least two persons per turbine must be present.
2. There should always be one vessel in the wind farm itself available if there is personnel working in one or more of the turbines
3. Depending on the vessel, there are wave limits above which access is not possible.

These regulations should be taken into account as constraints for different maintenance strategies and when performing maintenance and when developing an O&M model.

The three external factors and the safety constraints are translated into the next requirements for the O&M process.

Table 4: External factors process requirements

Nr	**Requirement** *For the stakeholders in the O&M process, in order to achieve an effective O&M, it shall be possible to*
P8	Deal with uncertain weather conditions
P9	Deal with uncertain failures of all the different turbine components
P10	Include the lead time of the different components
P11	Perform O&M according to the safety regulations

3.5. Decision Support Tool within the O&M Process

The model that will be developed in this thesis should function as a decision support tool within the O&M. The tool has to be useable for every wind farm (*generic*) and has to contain all the O&M aspects (*integrated*). Therefore, the next requirements for the use of the model within the O&M process and planning is formulated.

Table 5: Decision support tool process requirements

Nr	**Requirement** *For the stakeholders in the O&M process it shall possible to*
P12	Use an integrated decision support tool to get insight in the O&M process
P13	Use an integrated decision support tool to compare and optimize the effectiveness of different O&M strategies
P14	Use an integrated decision support tool to design a feasible and robust scheduled maintenance plan

3.6. O&M Process Requirements

The requirements identified in this chapter will be presented in one overview in this paragraph to have one list of requirements for the O&M process. This list will be the basis for the model requirements in the next chapter. A more detailed list, including sub requirements, can be found in Appendix B: Requirements for the O&M Process. Of all the requirements, the first four could be considered as requirements reflecting the O&M effectiveness, P5 till P7 reflect the strategies, P8 till P11 the external factors and the latter the use of a decision support tool. These three aspects will be elaborated into model requirements in the next chapter.

Table 6: O&M process requirements

Nr	Requirement
	For the O&M process it shall be possible for the stakeholders, in order to maximize the profit, to make decisions to…
P1	Maximize the time- or energy-based availability of the wind farm
P2	Maximize the production revenues
P3	Minimize the O&M costs
P4	Maximize the robustness of the maintenance plan
	For the stakeholders in the O&M process, in order to achieve an effective O&M, it shall possible to…
P5	Make decisions to adjust the resources (type and number of personnel and transport
P6	Make decisions to adjust the service level regarding spare parts inventory
P7	Perform different O&M strategies (incl. preventive and corrective maintenance)
P8	Incorporate uncertain weather conditions
P9	Incorporate uncertain failures of all the different turbine components
P10	Take the lead time of the different spare parts into account
P11	Perform O&M according to the safety regulations
	For the stakeholders in the O&M process it shall possible to…
P12	Use an integrated decision support tool to get insight in the O&M process
P13	Use an integrated decision support tool to compare and optimize the effectiveness of different O&M strategies
P14	Use an integrated decision support tool to design a feasible and robust scheduled maintenance plan

4. Requirements for an Integrated O&M Model

After Chapter 3, all the requirements for the O&M process are identified. The next step (figure 16) is to translate those requirements into requirements for the model that could serve as a decision support tool within the O&M planning and process.

> 3. *What are the requirements that should be included in an integrated O&M decision support tool?*

The model requirements are based on the process requirements, but are more detailed and should reflect the model capabilities. The model requirements, as fully listed in appendix D, are verified and completed by Van Buchem (2014b).

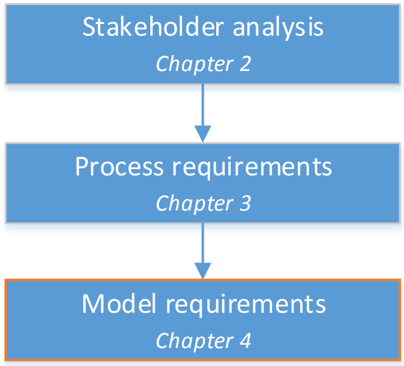


Figure 16: Identifying the requirements

To start a black box approach is used. A black box approach connects the input and output of a design, in this case the model (Dym et al., 2004). To this input-output black box approach also external factors are added as well as the O&M strategies, which could be varied to make the O&M more effective. The next figure (17) represents this black box and shows on a very high level how the model will be build. This figure includes the same aspects as in the process requirement; external factors; strategies and output. For the model also input is necessary, in this case the static parameters of the wind farm(s). The arrows from the top and bottom the considered as variable factor, where the green arrows are representing controllable, and the red uncontrollable. The yellow arrow represents the calculated output. At each arrow, the corresponding process requirements from chapter 3 are denoted in gray.

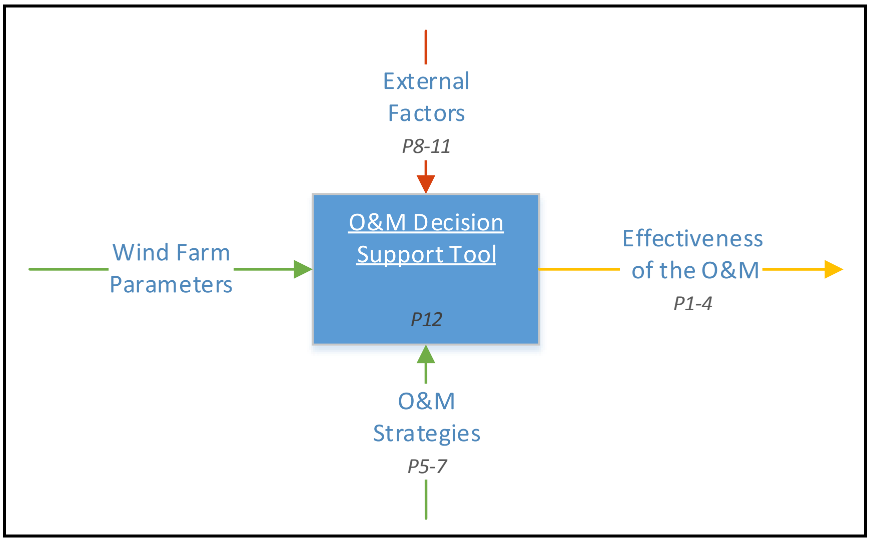


Figure 17: Black box overview of the model

This black box is translated into the next four, high level, requirements related to the four arrows of the black box. These requirements will be decomposed in the next paragraphs based on existing literature and interviews held with different persons in the offshore wind sector. Next to these four requirements, paragraph 4.5 will elaborate on model capabilities; what should the model be capable of in order to make the O&M more effective?

Table 7: High level model requirements

Nr	Requirement
	The model should be able to…
M1	Define wind farm specific parameters
M2	Take external factors into account
M3	Use different O&M strategies
M4	Present output on the KPIs to measure the effectiveness of the O&M

In this chapter first the desired wind farm parameter will be identified; which parameters determine a wind farm? In paragraph 4.2 the external factors that influence the O&M will be presented. Paragraph 4.3 elaborates on the different O&M strategies. The Key Performance Indicators (KPIs) assess how effective the O&M is will be stated in paragraph 4.4. Each paragraph will be translated into model requirements.

4.1. Parameterize an Offshore Wind Farm

To define the characteristics of an offshore wind farms, this paragraph identifies the parameter that describe a wind farm. There are several site properties identified that could serve as input for the model, based on interviews and current integrated tools.

By taking all the relevant wind farm properties into account, every offshore wind farm can be parametrized. This enables the user to specify each wind farm in the model, making the model *generic*. The (simplified) UML diagram in figure 18 gives a global overview of the parameters of an offshore wind farm, also decomposed into turbine and component.

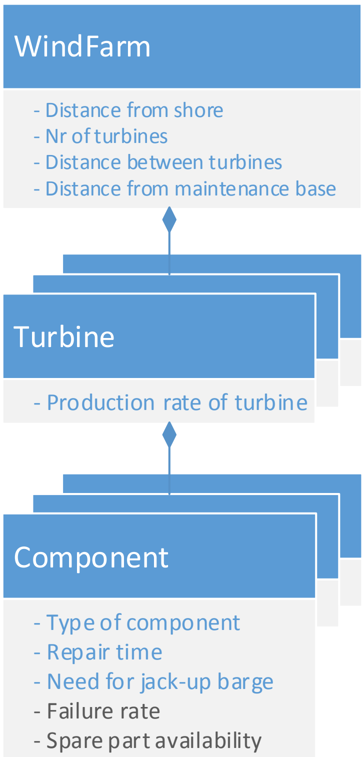


Figure 18: UML wind farm parameters

The leading integrated tool of ECN (Braam et al., 2011; Van de Pieterman, Braam, Obdam, Rademakers, & Van der Zee, 2011), considers as input characteristic (apart from the O&M strategies and external factors) mainly the distance from the shore, the number of turbines, the production curve to convert wind speeds into energy production and the breakdown of a turbine into components with their characteristics.

Apart from the distance from the shore and the number of turbines, two other characteristics are identified: the distance between turbines and the distance from the maintenance base.

Van Dongen (2014) mentioned that also the distance between the turbines, determining the size of the wind farm, is desired. For the distance between the turbines there exists a rule of thumb. In the prevailing wind direction the distance between the turbines should be seven times the rotor diameter. In the crosswind direction the distance between the turbines should be four times the rotor diameter (Van Dongen, 2014).

As last characteristic the distance from the maintenance base is included. This parameter accommodates for the option to include an offshore-based maintenance facility as described by GL Garrad Hassan (2013).

For the components ECN specified in their case study (Van de Pieterman et al., 2011) the type, the failure rates, the repair times (although numbers are not explicitly shown) and the need for a jack-up barge in case of a failure of a major component. Note further that the failure rates of the different types of components are considered as external factors not as an input parameter, but are included for completeness. The failure rates will be discussed further in the next paragraph. ECN specified in their case study (Van de Pieterman et al., 2011) also the availability of spare parts. According to Van Buchem (2014a), spare parts of minor components are normally on stock while the bigger components have to be ordered, implying a waiting time. This spare part availability or lead time (can be 0 for on stock components) for a component will be discussed also in the next (external factors) paragraph.

Above resulted in the more detailed sub requirement for requirement M1:

Table 8: Wind farm input requirements

Nr	Requirement
	The model should be capable to define…
M1	The wind farm specific parameters
M1a	The number of turbines
M1b	The distance between the turbines
M1c	The distance from the shore
M1d	The distance from the maintenance base
M1e	The production rate (power curve) of a turbine
M1f	The different types of the components
M1g	The repair time of each component, in case of failures
M1h	The need for a jack-up barge for each component, in case of failures

4.2. External Factors in the O&M Model

Paragraph 3.4 together with requirements P8-11 already described which external factors are important regarding the O&M of offshore wind farms; weather conditions, failures, components lead times and safety regulations. This paragraph elaborates more on these external factors. The last one, the safety regulation is directly used from the process requirements in the model requirements, the other three are more detailed and need some explanation. The weather conditions are decomposed into wave height and wind speed, the two most important according to Van Buchem (2014). Not only the two individual components are important, also the correlation between both should be taken into account for a realistic simulation of the weather. Next to the two weather components, wind and wave, also the historical correlation or trends are important, e.g. it is not realistic to have no wind at one day and full speed wind at the next. At last, the model should forecast the weather for the coming period in order to determine the accessibilities of the different transport modes. With respect to the failure rates, it should be possible to include the failure rates of all the components in the model. Randomness has to be included also for the lead time of the components between the stock location and the port, to make it as realistic as possible.

Table 9: External factors requirements

Nr	Requirement
	The model should…
M2	Be capable to take external factors into account
M2a	Include the wave height
M2b	Include the wind speed
M2c	Include the correlation between wave and wind
M2d	Include (historical) correlation / trends in the weather conditions
M2e	Forecast the weather to determine the accessibility
M2f	Include the failure rates of all the different turbine components, including randomness
M2g	Include the lead time of the different components, including randomness
M2h	Take the safety regulations into account

4.3. O&M Strategies in the O&M Model

In this paragraph the O&M strategies will be translated into model requirements. In the model it should be possible to use different O&M strategies and including requirements P5-7. In paragraph 3.3 the variable aspects of the strategies are already identified. The next more detailed model requirements are derived from these aspects:

Table 10: O&M strategies requirements

Nr	Requirement
	The model should be capable to…
M3	Use different O&M strategies
M3a	Vary the type of transporters (type of vessel or helicopter, including properties as costs, capacity, speed, wave and wind thresholds)
M3b	Vary the number of transporters
M3c	Vary the number of personnel
M3d	Vary the service level/amount of stock regarding spare parts inventory
M3e	Perform condition based maintenance
M3f	Perform predetermined (scheduled) based maintenance (including number of personnel per turbine, number of days per turbine and preventive maintenance threshold)
M3g	Perform corrective maintenance (including number of personnel per failure)

The maintenance strategy covering the above listed maintenance activities, resource configuration and deployment determines the result on the KPIs discussed in the next paragraph in order to assess the effectiveness of the strategies.

4.4. Output of the O&M Model

The fourth paragraph of this chapter will identify the output criteria for the decision support tool, also called the Key Performance Indicators (KPIs). The KPIs will measure the effectiveness of the O&M. In paragraph 3.1 (and appendix B &C) requirements P1-4 are identified as the main goals of the stakeholders from chapter 2. The four goals identified in paragraph 3.1, in order to maximize the profit, are:

1. High availability (either energy-based or time-based)
2. High production revenues
3. Low total O&M costs
4. Robust preventive maintenance plan

These four goals are decomposed into more detailed KPIs, listed below, in the next table and also visually presented in the objective tree in Appendix C:

- Total production (both in terms of MWh and time, in order to express both the time and energy-based availability), *derived from requirement P1*
- Lost production (also in terms of MWh and time), *derived from requirement P1*
- Production revenues (in M€), *derived from requirement P2*
- Lost production costs (in M€), *derived from requirement P3*
- O&M resource and spare part costs (in M€), *derived from requirement P3*

The robustness is specified as the risk that the maintenance is not finished on time. This is divided into two components; the exceedance probability and the exceedance impact:

- Probability preventive maintenance is not finished before a target date (in %), *derived from requirement P4*
- Exceedance of target date (in day) , *derived from requirement P4*

Table 11: Output KPIs

KPI	Description	Measure
C1	Energy-based availability Time-based availability	% total production / (total production + lost production) % online time / total time
C1.1	Total production	MWh hour
C1.2	Lost production	MWh hour
C2	Total production revenues	M€
C3	Total O&M costs	M€
C3.1	Lost Production costs	M€
C3.2	O&M resources costs	M€
C4	Robustness of preventive maintenance plan	day
C4.1	Probability target exceedance	% probability all scheduled maintenance is not finished before a target date
C4.2	Average target date exceedance	day

Note that there can be some overlap between the objectives. In case the total production is measured in terms of MWh (to measure the energy-based availability) the production revenues are directly correlated. This is not the case is the production is expressed in terms of time, therefore both production as production revenues are included for completeness. The calculation of these KPIs will be discussed during the implementation of simulation model in paragraph 9.3.3.

Besides the presentation of these KPIs it is also interesting to include the variability or bandwidth in the results. Some average results which seems to indicate a good performance could be misleading in case of some very extreme results. For example, an alternative that is able to perform the scheduled preventive maintenance on average before the target date could be have very negative results under some extreme weather conditions, making the alternative less robust. Or an alternative could have on average a very positive energy-based availability, but could perform less than other alternatives in some cases, resulting in penalties for the O&M party for not reaching the agreed availability level. Therefore the variability is covered by requirement M4g.

Table 12: Output requirements

Nr	Requirement
	The model should be capable to present…
M4	Present output on the KPIs to measure the effectiveness of the O&M :
M4a	The total production [MWh] and/or [hour]
M4b	The lost production [MWh] and/or [hour]
M4c	The lost production costs [M€]
M4d	The O&M resource and spare part costs [M€]
M4e	Preventive maintenance target date exceedance probability [% target exceedance]
M4f	Preventive maintenance target date exceedance impact [day]
M4g	Variability or bandwidth around the KPIs

4.5. Model Capabilities Requirements

After the requirements for the input, output, external factors and O&M strategies there are also a few model capabilities requirements derived from the process requirements P12-14 in paragraph 3.5 (Decision Support Tool within the O&M Process). The decision support tool should have three (main) functions:

Table 13: Model capabilities requirements.

Nr	Requirement
	The model should be able to…
M5	Give insight in the O&M process (e.g. visualization or process animation)
M6	Compare and optimize different O&M alternatives
M7	Design feasible and robust scheduled maintenance
M7a	Plan resources (personnel and material) for the scheduled maintenance
M7b	Plan feasible (w.r.t. to start and target date) scheduled maintenance
M7c	Plan robust (w.r.t. variability around target date) scheduled maintenance

4.6. O&M Model Requirements and Black Box Overview

All the requirements of this chapter are presented in one table in Appendix D. Furthermore, based on the insights of this chapter the black box overview in figure 17 could be filled in. This results in the next extended black box overview covering all the model requirements (figure 19). Integrating all these requirements will be the basis for a generic and integrated offshore wind O&M decision support tool.

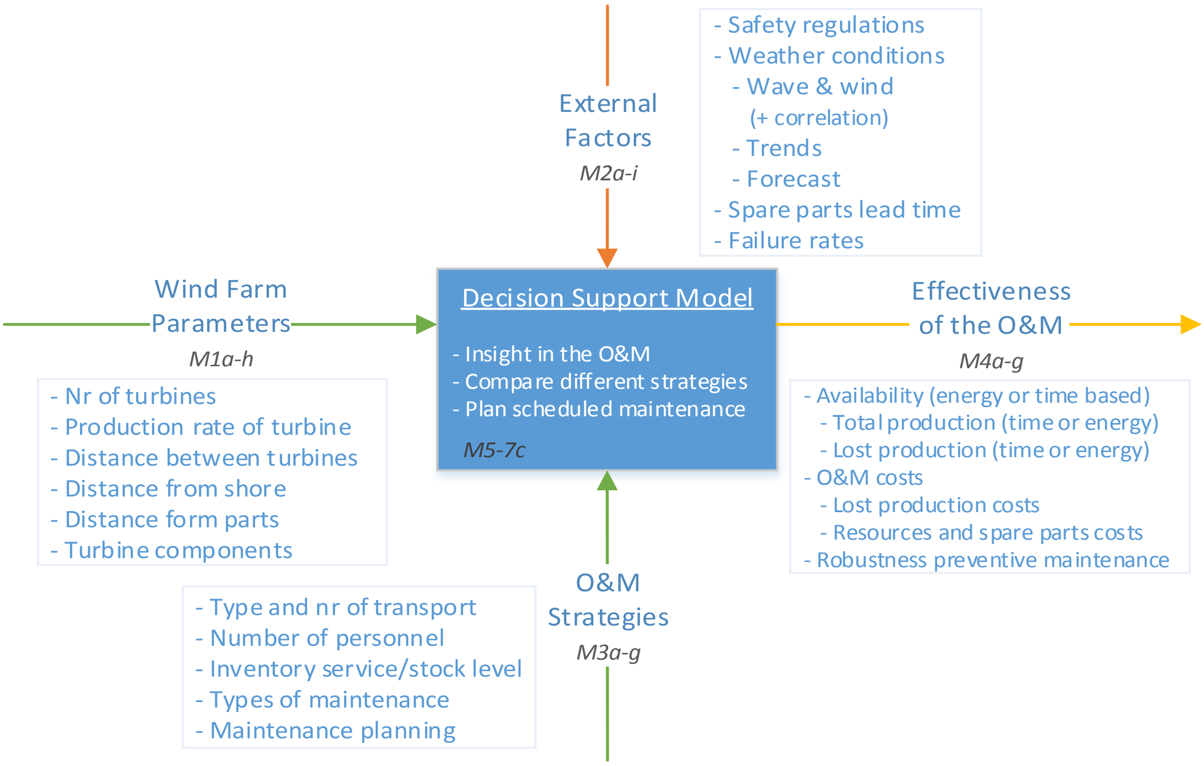


Figure 19: Extended black box overview

5. Assessment of Previous Research

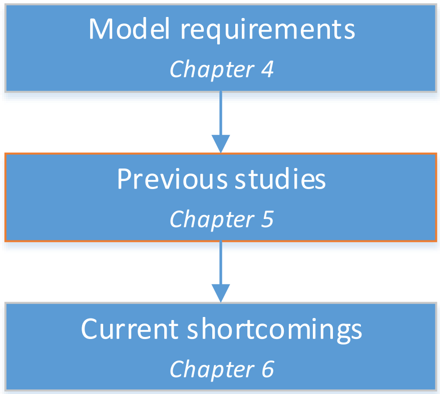


Figure 20: Previous studies analysis

In this chapter there will be discussed which requirements for an offshore wind O&M model, listed in Appendix D, are already researched and could be reused. This will be done for four aspects, also used in previous chapter; the input parameters, the external factors, the different O&M strategies, the output KPIs and model capabilities. Within these four aspects, different topics will be discussed and assessed what is already done. The assessment of previous research has two purposes:

Requirements that are already fulfilled by previous research could serve as building block for the decision support tool. This is mainly relevant for the external factor and O&M strategies. These elements can be reused in the decision support tool or can be included in the 'library' of the tool, from which a strategy can be selected. Therefore the external factors and O&M strategies will be discussed more elaborate.

Requirements that are not yet fulfilled by previous research could indicate the gaps between the identified requirements and the current knowledge.

> 4. *Which requirements are already included in current studies and tools?*

This question will be examined for the previous research listed in appendix E, to give a good and as complete as possible, though maybe not non-exhaustive, overview of the previous work. This is done by using different search engines such as Google Scholar, Scopus and Science Direct and the reference lists of the already found articles. For these search engines the next keywords in combination with 'offshore wind (farms)' were used: Operations, maintenance (types), (spare parts) logistics, challenges, problems, (discrete) simulation, weather simulation, (decision support) tool, planning and scheduling. This resulted into twelve previous research papers and two previous *integrated* O&M (simulation) tools to test different O&M strategies and to calculate the O&M costs. In Appendix F an overview is presented which of all the model requirements (listed in Appendix D) is already fulfilled by the existing studies and tools.

5.1. Input Parameters

Requirements M1a-h

- Nr of turbines
- Production rate of turbine
- Distance between turbines
- Distance from shore
- Distance form parts
- Turbine components

Figure 21: Input parameters

Although the input depends on the wind farm and the important import parameters are already identified in paragraph 4.1, there are some elements from previous research (re)usable for the decision support tool. The different main components including the failure rates, the repair times and the need for a jack-up barge in case of failures can be used from multiple studies. The number and type of components should be adjustable, but the components used in previous research can be a good starting point for the model. Therefore for the verification and validation the components with failure rates of Van Bussel & Zaaijer (2001) will be used. For the repair times and the need for a jack-up barge, multiple different number are found, therefore an interview with Vestas is performed. According to Van Buchem (2014a) from Vestas, the components of Van Bussel & Zaaijer (2001) could be divided in major and minor components. For the minor components there can be assumed that these spare parts are in stock and are normally repaired in one day. The major components require a jack-up barge and one day of preparation, one day of actual repair and one day of finishing works. The main delay in case of a major component failure is the waiting for the jack-up barge. This delay is normally around 7 days but could be less or even up to a couple of weeks (Van Buchem, 2014a).

The production, called the power curve, is important to translate the wind speeds into (lost) generated power. A couple of studies used different curves. E.g. Nielsen & Sørensen (2011) offer an analytical, differential equations, O&M model for a single wind turbine with a single component to evaluate the O&M costs. This study includes a power curve to determine the power generation per wind speed. This is also provided by Nnadili (2009). These could be useful for the actual tool, however turbine manufacturer Vestas also published the curves for all their turbines online (Vestas, 2014).

5.2. External Factors

Requirements M2a-i

To model the weather conditions mainly four different approaches are identified in the literature. Feuchtwang & Infield (2013) tested different probability function to simulate the probability for an access window and the expected waiting time. This method is also applied by ECN (also used in their tool) (Braam & Eecen, 2005). Aksoy, Fuat Toprak, Aytek, & Erdem Ünal (2004) identified different parameter based (time series) generation methods to generate wind speeds, including a Markov chain. A Markov chain is also provided by Scheu et al. (2012) to simulate the weather and production losses. With this Markov simulation there is a certain probability (based on historical data) on every time step each of the eighteen Markov chain states, representing different wave height, that it will change into one of the eighteen (including the current state) states. The last approach is to use plain historical data covering multiple years. So to simulate the weather there are roughly four approaches identified:

- Safety regulations
- Weather conditions
  - Wave & wind (+ correlation)
  - Trends
  - Forecast
- Spare parts lead time
- Failure rates

Figure 22: External factors

1. Historical data
2. Parameter based weather generation
3. Markov chain
4. Parameter based access probabilities

Historical data require multiple years or periods to simulate different conditions (replications). Stochastic approaches reduce information (e.g. trends, seasonal differences) and requires sufficient amount of data, but are able to generate enough replications. More on the (dis)advantages in the next chapter and the on the most suitable approach for integrate all the (weather) requirements in chapter 7.

Concerning the failures rates of different components, Karyotakis (2011) provided a useful literature study in his thesis including multiple studies that contain failure rates per component over different countries. Next to this research several other (not all included in appendices) authors provide failure rates per component (DOWEC team, 2002; Hancock, 2011 (onshore); Van Bussel & Zaaijer, 2001). These data serve as a useful plug-in into the decision support tool.

The lead times of the spare parts, in case of failures and not having part in stock, are detailed examined by Dewan (2014) and can be useful for the model. Also Nnadili (2009) included the lead times, but only tested two scenarios with a lead time of two or four weeks for each component. The ECN tool provides the user the option to specify the lead times of each component.

Regarding the safety regulations, none of the listed studies mention those explicitly.

5.3. O&M Strategies

Requirements M3a-g

- Type and nr of transport
- Number of personnel
- Inventory service/stock level
- Types of maintenance
- Maintenance planning

Figure 23: O&M Strategies

Nielsen & Sørensen (2011) provided two types of maintenance and used three transportation options. They compared two maintenance strategies: only corrective maintenance in case of failures and only condition based maintenance during scheduled service inspections. The failures and condition based maintenance are based on a damage function. In case of a service inspection the damage function for a component, including a probability of detection, will be evaluated. If the (detected) damage is above a specified level, the component will be replaced. To perform the two types of maintenance Nielsen & Sørensen (2011) identified three transportation options. The first and most straightforward option is to always use a boat. The second option is to repair as soon as possible to reduce the lost production. In this option a helicopter will be used if the weather conditions do not allow a repair by boat. The third option is a risk based alternative, whereby the cheapest solution, either boat or helicopter, is determined based on the weather conditions.

Comparable to Nielsen & Sørensen, Ding & Tian (2011) proposed a condition based maintenance strategy. Ding & Tian developed an analytical model with condition based maintenance after corrective maintenance based on the ageing or MTTF. In case of a failure, corrective maintenance will take place on the failed component and preventive replacement will be performed on other components in the entire wind farm, if their age is above a specified threshold. So in this case the two types of preventive maintenance, scheduled and condition (with age as the condition) based, are clustered.

In the PhD thesis of Karyotakis (2011) an analytical model with Monte Carlo simulations is developed to model the effect of redundancy of components and to simulate two preventive maintenance planning strategies: Preventive maintenance once a year during summer or preventive maintenance twice a year during the spring and autumn.

Scholz-Reiter et al. (2010) performed interesting study regarding maintenance planning. In this study an optimal *installation* schedule for the vessel usage based on (bad) weather conditions is developed. The result of the mixed integer linear programming model is a Gantt chart with the optimal installation schedule. The model can be used to estimate the building times, including Variability or risk, as a result of multiple runs with stochastic weather conditions. So far such a tool or study is not performed for the operational phase and the O&M, although such a scheduling tool could be very useful to plan the different resources for scheduled maintenance.

Besnard, Fischer, & Tjernberg (2013) present an analytical model to optimize the maintenance support organization by i.a. changing the type of resources. As decisions for a fictitious offshore wind farm they include the location of the maintenance accommodation (onshore or offshore), two types of transfer vessels, the use of a helicopter and two different work shifts.

Scheu, Matha, Hofmann, & Muskulus (2012) also researched different resource compositions. They simulated four different fleet compositions with different number of regular vessels and crane ships. They tested the effect of the fleet compositions on the park (time-based) availability in a MATLAB model. Furthermore, the effect of the availability on the lost production costs is estimated.

Dewan (2014) developed a MATLAB model and proposed four transportation strategies: 1) use of work boats, 2) use of mother vessel, 3) use of mother vessel with daughter work boats and 4) both mother vessel and daughter work boats. Also the use of an offshore accommodation is tested, as well as a stock optimization strategy.

Regarding the inventory policy in the offshore wind, not only the earlier mentioned thesis of Dewan is found, the thesis of Nnadili (2009) is found as well in the literature. He calculated the safety stock (costs) per component to back up for failures and corrective maintenance and estimated the costs for two different lead time and for two different service levels.

5.4. Key Performance Indicators

Requirements M4a-g

With respect to the KPIs, current literature and tools include most KPIs describes in paragraph 4.4, depicted in figure 24. The ECN tool, considered as the most used and leading tool in the sector to estimate the O&M effort in the operational phase, presents result on: the total production (in €), the lost production (in €), the downtime, the time-based availability and the O&M costs, including variability (Braam et al., 2011).

- Availability (energy or time based)
  - Total production (time or energy)
  - Lost production (time or energy)
- O&M costs
  - Lost production costs
  - Resources and spare parts costs
- Robustness preventive maintenance

Figure 24: KPIs

The energy-based availability, based on production and lost production, is less used in current studies, while the robustness of the preventive maintenance plan is not included in any of the examined studies. More on the shortcomings in the next chapter.

The KPIs used in previous studies are similar to the KPIs set in this thesis based on the requirements from offshore wind actors, apart from one or two missing indicators (discussed in next chapter). Therefore, the decision support tool will stick to the KPIs identified in paragraph 4.4 to be able to provide a complete picture of the performance of the O&M.

5.5. Model Capabilities

Requirements M5-7c

Most of the model capabilities (figure 25) of paragraph 4.5 are not covered by the current studies and tool. Current research and tools, including the ECN tool (Braam et al., 2011), compare different O&M strategies. Only one study (Scholz-Reiter et al., 2010) plans also resources, although it is for the *installation* of an offshore wind farm and not concerns the O&M. So, especially the last identified capability, designing a scheduled maintenance plan, is not included in any of the examined studies. This shortcoming will be discussed more elaborate in the next chapter.

Decision Support Model

- Insight in the O&M
- Compare different strategies
- Plan scheduled maintenance

Figure 25: Model capabilities

Insight in the O&M process, by means of visualization, is not supplied by any of the examined studies or tools.

With respect to the comparison of different strategies, multiple studies and both integrated tools offer the functionality to compare different strategies. The only improvement regarding the comparison could be to option to optimize with respect to one or more KPIs (e.g. minimize costs or maximize availability). In the next chapter (6.2) there will be elaborated on the optimization of strategies.

6. Shortcomings Previous Studies

In the previous chapter an overview of the previous research is presented and assessed. The detailed results could be found in Appendix F. In this chapter there will be determined what the shortcomings of the fourteen previous studies and tools listed in Appendix E are.

5. *What are the shortcomings of the previous research and tools?*

In this chapter the main shortcoming of the current studies will be discussed. This is done for the same studies as used in the previous chapter, an overview is listed in Appendix E, considered as a good and as complete as possible, though maybe not non-exhaustive, overview of the previous work. Paragraph 6.1 discusses the research papers (mostly) focused on single aspect(s). Paragraph 6.2 assesses the current existing integrated tools. Note that this assessment is done based on the published information, which could be a summary of the capabilities of a study or tool.

In Appendix F all the requirements that are currently (not or partly fulfilled) could be found, in this chapter a summary of the main outcomes of this literature review will be provided.

6.1. Single Studies

The first requirement that is not fulfilled by any previous research is the distance between turbines. All previous work assumed constant travel times towards each turbine from the port and neglects the travel times inside the wind farm. This minor shortcoming does not have significant influences on the results when the distances between the turbines is reasonable and the (preventive) maintenance sequence prescribes that always the direct next turbine is the next turbine that will be maintained. In case of other sequences or for bigger wind farms, the distance between the turbines could have a significant impact, therefore this requirement is still taken into account, but not met by other studies.

The second shortcoming relates to the inventory aspect. Only one paper (Besnard et al., 2013) includes an offshore spare parts location. In addition only a few research papers include the lead time of different components between the spare parts (manufacturer) stock location and the port. The option to vary the service level or the amount of spare parts in stock at the port is also covered by only a few studies. With respect to the inventory aspect, also the costs of the components is not included in most studies.

Condition based maintenance is performed in real-life based on actual measurements and distortions, making it difficult to simulate. Therefore only a few studies included condition based maintenance. For example, Ding & Tian (2011) assumed that condition based maintenance will be performed when a component is older than a certain threshold. The ECN O&M Calculator (Braam et al., 2011) is partly able to perform condition based maintenance on the turbines, see more paragraph 6.2.

Of all the different types of maintenance, only the ECN O&M Calculator provides the option to set the number of technicians and the duration of the maintenance. The option to perform preventive maintenance only during low wind speed is proposed by Besnard et al. (2009), but not included in an integrated tool yet, although ECN announced it already for 2014 (ECN, 2014).

Another shortcoming of many studies is the lack of variability or bandwidth. Most studies focus on averages (e.g. costs), not showing the bandwidth around it. This implies that is for example only possible to assess the performance of the maintenance on averages, not on the robustness. After all, an alternative that perform well on average could perform quite negative in some (extreme) cases, making the alternative less effective.

Regarding the weather conditions, a lot of studies fulfill the different weather conditions requirements. However, not all studies fulfil all the weather conditions requirements and/or at the same time. For example, some studies only include probabilities to determine the access every day. This neglects historical trends and makes the calculation of the (lost) production impossible since the actual wind speed at that point in time is unknown.

The planning of scheduled preventive maintenance is the biggest shortcoming in the current literature. None of the studies incorporate the feasibility (w.r.t. to start and target date) and robustness (w.r.t. variability around target date).

The last shortcoming concerns a visualization or animation of the O&M process. This minor shortcoming makes it impossible to get insight in the process, leaving the current tools as black boxes. Adding an animation gives the user insight in the process and is useful for the verification and validation.

6.2. Integrated Tools

Besides the different studies on several O&M aspects or on a specific wind farm, there are also already integrated tools available able to specify custom input (depending on the wind farm) and test different strategies. The two most used tool will be discussed in this paragraph: the CONTOFAX tool and the ECN tool. The ECN tool is considered as the current leading and most detailed tool and will therefore discussed more elaborate. The full assessment of both tools is discussed in Appendix F.

CONTOFAX

An earlier, analytical O&M tool, developed by the TU Delft, called CONTOFAX (1997) is quite similar to the ECN O&M tool. It is also designed for the planning phase, not operational, and is capable of estimating the long run average of the (time-based) availability of a wind farm, the accessibility of different types of vessels and the costs (Koutoulakos, 2010).

As far as publically found, the CONTOFAX tools has some major shortcomings. The main shortcomings are:

- Accessibility is an input, not calculated based on thresholds and weather conditions
- Only time-based availability
- No actual (lost) production based on wind speeds, only based on annual production (input parameter) times the time-based availability
- No visualization or process insight
- No preventive maintenance planning aspect

A more detailed assessment could be found in Appendix F.

ECN Tool

ECN developed the more detailed Operation and Maintenance Cost Estimator (OMCE) calculator (Braam et al., 2011; Van de Pieterman et al., 2011). The OMCE-Calculator could be considered as the most used and leading tool in the sector and is suitable to estimate the O&M effort in the operational phase. The OMCE calculator is programmed in MATLAB and include statistical details/Variability, different maintenance strategies (corrective, calendar based and condition based), clustering of repairs, spare part control and optimization of equipment.

The ECN O&M Calculator (Braam et al., 2011) is partly able to perform condition based maintenance on the turbines. A shortcoming of this tool regarding condition based maintenance is that this maintenance is performed at wind farm level and the interaction between condition based maintenance and unplanned corrective maintenance cannot be taken into account (Braam et al., 2011), this will be discussed more elaborate in chapter 8. Furthermore, the condition based maintenance in the ECN tool is simplified implemented; the user could decrease the failure rates (manually and independently) while increasing the number of visits.

Of all the different types of maintenance, only the ECN O&M Calculator provides the option to set the number of technicians and the duration of the preventive maintenance. This provides the realistic option to increase the number of technicians per turbine to reduce the number of (preventive) maintenance days and thus to reduce the lost production (Braam et al., 2011). The total available number of technicians cannot be specified in the ECN tool, although ECN announced it already for 2014 (ECN, 2014). The option to perform preventive maintenance only during low wind speed is proposed by Besnard et al. (2009), but not included in an integrated tool yet, although ECN announced it also already for 2014 (ECN, 2014). Besnard et al. (2009) on the other hand, included the preventive maintenance threshold, but neglected the number of personnel per turbine and the number of days per turbine

Furthermore, the planning aspect is not included in the ECN tool, as well as the process insight aspect.

The ECN tool is able to compare different O&M strategies by means of what-if analyses but is not able to use optimization. With optimization is will be possible to specify some control variables (the O&M strategies) and optimize with respect to one or more of the KPIs.

6.3. Current Gaps

To summarize the two previous paragraphs, below the requirements that are not or only partly fulfilled by current studies are listed:

Table 14: Requirements not fulfilled by current research

Nr	Requirement	✓/✗
M1b	The distance between the turbines	✗
M3f	Perform predetermined (scheduled) based maintenance (including number of personnel per turbine, number of days per turbine, preventive maintenance threshold)	✓
M4e	Preventive maintenance target date exceedance probability	✗
M4f	Preventive maintenance target date exceedance impact	✗
M5	Give insight in the O&M process (e.g. visualization or process animation)	✗
M6	Compare and optimize different O&M alternatives	✓
M7a	Plan resources (personnel and material) for the scheduled maintenance	✓
M7b	Plan feasible (w.r.t. to start and target date) scheduled maintenance	✗
M7c	Plan robust (w.r.t. variability around target date) scheduled maintenance	✗

The first requirement has only a (minor) significant impact in case of complicated maintenance sequences or for bigger wind farms. Requirement M3f is party fulfilled especially since none of the studies or tools is able set a preventive maintenance threshold (e.g. only preventive maintenance during low wind speeds). The other missed requirements are related to the planning of preventive maintenance, to the (lack of) insight in the process or the optimization aspect.

The shortcomings in the two previous paragraphs are all single shortcomings or single requirements that are not met by any of the studies or tools. Above requirements are not included in any of the studies or tools, individual studies of tools can miss more requirements. So there can be concluded that most studies cover a part, not all, of the requirements and only able to optimize single, isolated parts of the O&M. The implication of isolated optimization and oversimplifying is that not all the relations and dependencies of the system are included and will lead to inaccurate results. The integration of the requirement will be discussed in chapter 7.

Section 2: Towards an Integrated and Generic Model

Figure 26 describes the outline for Section 2. After section 1 all the requirements for an integrated model are clear, the aspect researched so far are identified, as well as the shortcomings of these studies. The previous studies and their shortcomings will serve as the basis towards an integrated and generic model in this section. In this section there will be attempted to integrate all the requirements, both those already fulfilled by previous studies as those not yet fulfilled, into a decision support tool. The integration of the requirements involves some challenges. These integration challenges, including their difficulty, will be discussed as part of sub question 5 in chapter 7. In chapter 8 a suitable approach and tool to fulfill (more) requirements and to overcome these integration challenges will be proposed. This approach will be executed in chapter 9, wherein the translation into the actual decision support tool will be discussed.

6. *What are the challenges when integrating the different requirements?*
7. *How could these challenges be integrated into an O&M model and how will such a model looks like?*

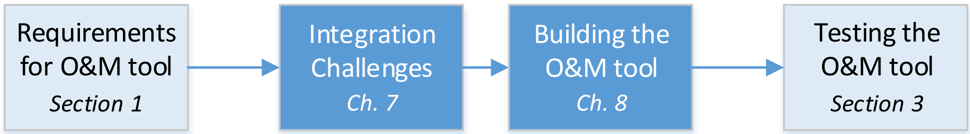


Figure 26: Outline section 2

7. Challenges to Integrate the O&M Aspects

The requirements and shortcomings are identified in the previous chapters, resulting in the gaps in the previous paragraph. Apart from the nine missed requirements by the examined research, there are some integration challenges. Integration challenges can be considered as two or more related and/or interdependent requirements which influences each other and therefore hard to combine.

6. What are the challenges when integrating the different requirements?

This chapter will identify the challenges when all the requirements have to be integrated into one integrated offshore wind O&M tool. In paragraph 7.1 four single challenges are identified and described. Paragraph 7.2 elaborates on the integration of these single challenges.

7.1. Integration Challenges

During the literature research and the interviews, the basis of section 1, there are four main integration challenges identified. This can concern either aspects that seems hard to integrate in the current studies without compromises or aspects that are not integrated so far in the current studies (as far as the author's knowledge). Note that these challenges not reflect single requirements that are not fulfilled by the current studies, this assessment is already performed in chapter 6.

1. <u>Weather condition components</u>

The weather conditions exist of different components. According to previous studies and the held interviews for the maintenance of the offshore wind farms two weather components are important; wave height and wind speed. To a smaller extent are the swell, fog and lightning important (Van Buchem, 2014a). The swell is not included in any weather data files found. Next, there are no fixed thresholds for swell which determine the accessibility. Therefore, Van Buchem (2014) suggested to not include the swell, since wave and wind are good indicators for the accessibility of vessels. Not only the single components are important, also the correlation between the two is. This correlation has to be taken into account when developing an accurate decision support model.

Next to the wave height, the wind speed and the correlation between them, are the trends important regarding the weather condition. E.g. each day a random probability for a certain weather condition neglects these trends.

Forecasting the weather for the coming period is necessary to determine the accessibilities of the different transport modes for a certain window called the weather window.

All these elements of the weather conditions have to be incorporated in the tool in order to represent the real system correctly.

Previous literature and tools (paragraph 6.2) used mainly four different approaches; 1) use of historical data, 2) use of parameter based weather generation, 3) use of a Markov chain and 4) use of access probabilities and expected delays before maintenance. The requirements mentioned above are satisfied by two approaches; historical data and Markov chain, as both wave heights and wind speeds are included in the states of the Markov chain. The latter approach assigns probabilities to state changes; the probability that the weather will change from one state to another. There are advantages and disadvantages for both the use of historical data and the use of a Markov chain, presented in the next table together with the other two approaches.

Table 15: Different weather simulation approaches

	Historical data	Parameter based weather generation	Markov chain	Parameter based access probabilities
Capable to include wave, wind, correlation, trends and forecast	Yes	No, only generation for one component, so no correlation. Trends not covered by all generation methods.	Yes	No, trends not possible
Number of replications possible to generate	Low, equal to amount of data	Unlimited	Unlimited	Unlimited
Amount of data required for fit	N/A	Sufficient amount (< Markov Chain) of data needed to fit the parameters	Sufficient amount of data needed to fit all state change probabilities	Sufficient amount of data (< Markov Chain) needed to fit access probabilities for each transporter
Data reduction	None	Low – High, depending on method	Low – high, depending on number of states	High, only access or not and expected delay

Later in this chapter and in the next chapter there will be elaborated on suitable approaches for the O&M decision support model.

2. Weather conditions & energy-based availability

The wind speeds, which should also be correlated with the wave height and should include a trend, are necessary to determine the production at each time (period) and thus to calculate the energy-based availability. On the same way the lost production, during maintenance, based on the actual wind speed should be calculated.

Access window probabilities not include the actual wind speeds and are thus not suitable to calculate lost production during maintenance accurately. The use of historical data, parameter based weather generation or a Markov chain overcomes this challenge. Parameter based weather generation is not suitable for challenge 1. A Markov chain is less accurate compared with the use of historical data, but is able to generate enough replications with less data.

So the availability of data will be decisive to choose for one of the two approaches. If enough weather data is available with enough years/periods (depending on the simulated period) for a sufficient amount of replications the suggested approach is to use historical data, while if not enough historical data is available for a sufficient amount of replications the suggested approach is to use a Markov chain with the highest possible number of states.

3. <u>Weather conditions, resources, type of maintenance and maintenance planning</u>

The correlated wave and wind weather conditions should determine the accessibility of the wind farm. This not only depends on the weather but also on the type of resources and the maintenance strategy. Different resources have different accessibility thresholds and different maintenance strategies have different access window durations and could also have different threshold (e.g. only performing preventive maintenance during low wind speeds to reduce lost production). The integration challenge is thus to be able to specify different thresholds for different resources and strategies and to be able to specify different windows lengths, which are all based on the (correlated) weather conditions.

The weather conditions, the failure rates and the spare parts lead times are not fixed and have variability. This variability influences the planning of preventive maintenance regarding the feasibility (*will the expected finishing date before the target date?*) and robustness (*the variability around the expected finishing date*).

To integrate the above aspects, variability is needed around the weather, failures and lead times. This requires weather data of multiple years or stochastic generation of weather, stochastic failures and stochastic lead times.

Furthermore, the tool has to be able to specify and deal with different thresholds for the resources and to adjust the maintenance w.r.t. weather thresholds and maintenance duration.

4. <u>Maintenance strategies</u>

Both the preventive (including condition based maintenance) and corrective maintenance, as described in paragraph 3.3, should be integrated into one model. Integrating both involves new relations, conflicts and interdependencies. These conflicts and interdependencies requires additional rules in the model.

Furthermore, both types of maintenance are necessary to include since they might use the same resources. So to obtain accurate and valid results on the feasibility and robustness of the scheduled resources for the preventive maintenance, it is desired to include random failures and thus corrective maintenance.

To cover this integration issue, it is suggested to include both types of maintenance together with strict rules for the use of shared resources. For the developed tool, the rules and assumptions are specified in Chapter 8 and 9 in order to maintain the internal consistencies.

7.2. Combining the Integration Challenges

The four integrations above challenges are identified as the main challenges when developing a valid O&M model. Besides these four single challenges, the biggest challenge is to integrate these four single challenges into one integrated model.

When these four challenges can be integrated into one model, some interesting and new opportunities arise. If integrated, it will be possible to design effective (also and in particular in terms of high energy-based availability) preventive maintenance regarding the feasibility and robustness of the maintenance plan.

To integrate the above four challenges it is needed to include the next elements: either plain historical data or a Markov chain, have variability around the uncertain external factors, specify different resources with different weather threshold, include both preventive as corrective maintenance and be able to assess the impact of the previous elements on the feasibility and robustness of the preventive maintenance.

In the next chapters the focus will be on 1) the above mentioned integration challenges and the development of an integrated and generic model that could contribute to an *energy-based effective scheduled maintenance planning* and 2) the nine missed requirements from paragraph 6.3 while still covering the other stakeholder's requirements.

8. Building the Integrated Decision Support Tool

In this chapter the actual model building will be discussed. After the previous chapters the requirements for a decision support model, the shortcomings and the integration challenges are clear. These shortcomings or gaps of the current knowledge from paragraph 6.3 and the integration challenges from the previous chapter, still covering the other identified model requirements from chapter 4, will be the basis for the development of the integrated O&M tool.

> 7. *How could the requirements and integration challenges be integrated into an O&M decision support model and how will such a model look like?*

In the first two paragraphs of this chapter the conceptual model will be explained by means of several high level flowcharts to identify the processes (paragraph 8.1) and UML class diagrams to identify the objects (paragraph 8.2). Furthermore, a requirement verification will be performed in paragraph 8.3 to check whether all the requirements are included in the conceptual model and to define the boundaries of the (conceptual) model.

8.1. Conceptual Model – Objects

This paragraph will try to capture the objects of figure 19 which are implemented in the conceptual model. Figure 19 represented all the identified and verified requirements for the decision support tool. So this paragraph will identify all the objects necessary for the O&M of a wind farm, including their attributes, based on the requirements.

Of the included objects UML class diagrams are pictured. This is done for the wind farm objects, all the weather (components), the maintenance types and the resources. Each diagram exists of classes, the objects, with attributes. All the attributes in the next UML diagrams are user defined in the actual model.

Wind Farm

The model covers one wind farm with a number of turbines with a certain distance from the shore. This is the basis for the maintenance and both inputs are used in all examined studies.

Each turbine has a production curve (dependent on the type) which converts the wind speed into an energy production. For the production curves the curves of Vestas (2014) are used, however the user can specify every curve.

Each turbine also exists of multiple components. The components have a failure rate (rates of Van Bussel & Zaaijer (2001) are used as default), a repair time, possibly a need for a jack-up barge in case of failure and the waiting time for a jack-up barge. This can be specified for each type of component, but is the same per turbine in the wind farm.

Note that not every element of paragraph 4.1, and thus not every requirement, is covered in the conceptual model. This will be discussed more elaborate in paragraph 8.3.

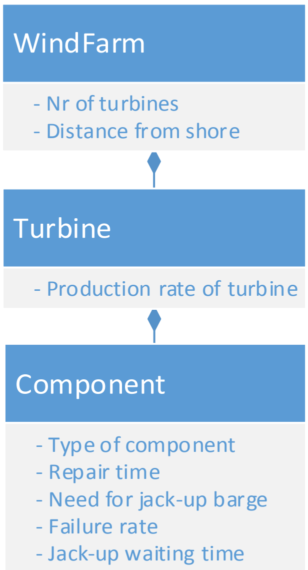


Figure 27: Conceptual model objects – wind farm

Weather

With respect to the weather, only the two main components are included; wave and wind. These components are included in most datasets, are used most studies such as the leading ECN tool (Braam et al., 2011) and suggested by Van Dongen (2014). The less important components such as fog, lightning, swell, etc. are not included in the current tool.

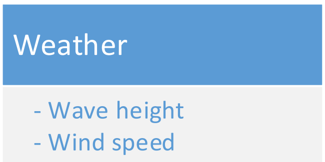


Figure 28: Conceptual model objects – weather

The tool will make use of historical data since in the previous chapter(s) this is considered as the most suitable approach to model the weather. So the use of a Markov Chain as used by Aksoy et al. (2004) & Scheu et al. (2012) is not supported by the current version, although this could be a feasible extension.

Maintenance

The different types of maintenance are presented in the next figure. In the actual model, the model will create a new entity for each maintenance action. The entities will follow the different processes (see more in next paragraph) until the required maintenance is performed at the turbine.

The maintenance entities are either preventive or corrective. For both the number of personnel and the number of required days are attributes and thus user defined. For failures also the need for a jack-up barge can be specified.

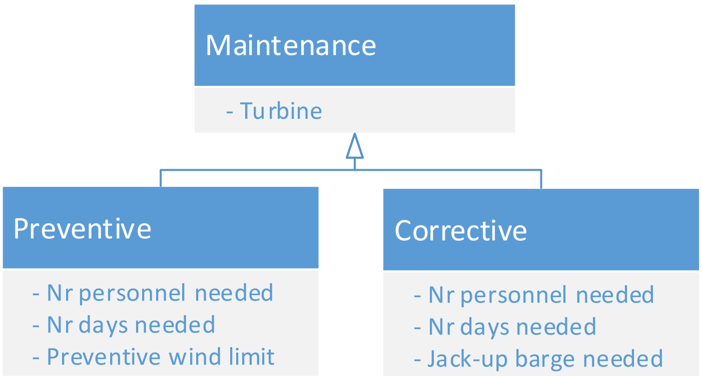


Figure 29: Conceptual model objects – Maintenance

The option to perform preventive maintenance only during low wind speed is proposed by Besnard et al. (2009), but not included in an integrated tool yet, although ECN announced (without releasing it yet) this feature already for 2014 (ECN, 2014).

Resources

Two types of resources are included in the model, personnel and transporters. For personnel only the number of personnel and their work schedule are necessary and included in the model. For the transporters also the amount is included as well as the capacity of the transporter. Furthermore, the weather thresholds are required and the waiting time (mainly for the jack-up barges). Currently, only two types of vessels are included; CTVs and jack-up barges. However, the model could be extended with different types of transporters (e.g. helicopter) in the future.

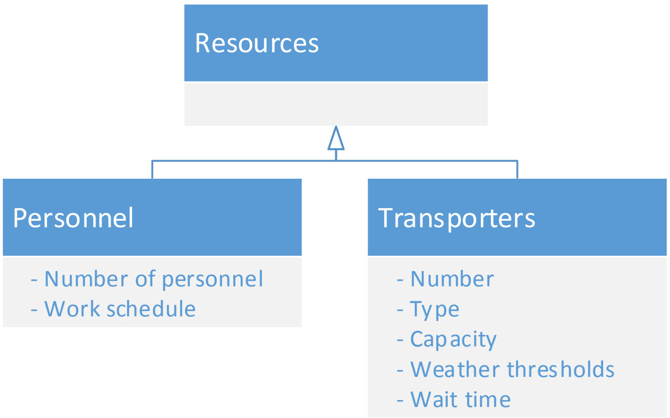


Figure 30: Conceptual model objects – Resources

The total available number of technicians cannot be specified in the ECN tool, although ECN announced it already for 2014 (ECN, 2014).

8.2. Conceptual Model – Processes

The flowcharts basically connect the input of the black box with the output and describe, on a high level how the model works. The model processes will be described textually and with supporting flow charts on the highest level, for the weather conditions and for the maintenance actions.

High Level Flowchart

On the highest level the model checks every day, at 7AM, whether or not corrective maintenance is needed (pull signal) or preventive maintenance is possible (based on remaining resources' availability, push signal). If yes, the model checks whether all the resources are available and checks the weather conditions. When maintenance is still possible after these checks, the maintenance is performed at the turbine for a, user defined, period. This logic will be followed each day.

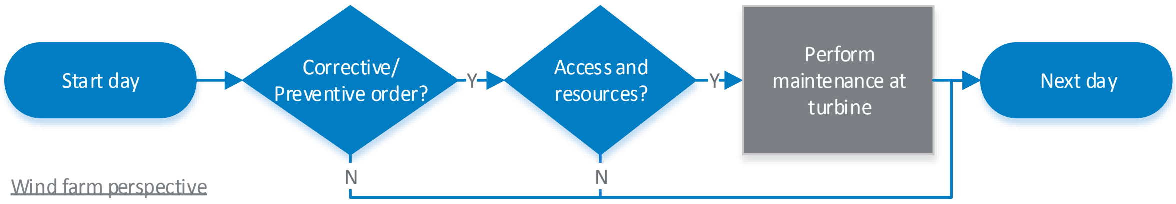


Figure 31: High level flowchart

Weather Flowchart

At the start of the simulation the model will select a user defined starting month in a random year of the historical dataset. Every time step (default: one hour) the model will read the corresponding wave height and wind speed. This process will be run during the entire simulation.

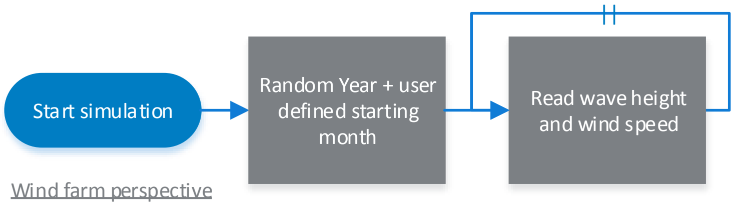


Figure 32: Weather flowchart

When a transporter, with its own user defined weather thresholds, is planning to perform a maintenance action, the model looks one hour ahead and checks if the weather conditions are below the thresholds. If yes, the model will look two hours ahead. This continues for a user defined weather window (e.g. 8 hours). When all the hours allow access the transporter can perform the maintenance actions.

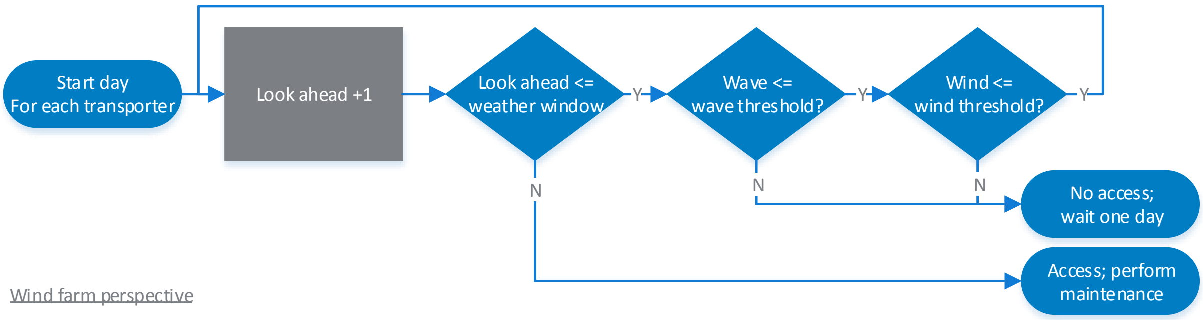


Figure 33: Weather accessibility flowchart

Maintenance Flowcharts

Corrective Maintenance is triggered (pull mechanism) when a component of a turbine is failed. If a failure occurs maintenance is demanded, the triggered process is described later in this paragraph. Preventive maintenance is only performed (push mechanism) when enough resources are available after corrective maintenance. So corrective maintenance orders can seize the resources first, preventive maintenance order can only seize when there are still resources available. The availability of resources depends on:

1. The number of personnel needed for preventive maintenance
2. The number of personnel needed for corrective maintenance
3. The number of days needed for preventive maintenance
4. The number of days needed for corrective maintenance
5. The total number of personnel
6. The number of transporters
7. The number of personnel possible per transporter

All these parameters are user defined and will be checked each time by the model.

Preventive Maintenance Flowcharts

If there are still resources available, a maintenance order will be placed for the next turbine and performed if possible. Preventive maintenance starts at turbine 1 and ends at turbine n (n is user defined).

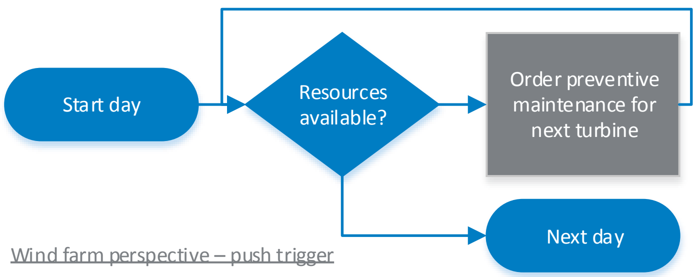


Figure 34: Preventive maintenance flowchart – wind farm perspective

When preventive maintenance is possible and ordered, the turbine waits until a preventive maintenance team arrives at the start of the day. The accessibility for the preventive maintenance team is determined by the logic visualized in figure 33. The preventive maintenance team performs their services and inspections for a user defined number of days.

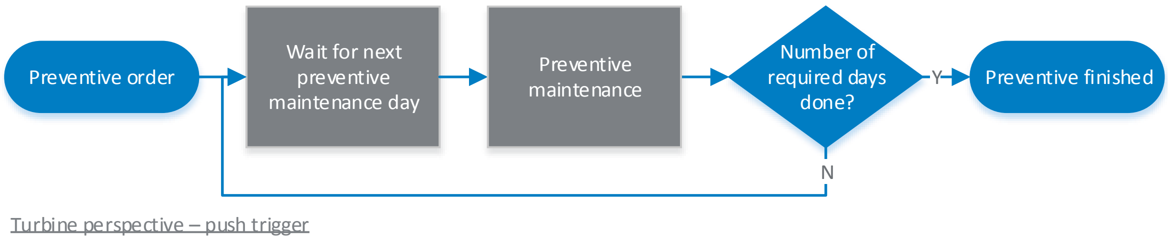


Figure 35: Preventive maintenance flowchart – turbine perspective

Corrective Maintenance Flowcharts

After a failure corrective maintenance is required at the failed turbine. For some components a jack-up barge is needed, this will be described after the process for components without a need for a jack-up barge.

A failed turbine orders a corrective maintenance team and waits for the team. The accessibility for the corrective maintenance team is determined by the logic visualized in Figure 36. The corrective maintenance team performs their repairs for a user defined number of days.

Figure 36: Corrective maintenance flowchart – no jack-up required

For the bigger components a jack-up barge has to be ordered together with a crew team. According to Van Buchem (2014a) a jack-up barge is required for the next components:

- Shaft & Bearing
- Generator
- Blade
- Blade tips
- Gearbox

In the actual tool the user can specify all the components and the need for a jack-up barge per component in case of a failure. When a jack-up barge is ordered the barge will arrive after a user defined (statistical distribution) delay. Before the actual repair by the jack-up barge, preparation is needed by the corrective maintenance team. After the repair, the corrective maintenance team has to perform the finishing. Above-mentioned times are all user defined.

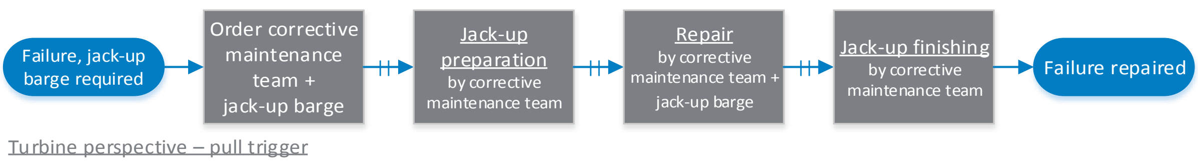


Figure 37: Corrective maintenance flowchart – jack-up required

After the jack-up barge is ordered the barge will arrive after a user defined delay. This order should be processed separately from the preparation activities performed by the regular CTV, so a delay in the preparation activities will not delay the arrival of the jack-up barge and vice versa. With these two parallel process, two situations can occur:

1. Jack-up arrives before preparation activities are finished
   In this case the jack-up waits at the port and starts the actual repair together with the CTV the first days after the preparation has finished (only if the weather allows both vessels)
2. Preparation activities are finished before the jack-up arrives
   In this case the CTV with corrective maintenance team and the jack-up barge start the actual repair the next day after the jack-up barge has arrived (only if the weather allows both vessels).

By using the above described process the user defined/assumed delay for the jack-up barge has no further impact on other processes; in all cases the actual repair only starts after both the jack-up has arrived and the preparation has finished.

8.3. Conceptual Model – Demarcation

This paragraph will elaborate on what is excluded from the model, due to time limitations most of the time.

The inventory related requirements are not covered by the model, due to time limitations. The lead time for the different spare parts and the service level of the parts are not included. It is assumed that minor components are in stock at the port. For major components, the wait time (user defined) for a jack-up barge is assumed to be the limiting factor and major components arrive together with the jack-up barge.

The distance to the spare parts location is also not included implying a dedicated offshore spare parts location is not (fully) possible in the current model. However it is possible to consider the port as the offshore location, by setting the distance to the port at (close to) zero or the speed of the transporters very high. This option should have no impact. The preventive maintenance is performed from the offshore platform in real and from the port in the model. The same holds for the corrective maintenance of small parts, these are kept on stock at the offshore platform in real and at the port in the model. For the large components it is assumed that the component arrives after a user defined delay together with the jack-up barge (which is required for the major components) at the port. So with zero or low distance these will arrive after the delay directly at offshore platform. This approximation of an offshore wind farms will only have an impact when maintenance processes are performed from both the port and the offshore platform or when minor components are stored at the port instead of the offshore platform.

The above discussed demarcation of the (conceptual) model will result in some missed requirements. A full requirement check that assesses which requirements from the stakeholders are included in the actual O&M tool is performed during the verification in paragraph 10.1 after the specification of the conceptual model in the next chapter.

9. Offshore Wind O&M Decision Support Tool

After the conceptual model of chapter 8, this chapter will implement the conceptual model in the in the simulation software and describes the specification of the decision support tool.

> *8. How will the (conceptual) model be specified into the decision support tool and how will the tool look like?*

In paragraph 9.1 the use of Discrete Event Simulation is substantiated. Paragraph 9.2 presents the simulation software Simio that is used for the development of the O&M decision support tool. Assumptions and simplifications are unavoidable when building a model, those will be discussed in paragraph 9.3.

9.1. Implementation Approach

The general research method in paragraph 1.5 already set and argued the use of simulation, still there are different simulation types. In this paragraph there will be argued that DES fits best for this thesis. First, a detailed a definition will be presented and thereafter there will be substantiated why DES is considered as the most suitable. The next definition of Hild (2000) is used in this thesis:

> "The *Discrete Event System Specification (DEVS)* assumes that the time base is continuous and that the trajectories in the system database are piecewise constant, i.e., the state variables remain constant for variable periods of time. The jump-like state changes are called *events*. The models specify how events are scheduled and what state transitions they cause. Associated simulators handle the processing of events as dictated by the models."

This type of simulation fits best for the development of an O&M decision support tool. The offshore is characterized by transitions and *events*; different types of maintenance events and failures. The energy production can be considered as the only continuous aspect. Therefore the production has to be discretized. However since all the historical weather data are also divided in time steps, the use of discrete simulation has no impact on the results compared to a continuous simulation approach.

To overcome all the identified integration challenges (chapter 7), the key elements are variability and the use of historical data or a Markov chain. The main features and advantages of DES for an O&M decision support tool are considered that a DES is able to 1) use stochastic parameters or state variables for e.g. weather conditions (wave and wind), failure rates, repair time and transfer times, 2) to include the resource (man and material) utilization to test their (un)availability and optimize their capacity, 3) include queues which make their able to test the (waiting) time within the entire process and identify bottlenecks, 4) to combine simulation and P&S, 5) to test different O&M strategies and 6) provide animation in order to get insight in the process. These are all necessary features to implement all the requirements into a decision support tool.

9.2. Implementation Software

To integrate all the requirements in one tool, suitable simulation software is required. *Simio* is considered as most suitable to develop the model. Simio is a discrete simulation software, which is considered as most suitable approach in previous paragraph. Simio models are built object-orientated and shows graphically the objects (Pegden, 2008). This is an interesting feature for this research in order to provide insight in the process for the user.

The most interesting feature of Simio for this research is the *Risk-based Planning and Scheduling (RPS)* feature. RPS takes variation fully into account and provides the necessary information to the scheduler to allow the upfront mitigation of risk and uncertainty (Pegden, 2008). To the author's knowledge, this is the only DES software that combines simulation and P&S in an easy, user friendly and graphical way. The P&S aspect of Simio enables to user to specify a planning. The RPS plug-in then plans the resources and test the feasibility in terms of a probability a specified target date is met, based on variability in multiple runs. So it does not provide the user the most optimal planning, it only assesses the planning provided by the user. Another interesting feature of Simio is the scenario (O&M strategy) comparison and the optimization capability by means of the OptQuest plug-in.

To give insight in the implementation in Simio, the next paragraph will discuss the specification of the conceptual model in Simio appendix G includes a screenshot of the Simio coding for (only) the accessibility of a crew transfer vehicle. Note that this is only a small part of the entire model, which can be requested from the author.

9.3. Specification of the Decision Support Tool

After the conceptual model of chapter 8, in this paragraph the conceptual model will be specified in the Simio software. This paragraph will present the interface including the inputs, the processes of the tool in a bullet-wise description and the output including the KPIs calculation, the results interface and the planning robustness analysis.

9.3.1. Interface

This paragraph will discuss the included input parameters related to all the input requirements and shows the visualization of the developed tool.

Inputs

The right figure shows the input parameters of the decision support tool with example inputs and the related model requirements in gray. The parameters related to the components can be specified in a separated table (see figure 39). The historical weather data can be imported as well as a data table, including time stamps, wave height and wind speeds (requirements M2a – M2e). The production curve (requirement M1e) of different turbine types could be specified as a (lookup) table including the different wind speeds and resulting power generation in kW, assuming linearity between the specified data point. See Appendix H for the power curves of multiple wind turbines.

⊟ WindFarm		
NrTurbines	60	M1a
⊞ DistanceShore	23	M1c
TurbineType	V80	M1e
⊟ Resources		
NrVessels	1	M3b
VesselWaveLimit	**1.5**	M3a
VesselWindLimit	100	M3a
VesselWindLimitPreventive	100	M3f
VesselSpeedKmh	37	M3a
VesselNrPersonnelCapacity	12	M3a
JackupWaveLimit	2	M3a
JackupWindLimit	11	M3a
JackupSpeedKmh	17	M3a
JackupWaitTime	Random.Triangular(3, 7, 21)	M3a
NrTotalPersonnel	12	M3c
⊟ Preventive		
PreventiveNrDays	4	M3f
PreventiveNrPersonnel	2	M3f
⊞ PreventiveFrequency	182	M3f
PreventiveStartingMonth	1	M3f
⊟ Corrective		
CorrectiveNrPersonnel	2	M3g
⊟ Costs		
⊞ PriceMWh	160	*M4a*
PersonnelYear	80000	M3c
ActiveVesselDay	1900	M3a
PassiveVesselDay	950	M3a
JackUpBargeDay	100000	M3a

Figure 38: Model input parameters

M1f	M1f	M2f	M2f	M1h	M1g	M1g	M1g
Component	c	Failure Rate	MTTF (Hours)	Jack Up	RepairTime (Days)	JackUpPreparationTime (Days)	JackUpFinishingTime (Days)
Shaft & Bearing	c1	0.02	438000	☑	1	2	2
Brake	c2	0.05	175000	☐	1	0	0
Generator	c3	0.05	175200	☑	1	2	2
Parking Brake	c4	0.05	175200	☐	1	0	0
Electric	c5	0.1	87600	☐	1	0	0
Blade	c6	0.11	79636.36364	☑	1	2	2
Yaw System	c7	0.15	58400	☐	1	0	0
Blade Tips	c8	0.14	62571.42857	☑	1	2	2
Pitch Mechanism	c9	0.14	62571.42857	☐	1	0	0
Gearbox	c10	0.15	58400	☑	1	2	2
Inverter	c11	0.16	54750	☐	1	0	0
Control	c12	0.17	51529.41176	☐	1	0	0

Figure 39: Components inputs

Visualization

The next figure shows the visualization aspect of the developed tool. During the simulation it is possible to get insight in the process with this visualization. The visualization element is also useful for the verification and validation of the model (chapter 10).

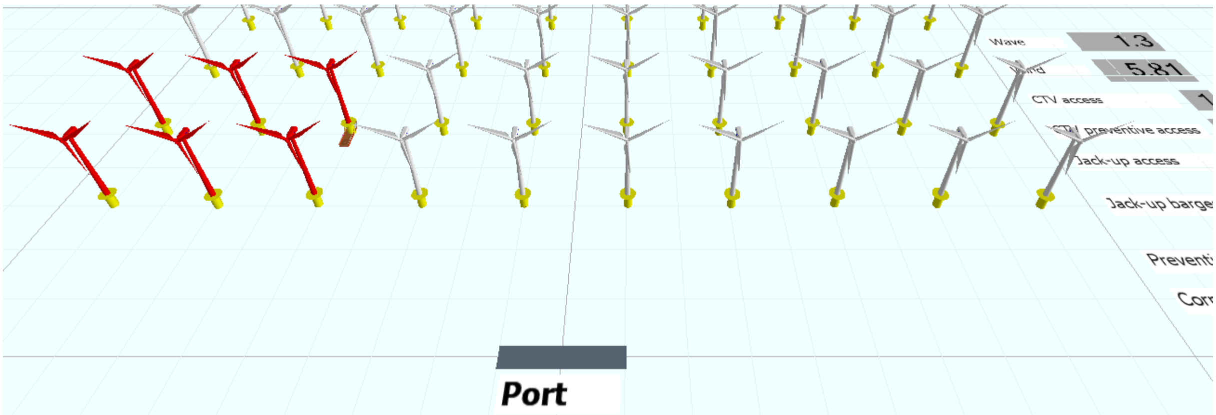


Figure 40: Visualization

During the animation, failures occur and the (jack-up) vessels are performing both types of maintenance. This capability covers requirement M5: *The model should be able to give insight in the O&M process.* Not any of the previous studies is able to provide insight in the process, they all only show numeric output neglecting the process.

9.3.2. Processes

This paragraph will present the processes and events as implemented in the actual DES model. This will be done in a textual, bullet-wise, summarized manner that has more details than the conceptual model, without presenting the actual coding. An example of the actual coding is presented in Appendix G. The model covered processes for the weather, the turbines, preventive maintenance, corrective maintenance, the port and the vessel.

Weather

1. A random number is selected from a uniform distribution with minimum the first year of the data set and maximum the last year of the data set +1. The random number selected from the distribution will be used in the floor function. This function returns the largest integer not greater than the specified number. This results in an integer value between the first year until and including the last year.
2. The selected year together with the user defined starting month will be searched in the weather data table, the first row with those values will be saved.
3. The wave height and wind speed of the selected row will be saved in two separate variables
4. After a delay, equal to the weather step size, the selected row will be increased.
5. Steps 3 and 4 will be repeated during the run.

Accessibility of transporters

1. At the start of each working day (7AM) the current weather row is saved under a new variable.
2. For that new variable there will be checked if the wave and wind values of that variable are below the threshold of the concerning transporter type.
3. The weather row will be increased with 1.
4. Steps 2 and 3 will be repeated until the number of rows that is checked is equal to the (user defined) weather window length (default 10 hours: 8 hours for maintenance and 2 hours for travelling)
5. When all the checks are passed there is access for the transporters, otherwise no access. When there is no access a dummy resource will be seized to visualize a weather day in the planning aspect.
6. Steps 1 – 5 will be repeated for each transporter type (CTV, jack-up barge and a separate check with the preventive maintenance wind limit for the CTV).

Turbines

1. At the initiation of the run the failure rates will be assigned to the components (independent sub objects of each turbine).
2. For the turbines lower and equal to the user defined parameter number of turbines the production and failure processes will be executed.

Production

1. The production curve of the user defined turbine type will be searched in the lookup tables.
2. The number of kWh will be saved based on the production curve and the current wind speed.
3. When a turbine is not failed the kWh will be added to the total production of that turbine
   When a turbine is failed the kWh will be added to the lost production of that turbine
4. Steps 1 – 3 will be performed for each turbine

Failure(s)

1. The component, as sub objects of each turbine, will independently fail based on an exponential distribution with the user defined MTTF.
2. When a component fails a signal will be given towards its 'parent' turbine.
3. The turbine will wait for a failure of one of its components and will also fail. This changes the state and color of the turbine.
4. A corrective maintenance entity is fired (see more in corrective maintenance section).
5. The failed component is saved as an attribute of the relevant turbine. The turbine will wait until the failure is repaired (see more in corrective maintenance section).
6. The turbine signals the repair towards the component and repairs both the turbine and components.
7. Steps 3 – 9 will be repeated during the run.

Preventive Maintenance

1. The model checks whether there are teams available (idle personnel / personnel required)
2. When there are teams available and turbines left to maintain a preventive maintenance entity is created
3. Steps 1 and 2 will be repeated every day.
4. Steps 1 – 3 will be repeated after the user defined frequency.
5. When a preventive maintenance entity is created the priority (low for preventive), next turbine and the time are saved and the entity will be transferred (0 time) to the port.
6. At the port the accessibility is determined and the actual loading into vessel is performed (see more in the port section)
7. When a preventive maintenance entity arrives at his turbine, the turbine will fail and repaired for x hours (user defined). The number of maintenance days is stored and this step will be repeated until the required (user defined) maintenance days are performed.
8. When all the maintenance days are performed and the entity is back at the port the time is written (for the planning analysis).

Corrective Maintenance

1. When corrective maintenance entity is created after a failure, the priority (high for corrective), component, turbine and failure count are updated.
2. When a jack-up barge is needed, a jack-up entity will be created.
3. Both the corrective maintenance entity and the eventual jack-up entity will be transferred (0 time) to the port.
4. At the port the accessibility is determined and the actual loading into vessel is performed (see more in the port section)
5. When a corrective maintenance or jack-up entity arrives at a turbine, each day there will be checked whether the jack-up preparation is done, whether the jack-up is already arrived, whether the number of repair days are done and (when all true) whether the jack-up finishing is done

Port

1. For all the entities (preventive, corrective and jack-up) the will be checked if they are finished their job (after maintenance). If so they are destroyed.

2a. For the preventive and corrective entities the turbine location is set, there will be checked whether there is access and sufficient personnel. For the preventive entity there is also checked whether it is weekend (during weekend no preventive maintenance) and whether the turbine has a failure (during failure no preventive maintenance). When the corrective entity needs a jack-up during the repair (not during the jack-up preparation prior to the repair) there is also checked if the jack-up barge has access (jack-up barge has other thresholds than the CTV)

2b. The jack-up entity has to wait first for the jack-up barge (user defined delay time). After that delay a jack-up barge transporter is created at the port. There will be checked whether there is access for the jack-up barge, sufficient personnel for the corrective maintenance (a CTV with personnel has to support the jack-up operation) and whether the jack-up preparation is finished.

3a. When all checks are passed the preventive and corrective entities request a ride from the CTV and saves the selected CTV, otherwise the entity will wait for a day. The CTV will wait until all waiting entities are loaded (dwell time of 10 second at the port) and saves which entities are loaded.

3b. When all checks are passed the entity requests a ride from the jack-up, otherwise the entity will wait for a day.

Transporters

1. When a CTV or jack-up barge loads or unloads, the correct (scaled) speed is assigned.
2. When a CTV loads at the port it will wait unit all waiting entities are load or until full and the number of loaded entities is saved.
3. After the maintenance the CTV loads the (same) entities at the turbines. This will be done for all the entities that were loaded at the port earlier that day.

4. After the loading of an entity at a turbine, the CTV checks whether all entities are loaded. If not, the CTV goes to the next entity (same entities and order as loaded at the port)

9.3.3. Output

This paragraph will discuss the calculation of the KPIs, the comparison of the results after the simulation and will present the planning analysis capability of the tool.

KPIs calculation

In the next table all the included KPIs are presented. This paragraph will elaborate on the calculation of these KPIs.

Table 16: Overview KPIs

KPI	Description	Measure
C1	Energy-based availability Time-based availability	% total production / (total production + lost production) % online time / total time
C1.1	Total production	MWh hour
C1.2	Lost production	MWh hour
C2	Total production revenues	M€
C3	Total O&M costs	M€
C3.1	Lost Production costs	M€
C3.2	O&M resources costs	M€
C4	Robustness of preventive maintenance plan	day
C4.1	Probability target exceedance	% probability all scheduled maintenance is not finished before a target date
C4.2	Average target date exceedance	day

At the end of the run the percentage of each turbine in the 'online' (not failed) state is summed. This is also done for the production and lost production (see previous paragraph for calculation of those). This is done for all the user defined turbines. To calculate the average the sums are divided by the number of turbine (KPI C1, C1.1 and C1.2). To calculate the energy-based availability (C1) the production is divided by the production plus the lost production.

The production revenues (C2) is the product of the total production (converted to MWh) of all the turbines and the price per MWh.

The total costs (C3) are the sum of the lost production costs (C3.1) and the O&M resources costs (C3.2). The lost production costs (C3.1) is the product of the lost production (converted to MWh) of all the turbines and the price per MWh. The O&M resources costs (C3.2) are the sum of the cost for personnel, CTVs and jack-up barges. The costs of personnel is the production of the number of personnel, the costs per year and the simulation time in years. The costs for the CTVs and jack-up barges are the product of the rate per day and the number of days the transporter is used. For the CTVs the unused days will be multiplied by the unused rate and added to the costs.

The robustness of preventive maintenance plan (C4) is the product of the probability target exceedance (C4.1) and the average target date exceedance (C4.2). C4.1 is derived from the planning analysis (see next paragraph). C4.2 is based on the time the preventive maintenance of the last turbine is finished and the target date (equal to preventive campaign frequency). When the last turbine is maintained before the target date, 0 target date exceedance days are recorded (for that replication). When the last turbine is maintained after the target date the number of days after the target date is recorded, unless the last turbine is not maintained at all before the simulation has finished. When the last turbine is not maintained before the simulation run has finished, the simulation time minus the preventive campaign frequency is recorded. E.g. the simulation time is one year and the preventive campaign frequency is 182 days, the exceedance is recorded as 183 days.

Planning analysis

Besides the normal run (as depicted in figure 40) and the results comparison (next paragraph), another capability of the developed tool is the planning aspect. Based on the same input it is possible for the user to create an entity plan per preventive maintenance (per turbine), see figure 41.

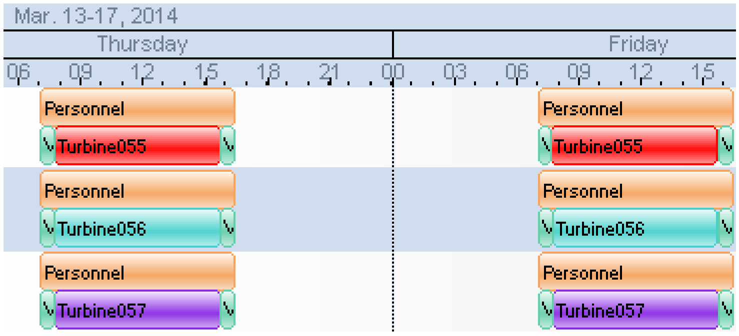


Figure 41: Preventive maintenance plan

This plan is derived from a single run without variability (e.g. weather and failures). To assess the robustness in terms a target date is met, a risk analysis can be performed, depicted in figure 42. During the risk analysis, the variability is enabled and the probability (including confidence interval) that target is met is analyzed, based on a user defined number of replications. The planned finishing time (without variability) of the last turbine is presented (red circle) as well as the probability that target is met (blue circle).

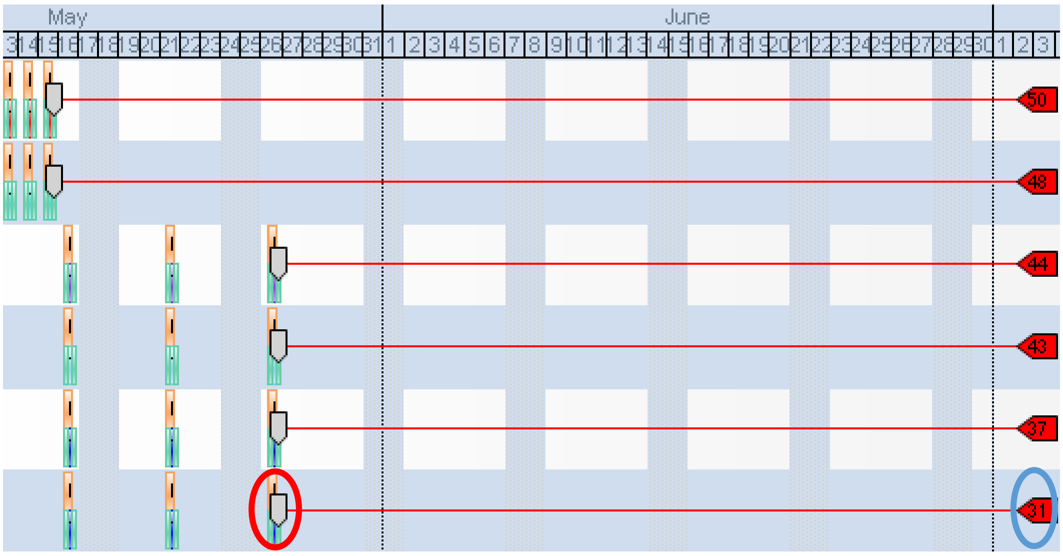


Figure 42: Case study - Preventive maintenance plan risk analysis

The planning analysis covers requirement M7: *The model should be able to design feasible and robust scheduled maintenance.* The planning of preventive maintenance is not included in the previous studies examined during this thesis. Only Scholz-Reiter et al. (2010) included a Gantt chart for the *construction* of an offshore wind farm.

Results comparison

To compare different alternatives, the user can specify different scenarios with their parameters (same as figure 38) as shown as in the example in the next figure

Scenario	Wind Farm - Controls			Resources - Controls			
Name	DistanceShore (Kilometers)	NrTurbines	TurbineType	NrVessels	VesselWaveLimit	VesselWindLimit	VesselWindLimitPreventive
A0	23	60	V80	1	1.5	100	100
A1	23	60	V80	1	1.5	100	9
A2	23	60	V80	1	1.5	100	100
A3	23	60	V80	1	2	100	100

Figure 43: Scenario inputs

After specifying the scenarios the user can run them all for a desired run length and number of replications. The results are presented after the simulation on all the KPIs. A snapshot of the first KPIs is presented in figure 44

Scenario	Responses				
Name	C1_0_TurbineEnergyAvailability	C1_0_TurbineTimeAvailability	C1_1_TotalProductionMWh	C1_1_TotalProductionTime	C1_2_LostProductionMWh
A0	96.7271	96.6252	444651	8464.36	15085.6
A1	96.9369	96.6577	445611	8467.22	14126.2
A2	96.8316	96.8158	445129	8481.07	14607.6
A3	97.1376	97.0319	446561	8499.99	13176

Figure 44: Scenario results

The tool can also display the results by graphical box plots, as depicted in the next figure. The box plot horizontal lines represent the 25% percentile with the 95% confidence interval in blue, median and the 75% percentile with confidence interval. The yellow dot shows the average with the 95% confidence interval in the yellow bar. The black vertical line indicates the total range of observations. All these are based on multiple replications.

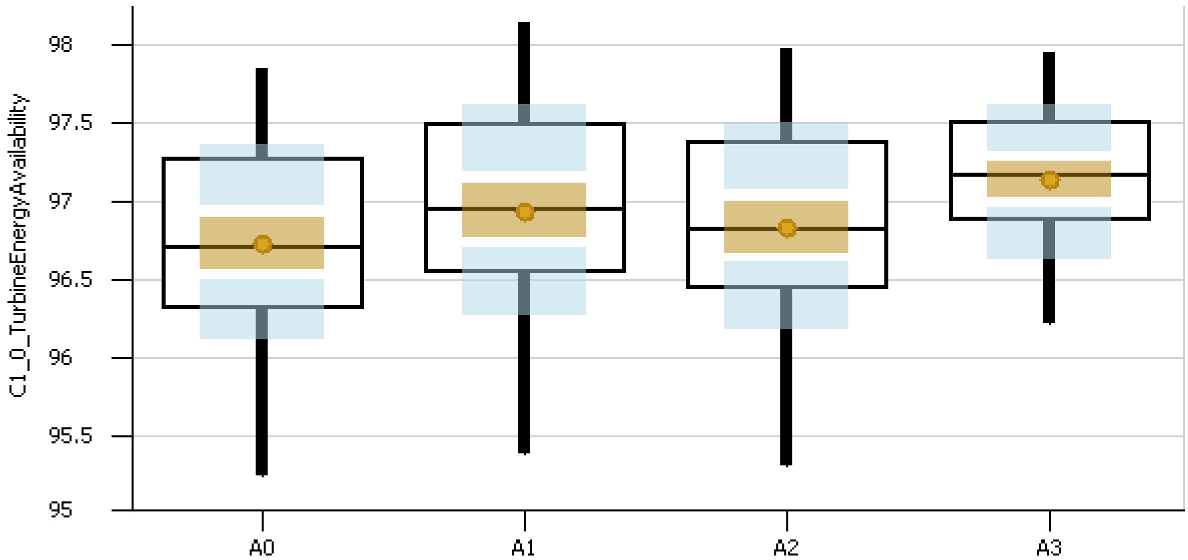


Figure 45: Results box plots

Besides the comparison of user defined scenarios it is also possible to use the optimization option, letting the model creates scenarios to find the optimal strategy. The optimization engine OptQuest, plugin within Simio, will search in an efficient way within user defined values to find the best strategy. The OptQuest Engine combines Tabu search, scatter search, integer programming, and neural networks into a single, composite search algorithm that provides maximum efficiency (OptTek Systems, n.d.). In chapter 11 the optimization aspect is demonstrated within a case study.

The results comparison covers requirement M4: *The model should be capable to present output on the KPIs* and requirement M6: *The model should be able to compare and optimize different O&M alternatives.* Requirement M4 is covered partly by previous studies. Most of the sub requirements of requirement M4 are researched before. Only the robustness of preventive maintenance, measured both as target exceedance probability and impact are not included in any of the previous studies. Requirement M6 is already covered by previous research, except from the visual presentation of the output by means of box plots and the optimization aspect. The (fictitious) case study in chapter 10 will demonstrate the optimization aspect more elaborate with an example.

9.4. Implementation Assumptions

Since a model is a representation of the real system, as described in the previous chapter, and since it is not feasible to model the entire real system, assumptions and simplifications are needed. This paragraph will shortly describe which assumptions and simplifications are used when the conceptual model is implemented in Simio. The use of assumptions and simplifications should demark the real systems and reduce the model complexity while no not having a significant impact on the results.

Assumptions and simplifications are made on different levels, see next figure. The highest level, assumptions and simplifications on the conceptual model (scope), is already discussed in paragraph 8.3. For example, the inventory related aspects are outside the scope of the (conceptual) model). This paragraph will discuss the assumptions one level lower; assumptions on the translation of the conceptual model into the Simio model. Assumptions for a specific case can be considered as the third level of assumption. Those assumptions are used for the validation in chapter 9 and for the (fictitious) case study in chapter 10. The used input parameters are assumed based on literature and held interviews and presented in the corresponding chapter. The decision support model is built to be a generic model. So most of the data are user defined parameters. The advantage of the use of parameters is that the model is more generic and the user can specify the input data implying that no hard coded numbers have to be assumed when data is unknown (for the author).

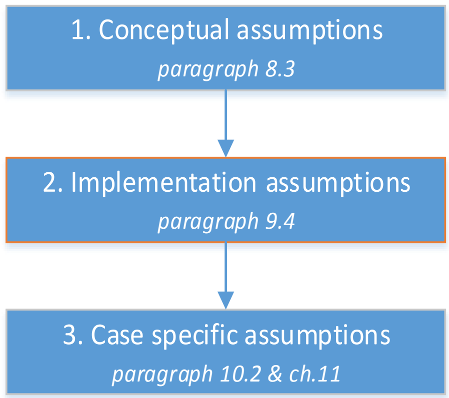


Figure 46: Assumptions levels

The assumptions that are made for the implementation of the conceptual model can be divided into two categories. Some assumptions can be considered as assumptions that can be solved when extending or improve the model; extendable assumptions. The other assumption can be considered as limitation of the model. The latter cannot be easily solved and are thus more severe assumptions.

Extendable assumptions

- For the minor components (no jack-up barge needed, in case of failure) unlimited availability is assumed at the port.
- For the major components (jack-up barge needed, in case of failure) no stock is assumed. It is assumed that the waiting time for the jack-up barge is the limiting factor; the larger components are also available within the waiting time for the jack-up barge. The components

that require a jack-up barge and the waiting time (all common statistical distributions possible) for the jack-up barge are user defined.
The consequence of these two assumptions is limited. Only for failures of major components there could be an implication. If a major components is not in stock in real and the lead time for that component is longer than the lead time for a jack-up barge, the model will behave different, since the limiting factor is the waiting time for a jack-up barge. In that situation the result of the decision support tool will be more optimistic than it should be. Since this applies only if a major component failed plus the lead time for a new component is longer than the jack-up barge lead time, this assumption will not have a major impact.

- Only CTVs and jack-up barges are included. Helicopter and mother vessels could be included in future extensions of the model, see more in chapter 11.
- Jack-up barges have unlimited availability (not unlimited accessibility). Only a user defined waiting is included between the failure and the arrival of the jack-up barge.
- It is assumed that there are no vessel failures.
  In some case this assumption can lead to more positive results. However some wind farms rent their vessels and will receive another vessel in case of a failure (Van Dongen, 2014), in that case the impact of this assumption is low.
- Only two main maintenance strategies are included; preventive scheduled maintenance and corrective maintenance. Condition based maintenance is partly included, similar to (Van de Pieterman et al., 2011). It is possible to increase the number of preventive scheduled maintenance and reduce the failure rates of the components, due to these additional preventive visits.
- During weekdays the number of personnel is user defined and are working 7AM – 5PM.
- During the weekend always one corrective maintenance team is on standby, for corrective maintenance only.

Limitations

- All the weather accessibility checks for the user defined weather window and the possibility to perform maintenance will be considered by the model per day at the start (7AM) of each day. Accessibility is determined for the next 10 hours (default, user defined).
- As many as possible preventive maintenance teams are pushed every day after the personnel is deployed for corrective maintenance. For example, if there are in total six maintenance teams and four are seized by failures, two teams are pushed to perform preventive maintenance.
- A failure can occur (based on failure distribution) during preventive maintenance. In that case, the failure will start after the preventive maintenance of that day and the repair will start the next day at 7AM. The preventive maintenance continues after the failure is repaired.
- If a turbine failed, no preventive maintenance will be initiated. Preventive maintenance will start after repair.
- A failure outside the working hours will be repaired with highest priority the next day starting from 7AM.
- The failure will occur based on an exponential distribution, with the same distribution over the total simulation period. So there is no 'bathtub effect', i.e. a higher failure rate during the first and last year(s) of the turbine's lifetime.

The assumptions listed above are made to reduce the modelling complexity while having no significant impact on the results. The (accuracy of the) output of the model is still highly dependent on the user input, however the relative differences between the scenarios/strategies should be still accurate.

Section 3: Testing the O&M Decision Support Tool

In section 2 the integration challenges and a suitable approach to integrate these challenges are identified. The challenges, and the requirements from section 1, are implemented in the actual decision support tool. In this sections the model will be tested in terms of correctness and validity in chapter 9. After the validation a (fictitious) case study is presented in chapter 10 to demonstrate the capabilities and added value of the model.

9. *To what extent is the developed integrated model correct and can it be validated for different wind farms?*
10. *What is the added value of the developed decision support tool and how can the tool serve the O&M planning and process?*

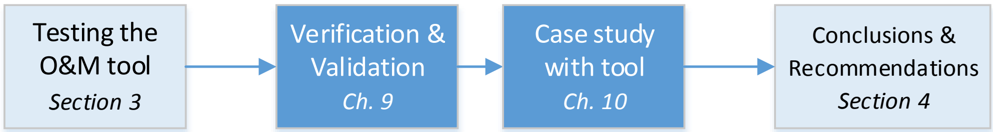


Figure 47: Outline section 3

10. Verifying and Validating the O&M Decision Support Tool

After the model building in the previous chapter, the model has to be checked. In this chapter sub question 8 will be answered.

> 9. *To what extent is the developed integrated model correct and can it be validated for different wind farms?*

In this chapter the focus is on the verification and validation of the model. The next definitions of Balci (1997) are used:

> *"Model* ***Verification*** *is substantiating that the model is transformed from one form into another, as intended, with sufficient accuracy. Model verification deals with building the model* right. *The accuracy of transforming a problem formulation into a model specification or the accuracy of converting a model representation from a micro flowchart form into an executable computer program is evaluated in model verification."*

> *"Model* ***Validation*** *is substantiating that the model, within its domain of applicability, behaves with satisfactory accuracy consistent with the modeling and simulation objectives. Model validation deals with building the* right *model."*

10.1. O&M Decision Support Tool Verification

According to the definition of Balci (1997), stated above, model verification deals with the accuracy of converting a model representation from a flowchart form into an executable computer program. In this paragraph there will be checked how the flowcharts of paragraph 8.1 are implemented in the Simio model. For the verification the next tests will be performed sequentially:

1. **Requirements Verification**: With this test the requirements identified in section 1 will be checked. The requirements' verification will demonstrate which requirements are included in the model and what the added value of the model is.
2. The second test will be a combination of the next three techniques:
    a) **Animation**: "The model's operational behavior is displayed graphically as the model moves through time." (Sargent, 2005)
    b) **Event Validity**: "The 'events' of occurrences of the simulation model are compared to those of the real system to determine if they are similar." (Sargent, 2005)
    c) **Model Walkthrough**: "The logic of the model is analyzed, its consistency is verified, and its completeness is determined. In an organized manner, the examiners walk through the details of the design or source code to perform the verification." (Whitner & Balci, 1989).

    Basically, all the main elements of the flowcharts presented in chapter 8 will be checked step-by-step by means of animation.

10.1.1. Requirements Verification

Most of the requirements, as listed in chapter 4, are covered. As already discussed in paragraph 8.3, due to these time limitations, some demarcations and assumptions are made to reduce the complexity of the model; therefore the inventory aspect is not included. So the inventory related requirements M1d, M2g and M3d are not or partly covered (yet). This paragraph elaborates on the remaining requirements. With the requirements' verification test all the model requirements will be checked whether they partly or fully implemented in the model. The full results of this test can be found in appendix I. This paragraph only discusses the remarkable results with respect requirements that are not inventory related.

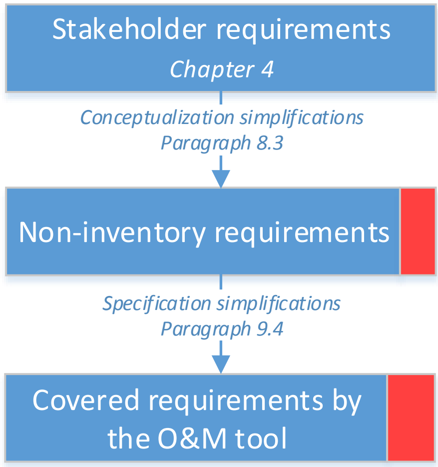


Figure 48: Requirements verification

The distance between the turbines is assumed to be 500m (scaled) fixed. This is not included as a user defined parameter, although the user can drag the turbines in the model to obtain the real distances between the turbines. So this requirement is not covered as a user defined parameter in the model and therefore considered as partly included. The assumption of 500m is considered as presentative and expected to not have a significant influence. This assumption has only an impact when turbines will be maintained in a different order across the whole wind farm, e.g. based on a user preference or based on monitoring data. The current model assumes sequential preventive maintenance, although an extension could be to use a user defined sequence.

Condition based maintenance is partly included. Like the ECN case study (Van de Pieterman et al., 2011), it is possible to simulate condition based maintenance by reducing the failure rates and increasing the frequency of the preventive maintenance manually. This approach has probably no significant influence on the results, however it is not a very neat and realistic implementation of condition based maintenance. A more desired approach is to use real monitoring data, preferably per turbine.

Table 17: Not or partly included requirements

Nr	Requirement	✓/✗
M1b	The distance between the turbines	✓
M1d	The distance from the (offshore) spare parts location	✓
M2g	Include the lead time of the different components, including randomness	✗
M3d	Vary the service level/amount of stock regarding spare parts inventory	✗
M3e	Perform condition based maintenance	✓

All the other, not to inventory related, requirements are (fully) fulfilled. The requirements which are not covered by the model and could be considers as extension options for future versions of the tool or future research, see more in chapter 12.

10.1.2. Model Walk-through

During the model walk-through verification, the model will be verified on different aspects. A selection is made with four main aspects to verify the model:

1. Failures of turbines
2. Repair of failures
3. Energy production
4. Combination preventive and corrective maintenance

Step-by-step, parts of the model will be tested whether the flow charts are implemented correctly and whether or not all the four aspects work properly.

Failures of Turbines

In this test there will be reviewed if the failures rates are implemented correctly and result in the expected number of failures, also called event validity by Sargent (2005). To test this, only failures are enabled with an exponential distribution and no preventive or corrective maintenance is enabled. Failures will repair themselves directly, only the number of failures is desired for this test. Therefore, 100 turbines with 10 components and failure rates for each component of (on average) one failure per day. The verification test is performed with 100 runs of 10 days. The expected result is to have 100 turbines * 10 components * 10 days = 10,000 failures per 10 days.

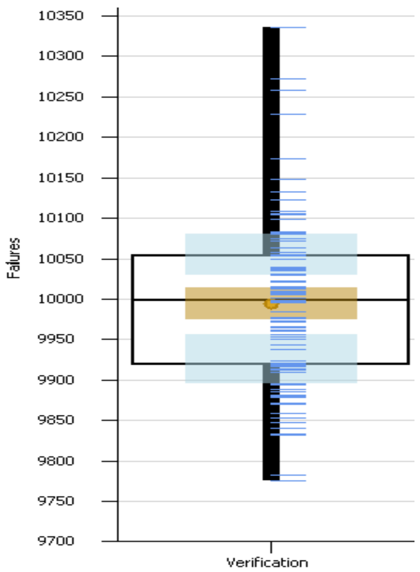


Figure 49: Verification – failures

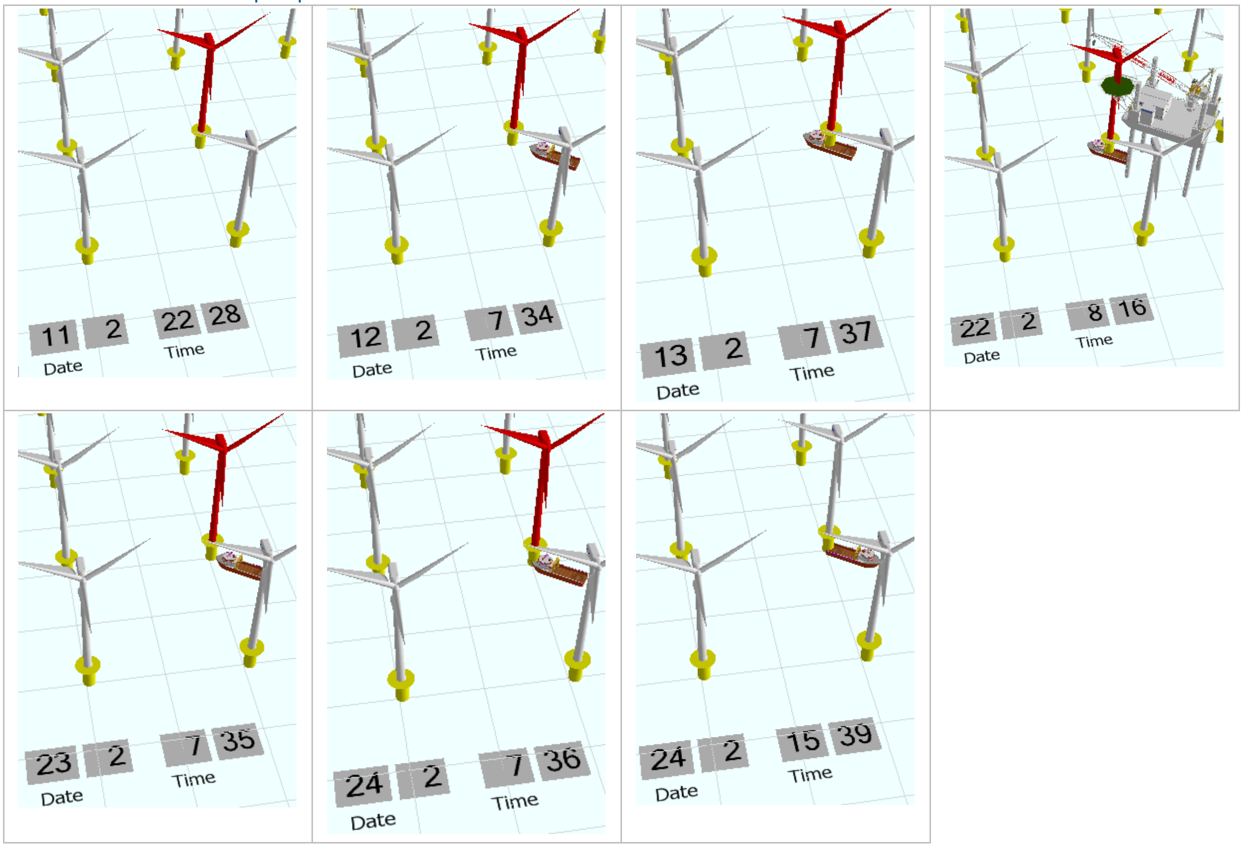
The figure above shows the results of the verification test. With a mean of 9,994.56 and a 95% confidence interval of [9,974.48 – 10,014.64]; this test can be considered as **passed** without issues.

Repair of Failures

For this test the repair process will be walked through step-by-step, by means of animation. A failure of a main component (jack-up barge required) is used, to check the most extensive repair. For this test the weather thresholds of the vessels are disabled and major components require 2 days of preparation, 1 day of actual repair and 2 days of finishing. The waiting time for a jack-up barge is for checking purposes set on a fixed delay of 10 days after failure.

In the table below, seven screenshots of the animation are added. The first figure shows a failure of a major component at a turbine at the 11th of February during the night. After the failure, two days of jack-up preparation are performed by a CTV. The jack-up barge is arrived at the port before the start of the 22nd. On that day the failed component is replaced by jack-up barge supported by a CTV. After the replacement, two days of finishing work are performed, before the turbine is repaired completely.

Table 18: Verification – repair process



No abnormalities are discovered during this check, so the test can be considered as **passed** without issues.

Energy Production

To verify the energy production aspect of the decision support tool, the output of the tool will be compared with the output according to the PV-curve calculated in Excel, using the PV-curve of a 2MW V110 (Vestas, 2014 - see also Appendix H) for both the tool as in Excel. This done for the first 25 days of the year 2000, using the German wind farm Sandbank (data available at Systems Navigator). Both are using a lookup function using the data point of Appendix H, assuming linearity between the data points.

The first figure presents the output of the developed offshore wind O&M decision support tool with the corresponding (scaled) wind speeds, the second one is the excel output. Both show kW on the left axis and the (25) days on the horizontal.

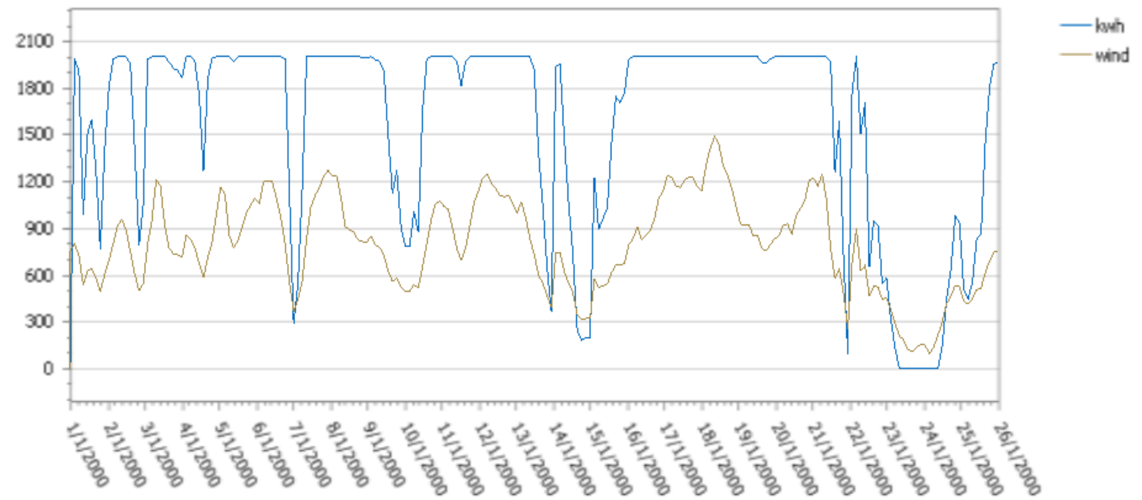


Figure 50: Verification – developed decision support tool output

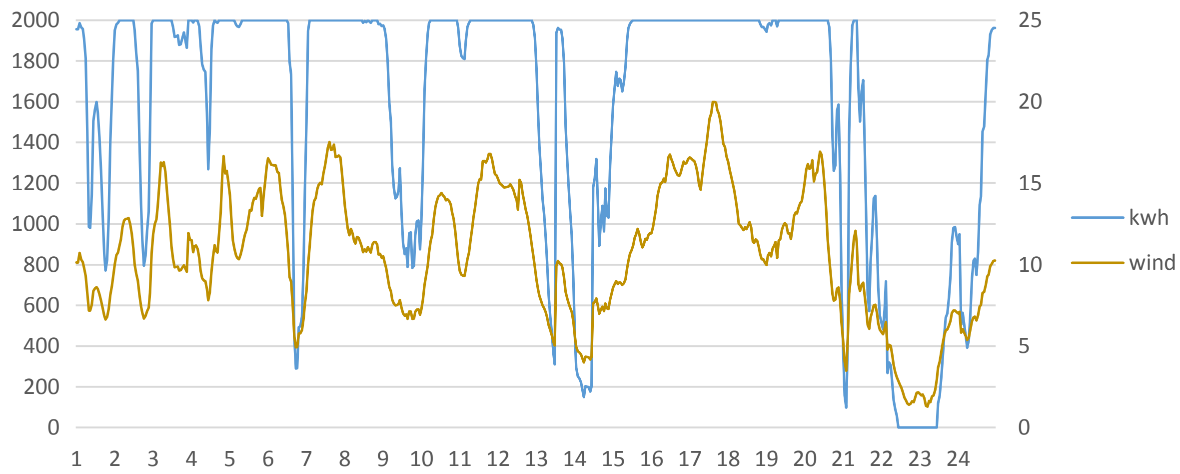


Figure 51: Verification – Excel output

Looking at both figures, there are no significant differences observed. Since the upper figure seems a bit smoother, a detailed data comparison is performed. For this comparison the model output per hour (for 25 days) is compared to calculated Excel energy production. The model calculated exactly 1-to-1 the same production as calculated in Excel; a correlation of 1. This is as expected since both use a (same) look-up function, so this test can be considered as **passed** without issues.

Combination Preventive and Corrective Maintenance

This test will elaborate on the conflicts between preventive and corrective maintenance, integration challenge 4 of paragraph 7.1. In the unlikely event of either (1) a failure during preventive maintenance or (2) preventive maintenance during failure the next two assumptions are made:

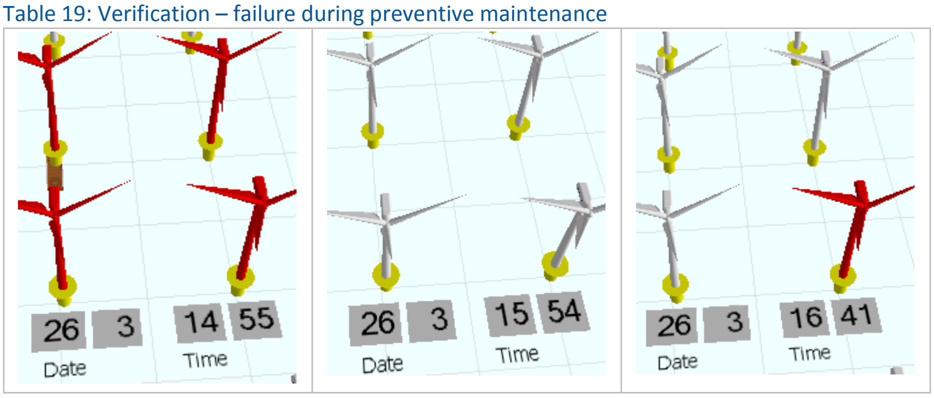
- A failure can occur (based on failure distribution) during preventive maintenance. In that case, the failure will start after the preventive maintenance of that day and the repair will start the next day at 7AM.
- If a turbine failed, no preventive maintenance will be initiated. Preventive maintenance will start after repair.

These assumptions are both tested by means of step-by-step animation walk-through.

Failure during Preventive Maintenance

As can be seen in the next table, normal preventive maintenance is being performed at four turbines. At 14:55, a failure is planned to occur, based on the exponential distribution. This failure is postponed until the preventive maintenance is finished for that day (second figure), after the preventive maintenance the failure will occur (third figure) and the normal repair process is started.

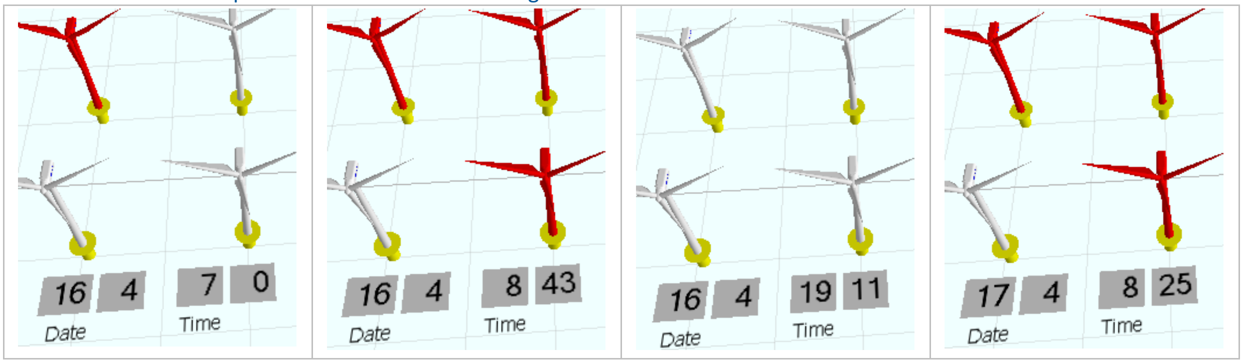
Table 19: Verification – failure during preventive maintenance



Preventive during Failure

If a turbine is failed (upper left turbine on first figure of the next table) and preventive maintenance is planned for that turbine, the turbine will be repaired first. Preventive maintenance will be performed at the other turbines and corrective maintenance will be performed at the failed turbine (second figure). At the end of the day preventive maintenance is done for that day and the failed (minor component) turbine is repaired (third figure). The next day preventive maintenance will be performed at the repaired and other turbines (fourth figure). Note that bottom left turbine is already been maintained.

Table 20: Verification – preventive maintenance during failure



During both tests, the processes are performed as expected before, so the tests are **passed** without issues.

10.2. O&M Decision Support Tool Validation

> *"Model **Validation** is substantiating that the model, within its domain of applicability, behaves with satisfactory accuracy consistent with the modeling and simulation objectives. Model validation deals with building the* right *model."* (Balci, 1997)

To validate the model, or to determine whether the right model is built, the O&M decision support model will be validated in this paragraph. The O&M tool will be validated by means of two validation techniques:

1. A comparison with another, validated model in paragraph 10.2.1
2. A 'face validation' together with an offshore wind farm O&M expert in paragraph 10.2.2

These techniques are considered the best available options for validation. After the comparison and the expert validation a real project together with an offshore wind O&M planner is recommended to examine the validity of the model within the real O&M process.

10.2.1. Comparison to Other Models check

With this technique, results of the simulation model being validated are compared to results of other (valid) models (Sargent, 2005). In this paragraph, the O&M decision support tool will be compared with the earlier mentioned ECN O&M Calculator. This is the only model in the sector that is validated by an independent party; in 2007 certification agency Germanischer Lloyd awarded the model with a validation statement (ECN, 2007).

The ECN O&M Calculator has similarities and differences with the developed O&M decision support tool as already discovered chapter 6. Despite the differences, the models will be compared on the overlapping aspects. For some differences, some data shaping is necessary. This is explained after the input data.

For the comparison of both model, the input and results of a previous case study with the ECN O&M Calculator will be used, performed by Van de Pieterman et al. (2011). The next table displays the input used in the case study with the ECN O&M Calculator.

Table 21: Validation – input parameters

Parameter	Validation input
Weather data	Sandbank offshore wind farm (2000-2011, German North Sea) [1]
Wind farm	
Distance to shore (km)	120
Number of turbines	130
Type of turbine	4.0MW [2]
Resources	
Number of CTV	3 [3]
CTV wave limit (m)	2.0 (Windcat, 2010)
CTV wind limit (m/s)	∞
CTV wind limit preventive maintenance (m/s)	∞
CTV speed (km/h)	120 [4]
CTV personnel capacity (#)	12
Jack-up barge wave limit (m)	2.0 (Dewan, 2014)
Jack-up barge wind limit (m/s)	11 (Dewan, 2014)
Jack-up barge speed (km/h)	120 [4]
Jack-up barge waiting time (day)	TRIA(3,7,21) [5] (Van Buchem, 2014a)
Number of personnel (person)	36
Preventive maintenance	
Number of personnel per turbine (person)	3
Number of days per turbine (day)	5 [6]
Frequency (day between preventive maintenance campaigns)	365 (1 campaign/visit per year)
Starting month (month number)	1 (January)
Corrective maintenance	
Number of personnel per turbine (person)	3
Costs	
MWh (€/MWh)	130

The light red cells contain values that are not found in the case study of Van de Pieterman et al. (2011). These parameters are still required for the model and are therefore assumed. The sources of these assumptions are displayed in the cells. Some remarks on the data shaping has to be explained:

1. The weather data of the 90km from the coast German wind farm Sandbank is used (available at Systems Navigator) since these data is available with enough years. The next graph presents the averages per year with respect to wave height and wind speed to get some insight in the weather data:

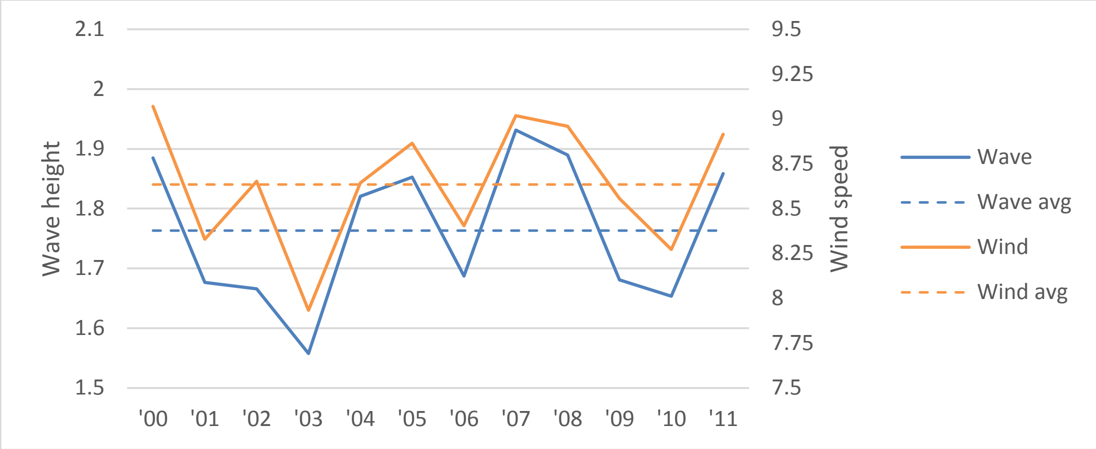


Figure 52: Validation – Sandbank weather

2. The same power curve is used as in the case study of Van de Pieterman et al. (2011); see Appendix H.
3. Three CTVs and one jack-up barge are used. A mother, diving and cable laying vessel are not possible (yet) in the model, the same holds for a helicopter.
4. The case study uses a mother vessel for the preventive maintenance and corrective maintenance of small components. In this validation this mother vessel is simulated in the developed tool as the port. To still have a transit time of one hour, as used in the ECN case study, the CTV has an (unrealistic) speed of 120km/h in the model from the shore/port to the wind farm.

   By this assumption the preventive maintenance is performed with one hour transit time in both models, so it is expected that the above assumption has no impact on the preventive maintenance.

   For the small components the ECN case study assumed that they are on stock at the mother vessel, so a transit time of one hour. The developed model assumed that these components are available at the port, so with the vessel speed assumption the transit time is still one hour. So for the repair of smaller components, this assumption has no impact.

   For the larger components (jack-up barge required), no information is mentioned in the case study regarding the waiting time. For this waiting time the next assumption (5) is used.
5. The TRIA(3,7,21) represents a triangular distribution with a minimum of 3 days, a mode of 7 days and a maximum of 21 days as waiting time before the jack-up barge arrives at the port. This delay is not influenced by the weather, however when the jack-up barge has arrived at the port the weather determines the accessibility of the wind farm. So after the triangular distributed waiting time, there might be some additional delay due to bad weather plus a transit time of one hour. This approximation is based on the held interview (Van Buchem, 2014a); jack-up barges have most likely a lead time of a week but it could be up to three weeks and a minimum of a couple of days. As mentioned in paragraph 8.3 the waiting time for the jack-up barge is assumed the limiting factor; the larger components are also available within the waiting time for the jack-up barge.

   The next figure presents the probability curve of this triangular distribution.

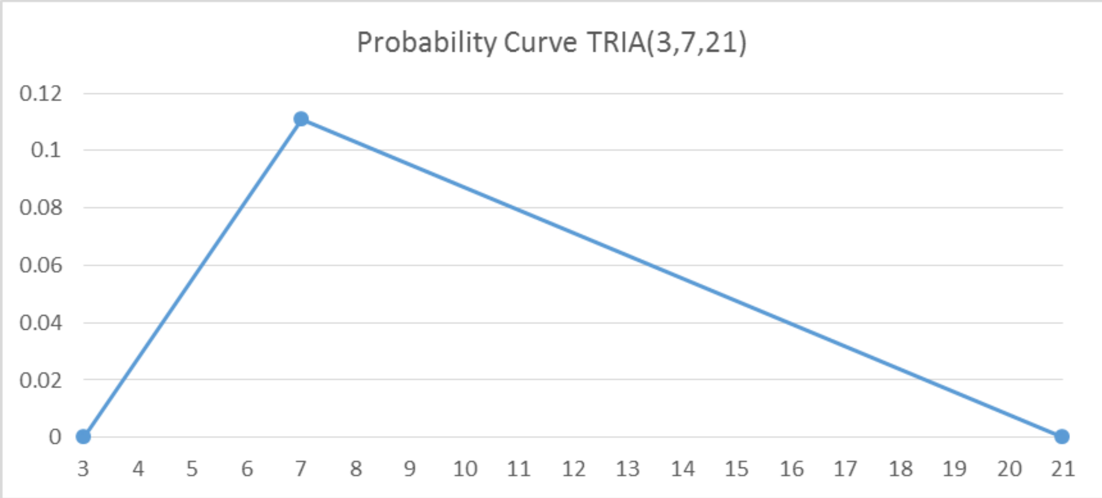


Figure 53: Validation – Triangular (3,7,21) distribution for jack-up barge delay, obtained via @RISK software

To investigate the impact of this approximation, a sensitivity analysis is performed. The next figure illustrates that after 100 runs with the triangular distribution, the sensitivity coefficient is -0.109 (see figure 46) with respect to the energy-based availability and -0.132 with respect to the time-based availability. In other words for each day increase (on average) in the waiting time, the energy-based availability will decrease with 0.109 (percentage points) and the time-based availability will decrease with 0.132 (percentage points).

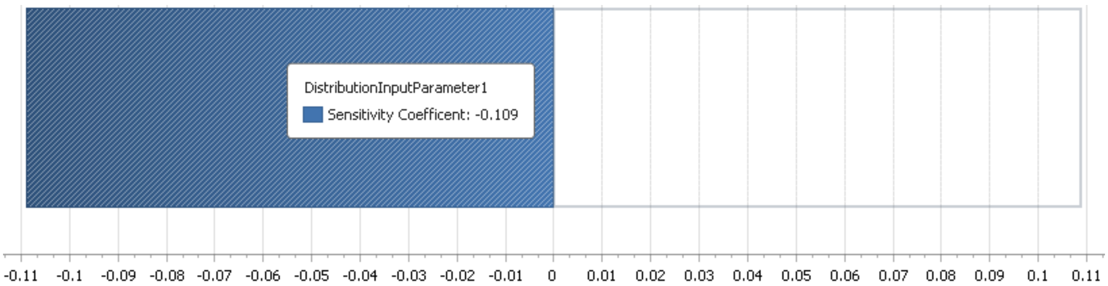


Figure 54: Sensitivity coefficient jack-up barge waiting time w.r.t. the energy-based availability

This approximation is expected to not have a significant influence on the results since the 95% confidence interval of both availabilities have a range of more than 1.1 percent points, see table 22 and 23. So increasing the waiting time with e.g. a week (on average) still have no significant impact.

6. More than 28 hours per turbine is spent on scheduled and condition based maintenance in the ECN tool case study. In the developed O&M decision support tool, this is translated as five working days of six hours preventive maintenance per turbine to cover both the scheduled and condition based maintenance.
7. The ECN case study simulated 1083.52 failure over the 130 turbines, or 8.33 failures per turbine. Of all the failures there are 5 remote resets. For the remote resets no downtime is assumed. The remaining 3.33 failures per turbine per year are included for same components as used by Van Bussel & Zaaijer (2001) based on an exponential distribution. Since they used 1.28 failures in total per turbine per year, all the failure rates of the 12 components are multiplied by 2.60, resulting in 3.33 failures (on average) per turbine per year.

8. The repair times are assumed to be 1 day for minor components. For major (jack-up required) components 2 days preparation, 1 day repair and 2 days of finishing are assumed, as explained by Van Buchem (2014a).

The two models are compared on the availabilities, the production criteria (C1.1 and C1.2) and the value of the (lost) production (C2 and C3.1). The O&M costs and scheduling criteria are not used. The costs criteria are not relevant to include and compare, since the costs input parameters for the spare parts and resources in the ECN model are unknown and only one costs output, without decomposition is known. The scheduling criterion is not included since the ECN tool is not able to handle this aspect.

Table 22: Validation – model comparison results

KPI	Description	Unit	ECN O&M Calculator	Developed O&M tool	
				Mean	95% confidence interval
C1	Energy-based availability	%	90.14	90.65	[89.96 – 91.35]
	Time-based availability	%	91.45	91.33	[90.74 – 91.92]
C1.1	Total production	MWh	1,761,361	1,905,880	[1,865,887 – 1,945,874]
		hour	8010.08	8000.61	[7949.08 – 8052.13]
C1.2	Lost production	MWh	192,678	197,540	[179,979 – 215,101]
		hour	749.92	759.39	[707.87 – 810.92]
C2	Total production revenues	M€	228.98	247.77	[242.57 – 252.97]
C3.1	Lost Production costs	M€	25.05	25.68	[23.40 – 27.96]

For the model comparison the model is run for twenty replications of one year (run length equal to ECN tool). The results are presented in the table above. There can be concluded that the red shaded total production (in MWh), the lost production (in MWh) and the production revenues are significantly different from the ECN results. Since both the total production and the lost production are higher, there can be concluded that potential production is too high in the developed tool. Since the used power curve by ECN is known and implemented exactly the same, the only explanation is that the wind speeds have to be higher in the used weather data.

In the used weather data the average wind speed is 8.63m/s, while according to Weisse, Gunther, & Feser (2002) the average wind speed at the location 'K13' as used by ECN is 8.14m/s, so the higher production and lost production can be likely explained by the higher wind speeds. To compensate for the higher wind speeds, the comparison is tested with a five percent reduction on all the wind speeds resulting in almost the same (average) wind speeds. The results are presented in the next table.

Table 23: Validation - model comparison results after wind reduction

KPI	Description	Unit	ECN O&M Calculator	Developed O&M tool	
				Mean	95% confidence interval
C1	Energy-based availability	%	90.14	90.62	[89.92 – 91.32]
	Time-based availability	%	91.45	91.36	[90.77 – 91.94]
C1.1	Total production	MWh	1,761,361	1,751,030	[1,710,494 – 1,791,565]
		hour	8010.08	8002.78	[7951.77 – 8053.79]
C1.2	Lost production	MWh	192,678	182,325	[165,891 – 198,759]
		hour	749.92	757.22	[706.21 – 808.23]
C2	Total production revenues	M€	228.98	227.63	[222.36 – 232.90]
C3.1	Lost Production costs	M€	25.05	23.70	[21.57 – 25.84]

The wind reduction resulted in a lower total production, lost production and production revenues. After this reduction there are no significant differences on the tested KPIs between the developed tool and the validated results of the ECN tool. So the differences could potentially be explained by the use of a different weather dataset, however to examine this more elaborate, the actual dataset used by ECN is desired as well as data for the assumed input of table 21.

10.2.2. Face validation through expert validation

After the comparison with the ECN model the O&M tool is already partly validated internally, although to test to what extent the tool is accepted by the actual actors in the sector an expert validation or 'face validation' is performed. For face validation the next definition of Sargent (2005) is used:

> *"**Face Validity**: Asking individuals knowledgeable about the system whether the model and/or its behavior are reasonable."*

For the face validation a (second) interview is held with Willem van Dongen (Director Operation UK at Vattenfall). Together with this expert a demonstration of the tool with a sample case study (based on Vattenfall's Offshore Wind farm Egmond aan Zee (OWEZ) in the Netherlands) is performed including a comparison of different O&M strategies, the planning robustness assessment and the animation of the O&M process.

All the desired requirements are included in the tool, except for the spare parts logistics. For this aspect assumptions are made and presented including sensitivities (for e.g. the jack-up barge wait time)

The outcome of this validation technique is an assessment of the developed O&M tool. According to Willem van Dongen (2015), the tool presents realistic results for the OWEZ wind farm based on the used inputs and shows the expected directional behavior for different strategies and the different used values for the jack-up barge wait time. Furthermore, the tool is considered valuable for the sector in two phases of the lifespan of an offshore wind farm:

1. Prior to the construction of the wind farm, in order to get insight in the O&M costs of the (planned) wind farm. The costs of the O&M is an important aspect of the profitability of the wind farm. A cost assessment of the maintenance is desired to obtain (internal) funding for the construction of a new offshore wind farm.
2. During the operation phase of the wind farm. The O&M tool could be useful to calculate the OPEX costs and to test potential CAPEX investments, e.g. the purchase of a new (improved) crew vessel.

During the operational phase, the developed O&M tool could be useful for i.a. the assessment of new vessels, purchasing a jack-up barge instead of renting it, the costs of the O&M, the investment in better turbine components (with reduced failure rates), the planning of preventive maintenance, the robustness of the actual planning and the use of an alternative planning in the worst case scenario with e.g. a serial fault and thus replacement of a major component for all the turbines (Van Dongen, 2015).

Furthermore, Van Dongen (2015) presented some possible improvements for the tool, which are part of the suggested future research (paragraph 12.2):

- The implementation of a helicopter to perform the maintenance
- Add costs of the different turbine components

- Extent the number of components
- A more user-friendly user interface, as well with the option to import data spreadsheets
- A 'pilot' study with the use of real data of an existing NUON/Vattenfall wind farm

Due to time limitations and the current scope the first three suggested improvements are not implemented yet, although the implementation of these three improvements should fit within the model and these improvements are considered as feasible extensions of the tool.

The fourth suggestion could be implemented with the use of the Scenario Navigator software developed by Systems Navigator. Scenario Navigator provides a user-friendly front end user interface, comprehensible for the end users.

The last suggestion is considered as a good next step in the development of a useful O&M tool for the sector. Due to time limitations this will not be part of this thesis, although a pilot project will be planned in the short-term together with Vattenfall and Systems Navigator to validate the tool with data and results of an existing wind farm.

After the two validation techniques, the model could be considered as representative according to the comparison with the validated ECN tool and the expert validation by Van Dongen (2015). In order to validate the model fully a case study with an existing wind farm is recommended as will be discussed in paragraph 11.2. A validation with a real farm can serve as 'accreditation' after the verification and validation. Accreditation assesses (often by the user or a third party) the extent a simulation model is acceptable for a specific application (Sargent, 2005).

11. Case Study with Offshore Wind O&M Decision Support Tool

To demonstrate the decision support tool capabilities, a fictitious case study mainly based on the Princess Amalia Wind Farm (Netherlands) will be performed. This cases study will present the added value of the tool and will elaborate on how the tool can serve in the O&M planning and process. The previous chapter not used all the criteria and not elaborated on the scheduling aspect. In this chapter four alternatives will be compared on all the criteria, including the criterion *robustness of preventive maintenance plan*, which shows the main added value of the developed tool.

> *10. What is the added value of the developed decision support tool and how can the tool serve the O&M planning and process?*

For the case study a baseline, three single alternatives and four combinations of these single alternatives are used. These alternatives are based on the findings during the held interviews (Van Buchem, 2014a) (Van Dongen, 2014) and mainly on the Princess Amalia Wind Farm (Netherlands). There are two possible O&M strategies to improve the energy-based availability.

Table 24: Case study – alternative O&M strategies

Strategy	Description
A0	Baseline
A1	Preventive maintenance only at low wind speeds
A2	Faster preventive maintenance with more personnel per turbine
A3	Better CTV vessels
A4	Faster preventive maintenance at low wind speeds (A1 + A2)
A5	Better CTV vessels + preventive maintenance at low wind speeds (A1 + A3)
A6	Better CTV vessels + faster preventive maintenance (A2 + A3)
A7	Better CTV vessels + faster preventive maintenance at low wind speeds (A1 + A2 + A3)

The first strategy (A1) to improve the energy-based availability is to perform preventive maintenance only during low wind speeds. In this O&M strategy turbines will not be maintained during full load wind speeds, to ensure the (high) production. In this alternative there will be no maintenance below 9/s, equal to more or less half the production capacity (see also Appendix H). In order words, in this strategy preventive maintenance is only performed if the turbines are operating under ~50% of their production capacity. However, this strategy will result in less days of access for preventive maintenance. The use of a separate wind threshold for preventive maintenance is not yet possible in the leading ECN O&M Calculator, although it was announced for the new release of 2014 (ECN, 2014), but this new release is not been published yet.

The second one (A2) is to have faster preventive maintenance by increasing the team size. Increasing the team size will reduce the downtime of a turbine during maintenance, however less turbines can be maintained at the same time.

The third (single) alternative (A3) will concern an improved vessel. For the current Dutch wind farms, crew vessels with a wind threshold of 1.5m are used. According to Van Dongen (2015) a consideration could be to replace those vessel for newer, better vessel with a threshold of 2.0.m. No exact (additional) costs are known for an improved vessel. It is assumed that the costs of an improved vessel are 33% higher since the wave threshold is also 33% higher.

The combination of these single strategies are included as A4-A7, see table 24.

11.1. Input Parameters

Below the input parameters are listed for a fictitious wind farm with 60 V80 (2MW) turbines 23 kilometers from the shore (as is for the Princess Amalia Wind Farm). The parameters are based on the held interviews, the ECN case study (chapter 10) and other sources and should represent realistic numbers comparable to the Dutch wind farms Princess Amalia or OWEZ. The strategies only differs on the green cells in the next table. Only A0-A3 are included in table 25 to maintain the overview, A4-A7 are composed of the alternatives A0-A3. These strategies serve as examples, more strategies can be designed (suggestions provided in paragraph 10.2.2).

Regarding the weather data, the Sandbank weather data (2000-2011, German North Sea) are used and scaled towards an average wind speed of 8.63m/s and an average wave height 1.23. This is comparable with the averages of OWEZ (NL) according to Wagenaar & Eecen (2009).

Table 25: Case study – input parameters

Parameter	A0	A1	A2	A3
Weather data	Sandbank wind farm (2000-2011, German North Sea) scaled down to OWEZ (NL)			
Wind farm				
Distance to shore (km)	23	23	23	23
Number of turbines	60	60	60	60
Type of turbine	V80 (2MW)	V80 (2MW)	V80 (2MW)	V80 (2MW)
Resources				
Number of CTV	1	1	1	1
CTV wave limit (m)	1.5	1.5	1.5	**2.0**
CTV wind limit (m/s)	∞	∞	∞	∞
CTV wind limit preventive maintenance (m/s)	∞	**9**	∞	∞
CTV speed (km/h)	37	37	37	37
CTV personnel capacity (#)	12	12	12	12
Jack-up barge wave limit (m)	2.0	2.0	2.0	2.0
Jack-up barge wind limit (m/s)	11	11	11	11
Jack-up barge speed (km/h)	17	17	17	17
Jack-up barge waiting time (day)	TRIA(3,7,21)	TRIA(3,7,21)	TRIA(3,7,21)	TRIA(3,7,21)
Number of personnel (person)	12	12	12	12
Preventive				
Number of personnel per turbine (person)	2	2	**3**	2
Number of days per turbine (day)	4	4	**3**	4
Frequency (day between preventive maintenance campaigns)	182	182	182	182
Starting month (month number)	1	1	1	1
Corrective				
Number of personnel per turbine (person)	2	2	2	2
Costs				
MWh (€/MWh) (DONG Energy, 2013)	160	160	160	160
Personnel (€/person/year) (Besnard et al., 2013)	80,000	80,000	80,000	80,000

Used CTV (€/vessel/day) (The Crown Estate, 2010)	1,900	1,900	1,900	**2,533**
Unused CTV (€/vessel/day) (unused CTV is half the costs according to Van Buchem (2014a)	950	950	950	**1,267**
Jack-up barge (€/vessel/day) (Rigzone, 2014)	100,000	100,000	100,000	100,000

The next table presents the used components with their failure rates, repair times and need for a jack-up barge in case of failure. These rates are based on Van Bussel & Zaaijer (2001) and is implemented in an exponential distribution to create randomness. According to Van Buchem (2014a) the repair time for all the components is normally one day, for the main components a few days are needed before and after the component replacement by the jack-up barge. Note that the repair time in the table below concerns the net repair time. This is not equal to the MTTR, since the MTTR also include the waiting time and transfer time (besides the repair time), more in paragraph 3.1.

Table 26: Case study – turbine components

Component	Failure rate (failure/ year)	MTTF (hour)	Repair time (day)	Jack-up needed? (yes/no)	Jack-up preparation time (day)	Jack-up finishing time (day)
Shaft & Bearing	0.02	438,000	1	Yes	2	2
Brake	0.05	175,200	1	No		
Generator	0.05	175,200	1	Yes	2	2
Parking Brake	0.05	175,200	1	No		
Electric	0.10	87,600	1	No		
Blade	0.11	79,637	1	Yes	2	2
Yaw System	0.15	58,400	1	No		
Blade Tips	0.14	62,571	1	Yes	2	2
Pitch Mechanism	0.14	62,571	1	No		
Gearbox	0.15	58,400	1	Yes	2	2
Inverter	0.16	54,750	1	No		
Control	0.17	51,529	1	No		
Total	**1.28**					

11.2. Results

Table 28 shows the results on the criteria of table 27 (same as paragraph 4.4) for the different O&M strategies after 50 runs of one year per strategy, without a warm-up period (see Appendix J for the substantiation). Table 28 shows the results with the mean and the half width. The mean minus the half width till the mean plus the half width determines the 95% confidence interval of the mean.

Table 27: Case study - KPIs

KPI	Description	Measure
C1	Energy-based availability	% total production / potential production
	Time-based availability	% online time / total time
C1.1	Total production	MWh
		hour
C1.2	Lost production	MWh
		hour
C2	Total production revenues	M€
C3	Total costs	M€
C3.1	Lost Production costs	M€
C3.2	O&M resources costs	M€
C4	Robustness of preventive maintenance plan	day
C4.1	Probability target exceedance	% probability all scheduled maintenance is not finished before a target date
C4.2	Average target date exceedance	day

Table 28: Case study – results (mean +- half width of 95% confidence interval of the mean)

KPI	Unit	A0	A1	A2	A3	A4	A5	A6	A7
C1	%MWh	96.73 +-0.16	96.94 +-0.17	96.83 +-0.16	97.14 +-0.12	97.02 +-0.17	97.47 +-0.12	97.27 +-0.12	97.54 +-0.12
	%hour	96.63 +-0.14	96.66 +-0.14	96.82 +-0.14	97.03 +-0.11	96.91 +-0.13	97.05 +-0.10	97.22 +-0.11	97.28 +-0.10
C1.1	MWh	444,651 +-7,203	445,611 +-7,195	445,129 +-71,99	446,561 +-7,330	445,975 +-7,203	448,093 +-7,369	447,188 +-7,366	448,422 +-7,374
	hour	8,464.36 +-12.53	8,467.22 +-12.17	8,481.07 +-12.34	8,499.99 +-9.31	8,488.93 +-11.73	8,501.53 +-9.18	8,516.16 +-9.31	8,521.88 +-8.72
C1.2	MWh	15,086 +-857	14,126 +-876	14,608 +-862	13,176 +-616	13,762 +-868	11,643 +-598	12,549 +-594	11,315 +-594
	hour	295.64 +-12.53	292.78 +-12.17	278.93 +-12.34	260.01 +-9.31	271.07 +-11.73	258.47 +-9.18	243.84 +-9.31	238.12 +-8.72
C2	M€	71.14 +-1.15	71.30 +-1.15	71.22 +-1.15	71.45 +-1.17	71.36 +-1.15	71.70 +-1.18	71.55 +-1.18	71.75 +-1.18
C3	M€	6.59 +-0.24	6.43 +-0.24	6.52 +-0.24	6.50 +-0.21	6.38 +-0.24	6.25 +-0.21	6.42 +-0.21	6.21 +-0.21
C3.1	M€	2.41 +-0.14	2.26 +-0.14	2.34 +-0.14	2.11 +-0.10	2.20 +-0.14	1.86 +-0.10	2.01 +-0.10	1.81 +-0.10
C3.2	M€	4.18 +-0.14	4.17 +-0.14	4.19 +-0.14	4.40 +-0.14	4.18 +-0.14	4.39 +-0.14	4.41 +-0.14	4.40 +-0.14
C4	day	0.00 +-0.00	0.44 +-0.43	0.29 +-0.35	0.00 +-0.00	12.81 +-4.92	0.00 +-0.01	0.00 +-0.00	6.28 +-2.87
C4.1	%	3.57 +-3.84	20.28 +-11.32	16.57 +-10.36	3.57 +-3.84	68.57 +-13.27	7.28 +-6.65	3.57 +-3.84	55.57 +-14.29
C4.2	day	0.00 +-0.00	2.18 +-1.71	1.78 +-1.80	0.00 +-0.00	18.68 +-6.20	0.07 +-0.11	0.00 +-0.00	11.30 +-4.26

Green cells in the table above indicates a statistically (with α = 5%) significant better performance of that strategy compared to the baseline (A0), red cells indicates a significant worse performance. See next paragraph and Appendix K for the method to assess significant differences. The tool can also display the results by graphical box plots, the yellow bars represent the 95% confidence interval of the mean:

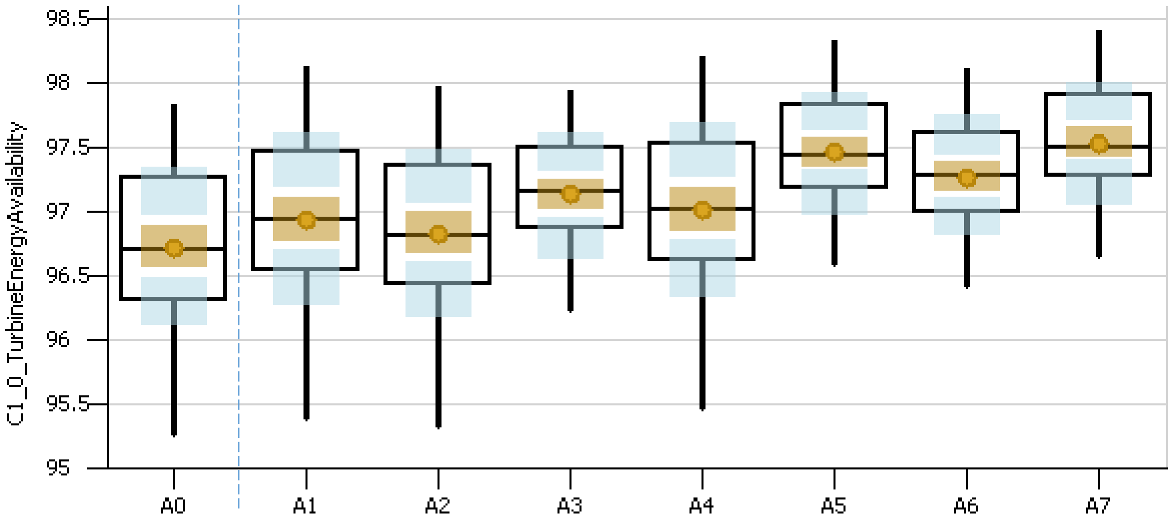


Figure 55: Case study – energy-based availability box plots (yellow bars display the 95% confidence intervals)

Note that confidence intervals that do not overlap are significantly different. Confidence intervals that do overlap are not necessary not significantly different; if they slightly overlap they could still be significantly different. According to Schenker & Gentleman (2001) the overlap method fails to assess significant differences frequently and a better method is to assess the interval of the differences. Another (visual) method to still assess two independent intervals is established by Cumming & Finch (2005). When two independent intervals have an overlap of 50% the corresponding p value is 0.05; in other words when two independent intervals overlaps half there is a significant difference (with a confidence level of 95%) (Cumming & Finch, 2005). For example the 95% confidence interval of A4 shows a slight overlap with the baseline, but assessing the interval of the differences results in a significant difference. The method of Schenker & Gentleman (2001) is used for table 28 and described in Appendix K more detailed.

Preventive Maintenance Planning

Insight in the robustness of the preventive maintenance is derived from the next Gantt-chart (exceedance probability) of the decision support model and the exceedance impact. The figure below presents the preventive maintenance plan of strategy A4. The expected finishing time (red circle), without uncertainty (one replication without variability such as failures and weather), of the last turbine is well before the target date (blue circle). When uncertainty is included, only 31.43 (+- half width of 13.27) percent of the time all the turbine are maintained before the target date. So there can be concluded that A4 is a feasible strategy, since the expected finishing date is before the target date, but is a significant less robust as the baseline.

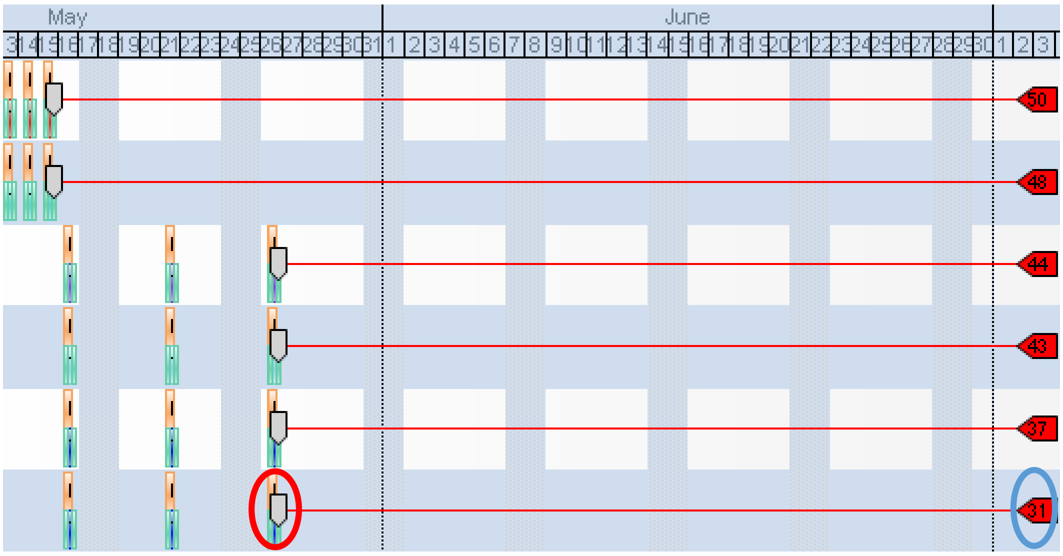


Figure 56: Case study - Preventive maintenance plan risk analysis

One part of the robustness is the exceedance probability as discussed above. The other is the exceedance impact. The next box plots with histograms show the delay in days of the strategies, including the variability and not only the average. Since the average also includes the 0-values in case there is no delay in a specific replication, the average can be misleading and a look at the distribution is required.

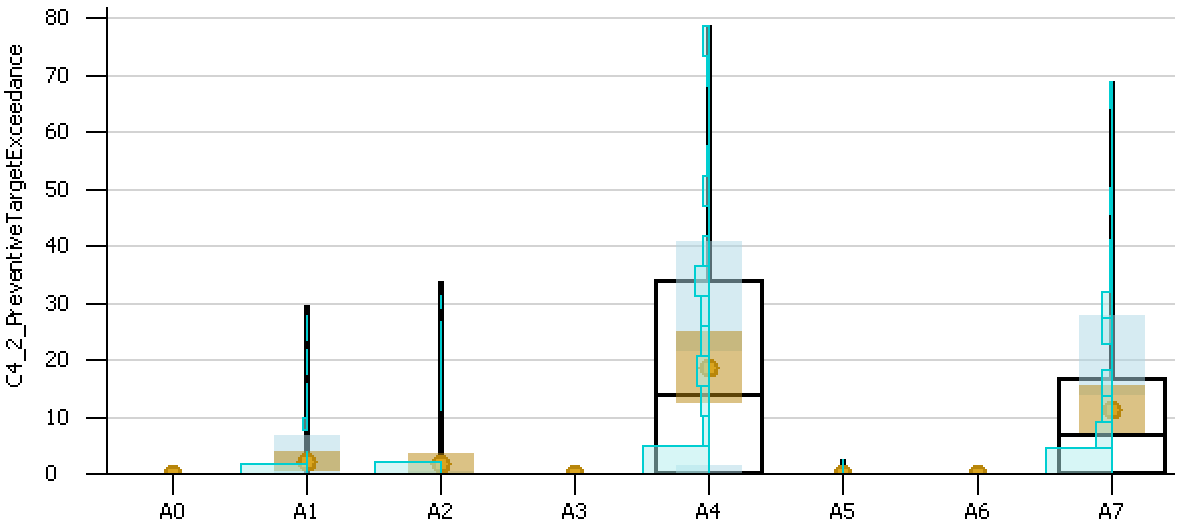


Figure 57: Case study - Average preventive maintenance target exceedance (yellow bars display the 95% confidence intervals of the mean)

The figure above shows the target exceedance impact in days and gives insight in the robustness of the O&M strategies. This target exceedance impact together with the target exceedance probability gives the user the total robustness (lower is better), included as criterion C4.

To conclude, strategy A5 and A7 performs significantly the best on both availabilities and the costs. Both are performing not significantly different form each other, except from the time-based availability whereon A7 performs significantly better and the robustness whereon A7 performs significantly worse. Strategy A7 is considered as not very robust since this alternative scores quite bad on KPI A4. So Strategy A5 is on first sight the most positive strategy. However at the end, the user or O&M planner has to decide which strategy is the most suitable for the concerned wind farm, based on the results of the decision support tool. So this case study provides the user insight in the tradeoff between the less robust but more profitable strategies and the more robust conservative strategies.

Optimization

Another feature of the developed O&M tool is the optimization aspect. With the developed tool it is possible to optimize with respect to one or more KPIs. Below a small, simple example is given for this case study.

In the case study in the previous paragraph strategy A5 was the most favorable on first sight. Strategy A5 consist of a better vessel (with a higher wave limit of 2.0m) and a preventive maintenance wind limit (only perform scheduled maintenance during wind speeds lower than 9.0 m/s). To examine further the optimal the wave limit and the preventive maintenance wind limit an optimization is performed around these two values to zoom in on the optimal variant of A5.

Table 29: Optimization of O&M strategies

Control	Minimum	Maximum	Increment	Nr. steps
CTV wave limit	1.5	2.5	0.1	11
CTV wind limit preventive maintenance	5	13	1	9

The optimization engine OptQuest will use the above minimum, maximum and increment values to find the best strategy. The OptQuest Engine combines Tabu search, scatter search, integer programming, and neural networks into a single, composite search algorithm that provides maximum efficiency (OptTek Systems, n.d.).

In this case there is minimized for the total costs, including the O&M costs and the lost production costs, and the preventive maintenance target exceedance although other objective(s) (functions) are possible. In this optimization example the weight of the total costs (in million) is set to 1 and the weight of the preventive maintenance target exceedance is set to 0.01; 100 days exceedance (on average) are considered equal to 1 million additional costs. This objective function is used to neglect strategies that are a bit cheaper but not finished the preventive maintenance within the simulation run.

The optimization uses the same inputs as for the case study in this chapter. It is assumed that the costs of an improved vessel are linear to the wave limits. E.g. the use a vessel with a limit of 2.5m will costs (2.5 / 1.5) times the costs of the use of a vessel with a limit of 1.5m (€1,900 per day).

The next figure shows the results of the optimization on the total costs. The optimization is performed for 50 replications of one year per scenario (same as case study in this chapter) with a maximum of 30 scenarios out of 11*9 = 99 scenarios (user defined).

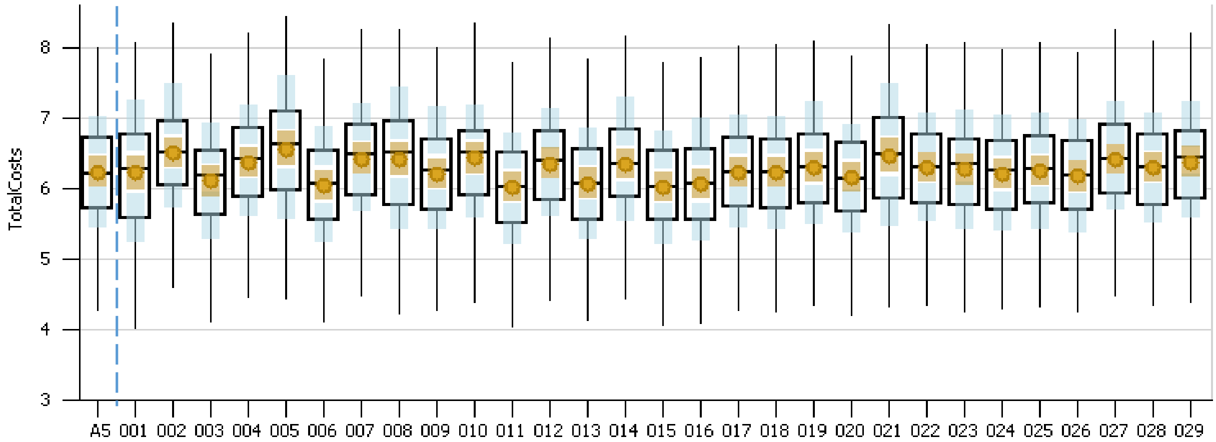


Figure 58: Optimization of strategy A5 – Average total O&M costs results (yellow bars display the 95% confidence intervals of the mean)

The results of the optimization shows only one significant result w.r.t. the total costs based on the method presented in Appendix K, compared to the initial strategy A5. Scenarios 005 performs significant worse than strategy A5. On the preventive maintenance target exceedance criterion all the scenarios are equal or worse than the initial A5 (no exceedance). The next figure shows the performances on the energy-based availability.

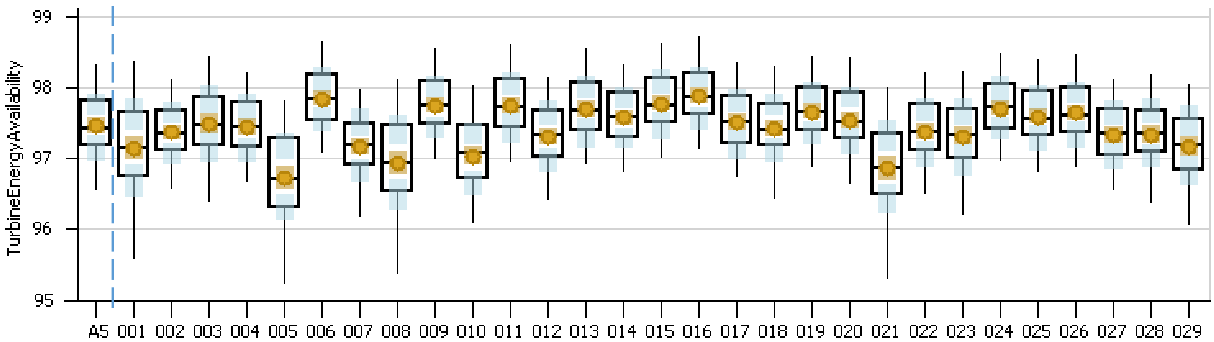


Figure 59: Optimization of strategy A5 – Average energy-based availability (yellow bars display the 95% confidence intervals of the mean)

Scenario 6, 9, 11, 13, 15, 16, 19, 24 and 26 performing significantly better (based on the method presented in Appendix K) on the energy-based availability, however of these scenarios 6, 11, 13, 15 and 16 exceed the preventive maintenance target unacceptably (see next figure). Scenario 9, 24 and 26 perform slightly but significantly worse.

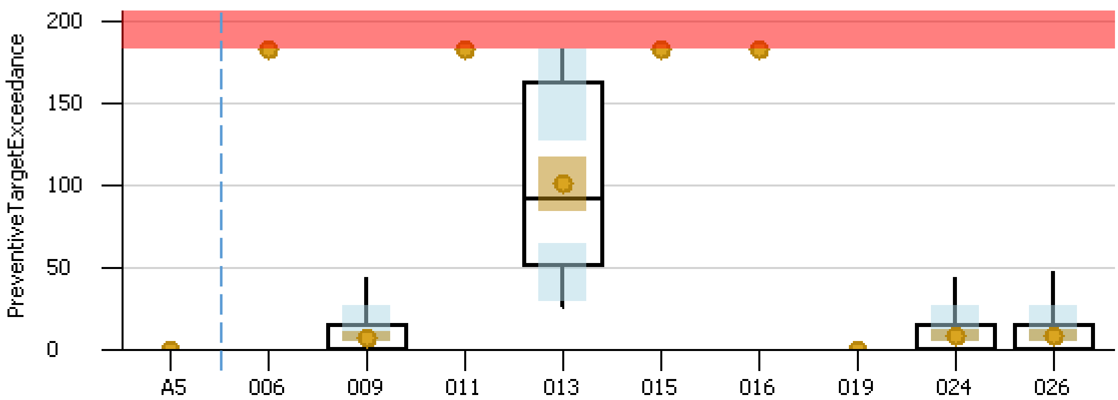


Figure 60: Optimization of strategy A5 – Average preventive maintenance target exceedance (yellow bars display the 95% confidence intervals of the mean, red limits display end of the simulation)

On first sight scenario 19 (of this optimization) performs best. Scenario 19 consists a wave limit of 2.5m and a preventive maintenance threshold of 9m/s. Scenario 19 doesn't perform differently on the total costs, although the O&M costs are significantly higher. However it performs significantly better not only on the energy-based availability but also on the lost production. So the higher O&M costs of the better vessel are compensated by the lower lost production costs still resulting in a higher energy-based availability.

Furthermore, during the optimization the next insights are gained:

- The higher the wave threshold of the CTV, the lower the lost production (cost). The lower lost production costs are compensated by the higher O&M costs resulting in no trend on the total costs when increasing the wave threshold.
- The lower lost production, when increasing the wave threshold, results also in both higher energy-based and high time-based availabilities.

- The higher the preventive wind limit, the higher the lost production and total costs.
- The higher the preventive wind limit, the lower the target exceedance. (Almost) no exceedance with the used weather data for limits from 9m/s and higher

There are some remarks to be discussed regarding this fictitious case study. The input data are not all exactly real figures (e.g. other weather data is used), due to a lack of some (private) data. However the data should be realistic, the strategies are comparable and their relative performance is representative. The focus is to demonstrate the decision support tool and less on the real numbers.

The outcomes of the model should be interpret by the user or O&M planner since the model serves as a decision *support* tool. The user has to decide which strategy is the most suitable for the wind farm.

The costs of the spare parts are not included, since these are unknown or concern private information. Only the costs of technicians and vessels are included, although the costs of a better vessel are assumed to have a linear relation with the wave limit of the vessel.

The optimal strategy from the optimization should not be considered as the absolute optimum. The optimization is only performed with one objective function (total O&M costs and preventive maintenance target exceedance) with two control variables and 30 scenarios. A more elaborate optimization could be useful for the actual user, this chapter demonstrated only the capability of the tool.

Section 4: Conclusions, Recommendations & Reflection

The last section (4) will answer the main research question by elaborating on the conclusions, recommendations and reflection. After the development of the model in section 2 and the verification & validation completed with a case study in section 3, this section will draw conclusions based on the previous sections and will present limitations of the tool and recommendations for the sector and for future research. The section will end with a personal reflection on the research process.

11. *What are the conclusions for the offshore wind sector and what future research is recommended?*

12. Conclusions and Recommendations

This chapter will present the final main conclusions and recommendations of this research. Paragraph 12.1 will answer the main research question and the sub questions implicitly. The limitations and recommend future research will be discussed in paragraph 12.2.

> *11. What are the conclusions for the offshore wind sector, what can be recommended and which elements require future research?*

After the conclusions and recommendations, paragraph 12.3 will provide a personal reflection on the research process of this thesis.

12.1. Main Conclusions

This paragraph will answer the main research question of this research:

> *What are the requirements for an integrated and generic offshore wind O&M decision support tool and how could such a tool contribute to an effective O&M planning and process for offshore wind farms?*

The main result of this research is an integrated and generic decision support tool. The tool integrated multiple aspects. The basis for the decision support tool, and the first part of the main research question, were the requirements set by actors within the offshore wind O&M sector. Requirements on multiple aspects are identified based on the process requirements (Appendix D), literature and interviews, the main are presented in the next table. The 35 sub requirements are fully listed in Appendix F.

Table 30: Main model requirements

Nr	Requirement
	The model should be capable to
M1	Define the wind farm specific parameters
M2	Take external factors into account
M3	Use different O&M strategies
M4	Present output on the KPIs
M5	Give insight in the O&M process (e.g. visualization or process animation)
M6	Compare and optimize different O&M alternatives
M7	Design feasible and robust scheduled maintenance

Of the full list of model requirements, nine were not (completely) implemented in the examined previous studies or tools (table 31), however the main gap in the current research is the integration of all requirements. The developed tool integrated all these requirements into one O&M decision support tool.

One of the requirements of table 31 is partly fulfilled and four other requirements are not completely incorporated in the developed tool. The missed requirements are discussed in the next paragraph and suggest further research.

Table 31: Fulfilled requirements by the developed tool

Nr	Requirement	Previous research	Developed tool
M1b	The distance between the turbines	✗	✓
M3f	Perform predetermined (scheduled) based maintenance (including number of personnel per turbine, number of days per turbine, preventive maintenance threshold)	✓	✓
M4e	Preventive maintenance target date exceedance probability	✗	✓
M4f	Preventive maintenance target date exceedance impact	✗	✓
M5	Give insight in the O&M process (e.g. visualization or process animation)	✗	✓
M6	Compare and optimize different O&M alternatives	✓	✓
M7a	Plan resources (personnel and material) for the scheduled maintenance	✓	✓
M7b	Plan feasible (w.r.t. to start and target date) scheduled maintenance	✗	✓
M7c	Plan robust (w.r.t. variability around target date) scheduled maintenance	✗	✓

The developed O&M decision support tool contributed to the current research by integrating the missed above requirements besides the other identified requirements. The developed tool is among others able to design and test energy-based robust strategies. The tool is able to test the energy-based availability of strategies and analyze the planning of scheduled maintenance, in terms of probability that a target date is met. The combination of planning and simulation is a main addition to current the current research in the offshore wind O&M sector. The tool also provides the user to option to include a preventive maintenance wind limit. This option enables to the opportunity to test strategies with separate accessibility thresholds for vessels during preventive maintenance; performing only preventive maintenance during low wind speeds. This element is not included yet in previous studies, however ECN is/was planning to implement preventive limits as well (ECN, 2014). These strategies can be tested on both the common KPIs as on the planning (robustness) aspect.

Other capabilities of the tool that provide added value for the actors in the sector are the process insight or animation element, the visual output on the KPIs including variability and the possibility to compare different O&M strategies. With the developed tool it is not only possible to compare strategies, it is also possible to optimize the O&M strategies with respect to one or more objectives. This capability is not implemented in the integrated O&M tools so far.

The developed tool is verified and validated by a comparison with the leading ECN O&M Calculator. The O&M Calculator is awarded with a validation statement by an independent company. The comparison showed no significant differences between the models on the results. Even with other weather data, with slightly higher wind speeds, the difference on the KPIs are all within ten percent and even within five percent after reducing the wind speeds towards comparable wind speeds.

Furthermore, the tool is validated by means of an expert validation. According to Willem van Dongen (2015), the tool presents realistic results for the compared wind farm (OWEZ) based on the used inputs and shows the expected directional behavior for different strategies and the different used values for the jack-up barge wait time. Furthermore, the tool is considered valuable for the sector.

The (fictitious) case study demonstrated the capabilities of the developed O&M support tool and provided the user insight in the tradeoff between the less robust but more profitable strategies and the more robust conservative strategies and demonstrated the optimization of O&M strategies.

12.2. Limitations and Future Research

Besides the new capabilities the developed tool has some limitations implying a demand for future research. The limitations and future researches will be discussed in four categories; correcting model errors, improving the realism, extending the model and improving the decision making process.

12.2.1. Correcting Model Errors

During the verification and validation no open errors were discovered. The verification and validation tests in chapter 10 does not show any signal for errors in the decision support tool. So no recommendations for future research for this category.

12.2.2. Improving the Realism

The realism of the current tool could be improved by adding some of the next elements. Currently the tool assumes that vessels not fail. It is recommended for future research to give the user the option to include and specify vessel failures (including randomness) as well to improve the realism of the tool. This minor improvement will make the tool more realistic. Van Buchem (2014b) added that failures of vessels has to be taken into account as well, including randomness, specified by the user.

Other elements to improve the realism are the implementation of more weather conditions (like swell, fog and lightning), however data has to be available as well.

The above-mentioned recommendations can improve the realism of the decision support tool, however the biggest share of the realism of the tool is derived from the input data.

12.2.3. Extending the Model

Making choices and demarcations is inherent to the use of simulation. Due to time limitations, the inventory aspect is simplified in the model. So the inventory related requirements (M1d, M2g and M3d) are not met as presented in table 32. In the current tool assumptions are made on the inventory aspect which may be less realistic, but no significant impact is expected.

Besides the inventory aspect, the distance between turbines and condition based maintenance is partly included in the tool. The distance between the turbines is assumed to be 500m (scaled) fixed. This is not included as a user defined parameter, although the user can drag the turbines in the model to obtain the real distances between the turbines. So this requirement is not covered as a user defined parameter in the model and therefore considered as partly included. The assumption of 500m is considered as presentative and expected to not have a significant influence. This assumption has only an impact when turbines will be maintained in a different order across the whole wind farm, e.g. based on a user preference or based on monitoring data. The current model assumes sequential preventive maintenance, although an extension could be to use a user defined sequence.

Like the ECN tool, the developed tool is able to simulate condition based maintenance by reducing the failure rates and increasing the frequency of the preventive maintenance. This approach has probably no significant influence on the results, however it is not a very neat implementation of condition based maintenance. A more desired approach is to include a possibility for the user to import real monitoring data or to specify an aging or deterioration parameter.

Table 32: Not included related requirements

Nr	Requirement	✓/✗
M1b	The distance between the turbines	✓
M1d	The distance from the (offshore) spare parts location	✓
M2g	Include the lead time of the different components, including randomness	✗
M3d	Vary the service level/amount of stock regarding spare parts inventory	✗
M3e	Perform condition based maintenance	✓

It is recommended to include the above listed missed requirements in future research. Besides the implementation of these requirements there are some other recommendations to extend the model. One of these recommendations is to extend the model with different transporters. Currently, only CTVs and jack-up barges are included. These could be extended with helicopters or mother vessels (option 2 and 3 of figure 14) for more remote wind farms.

To get more accurate insight in the O&M costs, it is also suggested (Van Dongen, 2015) to include the real costs structure for all the different spare parts, however this is still considered as user input.

Furthermore, extending the tool to make it more user-friendly by building a layer around the actual tool is recommended. This layer should protect the model (code) and should have a user-friendly way of specifying the model output and should display the results in the desired format, without opening or editing the actual tool. At Systems Navigator such software, Scenario Navigator, is available and could be recommended for future versions of this offshore wind O&M decisions support tool.

At least, integration with forecast weather data is recommended to enable day-to-day planning. With this option the user can assess and optimize the operational planning for the next days based on forecast data.

12.2.4. Improving the Decision Making Process

After the model is validated by means of a model comparison, a check is needed to assess how the model can contribute within the O&M process and planning. To validate the process requirements of decision support tool, to get accreditation by the actors in the sector and to test the benefits for the maintenance process, a validation project is recommended.

During the recommended validation project it is suggested to compare and optimize different O&M strategies, to plan the preventive maintenance of a wind farm and to execute that plan during the real maintenance campaign. With a validation project the model will be tested in real-life and parts of the model that are not been validated yet can be validated, especially the planning aspect. With the decision support tool the preventive maintenance can be designed before performing the maintenance and can be monitored and adjusted during the maintenance campaign. Especially the use of the tool *during* the maintenance campaign can be an interesting and new future project. During the maintenance the tool can be used to make decision for the O&M. For example, after a lot of bad weather and a lot of failures, the O&M campaign can be behind schedule. In that case, the O&M tool could support alternative O&M strategies to accelerate the process, e.g. faster maintenance or enlarge the number of resources.

The result of the validation project will be to what extent the decision support tool is valid for the offshore wind O&M plan and process and to get insights in the benefits for the maintenance process in real-life. Due to time limitations this was not part of this thesis, although a pilot project will be planned in the short-term together with Vattenfall and Systems Navigator in order to validate the tool with data and results of an existing wind farm.

12.3. Reflection

During this thesis the scope was reduced, due to time limitations. Initially the inventory related requirements were part of the scope. However along the way, this seemed to be too ambitious, especially in terms of planning. This resulted in an updated delineation; the inventory requirements were left outside the scope. For the inventory related aspects some assumptions were made to simply this aspect, while still taking into account the inventory aspects.

Furthermore, and more from a personal perspective, the research encountered some delays. The main reason for the delay was the starting of a new job for Systems Navigator, besides finishing this thesis. This required some additional time management and caused a (calculated) delay.

Interviews

Van Buchem, R. (2014a, June 26). Interview: Offshore wind O&M requirements. (H. Koopstra, Interviewer)

Van Buchem, R. (2014b, December 4). Personal communication: Requirements check.

Van Dongen, W. (2014, April 27). Interview: Offshore wind O&M requirements. (H. Koopstra, Interviewer)

Van Dongen, W. (2015, March 5). Interview: O&M tool validation. (H. Koopstra, Interviewer)

References

Aksoy, H., Toprak, Z. F., Aytek, A., & Ünal, N. E. (2004). Stochastic generation of hourly mean wind speed data. *Renewable Energy*, *29*(14), 2111–2131. doi:10.1016/j.renene.2004.03.011

Baarda, D. B., De Goede, M. P. M., Meer-Middelburg, A. G. E., & Van Der Meer, A. G. E. (2007). *Basisboek Interviewen: Handleiding voor het voorbereiden en afnemen van interviews*. Noordhoff Uitgevers B.V.

Balci, O. (1997). Verification validation and accreditation of simulation models. In *Proceedings of the 29th conference on Winter simulation* (pp. 135–141). IEEE Computer Society.

Besnard, F., Fischer, K., & Tjernberg, L. B. (2013). A Model for the Optimization of the Maintenance Support Organization for Offshore Wind Farms, *4*(2), 443–450.

Besnard, F., Patriksson, M., Strömberg, A.-B., Wojciechowski, A., & Bertling, L. (2009). An optimization framework for opportunistic maintenance of offshore wind power system. In *PowerTech, 2009 IEEE Bucharest* (pp. 1–7). IEEE.

Blanchard, B., & Fabrycky, W. (1990). *Systems Engineering and Analysis* (4th Editio.). New Jersey: Prentice Hall. Retrieved from http://sutlib2.sut.ac.th/sut_contents/H104135.pdf

Blanco, M. I. (2009). The economics of wind energy. *Renewable and Sustainable Energy Reviews*, *13*(6-7), 1372–1382. doi:10.1016/j.rser.2008.09.004

BP. (2013). BP Statistical Review of World Energy June 2013. Retrieved March 25, 2014, from http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf

Braam, H., & Eecen, P. (2005). Assessment of wind and wave data measured at IJmuiden Munitiestortplaats. Retrieved June 18, 2014, from ftp://130.112.2.101/pub/www/library/report/2005/c05060.pdf

Braam, H., Obdam, T. S., Van de Pieterman, R. P., & Rademakers, L. W. M. M. (2011). Properties of the O&M Cost Estimator (OMCE). Retrieved May 8, 2014, from http://www.dowes.nl/documents/documenten/properties_of_the_o&m_cost_estimator_july_2011.pdf

Cumming, G., & Finch, S. (2005). Inference by eye: confidence intervals and how to read pictures of data. *American Psychologist*, *60*(2), 170.

Dewan, A. (2014). *Logistic & Service Optimization for O&M of Offshore Wind Farms*. Delft University of Technology. Retrieved from file:///C:/Users/Hajo Koopstra/Downloads/mscThesis_4183010.pdf

Ding, F., & Tian, Z. (2011). Opportunistic maintenance optimization for wind turbine systems considering imperfect maintenance actions. *International Journal of Reliability, Quality and Safety Engineering*. Retrieved from http://www.worldscientific.com/doi/abs/10.1142/S0218539311004196

DONG Energy. (2013). Offshore Wind Cost-of-Electricity. Retrieved January 5, 2015, from http://assets.dongenergy.com/DONGEnergyDocuments/com/Business Activities/Wind Power/Cost of energy_presentation_EN.pdf

DOWEC team. (2002). Estimation of Turbine Reliability figures within the DOWEC project. Retrieved February 20, 2014, from https://www.ecn.nl/fileadmin/ecn/units/wind/docs/dowec/10048_004.pdf

Dym, C. L., Little, P., Orwin, E. J., & Spjut, R. E. (2004). *Engineering design: A project-based introduction*. New York: Wiley New York.

Echavarría, E. (2009). WE@ SEA 2004-012: RAMS for offshore wind farms.

ECN. (2007). Accurate estimation of maintenance costs offshore wind farms with ECN software tool. Retrieved December 24, 2014, from https://www.ecn.nl/news/item/accurate-estimation-of-maintenance-costs-offshore-wind-farms-with-ecn-software-tool/

ECN. (2014). New release of the ECN O&M Calculator v2.2. Retrieved January 9, 2015, from https://www.ecn.nl/news/newsletter-item-om/?tx_ttnews[tt_news]=1183&cHash=6f00eca40e049f2ffb22f8d9b8e33e1d

European Commission. (2007). Communication from the Commission to the European Council and the European Parliament - An energy policy for Europe.

European Commission. (2014). What is the EU doing about climate change? - European Commission. Retrieved April 2, 2014, from http://ec.europa.eu/clima/policies/brief/eu/index_en.htm

European Committee for Standardization. (2001). EN 13306.

European Wind Energy Association. (2013). Deep Water: The next step for offshore wind energy. Retrieved February 26, 2014, from http://www.ewea.org/fileadmin/files/library/publications/reports/Deep_Water.pdf

Feuchtwang, J., & Infield, D. (2013). Offshore wind turbine maintenance access : a closed-form probabilistic method for calculating delays caused by sea-state, (August 2012), 1049–1066. doi:10.1002/we

Freeman, R. E. (1984). *Strategic Management: A Stakeholder Approach*. Boston: Pitman.

GL Garrad Hassan. (2013). A Guide to UK Offshore Wind Operations and Maintenance. *Scottish Enterprise and The Crown Estate*.

Greenacre, P., Gross, R., & Heptonstall, P. (2010). Great Expectations: The cost of offshore wind in UK waters–. *UK Energy Research Centre, London*.

Hancock, P. (2011). SUPERGEN Wind 2011 General Assembly. Retrieved February 20, 2014, from http://www.supergen-wind.org.uk/docs/presentations/2011-04-20_7_SUPERGEN Wind2011GA_ReliableOffshoreWindFarms_PJT.pdf

Hewitt, S. (2002). *Comparing Analytical and Discrete-Event Simulation Models of Manufacturing Systems*. University of Maryland.

Hild, D. (2000). Discrete event system specification (DEVS) distributed object computing (DOC) modeling and simulation. Retrieved from http://scholar.google.nl/scholar?hl=nl&q=devs+hild+2000&btnG=&lr=#0

Karyotakis, A. (2011). *On the Optimisation of Operation and Maintenance Strategies for Offshore Wind Farms*. University College London.

Koutoulakos, E. (2010). *Wind turbine reliability characteristics and offshore availability assessment*. Delft University of Technology. Retrieved from http://www.windenergy.citg.tudelft.nl/fileadmin/Faculteit/LR/Organisatie/Afdelingen_en_Leerstoelen/Afdeling_AEWE/Wind_Energy/Education/Masters_Projects/Finished_Master_projects/doc/Efstathios_Koutoulakos_r.pdf

Markard, J., & Petersen, R. (2009). The offshore trend: Structural changes in the wind power sector. *Energy Policy*, *37*(9), 3545–3556. doi:10.1016/j.enpol.2009.04.015

Mattews, T. (2002). A Process Review and Appraisal of the Systems Engineering Capability for the Florida Department of Transportation: Tenchnical Memorandum No. 1. Retrieved May 7, 2014, from http://www.dot.state.fl.us/trafficoperations/its/projects_deploy/SEMP/030220-TMI-V2.pdf

Murray-Webster, R., & Simon, P. (2006). Making sense of stakeholder mapping. *PM World Today*, *8*(11), 1–5.

Musselman, K. J. (1998). Guidelines for success. In *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice* (pp. 721–743). Wiley Online Library.

Nakagawa, T. (2006). Maintenance theory of reliability. Retrieved from http://books.google.nl/books?hl=nl&lr=&id=1IhCEd1VH28C&oi=fnd&pg=PA1&dq=Maintenance+Theory+of+Reliability&ots=hDKJYL_GRz&sig=VnmgUtnaSZ2hroUNfwBhUBA8OT0

NASA. (2007). *NASA Systems Engineering Handbook*. Retrieved from http://www.acq.osd.mil/se/docs/NASA-SP-2007-6105-Rev-1-Final-31Dec2007.pdf

Nielsen, J. J., & Sørensen, J. D. (2011). On risk-based operation and maintenance of offshore wind turbine components. *Reliability Engineering & System Safety*, *96*(1), 218–229. doi:10.1016/j.ress.2010.07.007

Nnadili, C. D. (2009). *Floating Offshore Wind Farms - Demand Planning & Logistical Challenges of Electricity Generation*. Massachusetts Institute of Technology.

OptTek Systems. (n.d.). Tuning OptQuest for a particular problem. Retrieved April 7, 2015, from http://www.opttek.com/documentation/v66engine/OptQuest Engine Documentation/Default.htm#Tuning_OptQuest_for_a_particular_problem.htm

Papenbrock, J. (2008). Verfügbarkeit eines Rechners(ystems). Retrieved June 20, 2014, from http://www.solvium.de/blog/2008/verfuegbarkeit-eines-rechnersystems/

Pegden, C. D. (2008). Introduction to SIMIO. In *Simulation Conference, 2008. WSC 2008. Winter* (pp. 229–235). IEEE.

PwC. (2011). Offshore proof: Turning windpower promise into performance. Retrieved April 7, 2014, from http://www.pwc.nl/nl/assets/documents/pwc-offshore-proof.pdf

Rademakers, L. W. M. M., Braam, H., Obdam, T. S., Frohböse, P., & Kruse, N. (2008). Tools for estimating operation and maintenance costs of offshore wind farms : State of the Art.

Rademakers, L. W. M. M., Braam, H., Zaaijer, M. B., & Bussel, G. J. W. Van. (2003). Assessment and Optimisation of Operation and Maintenance of Offshore Wind Turbines.

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., … Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, *90*(5), 1933–1949.

Rhee, S. J., & Ishii, K. (2003). Using cost based FMEA to enhance reliability and serviceability. *Advanced Engineering Informatics*, *17*(3-4), 179–188. doi:10.1016/j.aei.2004.07.002

Rigzone. (2014). Offshore Rig Day Rates. Retrieved January 5, 2015, from http://www.rigzone.com/data/dayrates/

Sargent, R. G. (2005). Verification and validation of simulation models. In *Proceedings of the 37th conference on Winter simulation* (pp. 130–143). Winter Simulation Conference.

Schenker, N., & Gentleman, J. F. (2001). On judging the significance of differences by examining the overlap between confidence intervals. *The American Statistician*, *55*(3), 182–186.

Scheu, M., Matha, D., Hofmann, M., & Muskulus, M. (2012). Maintenance strategies for large offshore wind farms. *Energy Procedia*, *24*, 281–288.

Scholz-Reiter, B., Lütjen, M., Heger, J., & Schweizer, A. (2010). Planning and control of logistics for offshore wind farms. In *Proceedings of the 12th WSEAS international conference on Mathematical and computational methods in science and engineering* (pp. 242–247). World Scientific and Engineering Academy and Society (WSEAS).

Sociaal-Economische Raad. (2013). *Energieakkoord voor duurzame groei*.

The Crown Estate. (2010). *A Guide to an Offshore Wind Farm*.

The German Offshore Wind Energy Foundation. (2013). Cost Reduction Potentials of Offshore Wind Power in Germany. Retrieved March 25, 2014, from http://www.offshore-stiftung.com/60005/Uploaded/SOW_Download|EN_ShortVersion_CostReductionPotentialsofOffshoreWindPower.pdf

United Nations. (2010). Framework Convention on Climate Change. Retrieved April 15, 2014, from http://unfccc.int/resource/docs/2011/sbi/eng/inf02.pdf

Van Bussel, G. J. W., & Zaaijer, M. B. (2001). Reliability , Availability and Maintenance aspects of large-scale offshore wind farms , a concepts study ., *113*, 119–126.

Van de Pieterman, R. P., Braam, H., Obdam, T. S., Rademakers, L. W. M. M., & Van der Zee, T. J. J. (2011). Optimisation of maintenance strategies for offshore wind farms: A case study performed with the OMCE-Calculator. In *The Offshore 2011 conference*.

Vestas. (2014). Turbines. Retrieved May 21, 2014, from http://www.vestas.com/en/products_and_services/turbines#!

Wagenaar, J. W., & Eecen, P. J. (2009). Measurements of Wind, Wave and Currents.

Weisse, R., Gunther, H., & Feser, F. (2002). A 40-year high-resolution wind and wave hindcast for the southern North Sea. Retrieved January 16, 2015, from http://www.academia.edu/2549007/A_40YEAR_HIGH-RESOLUTION_WIND_AND_WAVE_HINDCAST_FOR_THE_SOUTHERN_NORTH_SEA

Whitner, R. B., & Balci, O. (1989). Guidelines for selecting and using simulation model verification techniques. In *Proceedings of the 21st conference on Winter simulation* (pp. 559–568). ACM.

Wind Energy Update. (2008). Does your O&M supply contract really meet your long-term requirements? Retrieved May 1, 2014, from http://social.windenergyupdate.com/operations-maintenance/does-your-om-supply-contract-really-meet-your-long-term-requirements

Windcat. (2010). Offshore Access Systems. Retrieved December 24, 2014, from http://www.mianederland.nl/files/Offshore Access Systems (WindCat)-4.pdf

Windpower Monthly. (2010). How to find the right maintenance contract. Retrieved May 1, 2014, from http://www.windpowermonthly.com/article/1009791/find-right-maintenance-contract

Appendices

Appendix A: Stakeholder Analysis

To assess the different stakeholders the interest, attitude and power matrix of Murray-Webster & Simon (2006) is applied. With this method all the stakeholder will be examined on three different dimensions: (1) power, (2) interest and (3) attitude. These dimensions could be positive or negative; from - till +. Murray-Webster & Simon (2006) gave the following definitions to the three dimensions:

1. **Power**: Potential to influence derived from their positional or resource power or credibility as a leader or expert.
2. **Interest:** Measured by the extent to which they will be active or passive.
3. **Attitude**: Measured by the extent to which they will support or resist.

When the actors are analyzed on each dimension they could, according to the analysis, be classified in eight different stakeholder types.

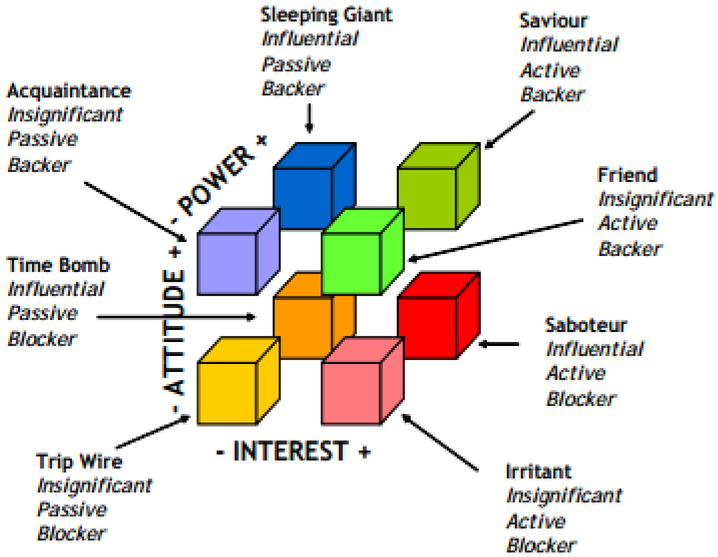


Figure 61: Stakeholder model (Murray-Webster & Simon, 2006)

This assessment is performed in the next table and is all regarding an effective O&M process and therefore a decision support tool that could assist them in achieving an effective O&M. Note that the same actors are included as in chapter 2 and that actors possible against the construction of wind farms, e.g. coastal residents and environmental organizations, are not included since the subject of this is the operational phase wherein the farms are already built.

Table 33: Actor analysis

Actor	Power	Interest	Attitude	Stakeholder type
Turbine manufacturer	+	+	+	Saviour
Wind farm constructor	-	-	+	Acquaintance
Wind farm owner	+	+	+	Saviour
Operation & Maintenance (operator)	+	+	+	Saviour
Power grid owner	-	-	+	Acquaintance

Appendix B: Requirements for the O&M Process

Table 34: Requirements for the O&M Process

Nr	Requirement
	For the O&M process it shall be possible for the stakeholders, in order to maximize the profit, to make decisions to…
P1	Maximize the time- or energy-based availability of the wind farm
P2	Maximize the production revenues
P3	Minimize the O&M costs
P4	Maximize the robustness of the maintenance plan
	For the stakeholders in the O&M process, in order to achieve an effective O&M, it shall possible to…
P5	Make decisions to adjust the resources (type and number of personnel and transport
P6	Make decisions to adjust the service level regarding spare parts inventory
P7	Perform different O&M strategies (incl. preventive and corrective maintenance)
P8	Incorporate uncertain weather conditions
P9	Incorporate uncertain failures of all the different turbine components
P10	Take the lead time of the different spare parts into account
P11	Perform O&M according to the safety regulations
	For the stakeholders in the O&M process it shall possible to…
P12	Use an integrated decision support tool to get insight in the O&M process
P13	Use an integrated decision support tool to evaluate the effectiveness of different O&M strategies
P14	Use an integrated decision support tool to design a feasible and robust scheduled maintenance plan

Appendix C: Objective Tree

Based on the literature and interviews the next objective tree is drawn for the maintenance party; turbine manufacturer, ISP or wind farm owner. The process requirements related to these goals are denoted in gray.

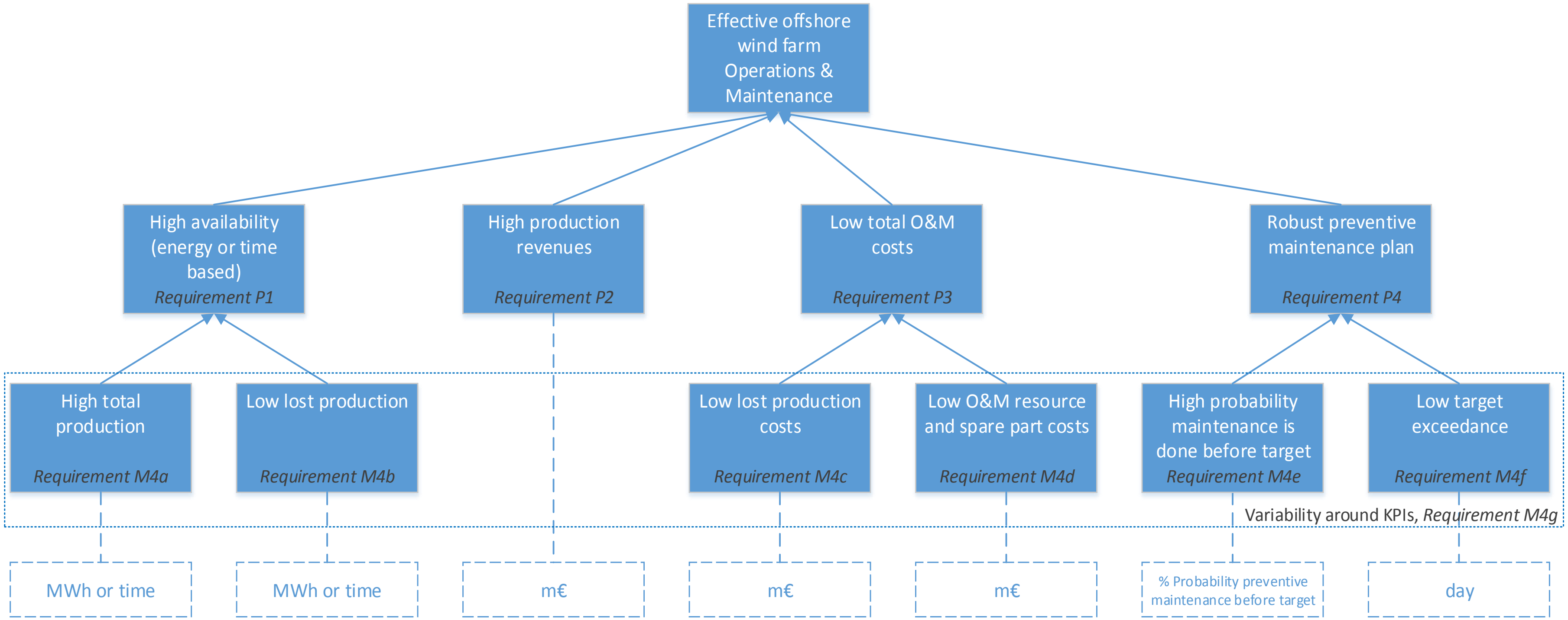


Figure 62: Objective tree

Note that there can be some overlap between the objectives. In case the total production is measured in terms of MWh (to measure the energy-based availability) the production revenues are directly correlated. This is not the case if the production is expressed in terms of time, so therefore both production as well as the production revenues are included.

Appendix D: Model Requirements for the O&M Decision Support Tool

Table 35: Requirements for the O&M Model

Nr	Requirement
	The model should be able to define
M1	The wind farm specific parameters
M1a	The number of turbines
M1b	The distance between the turbines
M1c	The distance from the shore
M1d	The distance from the spare parts
M1e	The production rate (power curve) of a turbine
M1f	The different types of the components
M1g	The repair time of each component, in case of failures
M1h	The need for a jack-up barge, in case of failures
	The model should
M2	Be capable to take external factors into account
M2a	Include the wave height
M2b	Include the wind speed
M2c	Include the correlation between wave and wind
M2d	Include (historical) correlation / trends in the weather conditions
M2e	Forecast the weather to determine the accessibility
M2f	Include the failure rates of all the different turbine components, including randomness
M2g	Include the lead time of the different components, including randomness
M2h	Take the safety regulations into account
	The model should be capable to
M3	Use different O&M strategies
M3a	Vary the type of transporters (type of vessel or helicopter, including properties as costs, capacity, speed, wave and wind thresholds)
M3b	Vary the number of transporters
M3c	Vary the number of personnel
M3d	Vary the service level/amount of stock regarding spare parts inventory
M3e	Perform condition based maintenance
M3f	Perform predetermined (scheduled) based maintenance (including number of personnel per turbine, number of days per turbine and preventive maintenance threshold)
M3g	Perform corrective maintenance (including number of personnel per failure)
	The model should be capable to present
M4	Output on the KPIs:
M4a	The total production (both in terms of MWh and time)
M4b	The lost production (both in terms of MWh and time)
M4c	The lost production costs (in M€)
M4d	The O&M resource and spare part costs (in M€)
M4e	Preventive maintenance target date exceedance probability [% target exceedance]
M4f	Preventive maintenance target date exceedance impact [day]
M4g	Variability or bandwidth around the KPIs

	The model should be able
M5	Give insight in the O&M process (e.g. visualization or process animation)
M6	Compare and optimize different O&M alternatives
M7	To design feasible and robust scheduled maintenance
M7a	Plan resources (personnel and material) for the scheduled maintenance
M7b	Plan feasible (w.r.t. to start and target date) scheduled maintenance
M7c	Plan robust (w.r.t. variability around target date) scheduled maintenance

Appendix E: Overview Previous Research and O&M Tools

Table 36: Overview previous research and O&M tools

Nr.	Authors (Year)	Subject
1	Aksoy, Fuat Toprak, Aytek, & Erdem Ünal (2004)	Comparison of different stochastic wind speed data generation
2	Besnard et al. (2013)	Maintenance support organization (cost) optimization for fictitious farm based on 1) offshore/onshore 2) work shift 3) two types of transfer vessels 4) helicopter support (yes/no).
3	Braam & Eecen (2005)	Weather data assessment to generate (good and bad) weather window probabilities and durations, used in ECN O&M Calculator
4	Dewan (2014)	Thesis: Logistic & Service Optimization for O&M of Offshore Wind Farms
5	Ding & Tian (2011)	Different opportunistic, condition based, maintenance approaches
6	Feuchtwang & Infield (2013)	Comparison of different weather simulation methods
7	Karyotakis (2011)	Optimization of O&M strategies focused on cost and production with limited aspects
8	Nielsen & Sørensen (2011)	Single turbine single component maintenance strategy for fictitious farm
9	Nnadili (2009)	General maintenance concepts and (non- transparent) inventory management
10	Scheu, Matha, Hofmann, & Muskulus (2012)	Markov chain weather simulation and different fleet compositions
11	Scholz-Reiter, Lütjen, Heger, & Schweizer (2010)	Optimal *installation* schedule based on weather conditions
12	Van Bussel & Zaaijer (2001)	Reliability, Availability and Maintenance aspects of large-scale offshore wind farms, a concepts study.
13	CONTOFAX (1997), found in Koutoulakos (2010), developed at TU Delft by Christian Schöntag and Gerard van Bussel in 1996	Software tool based on Monte Carlo simulations to estimate availability of offshore wind farms
14	ECN Operation & Maintenance Cost Estimator (OMCE) tool (Braam et al., 2011), case study by Van de Pieterman, Braam, Obdam, Rademakers, & Van der Zee (2011) and Previous ECN O&M tool (Rademakers, Braam, Obdam, Frohböse & Kruse, 2008)	Most detailed and integrated tool to calculate O&M costs. Estimated annual O&M costs and availability based on 1) failure rates 2) weather condition and 3) three maintenance strategies.

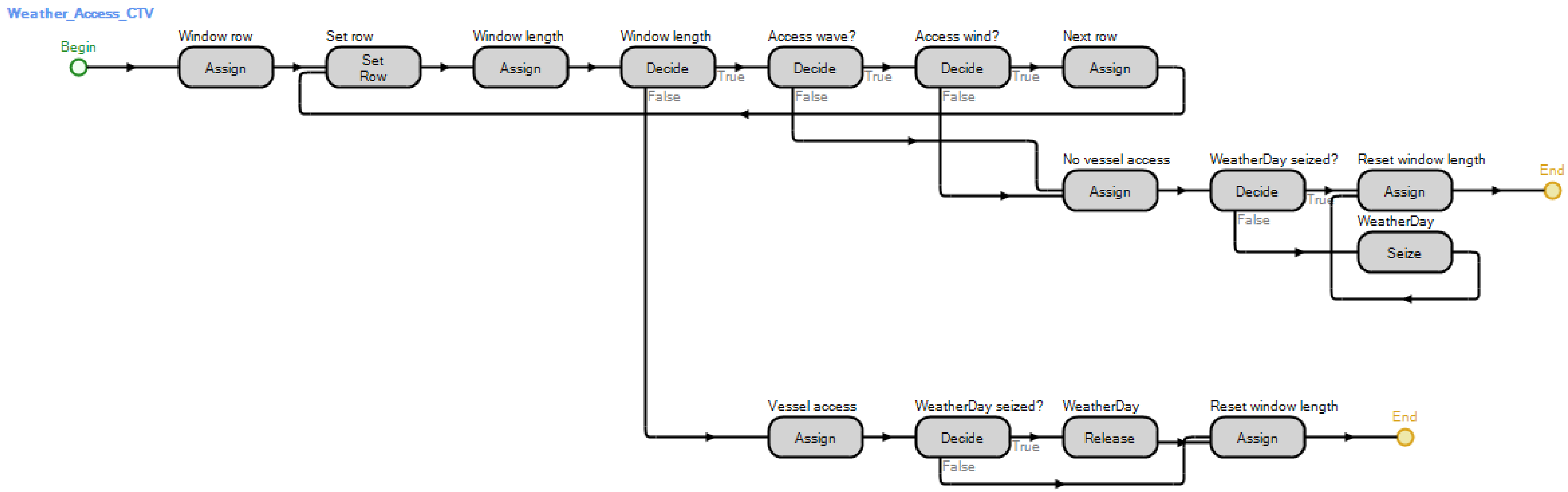
Appendix F: Model Requirements Fulfilled by Previous Research

Table 37: Model requirements fulfilled by previous research

Nr	Requirement	✓ / ✓ / ✗ *Including research nr.* *(See Appendix E)*
	The model should be capable to define	
M1	The wind farm specific parameters	
M1a	The number of turbines	✓ 2,4,5,7,11,13,14
M1b	The distance between the turbines	✗
M1c	The distance from the shore	✓ 2,4,7,13,14
M1d	The distance from the (offshore) spare parts location	✓ 2
M1e	The production rate (power curve) of a turbine	✓ 8,9,13,14 ✓ 7
M1f	The different types of the components	✓ 2,4,5,7,10,13,14
M1g	The repair time of each component, in case of failures	✓ 4,5,7,8,14 ✓ 2,10,13
M1h	The need for a jack-up barge for each component, in case of failures	✓ 4,7,10,13,14
	The model should	
M2	Be capable to take external factors into account	
M2a	Include the wave height	✓ 1,2,3,4,6,8,10,11,13,14
M2b	Include the wind speed	✓ 1,2,3,4,6,7,8,9,10,11,14
M2c	Include the correlation between wave and wind	✓ 1,2,3,4,6,8,10,11,14
M2d	Include (historical) correlation / trends in the weather conditions	✓ 1,2,4,6,8,11,14 ✓ 10
M2e	Forecast the weather to determine the accessibility	✓ 1,2,3,4,6,7,8,10,11,14 ✓ 13
M2f	Include the failure rates of all the different turbine components, including randomness	✓ 2,4,5,7,9,12,13,14 ✓ 8
M2g	Include the lead time of the different components, including randomness	✓ 4,9,14
M2h	Take the safety regulations into account	✓ / ?
	The model should be capable to	
M3	Use different O&M strategies	
M3a	Vary the type of transporters (type of vessel or helicopter, including properties as costs, capacity, speed, wave and wind thresholds)	✓ 2,4,8,14 ✓ 7,10,13
M3b	Vary the number of transporters	✓ 2,4,13,14

		✓ 10
M3c	Vary the number of personnel	✓ 2,4,13,14
M3d	Vary the service level/amount of stock regarding spare parts inventory	✓ 4,9,14
M3e	Perform condition based maintenance	✓ 5 ✓ 8,14
M3f	Perform predetermined (scheduled) based maintenance (including number of personnel per turbine, number of days per turbine and preventive maintenance threshold)	✓ 2,4,5,7,8,13,14
M3g	Perform corrective maintenance (including number of personnel per failure)	✓ 14 ✓ 2,4,7,8,10,13
	The model should be capable to present	
M4	Output on the KPIs:	
M4a	The total production (both in terms of MWh and time)	✓ 14 ✓ 7
M4b	The lost production (both in terms of MWh and time)	✓ 14 ✓ 2,4,7,8,9,10,13
M4c	The lost production costs (in M€)	✓ 2,4,7,8,9,10,13,14
M4d	The O&M resource and spare part costs (in M€)	✓ 7,9,14 ✓ 2,4,5,8,13
M4e	Preventive maintenance target date exceedance probability [% target exceedance]	✗
M4f	Preventive maintenance target date exceedance impact [day]	✗
M4g	Variability or bandwidth around the KPIs	✓ 13,14
	The model should be able	
M5	Give insight in the O&M process (e.g. visualization or process animation)	✗
M6	Compare and optimize different O&M alternatives	✓ 2,4,5,8,10,13,14
M7	To design feasible and robust scheduled maintenance	
M7a	Plan resources (personnel and material) for the scheduled maintenance	✓ 11
M7b	Plan feasible (w.r.t. to start and target date) scheduled maintenance	✗
M7c	Plan robust (w.r.t. variability around target date) scheduled maintenance	✗

Appendix G: Simio Implementation - Example



Appendix H: Turbine Power Curves

The next figures show the power curves for the four included turbines and their implemented lookup values. The first three are from turbine manufacture Vestas (2014). The last one is used for the validation and is used by Van de Pieterman et al. (2011) in the ECN case study.

Vestas V80

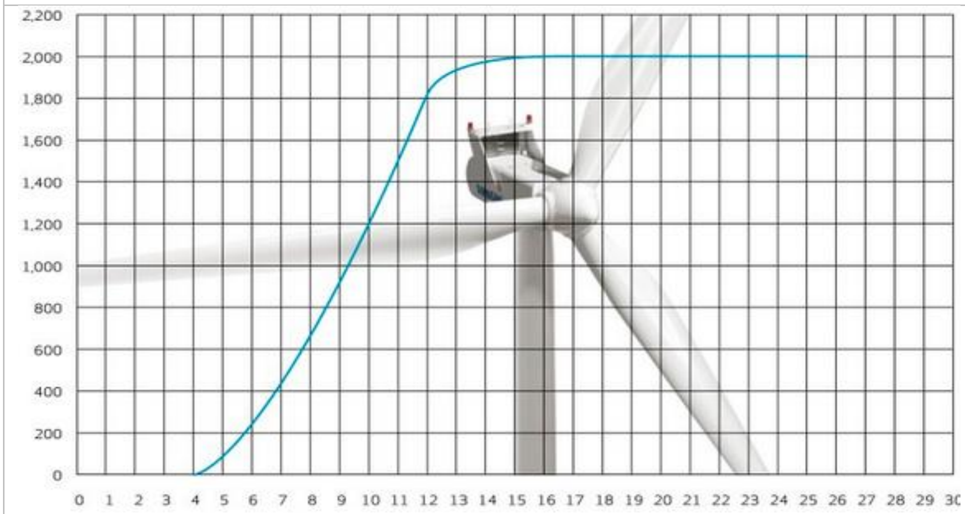


Figure 63: Vestas V80 power curve

Wind	kW
0	0
4	0
5	100
6	250
7	450
8	700
9	950
10	1200
11	1500
12	1800
13	1900
14	1950
15	2000
25	2000
25.001	0
50	0

Vestas V105

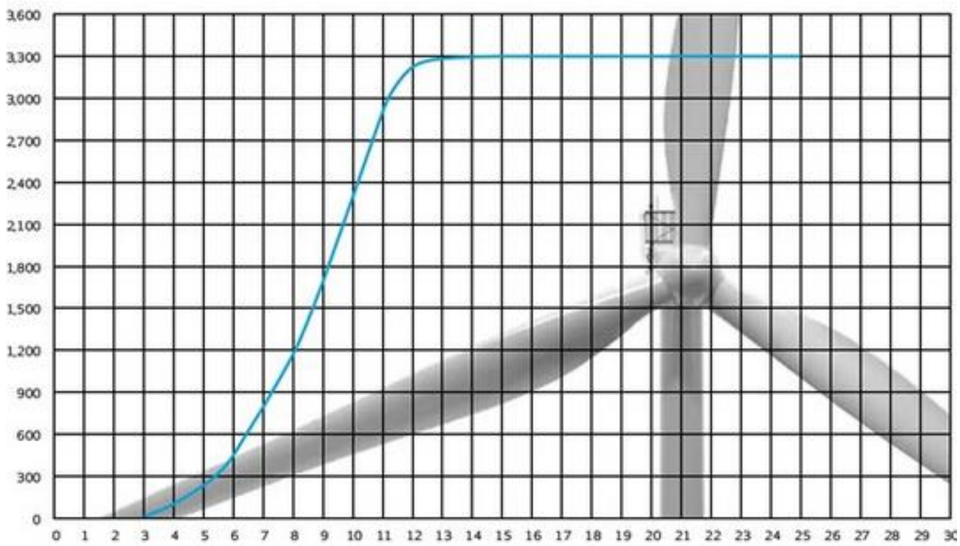


Figure 64: Vestas V105 power curve

Wind	kW
0	0
2.999	0
3	10
4	100
5	250
6	450
7	800
8	1200
9	1700
10	2300
11	2900
12	3200
13	3300
25	3300
25.001	0
50	0

Vestas V110

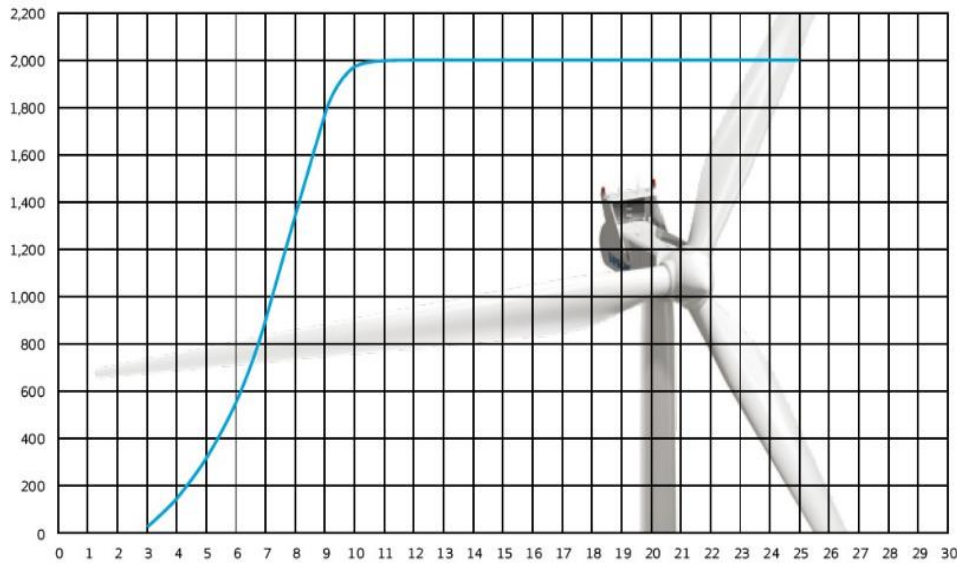


Figure 65: Vestas V110 power curve

Wind	kW
0	0
2.999	0
3	50
4	150
5	300
6	550
7	900
8	1350
9	1750
10	1950
11	2000
12	2000
13	2000
25	2000
25.001	0
50	0

ECN case study

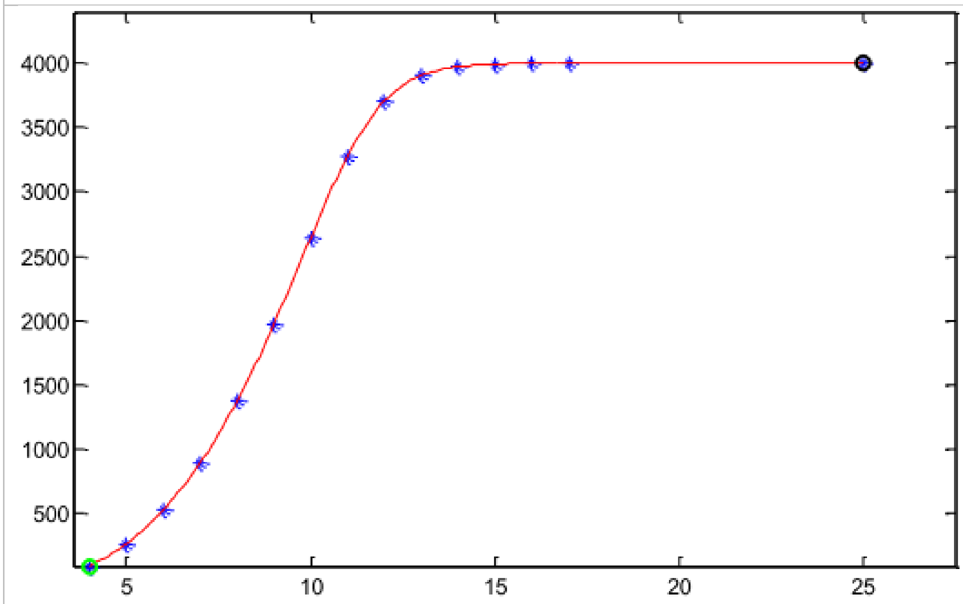


Figure 66: ECN case study turbine power curve

Wind	kW
0	0
2	0
5	200
6	550
7	900
8	1400
9	2000
10	2700
11	3300
12	3700
13	3900
14	3950
15	3975
16	4000
25	4000
25.0001	0
50	0

Appendix I: Requirements Verification

The next table checks whether the requirements are included in the model.

Table 38: Requirements Verification

Nr	Requirement	✓/✓/✗
	The model should be capable to define	
M1	The wind farm specific parameters	
M1a	The number of turbines	✓
M1b	The distance between the turbines	✓
M1c	The distance from the shore	✓
M1d	The distance from the (offshore) spare parts location	✓
M1e	The production rate (power curve) of a turbine	✓
M1f	The different types of the components	✓
M1g	The repair time of each component, in case of failures	✓
M1h	The need for a jack-up barge for each component, in case of failures	✓
	The model should	
M2	Be capable to take external factors into account	
M2a	Include the wave height	✓
M2b	Include the wind speed	✓
M2c	Include the correlation between wave and wind	✓
M2d	Include (historical) correlation / trends in the weather conditions	✓
M2e	Forecast the weather to determine the accessibility	✓
M2f	Include the failure rates of all the different turbine components, including randomness	✓
M2g	Include the lead time of the different components, including randomness	✗
M2h	Take the safety regulations into account	✓
	The model should be capable to	
M3	Use different O&M strategies	
M3a	Vary the type of transporters (type of vessel or helicopter, including properties as costs, capacity, speed, wave and wind thresholds)	✓
M3b	Vary the number of transporters	✓
M3c	Vary the number of personnel	✓
M3d	Vary the service level/amount of stock regarding spare parts inventory	✗
M3e	Perform condition based maintenance	✓
M3f	Perform predetermined (scheduled) based maintenance (including number of personnel per turbine, number of days per turbine and preventive maintenance threshold)	✓
M3g	Perform corrective maintenance (including number of personnel per failure)	✓
	The model should be capable to present	
M4	Output on the KPIs:	
M4a	The total production (both in terms of MWh and time)	✓
M4b	The lost production (both in terms of MWh and time)	✓

M4c	The lost production costs (in M€)	✓
M4d	The O&M resource and spare part costs (in M€)	✓
M4e	Preventive maintenance target date exceedance probability [% target exceedance]	✓
M4f	Preventive maintenance target date exceedance impact [day]	✓
M4g	Variability or bandwidth around the KPIs	✓
	The model should be able	
M5	Give insight in the O&M process (e.g. visualization or process animation)	✓
M6	Compare and optimize different O&M alternatives	✓
M7	To design feasible and robust scheduled maintenance	
M7a	Plan resources (personnel and material) for the scheduled maintenance	✓
M7b	Plan feasible (w.r.t. to start and target date) scheduled maintenance	✓
M7c	Plan robust (w.r.t. variability around target date) scheduled maintenance	✓

Appendix J: Replications and Warm-up for the Case Study

This appendix discusses the number of replications and the warm-up period the case study (also usable for other experiments).

Number of Replications

To determine the number of replications for the case study, six simulations of the base case of the case study (see chapter 10) are performed with 6,8,10, 20, 50 and 100 replications. The next figure shows the impact of the number of replications on the half width (half of the 95% confidence interval, measuring the variability) of the KPI *energy-based availability*. The lower the number of replications the lower the precision and the less significant results. The higher the number of replications the higher the precision and the higher the simulation time (a couple of minutes per replication of one year on current computers).

Looking at the next figure, 50 replications is considered as a good trade-off between precision and simulation time.

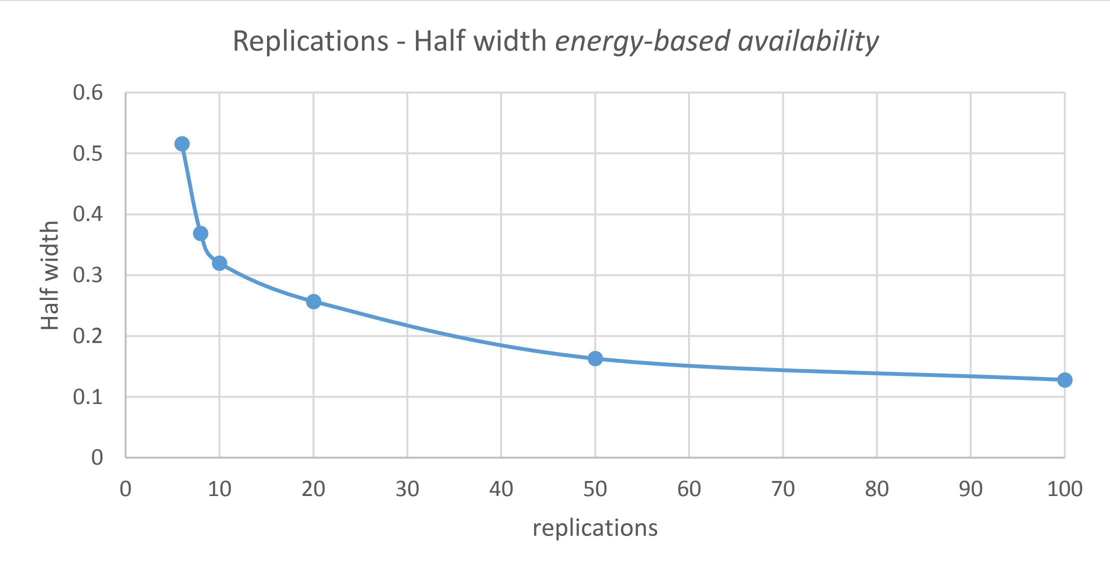


Figure 67: Number of replications - half width

Warm-up Period

The model is tested with and without a warm-up period. Both resulted in exactly the same results (regarding the mean and variability). Furthermore, the system should start with no entities in the system, since the maintenance will start in January; so no filled system is required at the start of the simulation.

Appendix K: Assessing the Significance of Differences of the O&M Strategies

To assess the significance of the differences of the O&M strategies, Schenker & Gentleman (2001) suggested to assess the confidence interval of the difference instead of looking whether or not of two confidence intervals of two strategies overlaps. The overlap method is performed at the end of this appendix to indicate the missed significances.

To obtain the confidence interval of the difference the next formula of Schenker & Gentleman (2001) is used. When this interval does not contain 0 the strategies are significantly different.

Equation 3: confidence interval of the difference based Schenker & Gentleman (2001), SE = standard error.

$$(Mean_1 - Mean_2) \pm \sqrt{SE_1^2 + SE_2^2}$$

This appendix performs the calculation of the significance of the strategies used in the case study of chapter 12 compared to the baseline (A0).

Step 1: Mean and half width of the strategies

The next means and half widths of the 95% confidence interval are obtained from the decision support tool:

Table 39: Means and half widths of the 95% confidence interval

KPI	Unit	A0	A1	A2	A3	A4	A5	A6	A7
C1	%MWh	96.73 +-0.16	96.94 +-0.17	96.83 +-0.16	97.14 +-0.12	97.02 +-0.17	97.47 +-0.12	97.27 +-0.12	97.54 +-0.12
	%hour	96.63 +-0.14	96.66 +-0.14	96.82 +-0.14	97.03 +-0.11	96.91 +-0.13	97.05 +-0.10	97.22 +-0.11	97.28 +-0.10
C1.1	MWh	444,651 +-7,203	445,611 +-7,195	445,129 +-71,99	446,561 +-7,330	445,975 +-7,203	448,093 +-7,369	447,188 +-7,366	448,422 +-7,374
	hour	8,464.36 +-12.53	8,467.22 +-12.17	8,481.07 +-12.34	8,499.99 +-9.31	8,488.93 +-11.73	8,501.53 +-9.18	8,516.16 +-9.31	8,521.88 +-8.72
C1.2	MWh	15,086 +-857	14,126 +-876	14,608 +-862	13,176 +-616	13,762 +-868	11,643 +-598	12,549 +-594	11,315 +-594
	hour	295.64 +-12.53	292.78 +-12.17	278.93 +-12.34	260.01 +-9.31	271.07 +-11.73	258.47 +-9.18	243.84 +-9.31	238.12 +-8.72
C2	M€	71.14 +-1.15	71.30 +-1.15	71.22 +-1.15	71.45 +-1.17	71.36 +-1.15	71.70 +-1.18	71.55 +-1.18	71.75 +-1.18
C3	M€	6.59 +-0.24	6.43 +-0.24	6.52 +-0.24	6.50 +-0.21	6.38 +-0.24	6.25 +-0.21	6.42 +-0.21	6.21 +-0.21
C3.1	M€	2.41 +-0.14	2.26 +-0.14	2.34 +-0.14	2.11 +-0.10	2.20 +-0.14	1.86 +-0.10	2.01 +-0.10	1.81 +-0.10
C3.2	M€	4.18 +-0.14	4.17 +-0.14	4.19 +-0.14	4.40 +-0.14	4.18 +-0.14	4.39 +-0.14	4.41 +-0.14	4.40 +-0.14
C4	day	0.00 +-0.00	0.44 +-0.43	0.29 +-0.35	0.00 +-0.00	12.81 +-4.92	0.00 +-0.01	0.00 +-0.00	6.28 +-2.87
C4.1	%	3.57 +-3.84	20.28 +-11.32	16.57 +-10.36	3.57 +-3.84	68.57 +-13.27	7.28 +-6.65	3.57 +-3.84	55.57 +-14.29
C4.2	day	0.00 +-0.00	2.18 +-1.71	1.78 +-1.80	0.00 +-0.00	18.68 +-6.20	0.07 +-0.11	0.00 +-0.00	11.30 +-4.26

Step 2: Calculate standard error

The half width of the 95% confidence interval is equal to the SE times 1.96. The next table shows the standard error by dividing the half width of the above table by 1.96.

Table 40: Standard error

KPI	Unit	A0	A1	A2	A3	A4	A5	A6	A7
C1	%MWh	0.08	0.09	0.08	0.06	0.09	0.06	0.06	0.06
	%hour	0.07	0.07	0.07	0.05	0.07	0.05	0.05	0.05
C1.1	MWh	3675	3671	3673	3740	3675	3760	3758	3762
	hour	6.39	6.21	6.30	4.75	5.98	4.69	4.75	4.45
C1.2	MWh	437	447	440	314	443	305	303	303
	hour	6.39	6.21	6.30	4.75	5.98	4.69	4.75	4.45
C2	M€	0.59	0.59	0.59	0.60	0.59	0.60	0.60	0.60
C3	M€	0.12	0.12	0.12	0.11	0.12	0.11	0.11	0.11
C3.1	M€	0.07	0.07	0.07	0.05	0.07	0.05	0.05	0.05
C3.2	M€	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
C4	day	0.00	0.87	0.92	0.00	3.17	0.06	0.00	2.17
C4.1	%	0.02	0.06	0.05	0.02	0.07	0.03	0.02	0.07
C4.2	day	0.00	0.22	0.18	0.00	2.51	0.00	0.00	1.46

Step 3: Calculate start confidence interval of the difference

For this step equation 3 is used. Only the start of the interval is needed if the absolute differences between the means are used. When the start of that confidence interval is above 0 there is a significant difference (either better or worse) with the baseline (A0). Yellow cells in the next table indicates a significant difference.

Table 41: Start of 95% confidence interval of the difference with the baseline

KPI	Unit	A0	A1	A2	A3	A4	A5	A6	A7
C1	%MWh		-0.02	-0.13	0.21	0.06	0.54	0.35	0.61
	%hour		-0.17	-0.01	0.23	0.08	0.25	0.41	0.48
C1.1	MWh		-9221	-9706	-8367	-8863	-6862	-7765	-6538
	hour		-14.61	-0.88	20.02	7.41	21.64	36.19	42.26
C1.2	MWh		-266	-738	854	103	2397	1494	2728
	hour		-14.61	-0.88	20.02	7.41	21.64	36.19	42.26
C2	M€		-1.48	-1.55	-1.34	-1.42	-1.10	-1.24	-1.05
C3	M€		-0.18	-0.27	-0.24	-0.13	0.01	-0.15	0.06
C3.1	M€		-0.04	-0.12	0.14	0.02	0.38	0.24	0.44
C3.2	M€		-0.19	-0.19	0.03	-0.19	0.02	0.04	0.03
C4	day		0.47	-0.03	0.00	12.47	-0.04	0.00	7.04
C4.1	%		0.05	0.02	-0.05	0.51	-0.04	-0.05	0.37
C4.2	day		0.02	-0.06	0.00	7.88	0.00	0.00	3.41

Differences with overlap method

The next table presents in green the significant differences based on non-overlapping confidence intervals and in red the strategies with an overlap with the baseline, but still significant different according to the previous table. The values represent the overlap in the units of the KPI.

Table 42: Overlap with baseline

KPI	Unit	A0	A1	A2	A3	A4	A5	A6	A7
C1	%MWh		0.12	0.22	-0.13	0.04	-0.46	-0.27	-0.53
	%hour		0.25	0.09	-0.16	0.00	-0.18	-0.34	-0.41
C1.1	MWh		13438	13924	12623	13082	11130	12032	10806
	hour		21.85	8.17	-13.79	-0.31	-15.46	-29.96	-36.28
C1.2	MWh		774	1241	-436	402	-1988	-1086	-2320
	hour		21.85	8.17	-13.79	-0.31	-15.46	-29.96	-36.28
C2	M€		2.15	2.23	2.02	2.09	1.78	1.93	1.73
C3	M€		0.32	0.41	0.37	0.27	0.12	0.28	0.07
C3.1	M€		0.12	0.20	-0.07	0.06	-0.32	-0.17	-0.37
C3.2	M€		0.27	0.27	0.06	0.28	0.06	0.04	0.05
C4	day		-0.47	0.03	0.00	-12.47	0.04	0.00	-7.04
C4.1	%		-0.02	0.01	0.08	-0.48	0.07	0.08	-0.34
C4.2	day		-0.02	0.06	0.00	-7.88	0.00	0.00	-3.41