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INNOVATIONS FOR MARITIME LOGISTICS Volume 2

Torsten Münsterberg

Simulation-based Evaluation of Operation and Maintenance Logistics Concepts for Offshore Wind Power Plants

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Simulation-based Evaluation of Operation and Maintenance Logistics Concepts for Offshore Wind Power Plants

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Preface of the Editor

Offshore wind turbine generators are becoming more important as an environmentally friendly energy supply for Germany and other coastal countries worldwide. The construction and operation of offshore wind power plants make high technological, logistical, and economic demands, especially in offshore wind power plants located several kilometers away from the coast. The electricity generation costs are of crucial importance for the acceptance and distribution of this environmentally friendly energy source.

In the operating phase of offshore wind power plants, which is usually 25 years, maintenance costs are a significant component of electricity generation costs. Transporting technicians and material to the offshore wind power plants is cost-intensive, particularly since the offshore wind power plants are often located far from the coast. This is amplified by the expensive transportation modes required, such as special ships and helicopters. In addition, the harsh weather conditions often lead to restrictions on the accessibility to the offshore wind turbine generators, leading to delays and increasing costs.

The design of the logistics concepts for the operating phase of offshore wind power plants is a key influence on the cost. Among other things, the mode of transportation to bring personnel and spare parts to and from the power plants is defined at this stage. In the present dissertation, Dr.-Ing. Münsterberg focuses on the question of which logistics concept is most suitable for a specific offshore wind power plant from an economic perspective.

For this purpose, the logistics concepts are classified by onshore-based or offshore-based concepts. The base station for onshore-based logistics concepts is usually a service port at the shore. From this, technicians and equipment are transported to and from the offshore wind power plants by helicopters and so-called crew transfer vessels. In offshore-based logistics concepts, the starting point for maintenance works are manned platforms, hotel and work vessels, or suitable islands such as Helgoland. The transportation to and from the offshore wind power plant is carried out by crew transfer vessels and helicopters, as well as by the work vessels themselves.

Dr.-Ing. Münsterberg uses the method of event-discrete simulation to investigate the system and the costs under different conditions. He develops a model which considers the logistics and maintenance-relevant characteristics of offshore wind power plants, as well as general conditions such as weather and waves. The model has a great depth of detail and a comprehensive scope, which goes far beyond previous approaches and offers considerable added value in terms of new scientific findings.

For various configurations of offshore wind power plants (number of wind turbine generators per power plant) and distances to the base station, numerous simulation experiments are carried out and evaluated for a period of 25 operating years. It shows that for defined general conditions the most cost-efficient logistics concept for the operating phase of offshore wind power plants can be determined with the model.

Dr.-Ing. Münsterberg derives many interesting findings from the simulations, including the fact that the onshore-based logistics concepts are economically superior when the offshore wind power plants are close to the shore. The offshore-based concepts generally lead to higher availability of the offshore wind power plants, but the increased costs for the additional equipment required reduces the profitability. For offshore wind power plants that are over 100 km away from the base station and that have at least 90 offshore wind turbine generators, offshore-based concepts are more cost-efficient than onshore-based concepts.

A central new finding, which has not yet been published and has not been generated by other event-discrete simulation tools, is the monthly trend of costs throughout the year. It turns out that no logistics concept is permanently the most cost-efficient. By combining different concepts throughout the year, up to 10 % of the total costs could be saved. Dr.-Ing. Münsterberg validates his comprehensive results through sensitivity analyses and comparisons with indicators from practice.

With this dissertation, Dr.-Ing. Münsterberg succeeds in demonstrating approaches for further cost reduction in the offshore wind industry, as well as in providing an important contribution to the scientific discussion in this field.

This dissertation is Volume 2 in the series *Innovations for Maritime Logistics*. I hope you find reading this dissertation to be interesting and informative.

Prof. Carlos Jahn

Head of the Institute for Maritime Logistics of the Hamburg University of Technology
Head of the Fraunhofer Center for Maritime Logistics and Services CML

Hamburg, December 2016

Acknowledgment of the Author

This thesis was developed in the period from February 2012 to November 2015 alongside my work as research associate at the Fraunhofer Center for Maritime Logistics and Services CML in Hamburg.

I poured my heart into this thesis, sacrificing a lot of leisure time and spending many late nights alone in the office. Little by little I reached the goal - which seemed to be unachievably far away - of finally finishing this thesis.

The completion of this thesis would not have been possible without the support and assistance of my colleagues from Fraunhofer, students from the Hamburg University of Technology, and many other people from offshore wind power plant operators and manufacturers, ship brokers, shipping companies and logistics service providers whose names may not all be enumerated. Their contributions are sincerely appreciated and gratefully acknowledged.

Particularly, I would like to express my deep gratitude to Prof. Carlos Jahn, who was my supervisor and first examiner. Only the professional exchange with him has enabled the success and the quality of this work. I also want to express many thanks to Prof. Wolfgang Kersten, who took on the role of the second examiner. Special thanks also go to Laura Walther and Jürgen Weigell, who both proof-read this thesis and gave me very good feedback and suggestions for meaningful amendments. Another thank you is due to Thorsten Hepp, whose work was a great contribution to my research.

To my family, friends and others who in one way or another showed their support, thank you.

Abstract

Electricity production costs of offshore wind power plants are high compared to other energy sources. The costs of offshore wind power have to be reduced to be attractive as a renewable energy source. The operational costs, especially logistics costs, have a great potential for cost reduction. In this thesis a modular simulation model for the operation of offshore wind power plants is developed by using the software *Enterprise Dynamics*. The model is able to represent offshore-based and onshore-based logistics concepts. The output is logistics and opportunity costs (revenue losses). The model is used to gain new findings on the correlation between different influencing factors (e.g. weather conditions), parameters (e.g. number and type of equipment) and the logistics concept performance (economic viability). Based on the developments in the German North Sea, multiple simulation experiments have been conducted on three different logistics concepts (with four variants each) and nine offshore wind power plant scenarios. The validity of the results has been demonstrated through sensitivity analyses for selected input parameters.

The investigation shows that for most German offshore wind power plants an onshore-based logistics concept is the most cost efficient option. An offshore-based concept only becomes the most cost efficient option for a large offshore wind power plant scenario with 90 wind turbine generators located 100 km away from the base station. The success of onshore-based concepts is related to the high additional equipment and personnel costs of offshore-based concepts. Other important findings are that no logistics concept is superior throughout the whole year, and that a combination of concepts leads to the best cost efficiency. The investigation also identifies that the influence of weather downtime (no mission possible because of bad weather conditions) on the availability of the offshore wind power plant is significantly higher compared to the downtime resulting from travel or repair works. The developed model distinguishes itself from other approaches by the event-discrete simulation character, transparent processes and the ability for monthly analysis.

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Abbreviations

ATV	Advanced transfer vessel
AC	Alternate current
BSH	Federal Maritime and Hydrographic Agency (German: Bundesamt für Seeschifffahrt und Hydrographie)
CBM	Condition-based maintenance
CCME	Central command for maritime emergencies
CM	Corrective maintenance
Compl.	Completed
CTV	Crew transfer vessel
DC	Direct current
Durat.	Duration
EEG	Renewable Energy Act (German: Erneuerbare-Energie-Gesetz)
EEZ	Exclusive economic zone
EWEA	European Wind Energy Association
FMECA	Failure modes effects and criticality analyses
HVDC	High voltage direct current
KPI	Key performance indicator
LCOE	Levelized cost of energy
m EUR	Million euros
MV	Offshore-based mother vessel concept
No.	Number
OWPP	Offshore wind power plant
ON	Onshore-based concept
O&M	Operation and maintenance
OMCE	O&M Cost Estimator
Opp.	Opportunity
PF	Offshore-based platform concept
PM	Planned maintenance
PSV	Platform supply vessel
SOV	Service operating vessel
SWATH	Small waterplane area twin hull
TV	Transfer vessel
WTG	Wind turbine generator

Symbols

A_P	Production-based availability
A_T	Technical availability
AEP	Annual energy production
AEP_P	Theoretical annual energy production
C	Capacity factor
$E(X)$	Expectation
E_{WTG}	Total energy yield
F	Permissible error
H_s	Significant wave height
$MTBF$	Mean time between failures
$MTTR$	Mean time to restore
$MTTF$	Mean time to failure
P_{el}	Electrical power production
S_i	Sensitivity index of parameter i
V_w	Wind speed
$\bar{X}$	Arithmetic mean
s	Standard deviation
s^2	Variance
λ	Failure rate
μ	Mean time to failure
θ	True mean

1 Introduction

1.1 Initial Situation and Objectives

The development of offshore wind energy in the last decade as well as in the future was and will be driven by the necessity to reduce green house gas emissions to slow down climate change. Due to the Fukushima catastrophy in 2011 the German government decided to phase out nuclear power, which has always been an important pillar of energy supply in Germany (91.8 TWh/a representing 14.1 % of power production in 2015) (INFORUM 2016).

Considering these facts there is a need to use an alternative like offshore wind for power production in Germany. Because of persisting winds in sea regions, this green energy resource presents a good opportunity. In 2015, onshore wind power plants produced 79.3 TWh/a (12.2 % of total power production) compared to a production of 8.7 TWh/a (1.3 % of total power production) by offshore wind power plants (OWPPs) (AEE 2016, p. 7). Driven ahead through politics, it is expected that the onshore production will rise up to 100 TWh/a until 2030, while offshore wind production is supposed to grow to 90 TWh/a in the same period of time. Therefore, in 2030, offshore wind energy production will be almost as large as onshore wind energy production (Nitsch et al. 2012, p. 115).

Recently, however, the European and German goals for the development of offshore wind energy were reduced. The European Wind Energy Association (EWEA) decreased their goals (based on the national plans) from 40 GW to 23.5 GW until 2020 (EWEA 2014, p. 7). The German goals were cut from 10 GW to 6.5 GW in 2020 and to 15 GW (former 25 GW) until 2030 (BMWi 2014, § 3(2)), (Fraunhofer CML 2014, p. 18). The adaption of goals became necessary due to problems with the offshore grid development and a difficult political framework.

But anyhow, even to achieve these reduced goals the cost of energy of OWPP has to be decreased significantly (Schultz 2013) otherwise it will not be competitive. Currently, 1 MWh of offshore wind power costs EUR 110 to EUR 180 compared to EUR 70 for onshore wind power (Mühlenhoff 2011, p. 7) (Arwas et al. 2012, p. VIII) (Roland Berger Strategy Consultant 2013, p. 19). The operation & maintenance (O&M) phase stands for about 20 to 30 %[1] of cost of energy, thus there is a high potential to cut the costs (WindResearch 2012, p. 24). On the one hand economic pressure is on the O&M phase and its logistics concept, which consists mainly of equipment (vessels, helicopters,

[1] Own calculation based on The Crown Estate (2012, p. 9, 65)

handling equipment), infrastructure (ports), defined processes and communication; on the other hand it also has to individually fit to a certain OWPP project with regard to influencing project parameters like distance to base station, weather conditions and OWPP layout (WindResearch 2012, p. 20).

The importance of cutting costs for offshore wind energy was also identified by the EU. In 2013, the EU initialized a research project called LEANWIND. The project aims to develop cost reduction solutions across the whole OWPP life cycle and supply chain. Thus, within the project lean principles are applied and state of the art technologies and tools are developed (UCC 2015).

Summarizing this, the challenge during the operating phase of OWPPs is to find high-performance and cost-efficient O&M logistics concepts to support the envisaged development of this industry. The logistics concepts are also supposed to be insensitive towards the above mentioned influencing factors. In other words it is the objective of this thesis to answer the question, which logistics concept fits best for a certain OWPP project. To be able to answer this question there is a need for a comprehensive evaluation method.

1.2 Scientific Relevance and Contribution

The scientific relevance of the topic can be proven by several recent studies, which identify logistics as a major research field for offshore wind energy. A study of Fraunhofer IWES, which represents the industry's opinion, shows that the offshore wind industry evaluates logistics and maintenance concepts as TOP 4 topic for further research in the future. (Fraunhofer IWES 2014, p. 11). Another survey conducted by Deloitte and Taylor Wessing showed that the wind energy market actors also see the highest cost savings potential in optimized offshore logistics in the O&M phase (Krüger et al. 2012, p. 13).

As logistics is in the focus of research it is essential to identify factors that influence the performance of logistics concepts. Thus, the main scientific objective is to understand the correlation between different external influencing factors, internal parameters and the logistics concept performance.

Thus, the following central research question can be formulated: Which impact do certain external influencing factors and internal parameters have on the economic viability of an O&M logistics concept for an OWPP? The identified main influencing factors and parameters comprise (Besnard 2013, p. 33), (Münsterberg and Rauer 2012, p. 1), (Karyotakis 2011, p. 69), (Rademakers, Braam, and Verbruggen 2003, p. 2):

- Weather conditions
- Failure rates of components
- Number of supplied wind turbine generators (WTGs)

- Distance between OWPP and base station
- Maintenance strategy
- Number and type of equipment

Being able to quantify the correlations between the above mentioned factors and parameters and the logistics concept performance it is possible to answer the question how an appropriate O&M logistics concept for a specific OWPP project should look.

To investigate the mentioned correlations a modular simulation model to rapidly model different logistics concepts is developed within this thesis. The term *modular* means that it consist of different modules for each logistics concept component. Simulation has been identified as necessary because of the high degree of complexity of the whole investigated system. To answer the main research question several simulation experiments have been conducted using the modular simulation model.

In summary, the scientific contribution consists of two parts. First, a new event-discrete modular simulation model has been developed and second, new findings about the correlation between logistics concept performance and external influencing factors and concept parameters by applying the developed model have been derived.

1.3 Methodology and Structure of the Thesis

In Chapter 1 the research objectives, research question as well as the motivation for this thesis have been presented (see Figure 1.1). Chapter 2 comprises the scientific and methodological background for the model development and the simulation experiments. The state of technology refers to offshore wind energy and current O&M logistics concepts. Logistics concepts are described in this chapter as well as current research on this topic. This chapter derives requirements as a foundation for the model development.

In Chapter 3 the requirements identified in Chapter 2 as well as assumptions are stated. Based on this, the structure of the modular simulation model is developed and explained. The model's modules and functions are explained in detail. The chapter closes with a model validation and verification. Existing data from literature and from experience of operating OWPPs are taken as an example to validate the model functionality.

Chapter 4 serves for the application of the model and to gain new findings. Different logistics concepts for different OWPP scenarios representing the German OWPPs in the North Sea are investigated. Also sensitivity analyses are conducted to ensure the results of experiments. In Chapter 5 the results of all experiments are compared and new findings are derived and critically discussed. In particular, correlations between the logistics concept performance and external influencing factors and concept parameters like environmental conditions, failure rates of components, number of supplied WTGs, distance of the OWPP to the base station are analyzed.

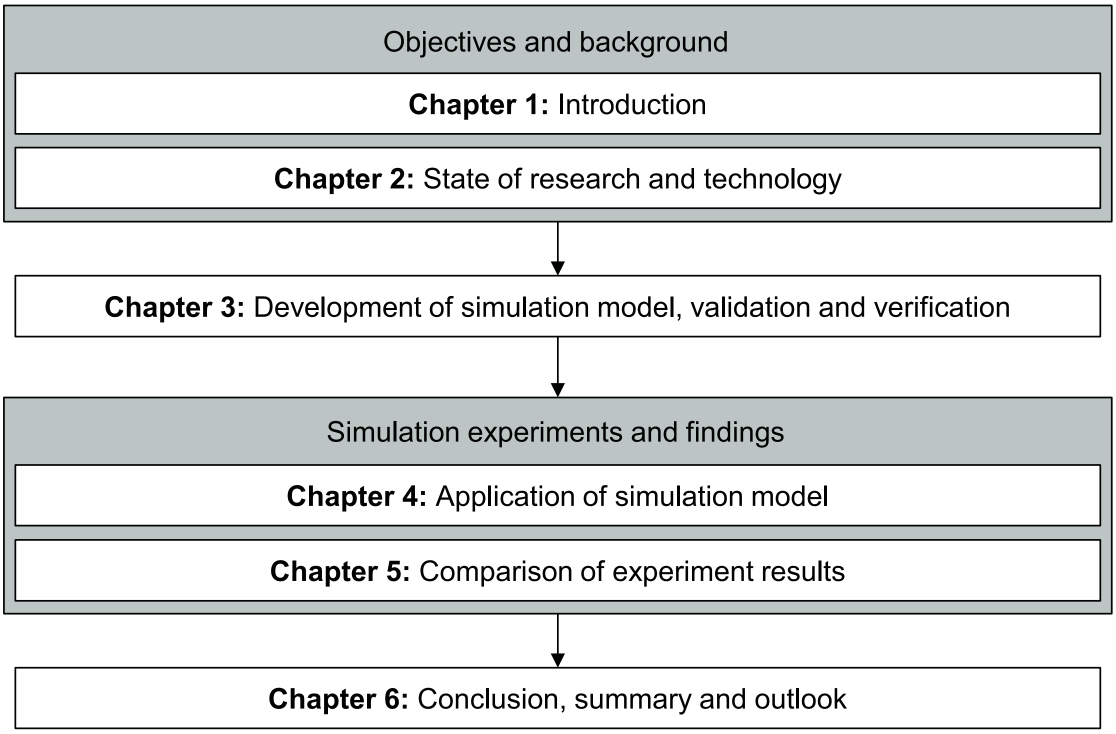


Figure 1.1: Approach and structure of the thesis

The last chapter summarizes the most important findings in terms of OWPP cost efficiency and gives an outlook on further possible research. It concludes how well the model supports the development and evaluation of different O&M logistics concepts.

2 State of Research and Technology

Hereafter the scientific and methodological background for the model development and the simulation experiments is given. Furthermore, the status quo for offshore wind energy and especially the O&M phase of OWPPs is investigated.

2.1 Scientific and Methodological Background

In the following sections, first, the scientific background is defined comprising logistics and the state of the art of O&M. The methodological background covers modeling, simulation, sensitivity analysis and statistical analysis.

2.1.1 Definition of Logistics

Schenk (2003) defines logistics as the science of designing and controlling of processes and structures of holistic systems to fulfill individual customer requests in a target-oriented and resource-efficient manner. A similar definition is given by Fleischmann (2008, p. 3). He describes logistics as design of logistics systems as well as the controlling of the logistics sub-processes. Baumgarten (2004, p. 2) sees logistics as holistic planning, management, execution and control of all internal and cross-company goods and information flows. There are similar definitions from Jünemann and Schmidt (2000, p. 2), who describe logistics as scientific theory of planning, management and surveillance of material, personal, energy and information flows of systems. Krampe and Lucke (2006, p. 21) say logistics deals with the managed flow of goods, persons and information in networks. Based on Plowman (1964), another famous definition of logistics describes the requirements for logistics with six plus one rights of logistics. The goal of logistics is to provide (Ziems 2004, p. 32):

- The right object
- In the right quality
- In the right quantity
- At the right place
- At the right time
- For the right cost
- Ecologically right

Similar definitions exist from Pfohl (2010, p. 12), Schenk et al. (2010, p. 226), Krampe and Lucke (2006, p. 21), Heidenblut and Hompel (2006, p. 207), Gudehus (2005, p. 7), Koether (2004, p. 21) and Schmigalla (1995, p. 348). Many similar definitions of logistics exist. Pfohl (2010, p. 13) gives an overview of logistics definitions. He divides the definitions into flow oriented, life cycle oriented and service oriented. Due to its topic, within this thesis the flow and life cycle oriented perspective on logistics is paramount.

2.1.2 Operation and Maintenance

Regarding OWPPs, operation refers to all activities contributing to the management of the asset like remote monitoring, environmental monitoring, electricity sales, marketing, administration and other back office tasks. Operations stands for a very small share of operation and maintenance expenditure. (Phillips et al. 2013, p. 9)

Maintenance accounts for by far the largest share of O&M effort, cost and risk. Maintenance activity is the upkeep and repair of the physical plant and systems. According to DIN 31051 the term maintenance stands for the combination of all technical and administrative measures as well as management measures during the life cycle of the device, which serve to preserve or restore the functional condition so that the required function can be fulfilled. (DIN 2012, p. 4)

The standard DIN 31051 (DIN 2012, p. 4) divides maintenance in four basic measures (see also Figure 2.1):

- Service[2]
- Inspection
- Repair[3]
- Overhaul

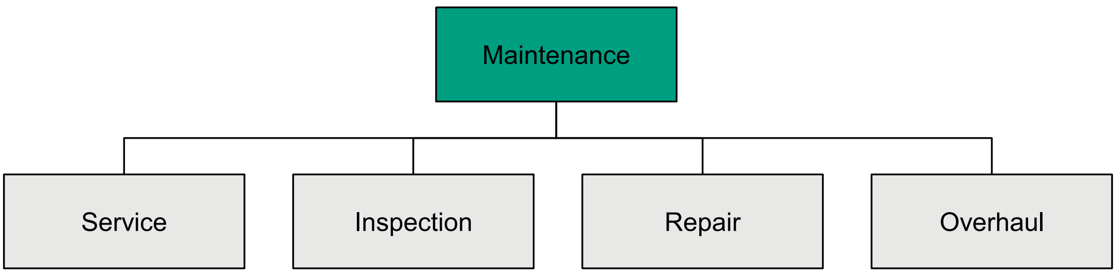


Figure 2.1: Basic measures of maintenance according to DIN 31051 (DIN 2012, p. 4)

According to DIN EN 13306 (DIN 2010) the term maintenance is classified into maintenance types with regard to the timing of the maintenance action (see Figure 2.2). The standard generally differentiates between preventive maintenance and corrective maintenance. Corrective maintenance means that maintenance is not carried out before a

[2]Service corresponds to preventive maintenance according to DIN EN 13306
[3]Repair is part of all maintenance types according to DIN EN 13306

failure has occurred. If a failure occurs it can be corrected immediately (immediate maintenance) or the correction can be postponed (deferred maintenance). Preventive maintenance means that maintenance is carried out before failure. There are two sub-types for preventive maintenance. The first is condition-based maintenance. It covers the condition determination and the implementation of required measures. The condition can be determined by physical inspection or remote monitoring. The condition determination can be either scheduled, requested or continuous. Predetermined or calendar-based maintenance is the second sub-type of preventive maintenance. It means that maintenance is done after a predefined time period (for example every six months).

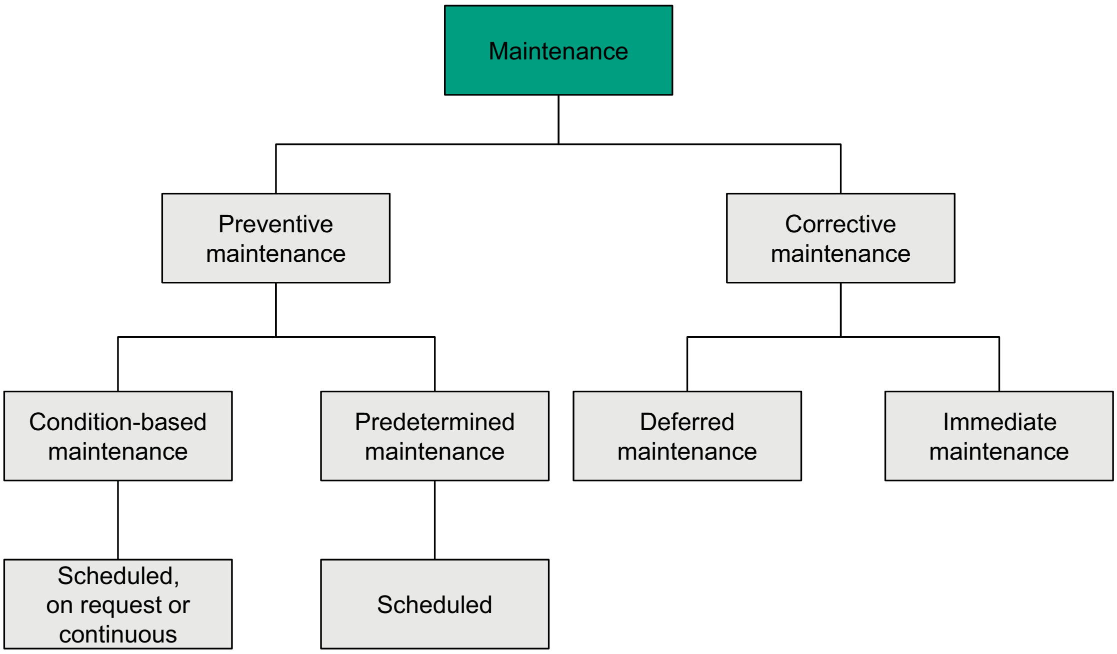


Figure 2.2: Types of maintenance according to DIN EN 13306
(DIN 2010, p. 38)

The above mentioned maintenance measures and types serve to meet company internal and external requirements and to coordinate company and maintenance objectives. Maintenance objectives are for example:

- Provide a particular technical availability
- Achieve a short reaction time for corrective maintenance
- Reduce cost
- Increase safety
- Protect environment
- Conserve the value of the maintenance object

Maintenance objectives have to be determined individually for a company (Biedermann 2008, p. 13), (Pawellek 2013, p. 51).

Maintenance strategy

The management approach to reach the maintenance objectives is called maintenance strategy. It comprises the allocation of resources or the outsourcing of services (DIN 2010, p. 6). Regarding a component or sign of wear maintenance strategies indicate a measure and a point in time (maintenance type) to guarantee a certain availability (Biedermann 2008, p. 19), (Pawellek 2013, p. 4). Current approaches comprise (Pawellek 2013, p. 4), (Karyotakis 2011, p. 45):

- Reliability-centered maintenance
- Total productive maintenance
- Risk-based maintenance

The choice of the right strategy should be done based on the probability of failure and the economical implications of inspections and repairs (El-Reedy 2012, p. 613). In the industry, in many cases there is a lack of required data for an informed decision about the maintenance strategy (Pawellek 2013, p. 130).

Availability and reliability

The maintenance strategy is directly connected to the availability of a system. The availability is defined as the ratio between the time a system is functional in a certain period and the total time of that period. The theoretical availability is the result of the reliability, the maintainability and the serviceability (see Figure 2.3). However, this theoretical availability is influenced by the accessibility of the site (time to gain access in case of failure) and the maintenance strategy, which leads to the actual availability.

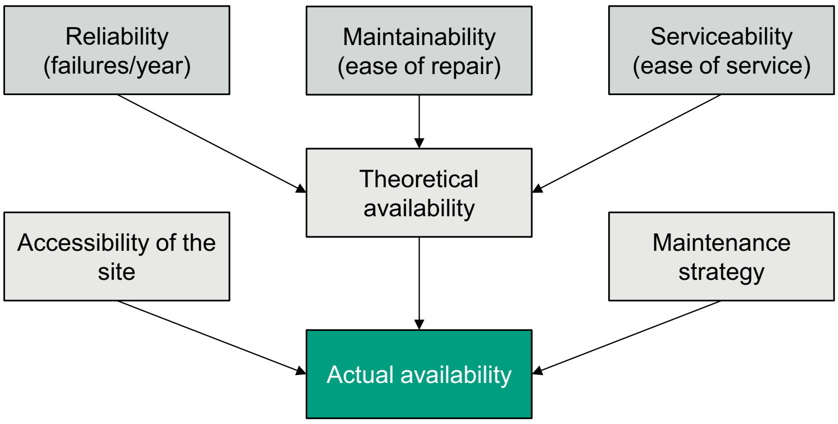


Figure 2.3: Availability of technical systems
(van Bussel et al. 2001, p. 2)

The reliability has a great influence on the availability. Reliability is the probability that a component or system does not fail to work continuously over a certain time period.

Thus, reliability is determined by the failure rate or probability of failure (unreliability) of a component or the system. The measure for reliability is the mean time between failures ($MTBF$). It can be derived from data bases or manufacturer data.

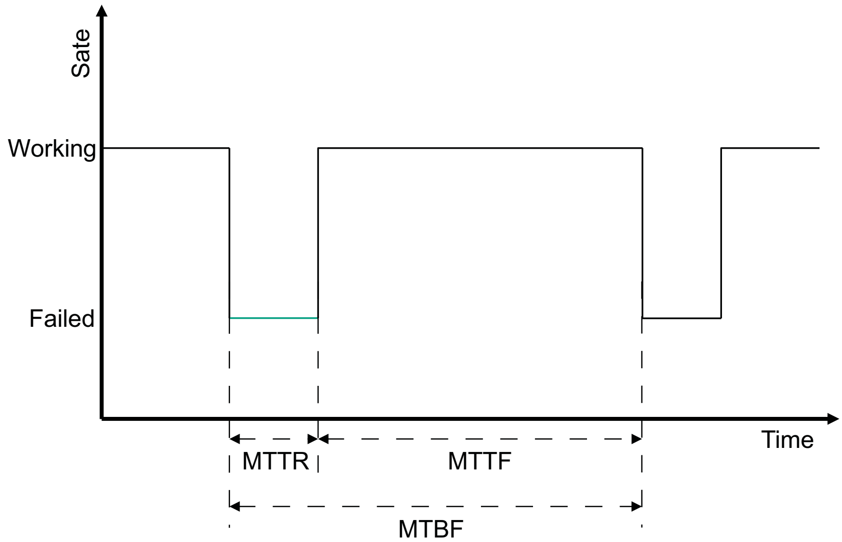


Figure 2.4: Mean time between failures
(Karyotakis 2011, p. 120)

MTBF is the sum of the average repair time (mean time to restore ($MTTR$)) and the average time to failure (mean time to failure ($MTTF$)). MTTF is connected to the reliability and MTTR depends on the chosen maintenance strategy. The relationship between all three parameters is illustrated in Figure 2.4. The displayed relationship can also be mathematically described in the following equation:

$$MTBF = MTTF + MTTR \tag{2.1}$$

MTTR is also called downtime. For OWPPs it consists of alarm duration, duration of spare part procurement, travel time, waiting time because of bad weather and the duration of repair (WSV 2012, p. 52). For OWPP MTTR is very small compared to MTTF, thus the following relationship can be assumed (Tavner 2012, p. 14):

$$MTBF \approx MTTF \tag{2.2}$$

The technical availability A_T for a system or a single component can be expressed with MTTF and MTTR as expressed in the following equation (Tavner 2012, p. 14):

$$A_T = \frac{MTTF}{MTTF + MTTR} = \frac{MTBF - MTTR}{MTBF} \tag{2.3}$$

Furthermore, the production-based availability A_P is a specific parameter for OWPP (see Equation 2.4). It describes the ratio of the annual energy production AEP to the theoretical annual energy production AEP_P, which would have been produced if the WTG had not failed.

$$A_P = \frac{AEP}{AEP_P} \tag{2.4}$$

Another specific parameter is the capacity factor C (see Equation 2.5). It is defined as the percentage of the annual energy production AEP over the product of the rated power output P of a WTG and the hours in one year (Tavner 2012, p. 14).

$$C = \frac{AEP}{P * 8760} \tag{2.5}$$

Failure process

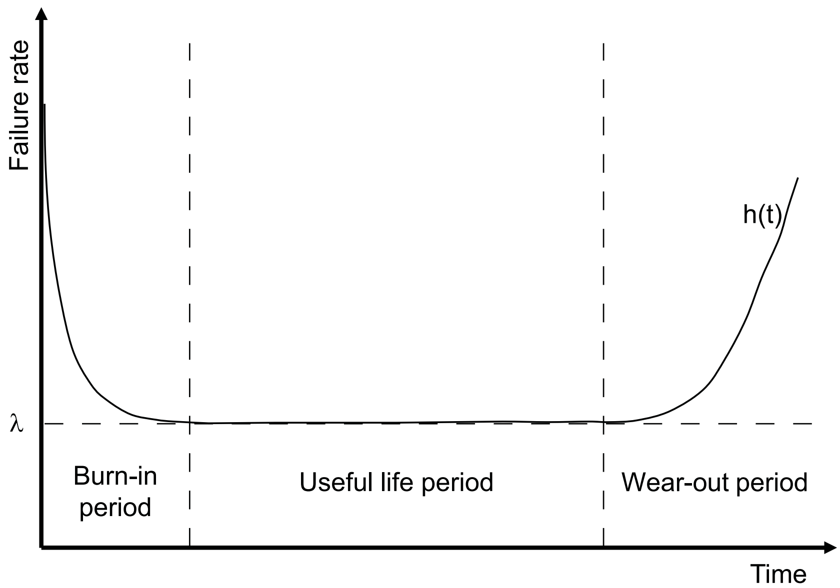


Figure 2.5: Bath-tub curve
(Andrews and Moss 2002, p. 121)

The failure process or the time to failure is determined by the failure rate λ. This rate is not constant. It is shown in Figure 2.5 and known as so called bath-tub curve (Andrews and Moss 2002, p. 121).

The curve can be divided into three parts. The first period called *burn-in period* is characterized by decreasing failure rates coming from a high level. The second part called *useful life period* is characterized by an almost constant curve. The third part represents the *wear-out period* in which the failure rate increases again.

Andrews and Moss have shown that the distribution function $F(t)$ with t as time indicating the probability of a failure can be described as follows (Andrews and Moss 2002, p. 121):

$$F(t) = 1 - e^{-\int_0^t h(t')dt'} \tag{2.6}$$

If the burn-in and wear-out phases are neglected and only the useful life of the system or component is considered, then $h(t) = \lambda$, thus the failure rate is constant. Substituting this into Equation 2.6 and carrying out the integration, the distribution function is obtained (Andrews and Moss 2002, p. 122):

$$F(t) = 1 - e^{-\lambda t} \tag{2.7}$$

Thus the distribution function is the difference of 1 and (the negative exponential function) $e^{-\lambda t}$. Because of the constant failure rate this function is often referred to as the *random failure distribution*. It is independent of the previous successful operating time. The matching density function is (Andrews and Moss 2002, p. 122):

$$f(t) = \lambda e^{-\lambda t} \tag{2.8}$$

The mean of the density function can be calculated by the following function, which describes the mean time to failure (MTTF) or also called μ (Andrews and Moss 2002, p. 122):

$$\mu = \int_0^\infty t f(t) dt = \int_0^\infty t\lambda e^{-\lambda t} dt \tag{2.9}$$

$$\mu = \frac{1}{\lambda} = MTTF \tag{2.10}$$

This is an important result. With a constant failure rate λ, μ (MTTF) is the multiplicative inverse of the failure rate.

2.1.3 Modeling and Simulation

Modeling describes the process of presenting real systems or problems in a simplified way (Scholl 2008, p. 36). A model is used to solve a specific task, whose execution would not be possible or too costly by using the original (Frank and Lorenz 1979, p. 26).

Models can be classified by different criteria. Concerning the decision situation, the model deployment and the available information models can be classified in the following way (Scholl 2008, p. 36):

- Description models
- Explanatory and causal models
- Forecasting models
- Decision respectively optimization models

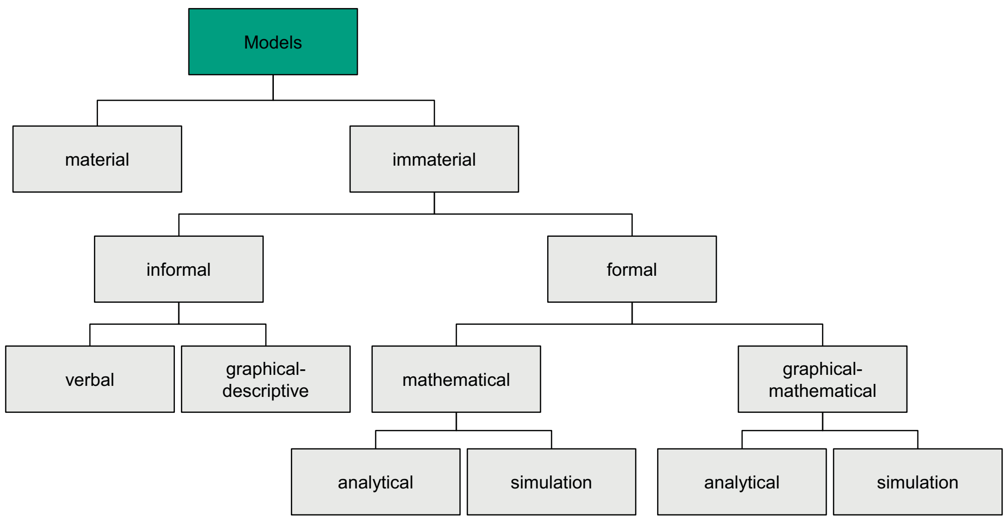


Figure 2.6: General model classification
(Page and Liebert 1991, p. 5)

Models can also be classified into material (physical) or immaterial (non-physical) models (see Figure 2.6). Immaterial models can be further divided into informal and formal. Simulation models, like the one developed within this thesis, are immaterial formal models. They can be described purely mathematically or graphical-mathematically.

Formal models can be investigated by simulation or analytically (Page and Liebert 1991, p. 5). Further comprehensive classifications of models can be found in Schenk and Wirth (2004).

For the term simulation at least three different common definitions are existing (Frank 1999, p. 50 f.):

- Experimentation with models
- Development of models and their experimental usage to analyze and evaluate the system behavior
- Imitation of the behavior of a real system by means of a dynamic model, i.e. model-based imitation of processes

Within this thesis simulation is understood according to a VDI guideline. This guideline describes simulation as a method for reproducing a system with its dynamic processes in an experimental model to gain insights that can be applied to reality. In a broader sense simulation is understood as the preparation, implementation and evaluation of targeted experiments with a simulation model (VDI 1996, p. 14). This definition corresponds to the above mentioned second definition. The definition also covers the model development. The third definition sets the term simulation narrower and only covers the simulation itself but not the development of the model. Simulation models can be distinguished by means of the three dimensions time behavior, contingency behavior and time lapse (see Figure 2.7).

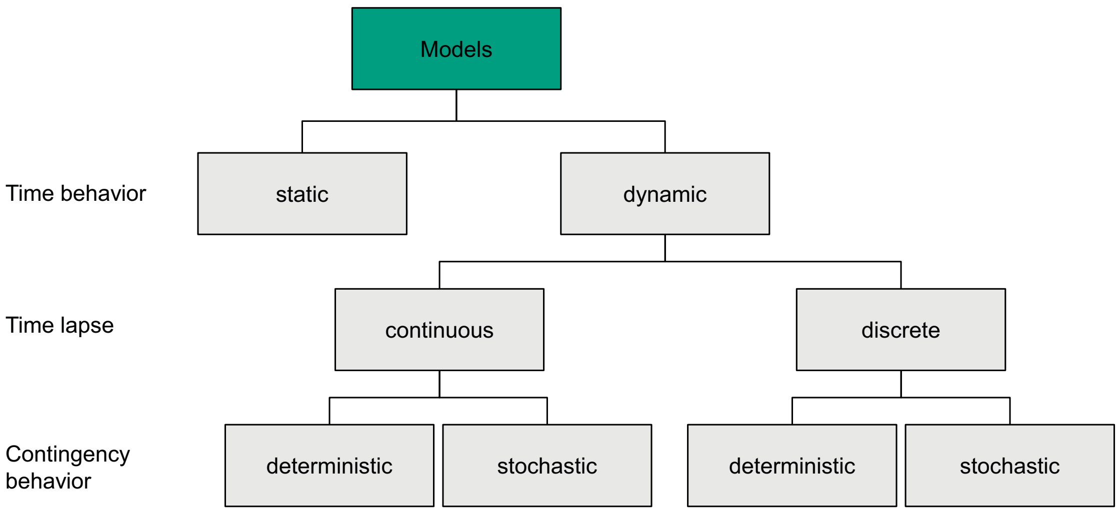


Figure 2.7: Simulation model classification
(Page and Liebert 1991, p. 6)

Regarding the time behavior the models can be distinguished between static and dynamic (Law and Kelton 2007, p. 5). Static models do not cover changes over the time domain. Dynamic models allow the variation of the system over the time. The model developed within this thesis is a dynamic model.

Concerning the state transition models can be categorized in discrete and continuous (Law and Kelton 2007, p. 6)(see Figure 2.8). In a discrete model the states of variables change erratically at certain discrete points in time (Page and Liebert 1991, p. 6). The modeling of logistics systems is mainly done by event discrete simulation models. Variable states change due to certain events.

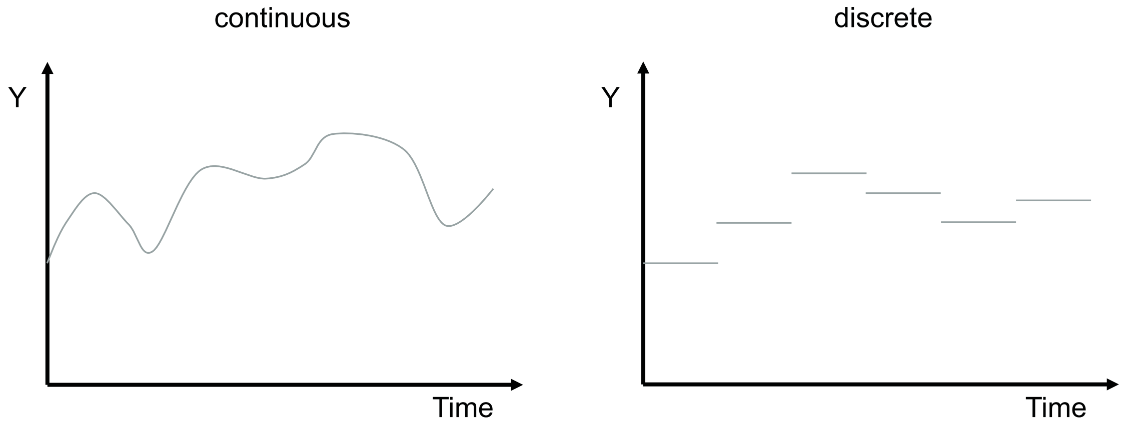


Figure 2.8: State transitions of continuous and discrete simulation
(Warschat and Wagner 1997, p. 13, 15)

In event discrete simulation models time axis and state axis are normally continuous, but only a finite number of state changes is possible in a finite time frame (Cellier 1991, p. 14). In event discrete models for logistics systems the state axis is often discrete because logistics flow objects are modeled as separate objects and not as flow parameter. In almost the same manner the time axis can be discrete if events only raise at certain times because of given constraints (Pritsker 1995, p. 52).

In continuous models the state variables change continuously over the time (Banks 2005, p. 12). This means that within a finite time the state of variables can change infinite times. Time continuous models are represented by differential equations (Cellier 1991, p. 12). To run these continuous models on personal computers time discrete models are used (time axis consists of discrete equidistant time steps). All continuous models have to be discretizised to make them computable on computers. The total number of time steps to calculate state changes has to be finite (Cellier and Kofman 2005, p. 11). If the time steps are small enough the model behaves almost like a continuous model. Almost all really existing systems are not fully discrete or continuous. But usually one of the two properties is dominant. According to the modeling objectives an appropriate classification can be done. (Law and Kelton 2007, p. 3)

Regrading the contingency behavior of the model it can be dived into deterministic and stochastic models. In deterministic models coincidence of parameters does not exist. For example the occurrence of events or their lengths are determined in advance. If contingencies are considered in the model it is called stochastic (Law and Kelton

2007, p. 6), (VDI 2000, p. 14). The simulation model developed within this thesis is dynamic, discrete and stochastic.

Simulation studies and application

Simulation models are used to reproduce the chronological behavior of production and logistics systems. They are deployed in the complete life cycle of a technical system, beginning with the planning, over the implementation up to the operation, whereas the planning is the classic use case. (Kuhn and Rabe 1998, p. 7)

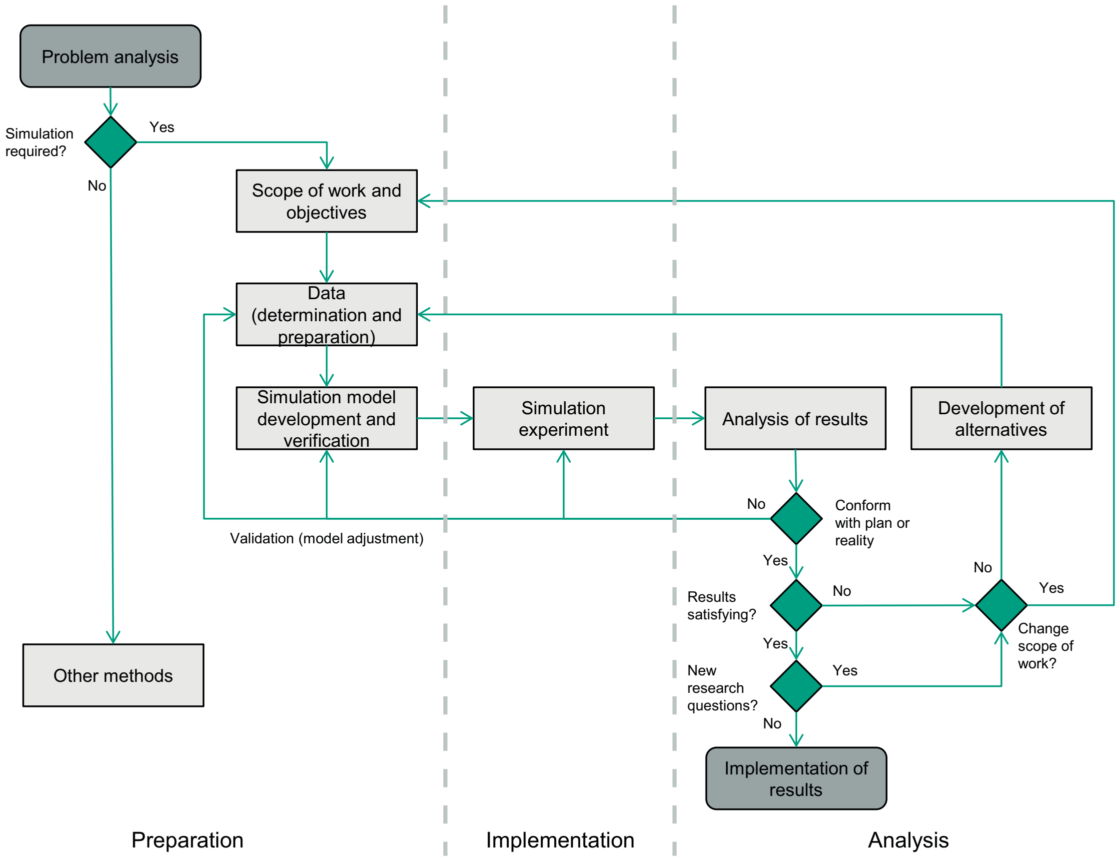


Figure 2.9: General Simulation approach
(VDI 2000, p. 11), (Reggelin 2011, p. 15)

The approach for a simulation study is divided into three phases according to VDI guideline 3633 (VDI 2000, p. 19)[4]. These three phases are:

- Preparation
- Implementation
- Analysis

[4]In the end of 2014, the guideline was updated (VDI 2014). Anyhow, the approach used for this thesis corresponds to the guideline from 2000

The content and work steps are illustrated in Figure 2.9. The effort for the different phases is distributed heterogeneously. The biggest effort has to be invested in the preparation phase. Especially data acquisition and processing as well as modeling take a lot of time. The simulation experiment in the implementation phase and the processing of results in the analysis phase are not as time-consuming as the first phase. (Reinhart et al. 1997, p. 22)

Methodological critique

Each research method, so in this case simulation, has its advantages, disadvantages and limits. Simulation projects always start with the question if simulation is required (see Figure 2.9). This question can be divided into the following sub-questions (Heß 2005, p. 14), (VDI 2014, p. 19f):

- Can the problem be solved by simulation?
- Is the cost benefit ratio reasonable?
- Is the problem not solvable by mathematical-analytical methods?
- Can the complexity be represented by simulation?
- Is the quality of the input parameters good enough?
- Is the model reusable?

All questions should be answered with yes to verify that simulation is a meaningful method for the existing problem.

Method	**Indication**
Simulation	• Analyses of very complex systems • Evaluation of stochastical systems and parameters • Investigation of extreme situations • Calculation of processes, which can block each other • Systems with coincidental processes and events, which occur at the same time • Experiments with real system are too expensive, too sensitive or not accessible
Analytical method	• If it is possible to solve the problem with an analytical model • If less information is available • If not much time is available and a rough calculation of results is satisfying • Meaningful for first calculations and verification of simulation models

Table 2.1: Simulation vs. analytical methods
(Warschat and Wagner 1997, p. 10f), (Wiedemann 2008, p. 4f)

Very important is the question if the problem is solvable with a mathematical-analytical method. Mathematical-analytical models consist of equations, which describe the relationship between input and output parameters. Normally these methods do not require such high efforts as simulation studies. Table 2.1 gives an overview of indications whether simulation or analytical methods should be used.

Also, diverse problems can arise when using simulation. The following problems in Table 2.2 show the limits of the method simulation very good.

Problem	**Description**
No consistent implementation	Often simulation studies are not successful in companies. This is due to the non-consistent implementation of all work steps (see Figure 2.9).
Distribution of input parameters	The distribution of input parameters has to be investigated exactly. It has to be in accordance with the real system. Otherwise the results will be incorrect.
Analyses of results	A popular mistake is the conduction of only one simulation run and the interpretation of the results as infallible fact. Therefore accurate statistic evaluation is always required for simulation studies.
Neglection of important system parameters	In some cases the model does not match with the real system because some parameters have been forgotten or have been underestimated regarding their impacts.

Table 2.2: Limits of simulation
(Warschat and Wagner 1997, p. 11f)

Another important criterion for simulation is the relationship between model complexity and simulation results (see Figure 2.10). The simulation model is not controllable above a certain model complexity. Even if the accuracy increases the acceptance and the explanatory power are decreasing (Aehringhaus and Komarnicki 1980).

For the development of the simulation model the degree of abstraction has to be chosen in a way, that an appropriate accuracy and a high explanatory power of the model is given at once. Furthermore it has to be considered that with higher model complexity the effort of the model development increases eventually exponentially. Generally, the high effort required for simulation model development is a big obstacle for the deployment of the method.

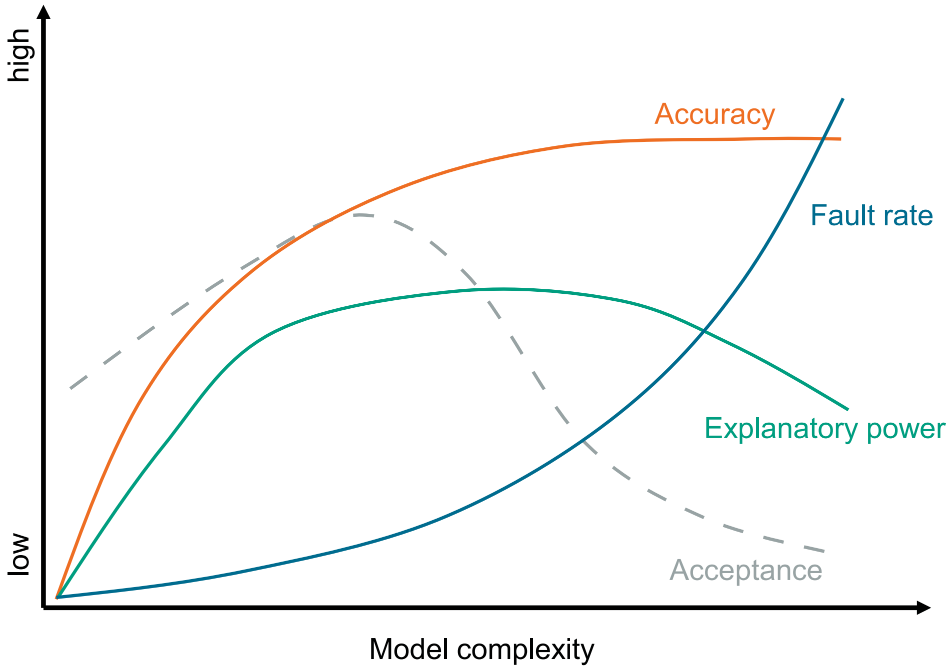


Figure 2.10: Model complexity
(Schmidt 2012, p. 28)

Validation and verification

The main reason for validation and verification of a model is to build up trust in the model (Rabe et al. 2008, p. 7). Verification is the proof of correctness, while validation checks the validity of the model, i.e. the adequate compliance of the model with the real system (Hedtstück 2013, p. 8), (VDI 2010, p. 36). Correctness means that the model was created in the right way, but validity means that the right model was created (Hedtstück 2013, p. 8).

Activities of validation and verification are not limited to a certain point of the project. They are rather used in all phases of a simulation study (Rabe et al. 2008, p. 7). In literature different techniques for validation and verification exist, but there is no standardized approach. Used and recommended validation and verification techniques are (Rabe et al. 2008, p. 96-111):

- Animation for transparent representation of the system behavior, particularly suitable for checking model sections for short periods
- Event validity tests for comparison of events and event patterns in the simulation model and reality
- Statistical techniques for evaluating the credibility of the output parameters, e.g. confidence intervals
- Sub-model testing by plausibility checks of input and output data of a sub-model

- Trace analysis for tracking and review of the logical behavior of individual objects in the model
- Comparison to other models using the same input data
- Historical data validation from a real system

2.1.4 Sensitivity Analysis

Sensitivity analyses are used to determine whether the preferability of a variant or result changes when changing the conditions, which have led to this variant or result (Haberfellner 2012, p. 286). Or to say it in another way, sensitivity analyses are used to measure the effect of a given input on a given output.

The behavior of individual parameters among each other, as well as their interaction and the impact of individual parameter variations on the output or an objective function can also be investigated by sensitivity analyses. The term sensitivity analysis comprises a set of procedures, which allows to understand the relationship between the variance of a single parameter and the variance of the model function. The variance of the model is therefore largely dependent on the variance of individual parameters or certain combinations of parameters.

Diverse methods of sensitivity analyses exist. Hence, choosing the right procedure is not always easy, since it depends on different factors. First of all, the investigated problem limits the applicable methods because not all methods are compatible with each problem. Furthermore, the selected method should fit to the structure of the model. However, in most cases the most important reason for choosing a specific method is the given time frame and the computing capacity. Sensitivity analyses can become very complex and extensive. The scope of the sensitivity analysis therefore is incumbent on the subjective decision of the modeler and must comply with the time restrictions of the project. (Saltelli 2004, p. 42ff)

A generally accepted classification of different methods of sensitivity analyses is the distinction between local sensitivity analysis, global sensitivity analysis and so-called screening methods. The local sensitivity analysis describes the behavior of a single model parameter with respect to the model output. Here, the investigated parameters are varied in percentage terms taking into account its statistical distribution, while the other parameters are fixed (Gattke 2006, p. 211). By repeating this procedure for each parameter the respective specific sensitivity is determined.

The local sensitivity analysis provides the modeler with the possibility to get a first overview of the sensitivity of individual parameters as well as a better understanding of the effect chain of the model. A first approach to quantify sensitivity is given by McCuen (1973, p. 39). He describes the sensitivity S_i of factor F_0 to changes in factor F_i as follows:

$$S_i = \frac{\delta F_0}{\delta F_i} \tag{2.11}$$

Roo (1993, p. 111) used a different mathematical approach to asses the sensitivity S_i. This time the result for S_i is calculated by the use of model results with a basic parameter value Q_0, a 10 % higher parameter value Q_{P10} and a 10 % lower parameter value Q_{M10}:

$$S_i = \frac{|Q_{P10} - Q_{M10}|}{Q_0} \tag{2.12}$$

The implementation of such methods is quite easy, but parameter interaction remains unconsidered. Changes of a parameter can initially seem to have no or only a small impact on the model output. But the variation of this parameter can possibly have a large effect on the impact of another parameter on the model output. This changed sensitivity is neglected in local sensitivity analyses.

Such parameter interactions are taken into account in global sensitivity analyses. Unlike the local sensitivity analysis, other parameters are also kept variable during the variation of a specific parameter. Interactions and their impact on the objective function of a model are investigated and can be quantified. The variability of each parameter is described by a distribution function. With the help of Monte Carlo simulations samples of the entire parameter space can be used to test many different parameter combinations. This form of sensitivity analysis delivers a higher accuracy than the local sensitivity analysis, however, the computational requirements increase significantly. Also Saltelli et al. (2000, p. 393) point out that different interactions within a model chain have to be taken into account. Especially when individual parameters can have a great variability and local methods lead to miscalculation of the sensitivity global sensitivity analyses should be applied.

Screening methods are a combination of local and global methods. They reduce the expense of global methods by fixing insensitive parameters. Parameters with low variability and low impact on the model chain are thus kept constant, while the remaining parameters stay variable according to their distribution functions. Screening methods are used to identify the qualitative influence of individual parameters and often to distinguish significant and non-significant parameters (Morris 2004, p. 8). Thus, screening methods are a good start to analyze the parameter sensitivity of the model developed within this thesis.

2.1.5 Statistical Analysis

Since simulation models usually process input variables, which are stochastically distributed, most results are also stochastically distributed. To evaluate such data and to obtain representative and meaningful results statistical procedures and methods are necessary. For the execution of statistical methods and to achieve significant results a sufficient amount of measured data is required. (Hedtstück 2013, p. 21), (Rose and März 2011, p. 18).

One of the most important statistical values for the analysis of data is the arithmetic mean. (Warschat and Wagner 1997, p. 63) For the estimation of the expectation n values are collected and the arithmetic mean $\bar{X}$ of the results $X_i = (1, ..., n)$ is calculated:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{2.13}$$

Here, $\bar{X}$ may be the ensemble mean (also ensemble average) or the time mean. The ensemble average results from the result values of the simulation runs (simulation with fixed end). The time average for the period-oriented approach results from observing values during a run to consecutive time steps at equal distances (simulation with open end) (Hedtstück 2013, p. 67f), (VDI 1997, p. 10). For the expectation $E(X)$ of X it consequently is:

$$E(X) = \lim_{n\to\infty} \bar{X} \tag{2.14}$$

The variance s^2 (2.15) and standard deviation s (2.16) of the sample provide information about the dispersion of the results (Ross 2013, p. 137).

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2 \tag{2.15}$$

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2} \tag{2.16}$$

The statistically determined mean approaches the true mean the more data exists for the determination. Therefore, the mean lies in an interval around the true mean, the so-called confidence interval. It is getting smaller with an increasing number of data, and thus, it further delimits the expected mean. (Warschat and Wagner 1997, p. 64)

The confidence interval of the expected value can be determined according to Equation 2.17. With a sample size of n result values the true mean $\theta = E(X)$ is within this interval with a given probability of $1 - \alpha$. For $n > 30$ $\bar{X}$ is approximately normally distributed. At a significance level of $\alpha = 0.05$, which corresponds to a 95 % confidence level, $z_{1-\alpha/2}$ is 1.96. (Eley 2012, p. 26ff) (Ross 2013, p. 141ff), (VDI 1997, p. 10). For small values of n (< 30) the quantile of the normal distribution is replaced by the $1 - \alpha/2$ quantile $t_{n-1,1-\alpha/2}$ of the student's t-distribution (Sandmann 2007, p. 3).

$$\bar{X} - z_{1-\alpha/2}\frac{s}{\sqrt{n}} < \theta < \bar{X} + z_{1-\alpha/2}\frac{s}{\sqrt{n}} \tag{2.17}$$

The required sample size for a permissible error F can be derived from Equation 2.18 and is given in 2.19 (Eley 2012, p. 29).

$$z_{1-\alpha/2}\frac{s}{\sqrt{n}} < F \tag{2.18}$$

$$n > (z_{1-\alpha/2}\frac{s}{F})^2 \tag{2.19}$$

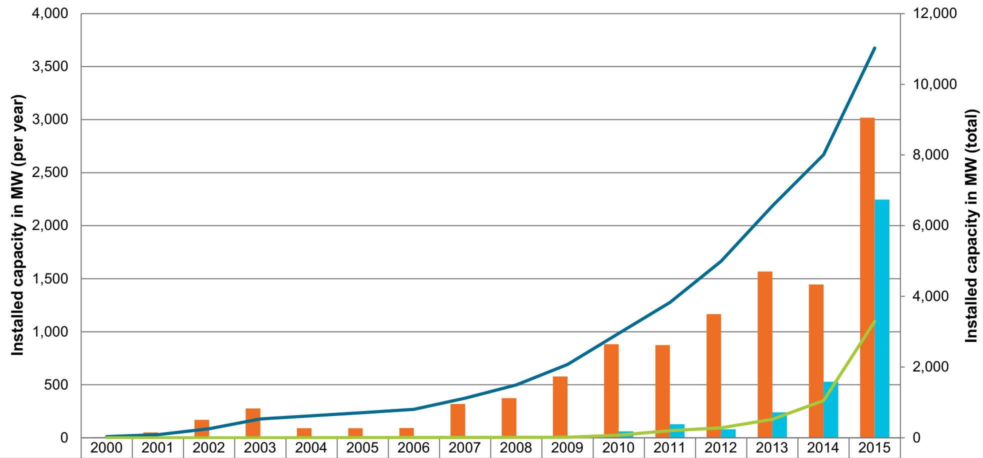
2.2 Offshore Wind Energy in General

Important aspects of offshore wind energy are presented in this section. This comprises the technology, environmental and economical conditions as well as the status quo of the offshore wind market. The chapter focuses on offshore wind in Germany, but also has a look at Europe.

2.2.1 Status Quo of Offshore Wind Energy

With the end of 2015 a total number of 3,230 WTGs produces electricity in 80 OWPPs in 11 countries across Europe. After the installation of 3,018 MW in 2015, the total installed capacity in Europe at the end of 2015 reached 11,027 MW (see Figure 2.11).

At the end of 2015 all OWPPs across Europe produce enough power to cover 1.5 % of the EU's total electricity consumption (EWEA 2016, p. 10). With 5,060.5 MW the UK has the largest share of all installed offshore wind power capacity in Europe (45.9 %). Germany is second with 3,294.9 MW (29.9 %). With 1,271.3 MW (11.5 % of total European installations), Denmark follows third. Belgium (712.2 MW $\widehat{=}$ 6.5 %), the Netherlands (426.5 MW $\widehat{=}$ 3.9 %) and Sweden (201.7 MW $\widehat{=}$ 1.8 %) are the other European countries with an installed capacity above 100 MW. The most installed WTGs were produced by Siemens (63.6 %), followed by WTGs from MHI Vestas with 23 % and Senvion (4.3 %). The most OWPPs are owned (in terms of installed capacity) by energy suppliers. DONG Energy is the biggest owner of OWPPs in Europe (15.6 % of the total installed capacity), followed by E.on with 9.6 % and RWE Innogy with 9 %. (EWEA 2016, p. 10-13)



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Per year (Europe)	4	51	170	276	90	90	93	318	374	577	883	874	1,165	1,567	1,446	3,018
Per year (Germany)	-	-	-	-	5	-	3	-	5	-	60	128	80	240	528	2,246
Total (Europe)	36	86	256	532	622	712	805	1,122	1,496	2,073	2,955	3,829	4,994	6,561	8,008	11,027
Total (Germany)	-	-	-	-	5	5	8	8	13	13	73	201	281	521	1,049	3,295

Figure 2.11: Development of the offshore wind market in Europe and Germany (Berkhout et al. 2015, p. 49, 51), (EWEA 2015, p. 11), (EWEA 2016, p. 11)

The installed capacity in Germany corresponds to 792 WTGs. Further 41 WTGs are already installed but not connected to the grid (246.0 MW). 546 WTGs (2,282.4 MW) were installed in Germany in 2015. Most of the German OWPP projects are located in the North Sea (2,956.1 MW of installed and connected capacity). In the Baltic Sea 338.8 MW are installed and connected. Besides the installed and not connected WTGs, further 956 MW were under construction in German waters by the end of 2015. (Lüers and Rehfeldt 2016, p. 1-3)

Recently the European and German goals for the development of offshore wind energy were reduced. The EWEA reduced their goals (based on the national plans) from 40 GW to 23.5 GW until 2020. The German goals were reduced from 10 GW to 6.5 GW in 2020 and to 15 GW (from 25 GW) until 2030. (EWEA 2014, p. 7), (BMWi 2014, § 3(2)), (Fraunhofer CML 2014, p. 18)

In the last years, the average size of WTGs installed in European waters has increased significantly. In 2000, the average size of installed capacity per WTG was 2 MW. During 2015, the average capacity of newly installed WTGs was 4.2 MW compared to 3.7 MW in 2014, which was a slight decrease compared to the years before (see Figure 2.12). This was due to the increased proportion of installed Siemens WTGs with 3.6 MW (EWEA 2015, p. 16), (EWEA 2016, p. 16). It is assumed that the average WTG capacity will further increase in future as some manufacturers already have developed 7 to 8 MW WTGs (Windkraft-Journal 2015b). The average size of OWPPs varied in

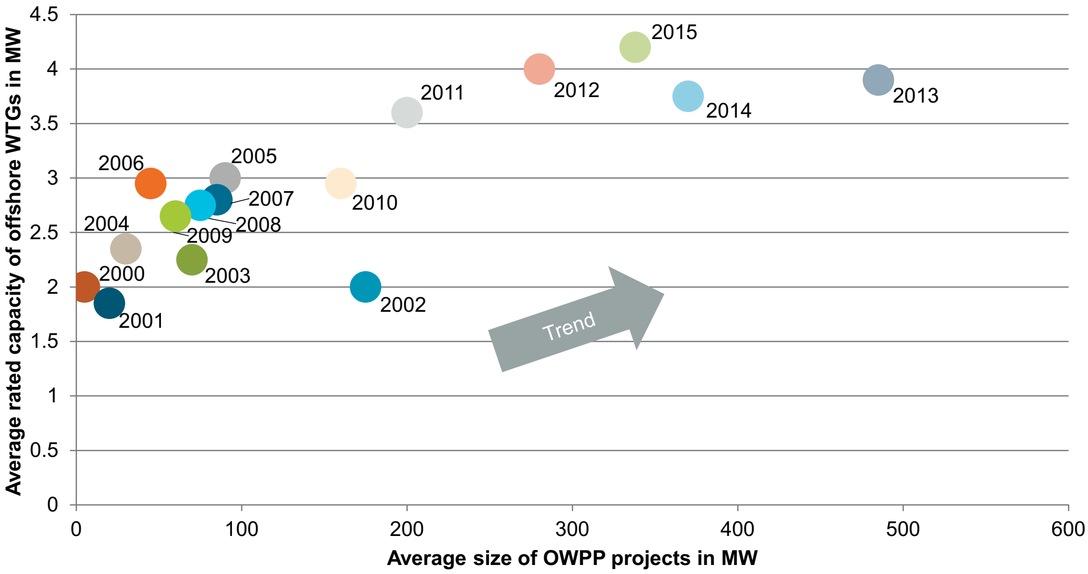


Figure 2.12: Size of OWPPs and offshore WTGs in Europe
(EWEA 2016, p. 16f)

the last years. But an increase in size could be observed. In 2012, the average size of connected OWPPs was 286 MW while in 2013 it was 485 MW. In 2014 and 2015, it decreased to 368 MW respectively 338 MW. This goes along with the construction of London Array (630 MW), which was completed in 2013. For the long term a further increase of OWPP size is expected (EWEA 2015, p. 17), (EWEA 2015, p. 17).

2.2.2 Wind Turbine Generators

WTGs are energy converters. Independent of their construction or the application WTGs are built to convert the kinetic energy of the wind into mechanic rotation energy. WTGs can be used for:

- Direct mechanic deployment: Propulsion for machines
- Conversion into hydraulic energy: Water pumps
- Conversion into thermal energy: Heater, Cooler
- Conversion into electrical energy: Grid feed, island operation

The most important application of modern WTGs is the generation of electrical power. They can be based on two different aerodynamic principles, the buoyancy force or resistance (see Figure 2.13)

Without power losses up to 16/27 (ca. 59 %) of the existing wind energy could be converted (Betz 1982, p. 12), but in practice only values of 50 % are achieved (Gasch and Twele 2005, p. 37). Considering aerodynamic, mechanical and electrical losses modern

WTGs reach approximately 45 % efficiency (Conrad and Gasch 2013, p. 463). Due to technical and physical reasons versions with horizontally oriented axis and three-blade rotor in the windward side of the tower have prevailed for large WTGs (Twele et al. 2013, p. 50-56).

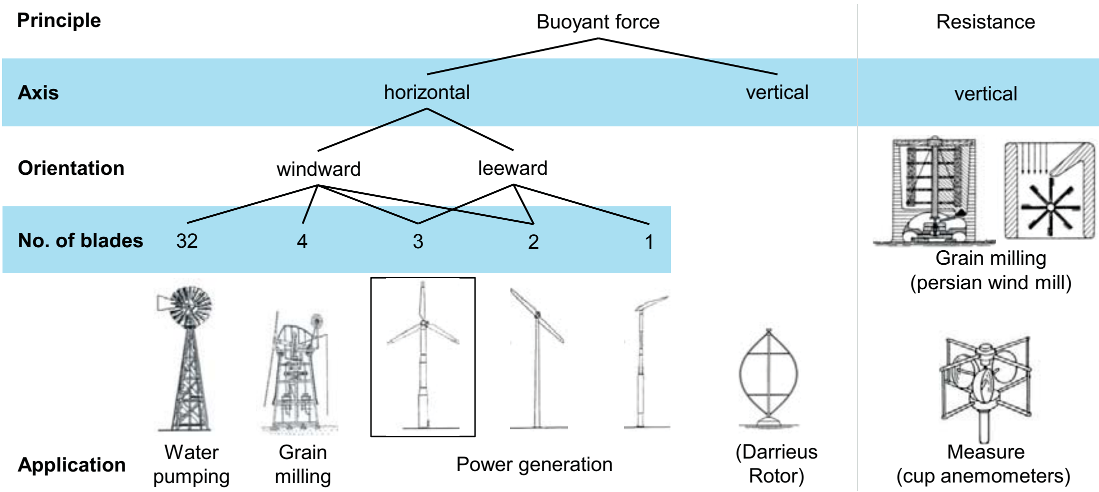


Figure 2.13: WTGs in general
(Ecosources 2013), (Twele et al. 2013, p. 51), (Hepp 2014, p. 5)

Mechanical construction

The components of an offshore WTG can be divided at a top level into two components:

- Support structure
- Turbine

The support structure includes all structural components between the seabed and the turbine, including the tower, the transition piece and the foundation. The turbine consists of the nacelle and usually a hub with three rotor blades (BSH 2007, p. 15).

The most common type of foundation is the Monopile (97 %[5]). This is a steel tube driven or drilled into the seabed (EWEA 2016, p. 7). Other used foundation types include Gravity, Jacket, Tripile and Tripod foundations (EWEA 2013, p. 12) (see also Figure 2.14). Currently, also tests are performed for floating foundations (Windkraft-Journal 2015a). The bottom of the fixed foundation is protected (e.g. by ballast stones) to prevent the exposure of the foundation to ocean currents, so called scour protection (Hau 2014, p. 728f), (Thomsen 2012, p. 161). The submarine cable lies beneath the seabed and conducts the generated power within the OWPP. It is called internal grid. Among current-carrying conductors it contains fiber signal conductors for the transmission of data (Hau 2014, p. 738).

[5]2015 annual market share

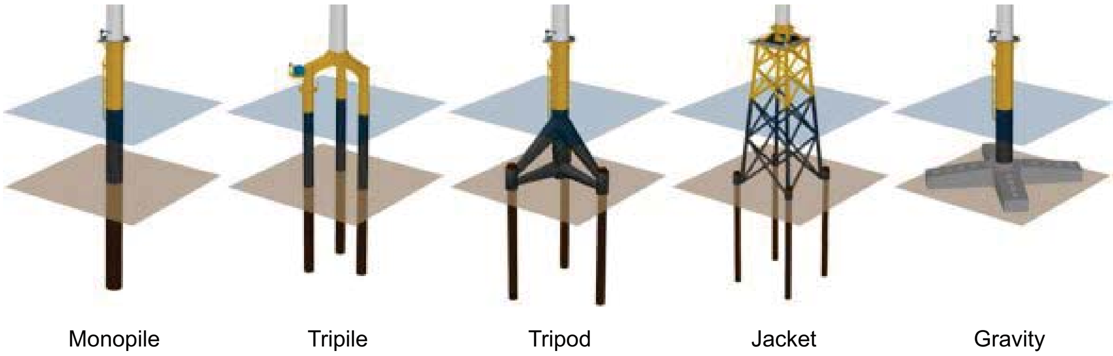


Figure 2.14: Types of OWPP foundations
(FINO3 2015)

The foundation and the transition piece are connected with grout (grouted joint). Thus, installation tolerances between the foundation and transition piece can be compensated to enable an exact vertical alignment of the transition piece (Kühn 2013, p. 560). Via the outer ladder of the foundation personnel (technicians) can reach the working platform from vessels. A crane on the platform can be used to lift tools and material from the vessel onto the foundation platform.

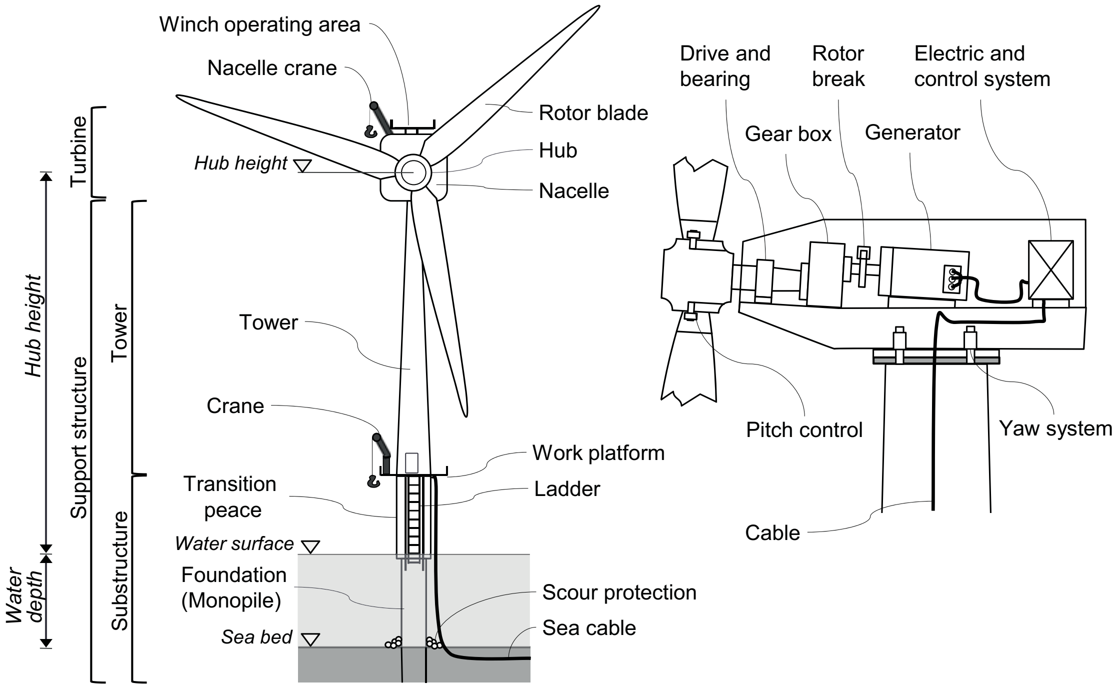


Figure 2.15: Offshore WTG
(BSH 2007, p. 11), (Hau 2014, p. 73), (Hepp 2014, p. 6)

Furthermore, there is the entrance to the tower. Inside the tower an elevator can be used to lift technicians and smaller parts up to the turbine (Franken 2010, p. 25). The turbine is mounted on the tower and can be rotated with the help of azimuth bearings (see Figure 2.15). State of the art rotor blades are made of composite fiber materials. They are connected to the rotor drive train through the hub (Hau 2014, p. 79, 282). To regulate the speed of the rotor and power output of the generator a pitch mechanism in the hub can be used to rotate the rotor blades across its longitudinal axis (Hau 2014, p. 71, 79). Personnel and equipment can be transferred to the WTG from a helicopter by a winch. Therefore, the turbine has its own winch operating area (Zaß 2012). Usually the nacelle has one or more hatches, which can be opened to insert heavy or large loads. The cranes of offshore wind turbines have a lifting capacity up to 6.6 t (Palfinger 2013, p. 8). Heavier loads require an external large crane in form of a jack-up repair vessel with an onboard crane (Franken 2010, p. 25), (Kaltschmitt 2013, p. 519).

The nacelle houses the drive train, electrical and control systems and the yaw (azimuth system). The drive train includes all rotating parts from the rotor to the electric generator. Different concepts for drive trains exist. In the shown classical design (in Figure 2.15) a transmission gear is located between the rotor and generator. Other alternative concepts renounce the gearbox and have a so-called direct drive. The *dissolved* design type has a separate bearing. For the *integrated* type the bearing components are part of the gear box. (Hau 2014, p. 321-337)

Operation

The operational management of WTGs is largely automated. Manual operation procedures are only exceptions. The operational system manages the control system and enables the fully automated operation based on environmental parameters, like wind speed and wind direction. (Hau 2014, p. 489f)

The operation of a WTG can be divided into different states of operation, which describe the automated operation cycle. This cycle includes the states of operation described in Table 2.3.

Idleness and Load operation are steady states. All other states are transition states between the steady states. (Hau 2014, p. 489) The control system maximizes the efficiency for each state of operation according to economical aspects. The system also aims to minimize mechanical loads to avoid unnecessary wear. (Hau 2014, p. 459)

State of operation	**Description**
Idleness	The plant is ready to operate, but not in operation
System inspection	The operation cycle starts with the inspection of the most important systems
Yaw control	After a positive inspection the rotor is moved into the wind direction
Commissioning	For the commissioning the breaks are released and the rotor blades are pitched. The rotor starts rotating
Start-up	The revolutions per minute are increased until 90 % of the rated revolutions per minute
Load operation	Electrical power is generated and fed into the grid. Depending on the wind speed it is distinguished between full load or partial load operation
Overload operation	If the revolutions per minute exceed the rated revolutions per minute. Before this happens the rotor blades are usually pitched to decrease the speed below the rated limit
Shut down	If the wind speed is lower than the minimum operational speed, the WTG is shut down by pitching the rotor blades and disconnecting the generator from the grid. This also happens in case of too high wind speeds
Standby	The number of revolutions per minute is reduced to zero and the WTG is in idle mode. The total stop of the WTG is reached by applying the mechanical brakes

Table 2.3: WTG states of operation
(Hau 2014, p. 489f)

Safety system

Each WTG is equipped with a safety system. The system has to ensure that in an emergency case the system is shut down immediately. Therefore, it has to be redundant and independent from the operational and control system. The system must process a great variety of security relevant data. This data comprises the state of operation of the WTG but as well the condition of different components. The most important data is:

- Revolutions per minute
- Generator power respectively torque
- Unusual vibration of certain components
- Temperature of critical components
- Electrical parameters connected with grid feeding
- Malfunction of power and speed control
- Inadmissible cable torsion

In case of a failure the security system activates primarily the brake system to stop the rotor. Additionally, the WTG is disconnected from the grid. For larger WTGs the stop of the rotor is initialized by aerodynamic measures at the rotor blades. (Hau 2014, p. 491), (Conrad et al. 2013, p. 422)

Main characteristics

The generated electric power depends on the wind speed. A typical power curve is shown in Figure 2.16. The curve can be divided into three areas: *idle*, *partial load* and *full load*. At wind speeds below the system-specific cut-in speed (usually 2.5 to 4.5 m/s) the rotor stands still or is trundling. That means the system is in idle mode without generating power or feeding the grid. Above the cut-in speed electric power can be generated during partial load operation. The steep rise of the power curve is due to the wind energy, which is proportional to the cube of the wind speed (Quaschning 2011, p. 247). Above the rated speed (typically: 10 to 16 m/s) the WTG is under full load and generates the rated power. The generated power is limited to the rated power over the complete full load range. This is achieved by the pitch-control, which reduces the revolutions per minute if necessary. To prevent the WTG from overloading and possible damage the system shuts down above the cut-out speed (typically 20 to 34 m/s). This means that the blades are brought into feathered position and the generator is disconnected from the grid (Conrad et al. 2013, p. 419f), (Quaschning 2011, p. 259f).

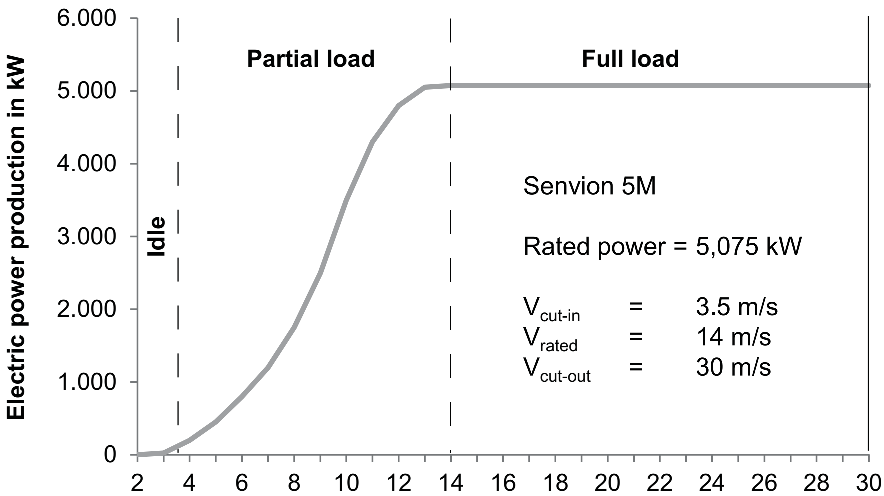


Figure 2.16: Power curve of a WTG
(Conrad et al. 2013, p. 419), (REpower 2012), (Hepp 2014, p. 8)

Table 2.4 shows currently deployed WTGs from the most important manufacturers.

	Siemens SWT-4.0-130[6]	**MHI Vestas V112-3.3 MW**[7]	**Adwen AD 5-135**[8]	**Senvion 6.2M126**[9]
Rated power in MW	4.0	3.3	5.0	6.2
Rotor diameter in m	130	112	135	126
Swept area in m^2	13,300	9,852	14,326	12,469
Nacelle mass in t	140	157	230	325
Rotor mass in t	100	-	140	135
$V_{\text{cut-in}}$ in m/s	3-5	3	3.5	3.5
V_{rated} in m/s	11-12	12	11.4	14
$V_{\text{cut-out}}$ in m/s	32	25	20	25

Table 2.4: Characteristics of selected WTGs

Energy yield

The potential energy yield over a period t can be determined based on the wind speed distribution at the site and the power curve of the WTG. The electrical energy yield can be obtained for each wind speed interval i by multiplying the time of occurrence with the electrical power generation P_{el} for that certain wind speed. The total energy yield of the WTG E_{WTG} can be calculated by taking the probability of occurrence h_i for each wind speed over the investigated period of time into account. The total energy yield is given by Equation 2.20:

$$E_{WTG} = \sum_{i=1}^{n} h_i \cdot P_{el} \cdot t \tag{2.20}$$

The energy production is proportional to the third power of the wind speed. This means that 10 % better wind conditions increase the annual production by more than 30 % (Twele and Liersch 2013, p. 530). Figure 2.17 illustrates the relationship between wind speed and energy yield (Kaltschmitt 2013, p. 511).

[6] Siemens 2015b.
[7] Vestas 2015.
[8] 4coffshore 2015b.
[9] Senvion 2015.

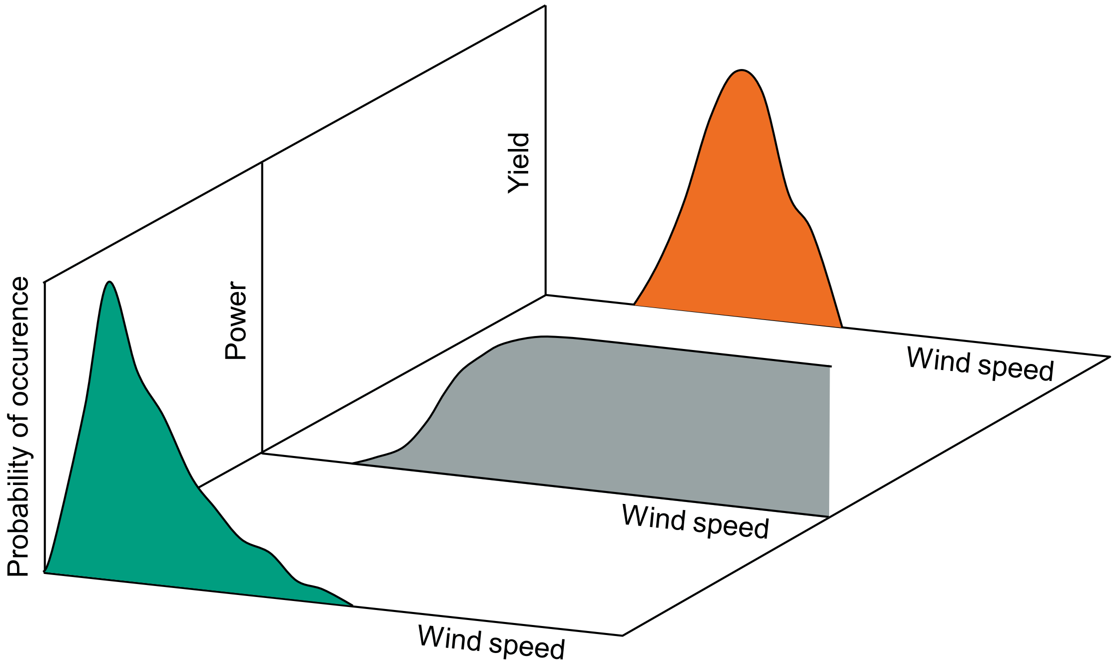


Figure 2.17: Energy yield of a WTG
(Kaltschmitt 2013, p. 511)

A parameter for the energy yield is the capacity factor C, which was already described in Section 2.1.2. Another characteristic parameter is the number of full load hours. It describes the number of hours that is needed to generate the overall energy yield of a WTG under full load (i.e. at rated power). The full load hours can be derived by multiplying the capacity factor C with the length of the observed period (Kaltschmitt 2013, p. 512).

2.2.3 Offshore Wind Power Plants

According to the German Renewable Energy Act (EEG), a wind power plant is called OWPP if it is located with a distance to shore of at least 3 nautical miles (BMWi 2014, § 5). An OWPP is the spatial and organizational set of WTGs at sea (Hau 2014, p. 783). In the prevailing wind direction the usual distance between the WTGs are six to eight times the diameter of the rotor star. Crosswise to the main wind direction a distance of four to six times is usually chosen. These distances are needed to reduce the wake losses to an acceptable level (Kühn 2013, p. 563). OWPPs can be characterized by the following parameters (Phillips et al. 2013, p. 11):

- Number, type (capacity) and reliability of WTGs
- Type of grid connection (alternate current (AC) or direct current (DC))
- Distance to base station (onshore)
- Environmental conditions

In Germany, for the transport of energy to the mainland, the generated power of each WTG is conducted via the inner plant cable to the substation where it is transformed to high voltage level (150 kV) (Hau 2014, p. 767). There are considerable efficiency losses with increasing distance for the power transmission to the mainland with high voltage three-phase AC cables (Hau 2014, p. 741f). The losses are lower via high voltage direct current (HVDC) transmission. From a distance of 60 km up to 100 km HVDC technology is seen as more cost-efficient (Hau 2014, p. 742), (Kühn 2013, p. 562). In order to use HVDC the power of multiple OWPPs is conducted to the converter platform (usually used in the German North Sea) where it is converted from AC to DC (BSH 2015a, p. 25). The converter platform is installed and operated by the transmission system operator. The dimensions of a 900 MW converter platform are about 65 m by 105 m (BSH 2015a, p. 29). A submarine cable conducts the power to the grid connection point on land. Here, the DC is converted back into AC power and fed into the high or very high voltage onshore grid. (Hau 2014, p. 743)

At the land side base stations (service ports for vessels and helicopters) are used as starting point for the transfer of personnel and equipment to the OWPP at sea. Depending on the logistics concept manned platforms can also be built on the OWPP site. Premises for the administration and management of the OWPP can be found on land as well, but not necessarily at the shore (Phillips et al. 2013, p. 3).

Geographical classification

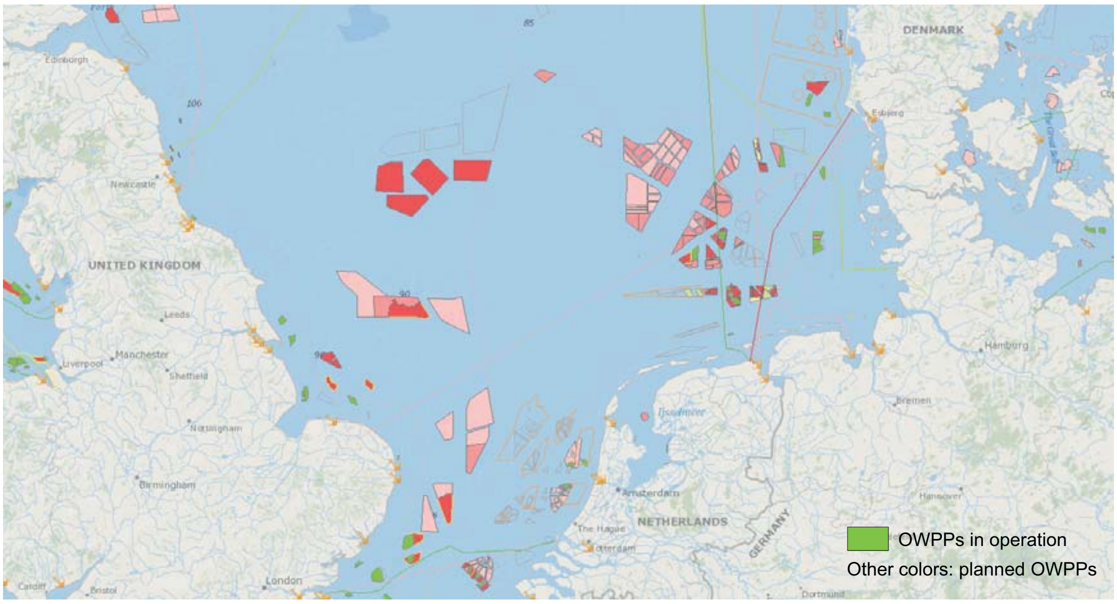


Figure 2.18: Operated and planned European OWPPs in the North Sea (4coffshore 2015a)

The European countries, which are active in the development of offshore wind power, use their sea area for exclusive commercial exploitation. This area includes the territorial waters and the exclusive economic zone (EEZ). Figure 2.18 shows the operated and planned European OWPPs in the North Sea.

The territorial waters (so-called 12 mile zone) extends from the coast line to 12 nautical miles (22 km) off the coast (Hau 2014, p. 754), (Nolte 2010, p. 79). However, in Germany the Wadden Sea is part of this zone. Due to ecological reasons the possibility for OWPP construction is very restricted (Berkhout et al. 2013, p. 42), (Hau 2014, p. 904). The EEZ is an area beyond and adjacent to the territorial waters, extending seaward to a distance of no more than 200 nautical miles (about 370 km) out from the coastal baseline. In the North Sea, it covers an area of about 28,600 km^2 (Baltic Sea: 4,500 km^2) (Nolte 2010, p. 79f).

In Germany, sustainable development and decision on the admission of OWPP in the EEZ is incumbent upon the Federal Maritime and Hydrographic Agency (BSH) (BSH 2015c). In the spatial plan priority areas are identified for offshore wind energy, where other uses are deferred (BSH 2013b). Furthermore, so-called clusters of OWPPs have been formed in the Federal Offshore Plan. These clusters should be primarily connected to the grid infrastructure. Taking into account the development goals of the federal government and a spatially efficient development the focus is on projects closer to the coast.

2.2.4 Environmental Conditions

For the description of environmental conditions at OWPP locations metocean data is used. Metocean data consists of meteorological (including wind, air pressure, temperature) and oceanographic data (e.g. waves, currents, salinity, ice). They are incorporated into the design of the plant and serve for the planning of installation and maintenance activities at sea (Hau 2014, p. 750), (Jacobsen and Rugbjerg 2005, p. 1, 10). Wind speed and wave height (height of swell and wind sea) have been identified as the major relevant parameters, which limit the accessibility of WTGs and reduce their availability (Thomsen 2012, p. 229), (Schenk et al. 2009, p. 36). The water depth, especially for the use of jack-up (repair) vessels, is another important limiting factor. Ice drift also has to be considered for the design and maintenance planning of an OWPP (Jacobsen and Rugbjerg 2005, p. 1), (Kühn 2013, p. 549). But for the North Sea, tidal range and salinity are of greater importance (Stohlmeyer and Ondraczek 2013, p. 335f).

To characterize the potential of an offshore site for the usage of offshore wind power generation, the mean annual wind speed is used. In Figure 2.19 the average wind speed (based on a computational model) for the southern North Sea is shown. With increasing height above the ground and depending on the surface profile the wind speed increases. This effect is more pronounced at sea than on land. Thus, stronger and steadier winds can be expected offshore. The first OWPPs have shown that the number of full load hours are significantly higher compared to onshore wind power plants (Fraunhofer IWES 2013, p. 6, 16).

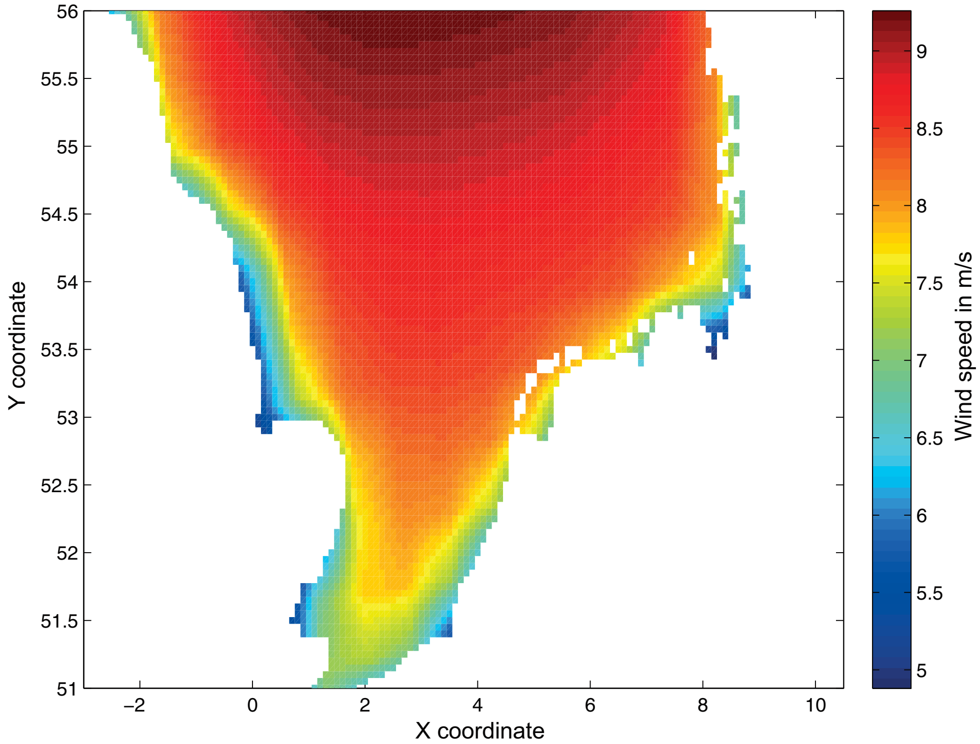


Figure 2.19: Average wind speed in the southern North Sea in 2005 (Helmholtz-Zentrum Geesthacht 2012)

The distribution of the wind speed V_w at sea can be described by the Weibull distribution (Hau 2014, p. 751), (Langreder and Bade 2005, p. 141f). During the year there are significant differences in wind speed. Usually in winter months the wind speed is higher than during the summer period (Barth et al. 2013, p. 401), (Schenk et al. 2009, p. 36). Figure 2.20 shows this effect. For the location 54°30'N 8°00'E the wind speed distributions and density functions from March to August and from September to February in 2005 are plotted. The average wind speed in 2005 for the summer period was 7.1 m/s and 9.2 m/s for the winter period. The comparison of both distributions shows that in winter only 80 % of the time the wind speed is below 13 m/s. In summer it is an amount of more than 97 %.

The common measure of the swell is the significant wave height H_s, which is defined as the average of the top third of all wave heights (Malcherek 2010, p. 191), (Loewe 2009, p. 93). In Figure 2.21 the distributions and density functions of waves are also shown for the location 54°30'N 8°00'E from March to August and from September to February for the year 2005. It can be seen that the significant wave heights are higher in winter compared to summer. This means that the accessibility of WTGs in winter is worse than in summer.

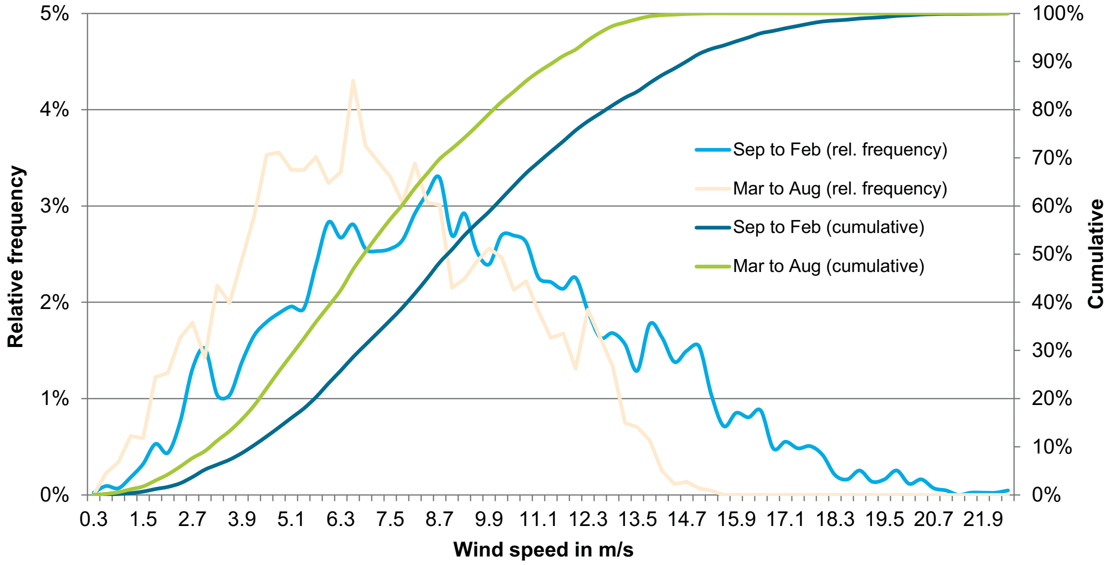


Figure 2.20: Wind speed at 54°30’N 8°00’E in 2005
(Helmholtz-Zentrum Geesthacht 2012)

The water depth in the German North Sea increases with the distance from the coast up to 40 m. A depth of 20 to 40 m can be expected at sites of larger OWPPs (Berkhout et al. 2013, p. 43), (Hau 2014, p. 751).

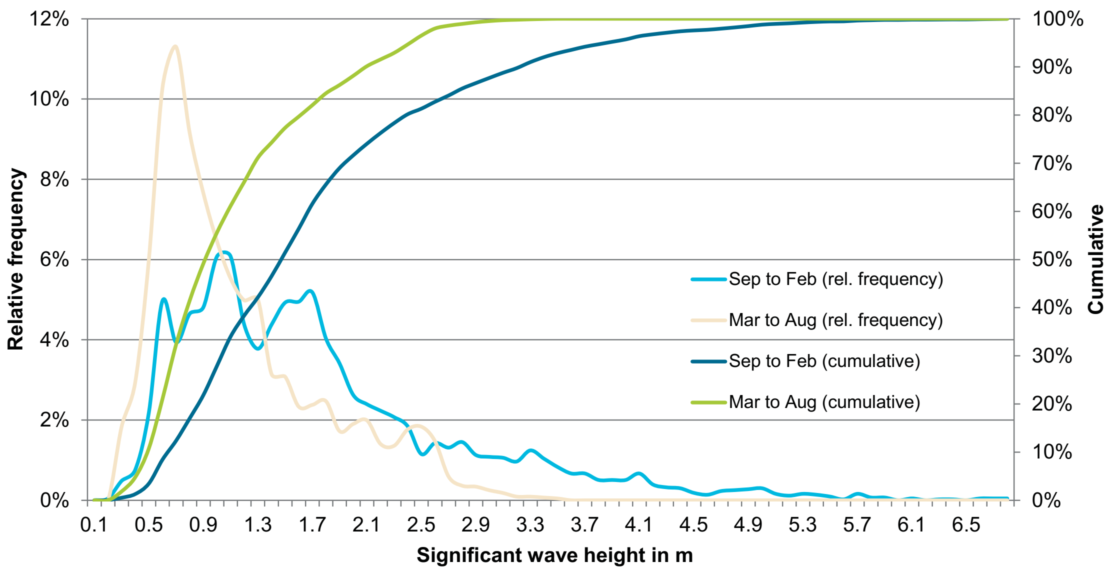


Figure 2.21: Significant wave height at 54°30’N 8°00’E in 2005
(Helmholtz-Zentrum Geesthacht 2012)

The water level changes in the North Sea due to the tide and other meteorological and hydrological conditions (Malcherek 2010, p. 33, 54). At the location of the research platform FINO 3, the water level varies with the tide by about 1 m (BSH 2013a).

2.2.5 Economical Aspects

To compare different electricity production technologies or projects the levelized cost of energy (LCOE) is used as measure (Hobohm et al. 2013, p. 34). The cost is derived from the capital expenditures (CAPEX), operating costs (OPEX) and the produced amount of energy. For the calculation of annual values the CAPEX are considered as annuities. The components of LCOE and their relations are shown in Figure 2.22 (Arántegui 2014, p. 45, 48)

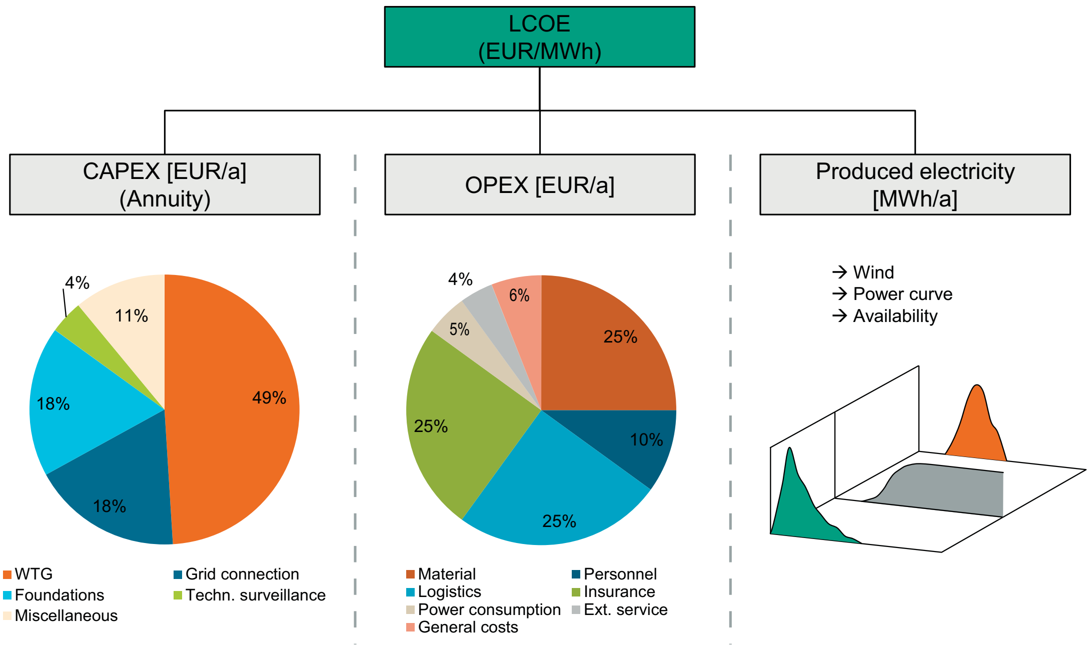


Figure 2.22: Components of LCOE
(Hau 2014, p. 902), (Kaltschmitt 2013, p. 511), (Megavind 2010, p. 8), (Neulinger et al. 2013, p. 452), (Hepp 2014, p. 30)

Cost structure

The capital expenditures for OWPPs consist mainly of investments for WTGs, foundations, cables, substation, certification and approval as well as costs for the installation. These costs are determined after the construction phase and cannot be reduced anymore. The design and construction of an OWPP has a high influence on the operational costs. The specific investment for current projects is in the order of EUR 4,000/kW installed capacity (Arántegui 2014, p. 43), (Berkhout et al. 2014, p. 62). The operating costs account for approximately 25 to 30 % of the total costs of an OWPP project (Pieterman 2012, p. 6). They can be calculated annually [EUR/a] or based on the installed capacity [EUR/MW] or the generated electricity [EUR/MWh] (Neulinger et al. 2013, p. 452). According to calculations by Berkhout et al. (2014, p. 63) they vary from EUR 32 to EUR 55/MWh. In the literature also lower and higher values depending on the assumptions are indicated (Arántegui 2014, p. 48). More than 50 % of the operating costs consist of direct maintenance measures (logistics, personnel and material). The other part of operating costs attributes to insurance and financing costs. The amount of energy produced depends on the wind speed, the wind distribution, as well as the power curve of the WTG. In addition to the wind also the availability of the WTG is important. The availability depends on the WTG's reliability and maintenance strategy. Usually OWPPs reach an amount of full load hours of 2,500 h to more than 4,000 h per year, compared to onshore with 1,700 h to 2,500 h per year (Berkhout et al. 2013, p. 55), (Berkhout et al. 2014, p. 60), (Neulinger et al. 2013, p. 449).

Levelized cost of energy

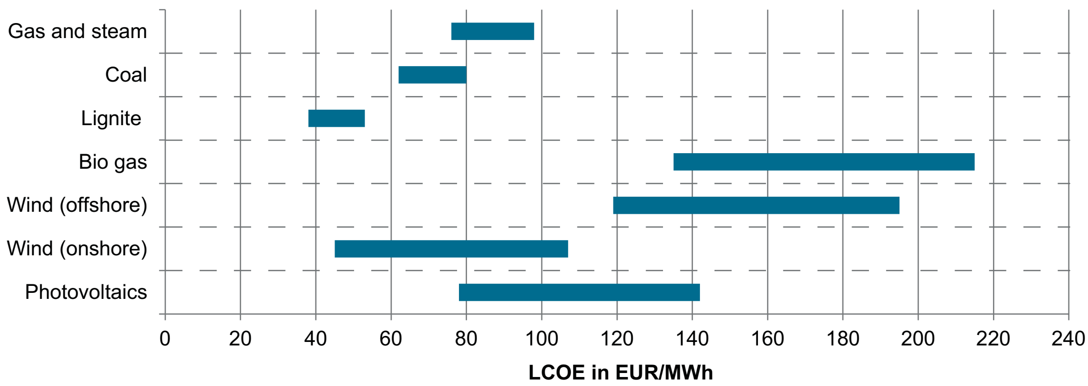


Figure 2.23: LCOE of different technologies
(Kost et al. 2013, p. 2)

The LCOE of OWPPs varies between EUR 119/MWh and EUR 194/MWh (Arántegui 2014, p. 50), (Berkhout et al. 2013, p. 56), (Kost et al. 2013, p. 2). Hobohm et al. (2013, p. 13) for example indicate EUR 128 to EUR 142/MWh, which is within the above mentioned interval. Figure 2.23 shows the LCOE of different electricity generating technologies. The exact LCOE of a technology always depends on the project specific site conditions. In a long term perspective prices for fossil power are expected to rise. In contrast, it is expected that the cost of renewable energies will continue to fall. Offshore wind energy shows a relatively high cost-cutting potential. LCOE of EUR 96 to EUR 151/MWh are estimated to be reached by 2030. The operator DONG Energy expects LCOE of below EUR 100/MWh already for projects in 2020 (Kost et al. 2013, p. 3f), (DONG 2013, p. 2). Also Hobohm et al. (2013, p. 75) predict a LCOE below EUR 100/MWh until 2023.

Tariff

In Germany, electricity produced from renewable energy sources will be compensated for 20 years in accordance with the EEG. OWPPs will be paid the first 12 years after the commissioning of the plant with an initial rate of EUR 154/MWh, then the basic compensation of EUR 39/MWh is paid for the last eight years. In the so-called compression model, which can be applied for a period of eight years, an increased initial compensation rate of EUR 194/MWh can be chosen (see Table 2.5). Depending on the distance to the coast and the water depth at the location of the OWPP the period of initial rate paying can be prolonged (Berkhout et al. 2013, p. 57), (BMU 2013, p. 13f). At the beginning of 2018 the initial compensation rates will be decreased by 7 %. In order to bring renewable energy closer to the market system, the direct marketing of the produced electricity is mandatory. According to the market premium model (BMWi 2014, § 34) the seller receives a changing market premium in addition to the sales price. By 2017 at the latest, the compensation will be determined by tender and not by statutory funding rates. (BMWi 2015)

Year of commissioning	**Basic tariff in Cent/kWh**	**Increased initial tariff in Cent/kWh**	**Initial tariff (compression model) in Cent/kWh**
2015	3.9	15.4	19.4
2016	3.9	15.4	19.4
2017	3.9	15.4	19.4
2018	3.9	14.9	18.4
2019	3.9	14.9	18.4

Table 2.5: Tariff for OWPPs in Germany
(BMWi 2015)

2.3 Operation and Maintenance of Offshore Wind Power Plants

In this section the O&M phase of OWPPs is analyzed. This includes a classification, goals, regulations and logistics concepts. The analysis is focused on German OWPPs.

2.3.1 Classification and Goals

The life cycle of an OWPP project consists of development, design, construction, O&M and decommissioning phase as shown in Figure 2.24.

Figure 2.24: Life cycle phases of an OWPP
(BSH 2007, p. 6)

The O&M phase starts in Germany with the approval of BSH (BSH 2012, p. 4) and has a duration of typically 20 to 25 years. After this time the approval expires, but an extension is possible (BSH 2015b).

If safety is neglected, the most important goal of OWPP operation is the maximization of profits. This goal is achieved by reducing operational costs or increasing the energy yield. The yield highly depends on wind speed and the availability of the OWPP. Wind is not influenceable, but the availability of the plant is. It can be influenced by O&M of the OWPP.

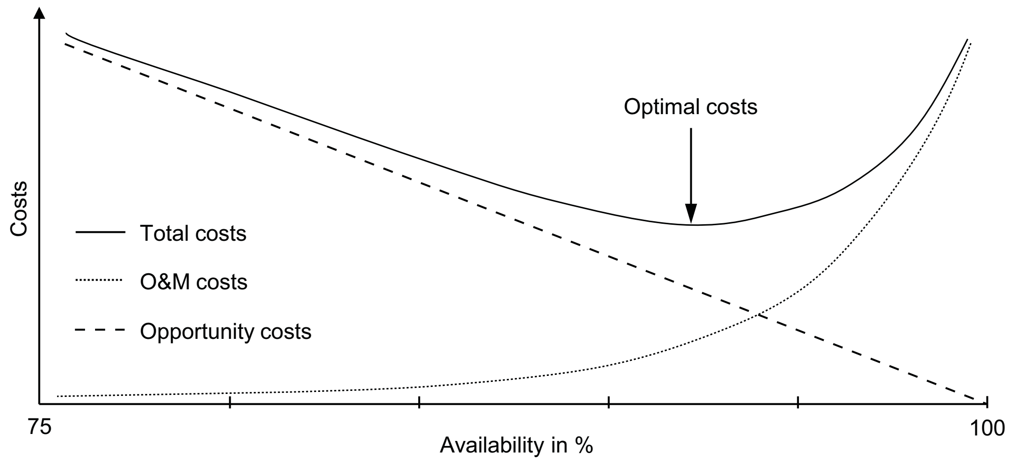


Figure 2.25: Costs vs. availability of OWPPs
(Phillips et al. 2013, p. 9)

With less O&M efforts availability decreases and opportunity costs increase, because less electricity is produced (yield loss). To ensure a high degree of availability high efforts are required, which leads to higher operating costs and lower marginal profits. Thus, the right balance between availability (yield) and operating costs must be found. This balance is called the cost optimal point. It can be found where marginal costs are equal to marginal profits. The point is illustrated in Figure 2.25. Hau (2014, p. 629, 920) says that a commercially viable situation for current wind power plant projects is in a range between 95 to 98 %. The point also depends on the production related reliability, which might differ from manufacturer to manufacturer.

2.3.2 Regulatory Requirements

Operation approval and perpetuation of approval

The operation of WTGs in the German EEZ requires an approval in accordance with the Offshore Installations Ordinance (BMJ and Juris GmbH 2012, § 1). The approval for installation and operation is incumbent upon the BSH and requires compliance with certain technical standards (BMJ and Juris GmbH 2012, § 2, § 4). The operations manual and the maintenance specifications sheet have to be available to enable the operation of the WTG. The operations manual contains operational procedures and information about communication channels, surveillance of the OWPP and grid connection.

Component group	**Test item**
Rotor blade	Damage to the surface, cracks, structural irregularities of the blade body, pretension of the screw connections, damage to the lightning protection devices
Drive train	Tightness, unusual noises, state of corrosion protection, lubrication condition, pretension of the screw connections, transmission conditions
Nacelle and force and torque-transmitting components	Corrosion, cracks, unusual noises, lubrication condition, pretension of the screw connections
Hydraulic system, pneumatic system	Damage, leaks, corrosion, proper function
Supporting structure (tower and substructure)	Corrosion, cracks, pretension of the screw connections, improper scours, location
Safety devices, sensors and brake systems	Functional checks, compliance with critical values, damage, wear
System control and electrical system	Connectors, mounting, proper function, corrosion, pollution
Documents	Completeness, compliance with regulations, audit documents, regular conduction of maintenance, possible modifications / repairs according to approval

Table 2.6: Regular inspection of OWPPs
(BSH 2007, p. 32)

The maintenance specifications sheet contains planned maintenance requirements, maintenance procedures and information about wear parts, parts under marine impact and scour protection surveillance. (BSH 2012, p. 4)

To perpetuate the status of the approval to operate an OWPP the structural and technical security have to be ensured by regular inspections (BSH 2007, p. 12). OWPP operators are obligated to inspect 25 % of their WTGs annually. This must be done by a certifier. The scope of this regular annual inspection is shown in Table 2.6.

Working hours

For offshore employees special requirements associated with the Offshore Working Hours Regulation (BMAS 2013) are applied. This regulation differs from the standard Working Hours Act (BMJ and Juris GmbH 2013). One major difference is a prolonged daily working time with a maximum of 12 h compared to 10 h. A working time longer than eight hours is considered as overtime and shall be compensated by days off. Overall, the daily work and transport times should not exceed 14 h from / to the collection point on land (compare Figure 2.26). Any extension of the transportation time above 2 h inevitably leads to a shortening of the available working time. Work of at least 2 h between 23:00 and 06:00 is considered as night work (BMJ and Juris GmbH 2013, § 2).

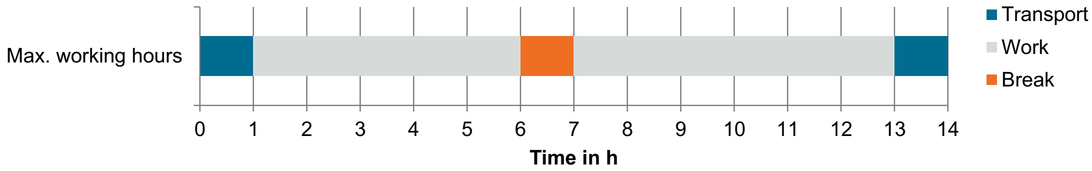


Figure 2.26: Working hours
(Hepp 2014, p. 29)

The permitted number of directly consecutive days at sea depends on the use of the prolonged working day. Within a 14 day stay offshore more than 7 days of prolonged working time are allowed. Within a 21 day stay offshore a maximum of 7 days with prolonged working time are allowed and not more than two days directly after each other. In contrast to the Maritime Labor Act, crew members of involved vessels are also allowed to work up to 12 h per day with at least 60 minutes break time.

Safety

Maintenance of offshore WTGs include safety critical activities such as work at sea, at high altitude and the lifting of heavy loads (Skiba and Reimers 2012, p. 35). To get the BSH approval for an OWPP a safety concept with a project specific contingency planning is required. In addition to the private economic arrangements, organizations such as the Central Command for Maritime Emergencies (CCME) are involved (Rehfeldt 2012, p. 23f). For instance, for emergency operations in the Vattenfall OWPP DanTysk a helicopter with crew and emergency doctor is always on standby. The flight time of this emergency team from its base station to the OWPP is about 30 min (Vattenfall 2013). In the first German OWPP Alpha Ventus at least three technicians are always on the same WTG due to safety reasons (Bartsch 2012, p. 5).

2.3.3 Currently Used Logistics Concepts

Most of the planned and currently used O&M logistics concepts can be classified by the location of the base station (see Figure 2.27). The location is either onshore-based (in many cases close to a port) or it is offshore-based within or close to an OWPP.

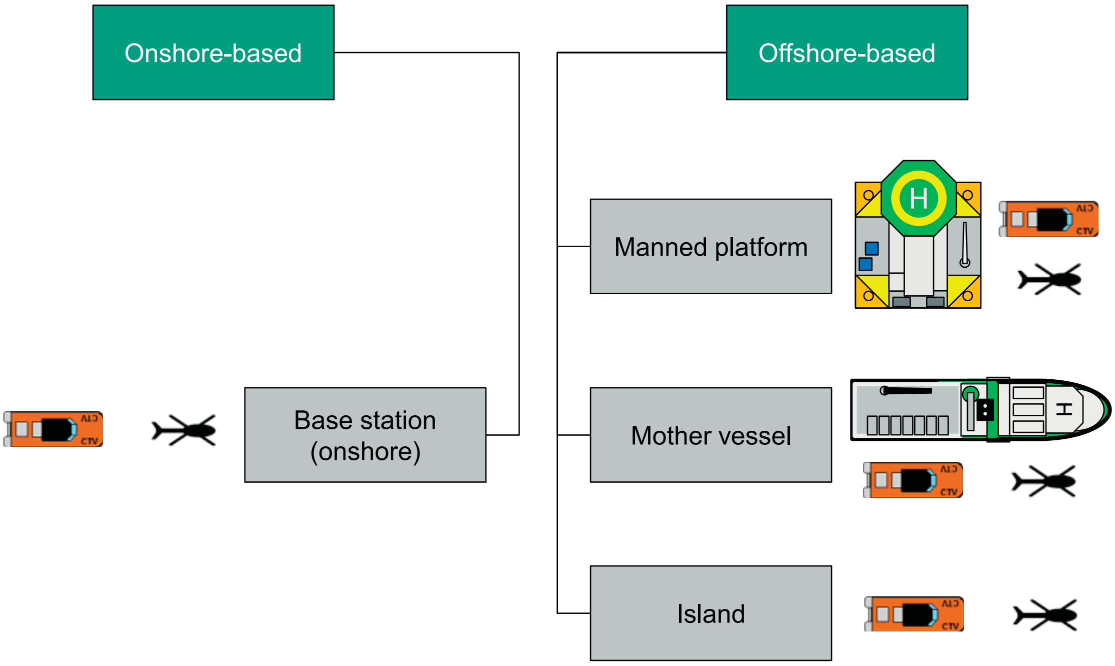


Figure 2.27: Logistics concepts
(Rehfeldt 2012, p. 10-13), (Jahn and Münsterberg 2013, p. 289ff)

Onshore-based concepts

Onshore-based concepts are generally applied if the OWPP is located 30 to 40 km away from a base station, which allows a short travel time to the OWPP in less than two hours by vessel. All sizes of OWPP can be supplied by an onshore-based concept (Rehfeldt 2012, p. 19). Onshore-based concepts are used for most of the near shore OWPPs in the UK and Denmark. There are two different types of onshore-based concepts:

- Crew transfer vessel
- Helicopter

For the crew transfer from a base station to an OWPP, crew transfer vessels (CTV) are deployed. The transport of up to 12 technicians is allowed on these vessels[10]; however for the transition to the WTG a low significant wave height (1 to 1.5 m) is required (Thomsen 2012, p. 246). For harsh weather and sea conditions more stable and faster advanced transfer vessels (ATV) can be utilized. Due to their stability and their speed they can exploit shorter weather windows and allow a transfer to the WTG for up to 1.5 to 2 m significant wave height (Thomsen 2012, p. 252). This is possible due to special transfer equipment (e.g. Ampelmann) or design (e.g. SWATH[11]).

[10] Meanwhile the transport of even 24 technicians with one transfer vessel is allowed (Ems Maritime Offshore GmbH 2015).
[11] Small waterplane area twin hull (SWATH)

In urgent cases a helicopter can be the right choice for the transfer to the OWPP. Its advantages are high speed and high accessibility even in bad weather conditions, the negative aspects are high cost, limited space and capacity as well as a complex transit procedure using a cable winch. It is also possible to combine vessels and helicopters in one concept (see Figure 2.28).

Figure 2.28: Onshore-based concepts

Offshore-based concepts

In offshore-based concepts, the technicians are based and accommodated within the OWPP. These concepts are generally applied if the OWPP is more than 30 to 40 km away from a base station (onshore) and the plants consist of more than 50 WTGs (Rehfeldt 2012, p. 19). There are three different types of offshore-based concepts, which can be supported by a helicopter, involving:

- Mother vessel / Floatel[12]
- Manned offshore platform
- Island / Artificial island

Mother vessels offer accommodation for technicians and also provide room for repairs. The mother vessel stays within the OWPP and usually has berth opportunities for smaller CTVs and a helipad (see Figure 2.29). On the one hand its location within the OWPP leads to short transfer times to the WTG and the accessibility of the WTGs is ensured most of the time during the year (possible transfer for up to 2.5 m significant wave height, for up to 3.5 m if SWATH). However, on the other hand charter rates or

[12]Floating hotel

investment costs are very high for such a floating solution. During bad weather periods the mother vessel can find shelter in a port, which can also be used for supply purposes. If the mother vessel is supposed to stay in the OWPP continuously a separate supply vessel is needed. One of the biggest advantages of a mother vessel is its flexibility to change the dedicated OWPP if necessary. The floatel concept is very similar to the mother vessel concept, but there is no room for repairs on a floatel, which is only an accommodation for technicians. (Jahn and Münsterberg 2013, p. 291)

Figure 2.29: Offshore-based mother vessel concept

Manned offshore platforms can be used as warehouses for spare parts and as accommodation for technicians. On the one hand the greatest advantage is their fixed position, so the technicians do not suffer from sea sickness. On the other hand it is relatively expensive and the transfer to the WTGs must be managed. This can be done by transfer vessels or helicopters (see Figure 2.30). Also the platform is inflexible and has to be maintained and supplied, so another large vessel is needed to fulfill this job.

Islands like Helgoland in the German North Sea work as maintenance bases for OWPPs. They have enough space for warehouses and shops of different OWPP operators. Multiple plants can be supplied from one island. One of their advantages is the short distance to the OWPPs. Neglecting the supply logistics of the island, it is actually very similar to onshore-based concepts.

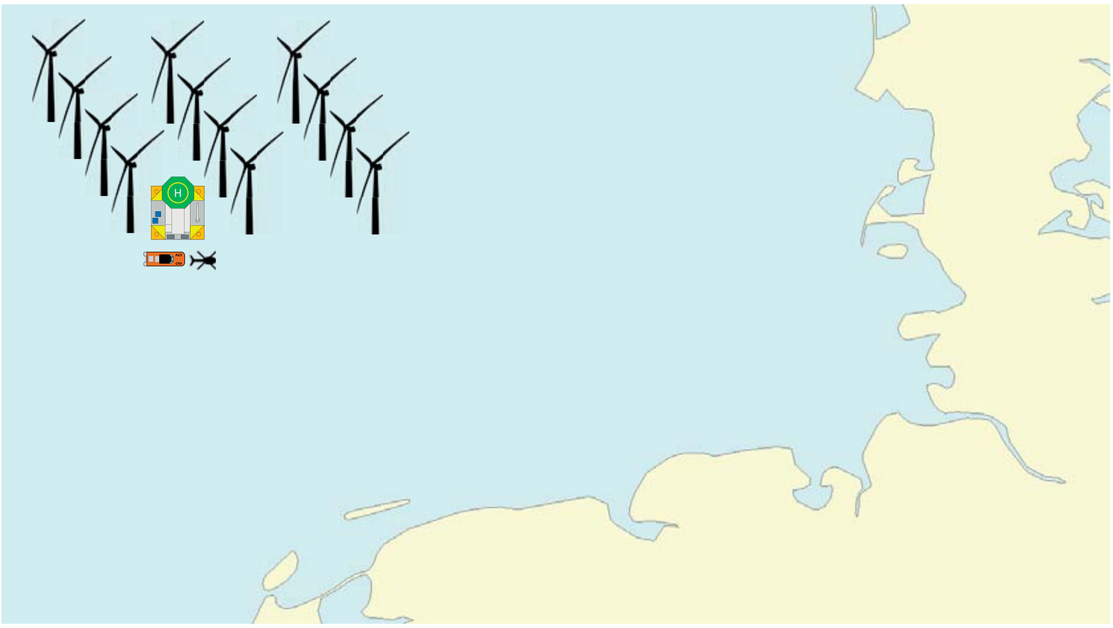


Figure 2.30: Offshore-based platform concept

A combination of different concepts is also possible and might be beneficial in some cases. On request, all concepts are supported by a large jack-up repair vessel for major failures of WTGs.

Influencing factors

The performance (economic viability) and therefore the choice of a logistics concept is influenced amongst others by the following factors and parameters (Besnard 2013, p. 33), (Münsterberg and Rauer 2012, p. 1), (Karyotakis 2011, p. 69), (Rademakers, Braam, and Verbruggen 2003, p. 2):

- Weather conditions
- Failure rates of components
- Number of supplied WTGs
- Distance of OWPP to base station
- Maintenance strategy
- Number and type of equipment

Which logistics concept is most appropriate for an offshore wind farm depends largely on the characteristics of the influencing factors and parameters.

O&M process

The OWPP is monitored by an OWPP manager who works for the OWPP operator. The OWPP manager receives actual remote operational data from the OWPP. If a failure occurs which cannot be repaired remotely, the manager usually contacts the manufacturer and a maintenance team. The maintenance team obtains its required material (spare parts and tools) usually from the WTG manufacturer. The OWPP manager usually plans and decides, depending on the failure event and the metocean conditions, which means of transport are used to take the maintenance team to the failed WTG. If the metocean conditions are acceptable the transport is executed and the WTG is repaired by the maintenance team. After a successful repair the team leaves the WTG, which is restarted afterwards (Albers 2002, p. 53). Figure 2.31 shows the simplified maintenance process.

Figure 2.31: Simplified O&M process
(Münsterberg and Jahn 2015, p. 587)

2.3.4 Evaluation of Logistics Concepts

Evaluation is understood as a process of systematic collecting and analyzing of data or information with the objective to enable a criteria based judgment or decision which is proven and understandable. (Rolff 2001, p. 82)

To derive evaluation criteria it is important to understand the goals of O&M logistics concepts for OWPPs. O&M logistics concepts allow for an efficient execution of maintenance and repair activities and serve to maintain the OWPP operation. The overall economic objectives of the operation is the optimization of operating costs and the produced amount of electricity (see also 2.3.1). The time between failure and re-commissioning (downtime) and costs for logistics, personnel and spare parts can be used as evaluation criteria for O&M logistics concepts (Neulinger et al. 2013, p. 435f). The downtime can also be expressed monetarily in terms of lost revenues (opportunity costs) (Phillips et al. 2013, p. 12). The resulting total costs allow a comparison of different logistics concepts. Another important benchmark for OWPP projects in general is the technical or production-based availability (Phillips et al. 2013, p. 9).

The necessity to evaluate and improve O&M logistics concepts, as explained in Chapter 1, leads to a great demand for supporting modeling tools. There are already tools for commercial purposes on the one hand and research purposes one the other hand that have been developed in the last years to model the operation phase of OWPPs. This is an overview of the most important identified tools, which provide a base for other successional tools (Rademakers et al. 2009, p. 14), (Hofmann 2011, p. 6f):

CONTOFAX from Delft University of Technology (TU Delft)

CONTOFAX was developed at TU Delft to determine the overall site specific availability of an OWPP. The tool derives the necessary and possible operations for an OWPP for a given maintenance strategy and failure rates. This also comprises the assessment of spare part logistics. Input parameters are e.g. number of crews, number of shifts per 24 hours and days worked per week, kind and quantity of equipment. Different maintenance strategies can be compared. The output consists of the total O&M costs, achieved availability and produced energy of OWPP. Metocean data is represented by stochastic weather data with inaccessibility percentages and average wind speeds (van Bussel and Bierbooms 2003, p. 386f). The simulation runs are based on a Monte Carlo simulation, which was initially used by Bossannyi and Strowbridge in 1994 for onshore wind (Bossannyi and Strowbridge 1994, p. 14).

MWCOST based on SLOOP from BMT

MWCOST stands for *Modeling Windfarm Capex & Opex with Sloop Technology*, it is also based on a Monte Carlo simulation. The tool is able to model operative costs and investment costs for OWPPs. Based on a Failure Modes Effects and Criticality Analysis (FMECA) five groups of different failure modes of the WTG with different requirements in terms of utilized equipment have been identified. The environmental input of the tool includes wind speed at hub height, significant wave height, day and night time as well as tide heights. An important part to calculate the time of unavailability is to know the repair time and the waiting time until repair, this time consists of waiting time for spare parts, resources, access and transport. The tool is able to predict the loss of revenue in case of unavailability, the energy yield and the level of necessary maintenance support (spare parts, deployment of crew, dedicated service boats, etc.). (Stratford 2007, p. 1-4)

O&M Cost Estimator (OMCE) from ECN

OMCE comprises cost and downtime caused by unplanned, calendar-based and conditional-based maintenance. The tool should be used in the operational phase and not in the planning phase of an OWPP. The tool consists of five blocks: O&M, Logistics, Loads & Lifetime, Health monitoring and Weather conditions. Similar to the above mentioned tools the ECN tool assigns failures to different failure classes, which have different requirements. The tool deals with simple logistics aspects e.g. the question whether to buy or to hire certain equipment or how many vessels are needed. Maintenance and spare part strategies can also be investigated by the tool. (Rademakers et al. 2009, p. 3, 15, 21, 23)

O&M Tool from ECN

The *O&M Tool* from ECN is the market-leading tool to analyze O&M aspects of OWPPs. The tool consists of different *MS Excel* spread sheets and is used to determine the average annual costs for the operation of OWPPs. The tool is mainly designed for assessing the incurring O&M costs already during the planning phase of the OWPP

(Eecen et al. 2007, p. 4). The input data of the tool comprises site specific data (metocean data), WTG and OWPP data (e.g. number of WTGs and failure behavior) and the maintenance strategy. As results the tool provides e.g. average downtime, repair costs and revenue losses. The results are also based on a Monte Carlo simulation. (Obdam et al. 2011, p. 19, 71)

O2M and the successor O2M plus from GL Garrad Hassan

O2M plus is also based on a Monte Carlo simulation for WTG failures and it runs forward in the time domain on an hourly basis, which also applies to wind and wave data. The tool's inputs can be divided into three areas. The first one refers to strategic options like O&M strategy, choice of equipment (e.g. helicopter) and crew resources. The second area is dedicated to project options, which include distance to port and number of WTGs. The third one comprises climate conditions and reliability input. For WTG failures different categories exist that have different equipment requirements (e.g. jack-up repair vessel or helicopter). The actions in this tool consist of planned and unplanned maintenance, which can be deferred if a lead time for an equipment is defined. The tool can be applied for instance to measure the impact of serial defects. (Redfern and Phillips 2009, p. 1f)

Other tools, which should also be mentioned here, are the *NREL O&M Cost Model* (Maples et al. 2013) and the tools from Besnard (2013) and Karyotakis (2011). The EU funded LEANWIND project also aims to develop an O&M tool, but currently no results are available (LEANWIND 2014, p. 53). A comprehensive overview of more tools, which is not only limited to the O&M phase, can be found by Hofmann (2011).

The identified tools mainly focus on the cost which result from unplanned corrective maintenance. Most of the tools have in common that the failure rate is modeled by Monte Carlo simulation. Often these tools are only analytic calculation tools, which means that they merely consist of a spread sheet. Also the consideration of logistics is often poor in these tools. However, considering many different influences on the operational processes it is difficult to incorporate all of these into an analytical spread sheet, if not only static statistics and average values are used. None of the above mentioned tools are programmed in an event-based simulation environment and none of them has extensively investigated different logistics concepts like offshore-based or onshore-based. Another issue with most of the tools is the lack of transparency and the yearly or seasonal but not monthly analysis opportunity (see Table 2.7). This indicates a gap within the existing tool landscape.

	CONTO-FAX[13,14]	**MW-COST**[15,16]	**OMCE**[17]	**O&M Tool**[18]	**O2M plus**[19]
Organization	TU Delft	BMT	ECN	ECN	GL Garrad Hassan
Considered aspects					
Turbine	Yes	Yes	Yes	Yes	Yes
Support structure	No	Yes	No	No	No
Logistics	Yes	Yes	Yes	Yes	Yes
Metocean conditions	Yes	Yes	Yes	Yes	Yes
Maintenance strategy	Yes	Yes	Yes	Yes	Yes
Failures	Yes	Yes	Yes	Yes	Yes
Features					
Software	MS Excel	Not specified	MatLab	MS Excel	Not specified
Event-based simulation	No	No	No	No	No
Process visualization	No	No	No	No	No
Min. investigation period	Seasonal (only two)	Seasonal	Seasonal	Seasonal	Annual
Time horizon	Long term	Long term	Long term	Long term	Long term
Model output focus	Costs	Costs	Costs	Costs	Costs

Table 2.7: Selection of evaluation tools for logistics concepts

[13] Zaaijer 2003.
[14] Rademakers, Braam, Zaaijer, et al. 2003.
[15] Stratford 2007.
[16] Hofmann 2011.
[17] Rademakers et al. 2009.
[18] Obdam et al. 2011.
[19] Redfern and Phillips 2009.

3 Development of a Simulation-based Evaluation Model

At the beginning of this chapter the scope of the model and specific requirements are defined. Furthermore model assumptions are made. After a detailed introduction into the model architecture, its contents, input and output data as well as the central model procedure are explained. The model is finally verified and validated.

3.1 Model Scope and Requirements

To develop a sufficient model it is necessary to point out requirements in the following sections. These requirements comply with the research goal of this thesis, which is described in the chapters before. Besides the requirements a clear definition of the model and system scope has to be given.

The model has to:

- Cover corrective, condition-based and planned maintenance events
- Cover logistics processes (transport of crew and material) between base station and OWPP
- Process hindcast metocean data
- Be adaptable for OWPP size and distance to base station
- Be adaptable for vessel specifications
- Be flexible for different logistics concepts
- Process several (stochastically distributed) events at a time
- Visualize logistics processes (transparency)
- Calculate energy yields and lost yields
- Calculate economic data of OWPPs
- Summarize key performance indicators (KPIs) data of WTGs and OWPP on a monthly basis

The focus of the model is on the evaluation of logistics concepts in the operation phase of OWPPs. The model comprises WTGs and the equipment for maintenance above sea surface. Sub-sea cables and balance of plant are not part of the model scope.

3.2 Model Assumptions

On the one hand the aim of the model is to represent the reality almost exactly, but on the other hand this would make the model too complex. This relationship has already been described in Figure 2.10. A too complex model would take too much time to generate results. Thus, meaningful assumptions to simplify the model have to be made. The correctness of the model is not affected by these assumption. Also, the assumptions are applied for all investigated concepts in the same manner. Subsequently, possible effects can be neglected as they are the same for all concepts. Hereafter, the main assumptions of the model are listed:

- No personnel is absent due to sea sickness.
- Work orders are always dividable into several missions.
- Personnel and equipment are always available during working hours (except jack-up repair vessel).
- Accessibility of WTGs is only determined by wave height and wind speed.
- If weather conditions allow access to the WTG, the transfer by vessel is always possible.
- Vessels always take the shortest path to the destination.
- Missions always start / continue with the failed WTG closest to the deployed vessel or helicopter.
- Hourly weather data (metocean data) for the whole OWPP describes the environment sufficiently.
- Offshore-based vessels stay offshore all the time.
- The OWPP operator is responsible for the logistics concept.

3.3 Model Architecture

Due to the high system complexity and the specific requirements the model developed within this thesis is based on simulation. It has been developed in the software *Enterprise Dynamics*[20]. This simulation software was chosen due to its high flexibility regarding nonstandard processes (good programmability) on the one hand and the comprehensive library of modules for standard processes on the other hand. The main model input parameters (see Figure 3.1) are information about the OWPP and the WTGs, the equipment used for the logistics concept, the planned maintenance strategy as well as the environmental data at the OWPP. All input parameters except the environmental data are loaded via an *ActiveX* interface from *MS Excel* into the model. Within the model the data is stored in tables. The environmental data is saved in the model itself due to performance reasons. With regard to the OWPP the number, rated power and failure rates of WTGs are transferred, among others, into the model.

[20]Version 8.2.5, INCONTROL Simulation Solutions

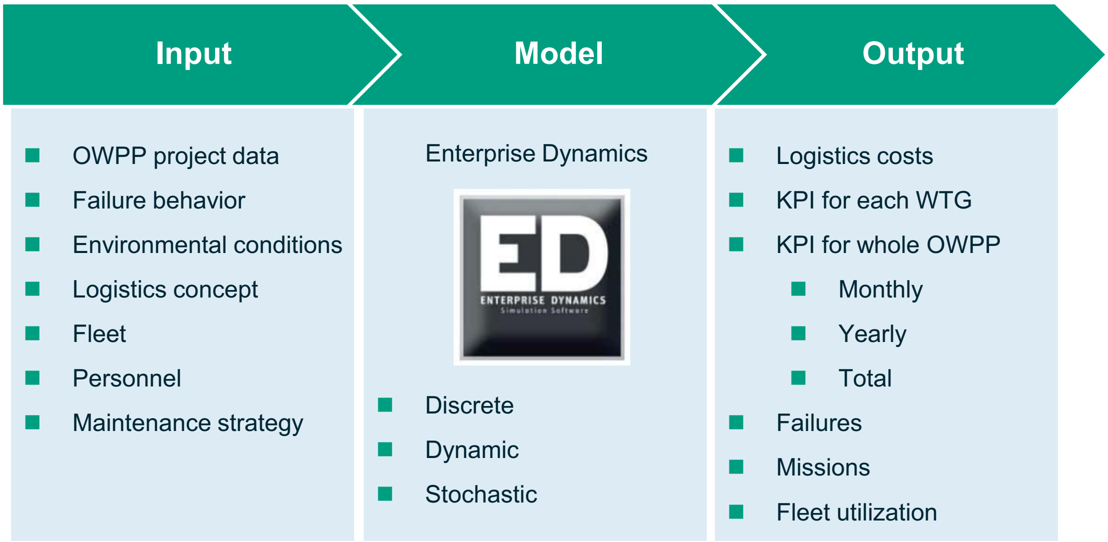


Figure 3.1: General model in- and output

The generated logistics concept is specified in detail in *MS Excel*. Thus, the number of transfer vessels and helicopters can be varied. The model is capable of onshore-based and offshore-based concepts. In terms of maintenance strategy, the priority of the failures as well as the mission order of the available vehicles can be varied.

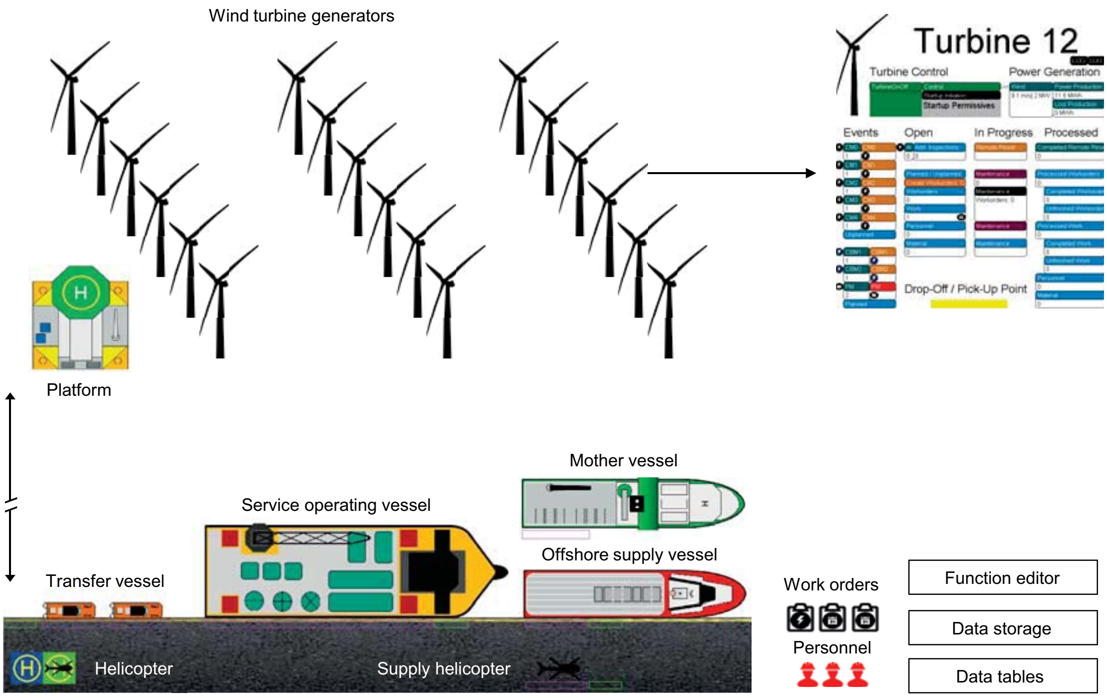


Figure 3.2: Model layout

The main output data of the model are total logistics costs (costs for vehicles and personnel) plus the opportunity costs from lost electricity yield. In addition, the model calculates several OWPP KPIs like availability (or e.g. failure rate, capacity factor and electricity production) of each WTG and the entire OWPP on a monthly, yearly and total basis. Other important outputs are the utilization of equipment and the distribution of the downtime per WTG failure (into travel, work, weather and waiting time). Result data is automatically exported to *MS Excel* after the simulation run for evaluation.

Figure 3.2 shows the layout of the simulation model in *Enterprise Dynamics*. The model consists of different modules, functions, data tables and (temporary) objects. Modules are for example vehicles (vessel and helicopter) and WTGs; personnel and material are objects. Functions for example control the logistics concept or calculate the weather windows for offshore work. Temporary objects are work orders, which appear and disappear after completion. Data tables are used to store temporary and final results. The most important components of the model are described in the following sections.

3.3.1 Modules

The modules of the model are components, which can be selected very flexibly by a user. The two main classes of modules are vehicles (vessel and helicopter) and WTGs. Concerning WTGs the user can select the number and the position of the WTGs. With these modules it is possible to build different logistics concepts and OWPP scenarios very quickly and easily.

Vessels

Basically it can be chosen between onshore-based and offshore-based concepts in the model and the associated vehicles. There are six different types of vessels (see Figure 3.2) that can be selected. Transfer vessels and helicopters are used for the daily transport between the base station and the WTG. It is also possible to carry material with them. The mother vessel is also used for the daily transport and additionally as a base station. The number of transfer vessels, mother vessels and helicopters can be varied. The service operating vessel (SOV) is a large jack-up repair vessel with an own crane. This vessel is used for major failures and repairs. The personnel of six technicians is dedicated to the vessel and works 24/7. The platform supply vessel (PSV) is used for supply purposes for offshore-based concepts, as well as the supply helicopter, which is used for the shift change after a defined interval. The SOV is always part of the model if major failures are considered. PSV and supply helicopter are only used for offshore-based concepts. All vehicles are based on the advanced transporter atom in *Enterprise Dynamics*.

Wind turbine generator

Each WTG consists of several parts, which contain basic *Enterprise Dynamics* atoms (as shown in Figure 3.3). A central part are the event generators, which generate failures and work orders for each failure class for corrective, planned and condition-based maintenance.

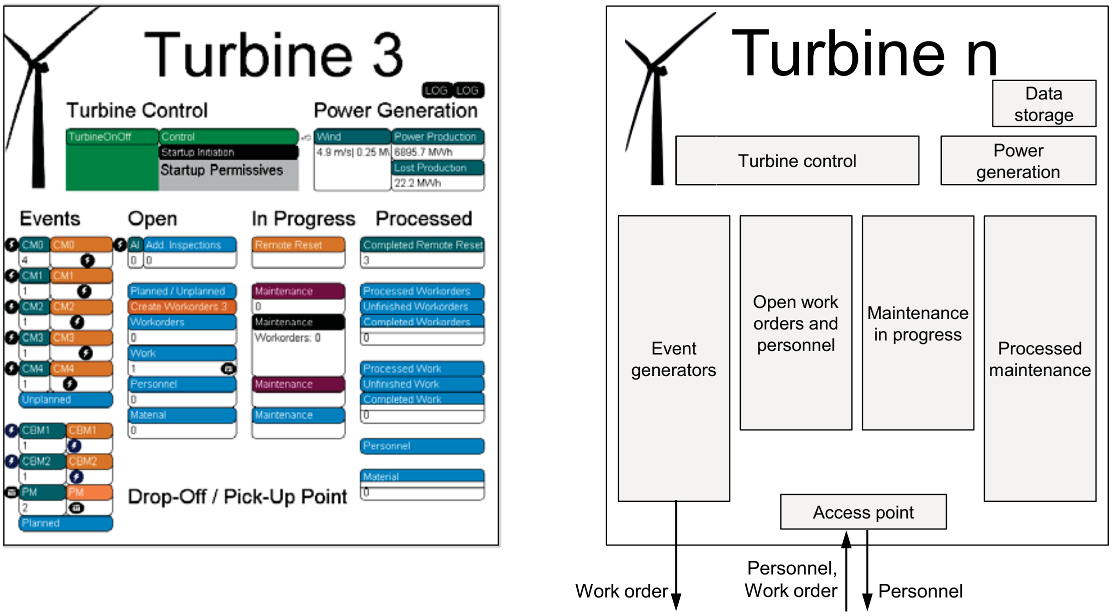


Figure 3.3: WTG

The MTTF is represented by the processing time of products in server atoms. After the processing a failure occurs, which leads to the creation of a work order. The work orders move to a central work order pool. They are displayed in *open work orders and personnel* as well. The access point of each WTG is the transition point for personnel and material. The work is conducted in the part *maintenance in progress* (consists of a central multi service atom). Each finished work order ends in a sink within the part *processed maintenance*.

The part *power generation* calculates the power in relation of the wind speed. This is based on a defined power curve. The power curve can be adapted for different types of WTG. The WTG stops operation if a failure occurs or a person enters the plant. For a restart the failure must be repaired, no other corrective work order is allowed to exist and no personnel is allowed to be on the WTG. The part *data storage* stores information about the generated power and the lost power production. *Data storage* also forwards the information to a central data storage.

3.3.2 Tables

The model uses tables to store input and output data but also to process data during the simulation runs. The most important internal input and output tables shall be briefly explained in this section. These tables correspond to the external input and output tables in *MS Excel* which are described in Section 3.3.5. Central internal input tables of the model are:

- General
- Maintenance
- Vessels
- Metocean

The table *General* contains information about the number and type of WTGs, the start time of the simulation run and its name. It also contains important information about the selected logistics concept and the number of vessels and personnel. Furthermore, additional information about shift system (12/7 or 24/7) and shift change interval is indicated. These intervals are only relevant for offshore-based concepts.

The table *Maintenance* contains information about the different maintenance and failure classes, especially how often the failure occurs and how much time it takes to conduct maintenance or to repair failures. For each failure class it is indicated which resource is needed to repair the failure (e.g. transfer vessel or SOV) and the required team size. It is also possible to enter an allocation time for material per failure class. This can be used especially for large components which can need a certain time to be available.

The table *Vessels* stores all relevant information about the deployed vessels. This information comprises:

- Name
- Passenger capacity
- Resource number
- Maximum significant wave height for WTG access
- Maximum wind speed for WTG access
- Speed inside and outside the OWPP
- Minimum weather window
- Cost per year, day and hour

The table *Metocean* contains hindcast data about wind speed and significant wave height, this data is given in the table on an hourly base.

To be able to analyze the generated model results, they are stored in several data tables. The most important internal output tables are:

- ParkStats
- MissionLog
- FailureLog

The table *ParkStats* exists on a monthly, yearly and total base. It contains summarized statistics about the OWPP and the logistics concept performance. For example data about power production and losses, capacity factor, availability, downtime and uptime are stored in this table. The number of failures and the number of repaired failures are specified as well. In addition, information about the operation time of vessels and helicopters as well as their traveled distance can be found. Based on this data the costs per vessel and the total costs are calculated. The table *MissionLog* tracks all missions and stores the mission start time as well as the mission end time. It provides information about the involved WTG and the number of involved personnel. The table *FailureLog* documents all failures chronologically with the time of occurrence, the required number of missions, weather and waiting time, travel time and the resulting downtime.

To guarantee an efficient simulation run, it is possible to store temporary data in tables, which is used from different functions. Necessary tables for the simulation run are:

- Vesselx
- MissionVx

Each vessel has two own assigned tables. The first one is called *Vesselx*, this tables temporarily stores the content of the vessel, personnel and work orders. The table *MissionVx* stores the current missions of the vessel, this is needed especially for multiple missions going on at the same time for one vessel.

3.3.3 Functions

The model has five different classes of functions (see Table 3.1). The first class of functions is for the definition of global variables. This set of functions is executed with each start of the model. The second class of functions generates and destroys model instances representing different OWPP scenarios and logistics concepts.

Variable definition	**Model generation**	**Work order dispatching**	**Vessel control**	**Data collection**
GlobalVar-Definition	CreateOWPP	Fleet	NextTask	EventLog
GlobalVar-Maintenance	DestroyOWPP	Weather-Window	LoadNext	ExportData
	CreateLogis-ticsConcept	MissionTime	UnloadNext	
	DestroyLogis-ticsConcept	Vessel	Unload-Personnel	

Table 3.1: Model functions

The third class of functions is for work order dispatching. These functions are used to dispatch the different work orders, the personnel and material to the different vessels according to weather and working conditions. The fourth class of functions has the task to control the vessels' movements and actions. The functions of classes three and four can also be understood as model control functions. The last class of functions supports other functions or helps to store generated data. In the following text the functions are briefly described. The functions with a central role for the functionality of the model are described in greater detail.

GlobalVarDefinition

This function defines all global variables, which are used within the model. These global variables are for example:

- Total number of WTGs
- WTG version
- Total number of vessels
- Logistics concept

GlobalVarMaintenance

In this function the failure classes of a WTG are defined with all their attributes. A failure class can be corrective maintenance, planned maintenance or condition-based maintenance. The attributes of failure classes, which are also defined within this function, comprise:

- Occurrence
- Priority
- Duration of repair / maintenance
- Required resource
- Required team size
- Required quantity of inspections

Occurrence describes the frequency of failures per year λ (see also Equation 2.10). Priority indicates the importance of treatment of a failure. Duration stands for the time, which is required to repair the failure. Resource refers to the type of vessel required for this failure class. Team size indicates the number of personnel needed to repair the failure. For major failures prior inspections are required. This attribute indicates the number of required prior inspections.

CreateOWPP

This function creates all WTGs within an OWPP. It locates the defined number of WTGs to their defined geographical position. This function is always used when a new OWPP scenario is created in the model.

DestroyOWPP

The function *DestroyOWPP* deletes all WTGs, which are part of the present model. This function has to be executed before creating new WTGs by using the function *CreateOWPP*.

CreateLogisticsConcept

The task of this function is to generate the selected logistics concept (e.g. onshore-based or offshore-based). The function inserts the chosen vessels (e.g. mother vessel, transfer vessel and helicopter) at their defined position. In case of an offshore-based manned platform concept the platform is also inserted into the model.

DestroyLogisticsConcept

This function is used to delete the existing logistics concept in the model in order to create a new one by executing the function *CreateLogisticsConcept*. The function deletes mother vessels, transfer vessels, helicopters and platforms if they exist.

Fleet

The function *Fleet* is the main function and includes the functions *WeatherWindow*, *MissionTime* and *Vessel* to dispatch work orders and personnel to the different vessels (see Figure 3.4).

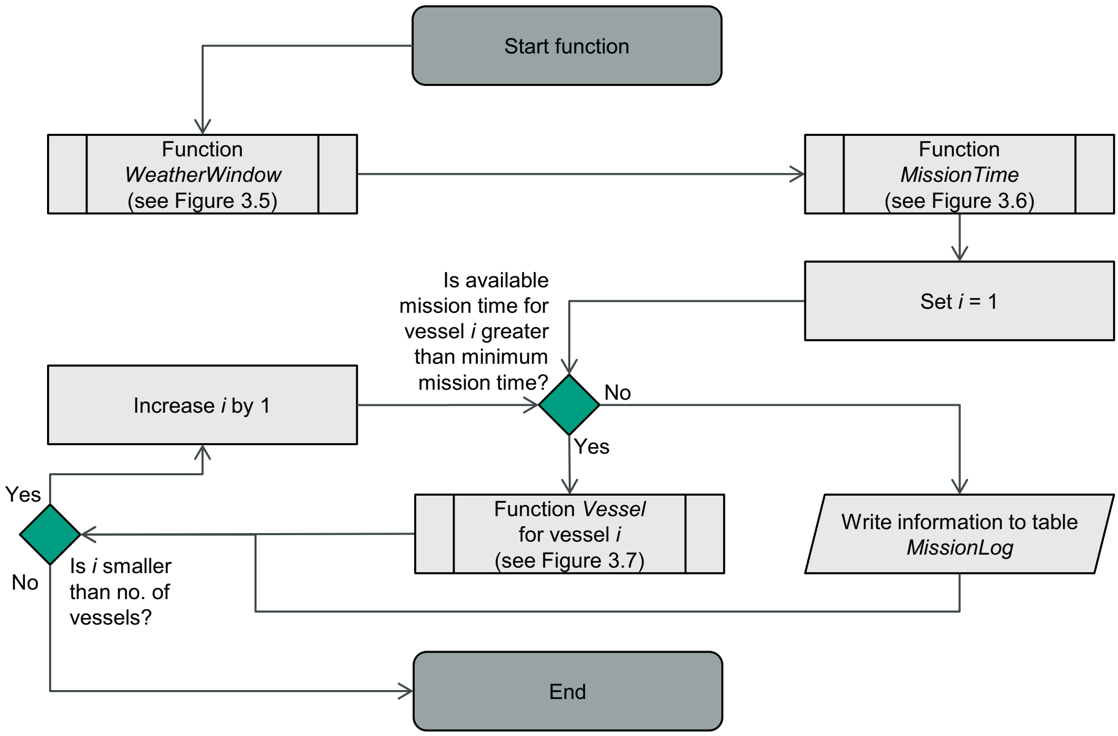


Figure 3.4: Function *Fleet*

The function starts with the execution of the function *WeatherWindow* to determine the next possible weather windows for offshore maintenance work for all vessels. Based on the weather window identification the maximum mission time is derived for all vessels in the function *MissionTime*. A check is carried out for each available vessel in the model if the weather window provides sufficient time to work (maximum available mission time must be greater than the specified minimum mission time). If yes, the function *Vessel* is executed for vessel i. If the identified next weather window respectively the maximum available mission time is too short this information is stored in table *MissionLog*. After the check of the available mission time has been executed for all existing vessels the function *Fleet* is terminated.

WeatherWindow

The function *WeatherWindow* searches in the table *Metocean* (containing rows with date (year, day and time), significant wave height and wind speed) for the next weather window beginning with the time at the moment of the function execution. The function searches for the next row (*StartRow*) in which constraints for wave height and wind speed are fulfilled. This is the start time for the weather window.

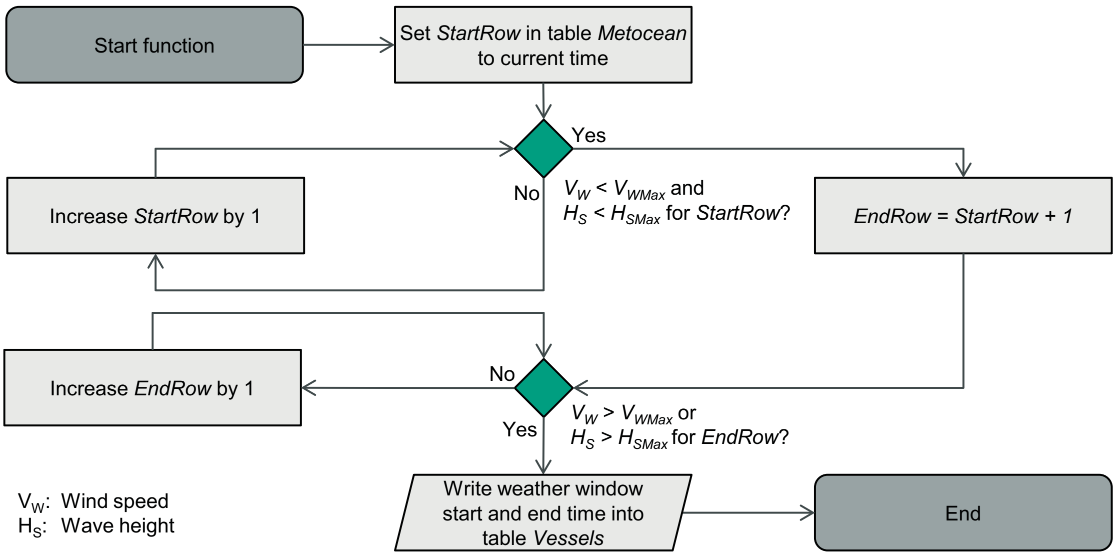


Figure 3.5: Function *WeatherWindow*

If a start time is found, the *EndRow* is set to *StartRow* plus one and the end row is increased as long as the constraints for wave height or wind speed are no longer fulfilled. If this is the case for a row, the weather window end time is set to the date in this row. The length of the weather window is determined by the time difference of the identified start (*StartRow*) and end time (*EndRow*). The information about start, end and length of the weather window is written in table *Vessels* (see Figure 3.5).

MissionTime

The function starts with a verification if the option *NightShift* (24/7) is selected. If yes, *ShiftStart* is equal to the moment of the function execution, if not, *ShiftStart* is the standard time (determined in table *Personnel*). The duration of the shift is set to the preferences from table *Personnel* as well.

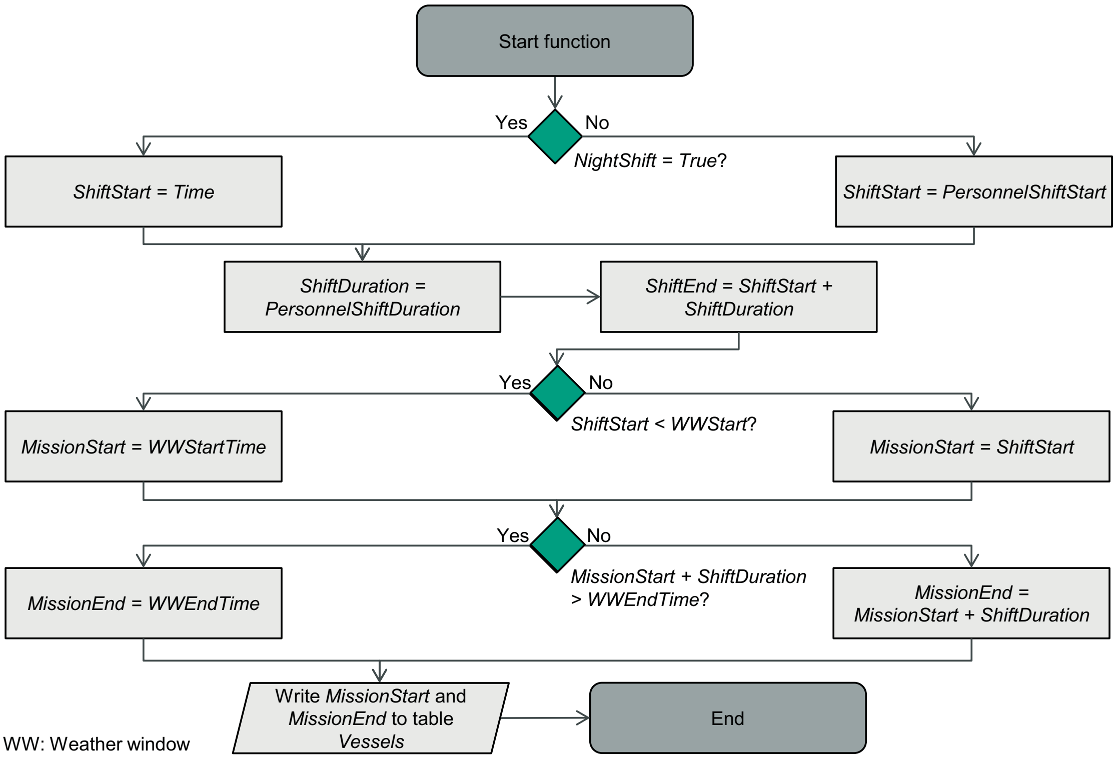


Figure 3.6: Function *MissionTime*

The end of the shift is then the sum of *ShiftStart* and *ShiftDuration*. If *ShiftStart* is earlier than the beginning of the next weather window, *MissionStart* is set to the start time of the weather window otherwise it remains the value of *ShiftStart*. If the sum of *MissionStart* and *ShiftDuration* results in a time later than the end of the weather window, *MissionEnd* is set to the weather window end time. If not, it remains equal to the sum of *MissionStart* and *ShiftDuration*. The function ends with the storage of *MissionStart* and *MissionEnd* values in table *Vessels* (see Figure 3.6).

Vessel

This function has a central role within the model. It assigns personnel and work orders to a vessel. The function begins by checking if a planned or unplanned work order is in the work order pool for a certain vessel. If this is the case unplanned work orders have a higher priority. The table for unplanned work orders is searched through for a work order that fits to the vessel class. It is also checked if the capacity for personnel on the vessel is available and if the necessary personnel is available at the base station at all. Another checked criterion is if there is no ongoing work at the WTG. If all criteria are fulfilled, the work order and the personnel are assigned to the vessel. The information about the assignment is stored in table *MissionLog* (see Figure 3.7). Afterwards it is checked if more unplanned work orders exist. If this is not the case the above described search procedure is done for planned work orders. If no more fitting work orders are found, the function is executed.

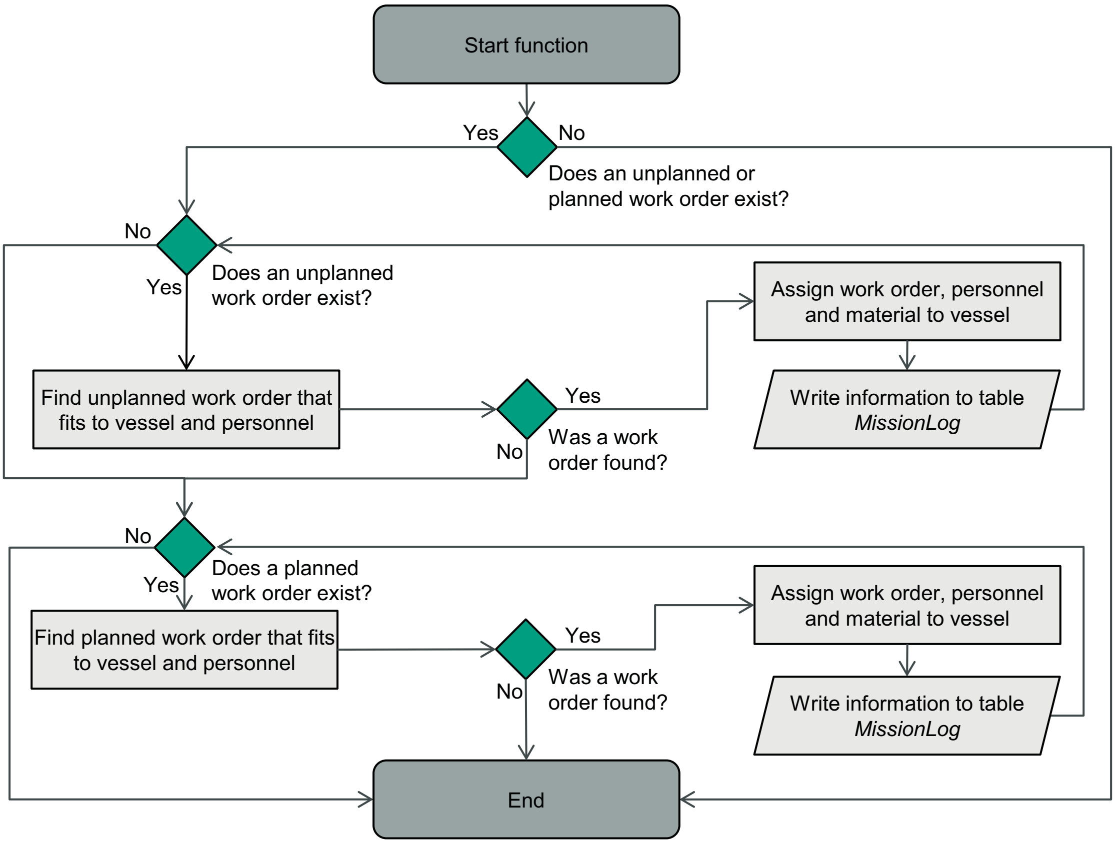


Figure 3.7: Function *Vessel*

NextTask

This function controls a vessel and provides the information where a certain vessel has to go and what is has to load or unload. This mainly depends on the loading status of the vessel. The function differentiates between three different vehicle loading status (see Figure 3.8):

- Open work orders and personnel on board
- Open work orders but no personnel on board
- No more work orders on board

In the first case, the vessel sails to the nearest OWPP and unloads the personnel if it is an unloading action. Afterwards the function is terminated. In the second case, the function searches for pick up requests. If there are none, the vessel stays on standby in the OWPP. Otherwise it picks up the personnel. Afterwards the function is terminated. In the third case, the function checks for open pick up requests. If no pick up request exists and all personnel is picked up, the vessel sails home. Otherwise it picks up the personnel or stays on standby in the OWPP. Afterwards the function is terminated.

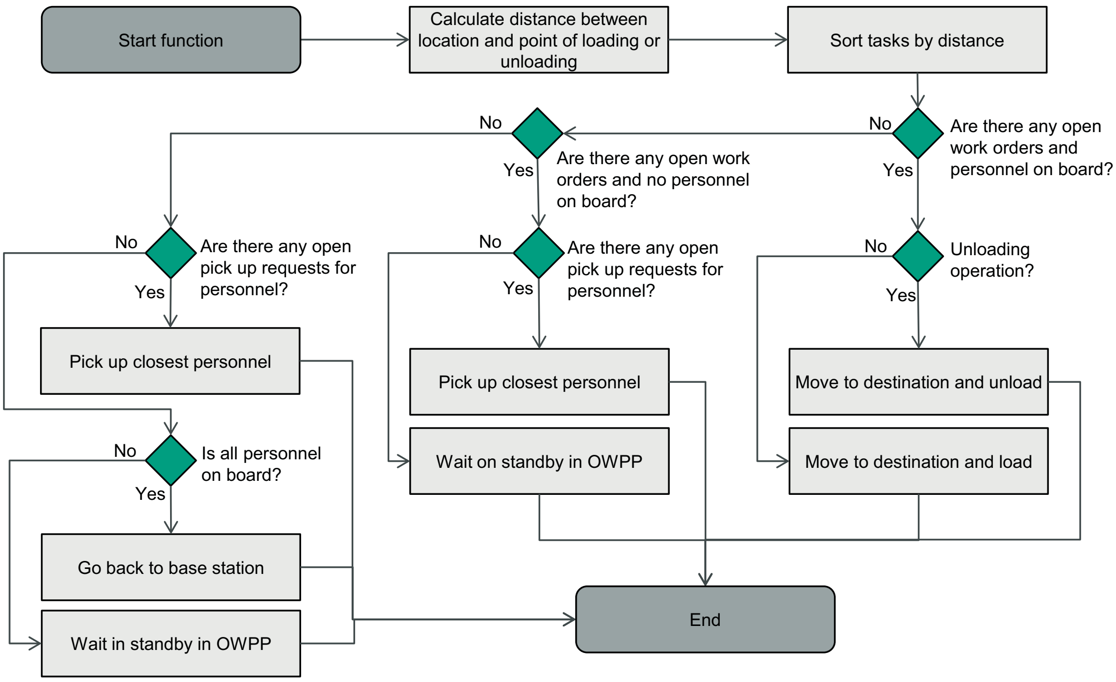


Figure 3.8: Function *NextTask*

LoadNext

If a vessel loads something, this function is triggered. It ensures that everything that has to be loaded at this point will be loaded. The function searches for objects at the current vessel position that are supposed to be loaded. If no more object has to be loaded, the function *NextTask* is triggered.

UnloadNext

If a vessel unloads something, this function is triggered. It ensures that every cargo that has to be unloaded at this point will be unloaded. The function searches for cargo on board which is designated to be unloaded at the current position. If there is no more cargo to unload, the function *NextTask* is triggered.

UnloadPersonnel

If a vessel unloads something, this function is triggered. It ensures that every personnel that has to be unloaded at this point will be unloaded. The function searches for personnel on board which is designated to be unloaded at the current position.

EventLog and ExportData

The function *EventLog* is only optional. It can be used to track detailed model events. The function stores the time, vessel ID, WTG ID, work order ID and a short description of the event in a table. The function *ExportData* is used to export all relevant results from *Enterprise Dynamics* to *MS Excel*.

3.3.4 Procedure

The first part of the global procedure is almost the same as displayed for the function *Fleet*. After the function *Vessel* is executed, it is checked if work orders and personnel are assigned to vessels. If yes, the vessels start their missions at the defined time. If no, nothing will happen. For a better understanding an example is used to explain the procedure.

It is assumed that two WTGs stop operation due to a minor failure, which has to be repaired by technicians. These failures in the form of work orders are send from the WTG to a central work order pool. Every day at 06:00 (standard) or at another defined time or event the function *Fleet* is executed. This function (indirectly) checks the weather conditions (function *WeatherWindow*) and calculates the possible mission time (function *MissionTime*). After this has been done for the available transfer vessel (maximum capacity of 12 technicians and no assigned work orders so far) it is checked whether open work orders are available in the work order pool. Two work orders relating to the above mentioned failures are found in the work order pool. It is checked whether the transfer vessel is appropriate for these failures and whether it has sufficient capacity to transport the required technicians. If this is the case, the work orders are assigned to the transfer vessel. In this example both work orders can be assigned to the vessel. Also three technicians are necessary for each work order. Thus, six technicians are assigned to the vessel. The start of the transfer vessel is planed for the next possible time (usually 06:00, but could be later due to bad weather conditions). The function *NextTask* is triggered at the defined mission start time. The function (and also the function *LoadNext*) ensures that the work orders and technicians are transferred from the base station onto the vessel.

The transfer vessel starts its mission and sails directly to the affected WTG, which is closest to the base station. The transfer vessel always tries to minimize the distance traveled. The technicians transfer to the WTG (initialized by the functions *UnloadNext* and *UnloadPersonnel*). Afterwards, the transfer vessel sails to the other affected WTG (function *NextTask*) and leaves the technicians on the WTG. The transfer vessel waits in front of the second WTG (function *NextTask*) because it is empty (no personnel on board). After the technicians on the first WTG have finished their work the vessel is called to pick them up (the function *NextTask* is executed). The transfer vessel sails back to the first WTG and picks up the personnel. It waits there until the technicians on the second WTG have finished their work and call the transfer vessel to pick them up. The personnel from the second WTG transfers back to the vessel. When the vessel has loaded all technicians it starts to go back to the base station. The mission is completed.

3.3.5 Input and Output

The model has several input and output data. Figure 3.9 shows simplified categories of input data and where they are used in the model as well as the output data after a simulation run.

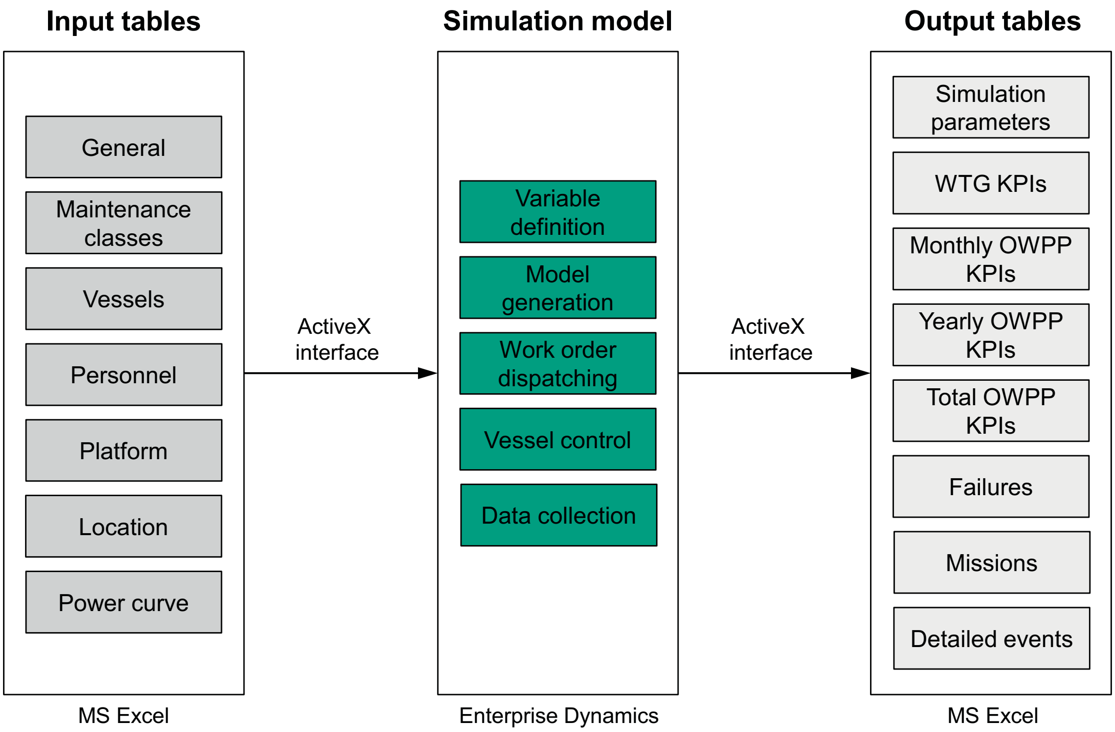


Figure 3.9: Model's in- and output tables

Input parameters are required to built a model scenario (e.g. number of vessels, number of WTGs). The parameters also determine properties of objects and modules (e.g. speed of vessels). These input parameters are entered in *MS Excel* on different spread sheets (tables) which mainly correspond to the internal tables of the simulation model (which have already been described before). Through an *ActiveX* interface all data is loaded into the simulation environment and the simulation model is built automatically according to the input parameters. The following table (see Table 3.2) gives an overview of the existing input tables in *MS Excel*.

Table	Description
General	General information about the model
Location	Information about the OWPP's location
Vessels	Properties of vessels
Personnel	Information about the personnel (e.g. working time, salary)
Maintenance classes	Information about the different maintenance types and their frequency of occurrence and required maintenance time
Power curve	Information about the power, which is generated in relation to the current wind speed
Platform	Information about the platform location and the annual costs

Table 3.2: Input tables of simulation model

During a simulation run data is generated and stored in internal output tables (which have already been described before). At the end of each simulation run, the data is automatically exported through the *ActiveX* interface into a new *MS Excel* file. The different output tables in *MS Excel* contain statistics from the simulation runs (see Table 3.3).

Table	Description
Simulation parameters	General information about the simulation run, selected input parameters
WTG KPIs	Performance parameters for each WTG covering the whole simulation time
Monthly OWPP KPIs	Performance parameters of OWPPs, information on failures, missions and costs, more than 80 parameters
Yearly OWPP KPIs	Like monthly view, but for one year
Total OWPP KPIs	Like monthly, but for the whole simulation run
Failures	List of all corrective and condition-based maintenance with downtime, repair time and travel time
Missions	List of all executed missions
Detailed events	List of selected events of the simulation run for debugging and validation purpose. For a better simulation performance this function can be turned off.

Table 3.3: Output tables of simulation model

With each simulation run a new *MS Excel* file is created. The content data can be used for in depth analysis and evaluation.

3.4 Model Verification and Validation

Under this section the previous introduced model is verified and validated. The model is verified by checking the model results for a random day. For validation the model results are compared to other model results and real system data.

3.4.1 Verification

To avoid model failures from the beginning the model has already been tested extensively during the built up and set up phase. Especially the right interdependence between the model's modules (vehicles and WTGs) has been tested in early development stages of the model.

To prove that the model is working correctly and all calculations and results are correct, manual controls have been done for several situations and periods. To illustrate these controls an example from April 24, 2000 is presented in the following text. The data base is the model output in the tables *Detailed events*, *Missions*, *Failures* and the data in the table *Metocean*. The example consists of an OWPP with 90 WTGs located 100 km from the base station. The logistics concept comprises an offshore-based mother vessel concept with a helicopter and one transfer vessel. The maximum wind speed at that day is 5.8 m/s. The maximum significant wave height is 0.58 m at that day (see Figure 3.10). So it is possible for all vessels and the helicopter to operate all day long and transfer the technicians to the WTG.

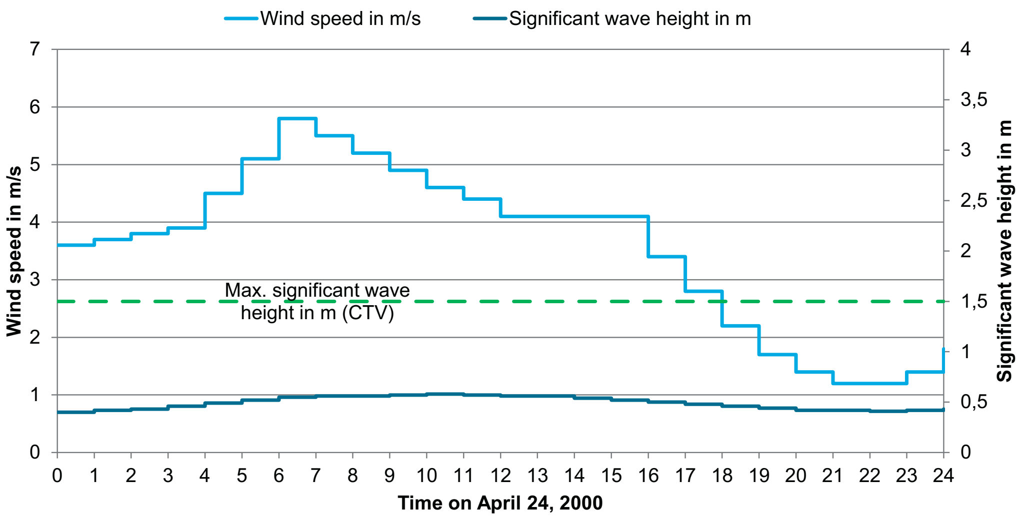


Figure 3.10: Environmental conditions

Based on model tables the chronological sequences of missions on April 24, 2000 are explained in the following. According to weather data and work order situation all technicians and all vehicles are in operation. Figure 3.11 illustrates the movements of the vessels and the helicopter on this day.

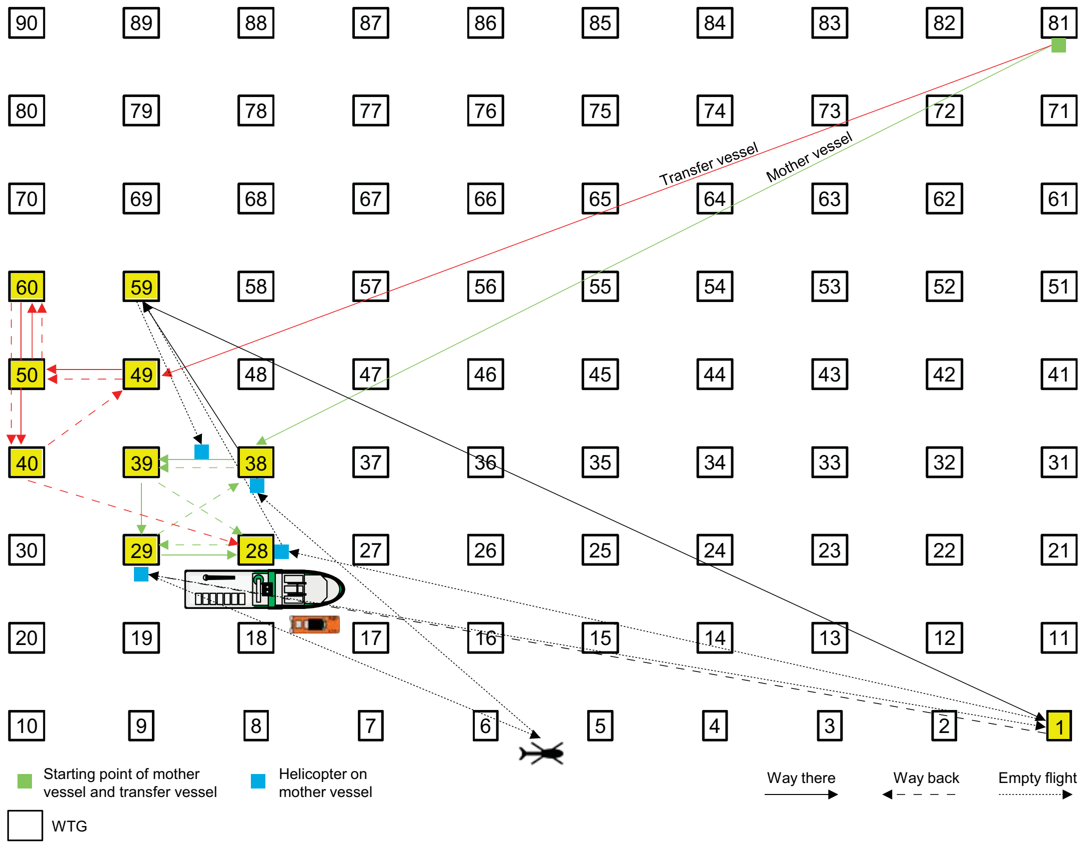


Figure 3.11: Routes of vehicles

Helicopter

06:00	Helicopter starts on shore.
06:30	Helicopter picks up technicians from mother vessel at WTG 38.
06:37	First technician enters WTG 59.
06:41	Technicians start working on work order T59-CM4-1 at WTG 59. Helicopter flies back to mother vessel located between WTG 38 and 39.
10:41	Work order T59-CM4-1 is accomplished. Pick up is requested.
10:48	All technicians have boarded the helicopter coming from mother vessel at WTG 28. WTG 59 is restarted. Helicopter heads towards WTG 1.
10:55	First technician enters WTG 1.
10:59	Technicians start working on work order T1-CM1-1 at WTG 1. Helicopter flies back to mother vessel located at WTG 28.
14:59	Work order T1-CM1-1 is accomplished. Pick up is requested.
15:08	All technicians have boarded the helicopter coming from mother vessel at WTG 29.

15:12	Technicians leave from helicopter to mother vessel located at WTG 29. Helicopter flies back to onshore base. The mission took 9.2 h, the helicopter operation time was 1.86 h and the traveled distance was 240.19 km.

Mother Vessel

06:00	Mother vessel starts with 12 technicians from WTG 81 towards WTG 38.
06:21	WTG 38 is shut down. First technician enters WTG 38.
06:39	Technicians start working on work order T38-PM1-1 at WTG 38. Mother vessel heads towards WTG 39.
06:48	WTG 39 is shut down. First technician enters WTG 39.
07:00	Technicians start working on work order T39-PM1-1 at WTG 39. Mother vessel heads towards WTG 29.
07:09	WTG 29 is shut down. First technician enters WTG 29.
07:21	Technicians start working on work order T29-PM1-1 at WTG 29. Mother vessel heads towards WTG 28.
07:30	WTG 28 is shut down. First technician enters WTG 28.
07:42	Technicians start working on work order T28-PM1-1 at WTG 28. Mother vessel waits in front of WTG 28.
11:33	Work order T29-PM1-1 is accomplished. Pick up is requested.
11:54	Three technicians have boarded mother vessel, WTG 29 is restarted.
16:09	Work order T38-PM1-1 is partly accomplished. 5 h of work remain. Pick up is requested.
16:30	Work order T39-PM1-1 is partly accomplished. 5 h of work remain. Pick up is requested.
16:31	Three technicians have boarded mother vessel, WTG 38 is restarted.
16:42	Three technicians have boarded mother vessel, WTG 39 is restarted.
17:12	Work order T28-PM1-1 is partly accomplished. 14.5 h of work remain. Pick up is requested.
17:34	Three technicians have boarded mother vessel, WTG 28 is restarted.
17:34	All technicians are on board. The mission took 11.57 h, the mother vessel operation time was 2.96 h and the traveled distance was 13.41 km.

Transfer Vessel

06:00	Transfer vessel starts with 12 technicians from WTG 81 towards WTG 49.
06:17	WTG 49 is shut down. First technician enters WTG 49.
06:21	Technicians start working on work order T49-PM1-1 at WTG 49. Transfer vessel heads towards WTG 50.
06:25	WTG 50 is shut down. First technician enters WTG 50.
06:29	Technicians start working on work order T50-PM1-1 at WTG 50. Transfer vessel heads towards WTG 60.

06:33	WTG 60 is shut down. First technician enters WTG 60.
06:37	Technicians start working on work order T60-PM1-1 at WTG 60. Transfer vessel heads towards WTG 40.
06:43	WTG 40 is shut down. First technician enters WTG 40.
06:47	Technicians start working on work order T40-PM1-1 at WTG 40. Transfer vessel waits in front of WTG 40.
16:39	Work order T49-PM1-1 is partly accomplished. 5 h of work remain. Pick up is requested.
16:48	Three technicians have boarded transfer vessel, WTG 49 is restarted.
16:47	Work order T50-PM1-1 is partly accomplished. 13.7 h of work remain. Pick up is requested.
16:53	Three technicians have boarded transfer vessel, WTG 50 is restarted.
16:55	Work order T60-PM1-1 is partly accomplished. 3.4 h of work remain. Pick up is requested.
17:03	Three technicians have boarded transfer vessel, WTG 60 is restarted.
17:05	Work order T40-PM1-1 is partly accomplished. 13.7 h of work remain. Pick up is requested.
17:14	Three technicians have boarded transfer vessel, WTG 40 is restarted. Transfer vessel moves towards mother vessel located at WTG 28.
17:16	All technicians are on board the mother vessel. The mission took 11.28 h, the operation time of the transfer vessel was 1.33 h and the traveled distance was 15.91 km.

The procedures show that everything is in accordance with the assumptions and requirements of the model. The duration of each mission is not longer than 12 hours. In Figure 3.11 it is possible to understand the route of the vessels and the helicopter. It is noticeable that the vessels and the helicopter always take the shortest distance.

Unplanned work orders

On the investigated day three unplanned work orders are accomplished (see Table 3.4). The first two items in the table are work orders for remote resets.

No.[21]	**Work order**	**WTG**	**Event time**	**Completion time**	**Downtime in h**
1	T43-CM0-4	43	2000-04-24 17:39	2000-04-24 18:40	1.03
2	T26-CM0-1	26	2000-04-24 03:04	2000-04-24 04:42	1.65
3	T1-CM1-1	1	2000-04-23 22:42	2000-04-24 15:08	16.45

Table 3.4: Unplanned work orders

The third item is a work order for corrective maintenance, which is processed within the helicopter mission (see chronological description of helicopter mission above). The first work order for the helicopter on WTG 59 is a first-time inspection due to a major

[21] Number

failure (CM4). The WTG is still down, because it has to be repaired by a jack-up repair vessel.

Electricity yield

The electricity yield of WTG 20 and WTG 28 is shown in Table 3.5. WTG 20 is operating the whole day. WTG 28 is out of operation from 7:24 to 17:34 because of planned maintenance. The manual calculation based on wind speed and power curve confirms the values calculated by the model. The model calculates the data in intervals of 15 minutes.

	Production in MWh	**Lost Production in MWh**	**Uptime in h**	**Downtime in h**
WTG 20				
2000-04-24 00:00	6,735.85	15.71	2,730.75	5.25
2000-04-25 00:00	6,739.85	15.71	2,754.75	5.25
Delta (Model)	4.00	0.00	24.00	0.00
Own Calculation	4.00	0.00	24.00	0.00
WTG 28				
2000-04-24 00:00	6,719.68	31.88	2,714.50	21.50
2000-04-25 00:00	6,721.49	34.07	2,728.25	31.75
Delta (Model)	1.81	2.19	13.75	10.25
Own Calculation	1.81	2.19	13.75	10.25

Table 3.5: Electricity yield

Coincidence of events

Table 3.6 summarizes the input for the frequency of events for the defined maintenance classes. The frequency of events per WTG and year over all simulation runs differs from -6.4 % to +1.8 % from the input values.

Maintenance class	**Input**	**All simulation runs**	**Deviation**
CM0	5.0000	4.8640	-2.8 %
CM1	2.3909	2.2884	-4.5 %
CM2	0.7124	0.6644	-7.2 %
CM3	0.7888	0.7622	-3.5 %
CM4	0.1784	0.1689	-5.6 %
CBM1	0.2011	0.2049	+1.8 %
CBM2	0.2284	0.2147	-6.4 %

Table 3.6: Frequency of events per WTG and year

The frequency of events determines the mean time between failures. If the operation time of the OWPP is below 100 %, the number of events has to be lower. Averaging all simulation runs the OWPP is out of operation in 4.0 % of the time. Thus, the deviation of event frequency in the model is as expected.

The values and outputs generated by the model correspond to the calculated and expected values. The model complies with the initial setup requirements.

3.4.2 Validation

The model validation is done in the following two ways to ensure that the model and its results most adequately represent the real system:

1. Comparison with other models
2. Comparison with recorded data from real systems and literature

On the one hand the model is compared with the *O&M Tool* from ECN. Both models are run with the same input parameters and the results are compared. On the other hand the developed model is quantitatively and qualitatively compared to existing empiric data from real OWPPs and literature.

Two different logistics concepts for one OWPP scenario are investigated with the developed model and the ECN *O&M Tool*. The most important results are compared (see Table 3.7). The scenario is again an OWPP with 90 WTGs located 100 km away from the base station. The first investigated logistics concept is onshore-based with two transfer vessels and one helicopter, the second concept is offshore-based including a mother vessel and a helicopter. All input parameters in terms of costs, failure frequencies, weather conditions, WTG capacities and working times are set to the same values in both models.

	Onshore-based concept		**Offshore-based concept**	
	Model	**O&M Tool**	**Model**	**O&M Tool**
Availability in %	93.3	93.6	97.0	96.9
Cost in m EUR p.a.	31.05	33.19	30.16	33.00
Revenue losses in m EUR p.a.	14.10	12.56	6.32	6.38
O&M costs in m EUR p.a.	16.95	20.63	23.85	26.62
No. of missions	557	675	473	660

Table 3.7: Comparison with ECN *O&M Tool*

The results of the model comparison show that the calculated availabilities are almost the same for both models. For the onshore-based concept the availability calculated with the *O&M Tool* is 0.3 percentage points higher than with the model developed in this thesis. For the offshore-based concept the availability obtained with *O&M Tool* is 0.1 percentage points lower. Regarding the costs, both models deliver results between

EUR 30.1 million and EUR 33.2 million. The differences can be explained more clearly if the costs are divided into revenue losses due to downtime and O&M costs (vehicles and technicians). For the onshore-based concept the results for revenue losses differ by around EUR 1.5 million.

This is due to the fact that the *O&M Tool* calculates the revenue losses based on statistical weather data and average downtime. The model developed here uses real hindcast weather data and combines it with the power curve information when a WTG is not operating due to failure or planned maintenance. It seems as if the downtimes are longer in strong wind periods (winter) in the developed model and distributed equally in the *O&M Tool*. There is almost no difference between the revenue losses in both tools for the offshore-based concept. It appears that the before mentioned effect has no impact on such a little revenue loss. The *O&M Tool* calculates EUR 2.6 million to EUR 3.7 million higher O&M costs. This results from the higher number of missions undertaken in the *O&M Tool*. The dynamic approach of the developed model makes it possible to combine different work orders with each other. Thus, a high potential for synergies exists, which cannot be detected by an analytical tool. In summary, both models lead to similar results. The existing differences can be explained in a plausible way. Even if the results differ, both model results indicate that the offshore-based concept is superior.

The second validation step is a comparison of model results (again for 90 WTGs, 100 km away from base station) with publicly available data generated by other models or from existing OWPPs. The comparison is done quantitatively and qualitatively. The model results refer to the lowest and highest values per parameter. In the following sections the model is validated with regard to the following indicators:

- Costs for transfer vessels
- Number of deployed transfer vessels
- Costs for helicopters
- Costs for jack-up repair vessel
- Costs for personnel
- Availability (total and monthly)
- Capacity factor

Figure 3.12 shows that the costs for transfer vessels in the developed model vary from EUR 1.0 million to EUR 4.0 million p.a., which is analog to EUR 2.8 million to EUR 4.2 million p.a. for an 500 MW OWPP according to literature (Phillips et al. 2013, p. 33). In addition, the number of deployed transfer vessels is in the same range in the developed model (one to four) and the literature (one to three) (Zhao et al. 2012, p. 4). The observed costs for helicopters correspond as well to the literature data regarding an 500 MW OWPP (EUR 2.4 million to EUR 2.6 million p.a. compared to EUR 2.1 million to EUR 4.2 million p.a.) (Phillips et al. 2013, p. 34). For jack-up repair vessels the generated costs of approximately EUR 7 million p.a. lie within the range of the literature data

(Phillips et al. 2013, p. 34). Moreover, the range for personnel costs (EUR 1.5 million to EUR 8.3 million p.a.) of the developed model and the literature overlap (Phillips et al. 2013, p. 35).

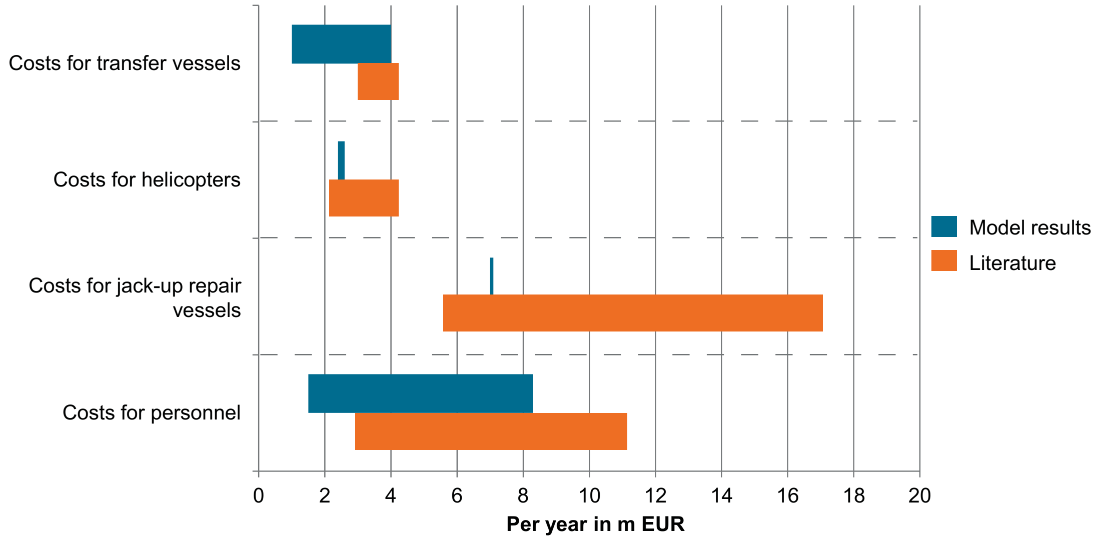


Figure 3.12: Validation of cost results

Besides the costs another important evaluation criterion for the model, the calculated availability, shows a similar trend like real data (see Figure 3.13). It can be seen that in both cases the availability in winter months is lower than in summer month. The figure shows the monthly availability based on model results and the availability of the OWPP Egmond aan Zee in 2007.

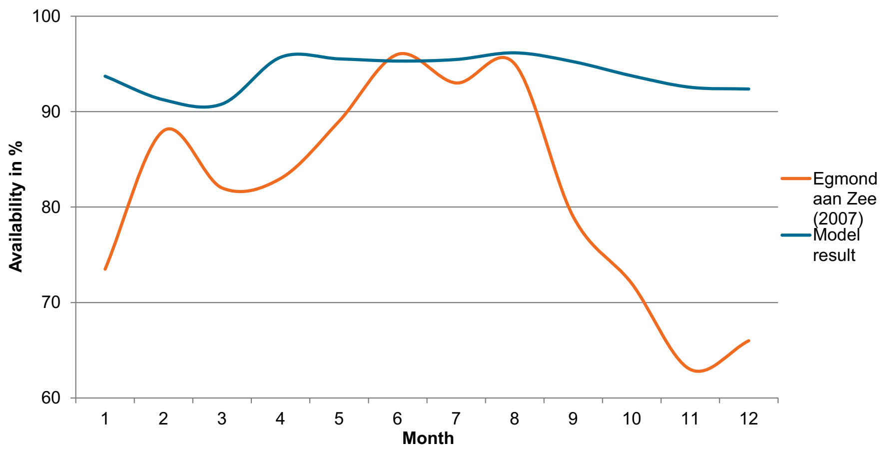


Figure 3.13: Validation of monthly availability results

In this year the availability of Egmond aan Zee was relatively low because of extensive works on all WTGs (Brug et al. 2009, p. 7). Anyway, the data is sufficient for a qualitative comparison of the monthly availability.

The average annual availability of 94 to 97 % of the developed model (see Figure 3.14) is almost the same as the measured average availability of real OWPPs (94 to 97 % for Alpha Ventus and Egmond aan Zee in 2010 and 2011) (Berkhout et al. 2014, p. 61). Furthermore, the calculated capacity factor of the developed model varies between 32.9 and 34.3 %, which conforms with typical capacity factors from real OWPPs (e.g. 33 % for Egmond aan Zee (Berkhout et al. 2014, p. 60) or 31.27 % for Thanet (LORC 2014)).

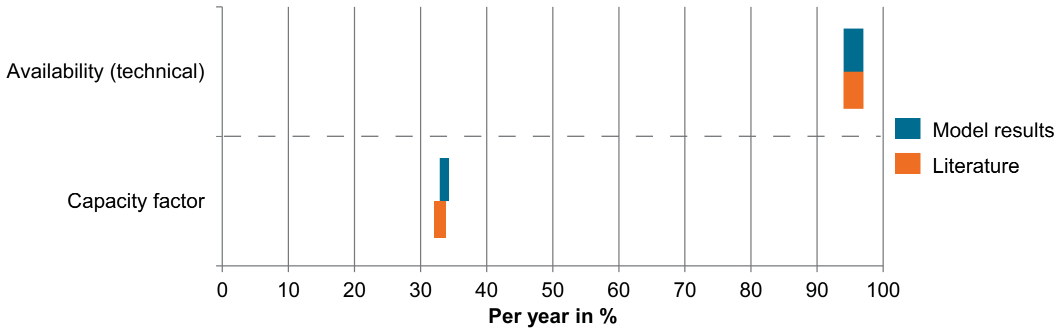


Figure 3.14: Validation of KPI results

The validation shows similar results with the *O&M Tool* and the literature respectively the real OWPP data. Thus, it is assumed that the model is appropriate to predict real system behavior.

4 Application of the Simulation-based Evaluation Model

In this chapter the previously developed simulation model is applied in simulation experiments for various scenarios of OWPPs and different variants of onshore-based and offshore-based logistics concepts.

In the following figures and tables the onshore-based concept is abbreviated by ON, the offshore-based mother vessel concept by MV and the offshore-based platform concepts by PF. A number after the mentioned abbreviations indicates the number of deployed transfer vessels.

4.1 Investigated Logistics Concepts

For the application of the model three different logistics concepts are investigated with four variants each. The investigated concepts have already been described in depth in Section 2.3.3.

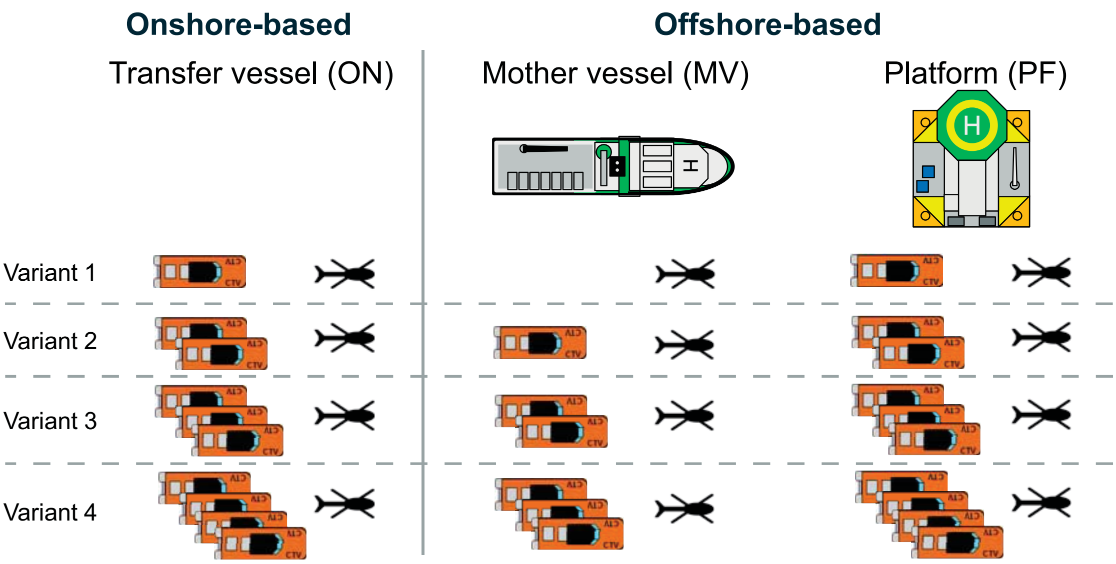


Figure 4.1: Investigated logistics concepts

There is a general distinction between onshore-based and offshore-based concepts. The offshore-based concepts are divided into mother vessel concept and platform concept.

The number of transfer vessels varies between one to four for the onshore-based concept and the platform concept. Regarding the mother vessel concept the number of transfer vessels varies from zero to three because the mother vessel itself can transfer technicians to a WTG. All concepts are supported by helicopters as it has already been shown that helicopter support leads to a better performance of logistics concepts (Münsterberg et al. 2015, p. 2). The helicopter base is always onshore, but for the offshore-based concepts the helicopter stays offshore during its mission. Figure 4.1 illustrates the investigated concepts. All concepts are also supported by a large jack-up repair vessel with an onboard heavy lift crane for major failures. Both offshore-based concepts have two additional supply vehicles. One vessel is needed every week for the supply of material and consumables. The other is a helicopter required for the replacement of technicians every two weeks.

4.2 Definition of Simulation Scenarios

The performance of the different logistics concepts is investigated in nine different scenarios according to the size of the OWPP and the distance to the base station. The scenarios are illustrated in Figure 4.2.

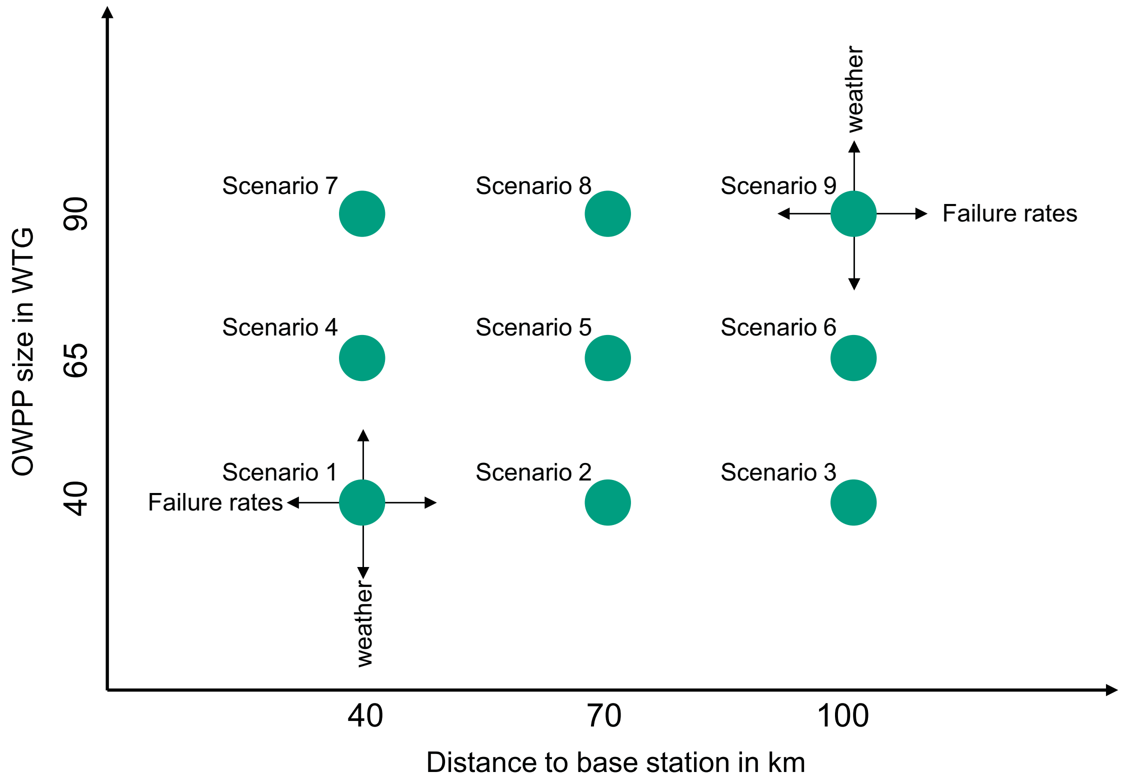


Figure 4.2: Simulation scenarios

The choice of the scenarios corresponds to the OWPPs in the German North Sea. The average size of constructed and authorized German OWPPs is about 65 WTGs with an average distance of 70 km from shore.[22] This corresponds to scenario 5. Relating to the other scenarios, size and distance correspond to the average of the lower 25 % respectively the upper 25 % (in terms of distance to shore and size) of the German OWPPs (constructed and authorized).

For all scenarios three logistics concepts with four variants each are simulated. This results in 108 different simulation experiments.

Sensitivity Analysis

To show the robustness of the results and the performance of the concepts a sensitivity analysis is conducted using two scenarios (1 and 9) for the weather conditions and the failure rates of WTGs (see Table 4.1). Previous tests have shown that these two input parameters have a significant impact on the model's output. In the lower scenario for weather conditions, the share of hours in which the significant wave height is greater than 1.5 m[23] is applied, for the whole investigated time period, to the share of the year with the best weather conditions (lowest share of hours with more than 1.5 m significant wave height). This means a decrement of 20 % of hours with more than 1.5 m significant wave height compared to the normal wave conditions. In the upper scenario the hours with a significant wave height of more than 1.5 m is increased by 20 % compared to the normal wave conditions. In the scenarios for failures rates the failures per year vary from -50 % to +50 % compared to the normal failure rates. This corresponds to the investigation performed by Besnard (Besnard et al. 2013).

	Lower scenario	**Upper scenario**
Failure rate (failures per year)	-50 %	+50 %
Weather conditions (hours $H_s > 1{,}5$ m)	-20 %	+20 %

Table 4.1: Sensitivity analyses

Finally, for scenario 1 and 9 a sensitivity analysis concerning the costs is conducted as the costs are an important input parameter as well. This sensitivity analysis can be done after the simulation. For the two before mentioned sensitivity analyses the scenarios have to be simulated again. But as the operating time of vessels and helicopters is tracked and the costs are proportional there is no need for further simulation concerning cost sensitivity.

[22]Own calculation based on 4coffshore (2015a)
[23]Usual limit for personnel transfers between vessel and WTG for transfer vessels

4.3 Simulation Experiments

In total 132 simulation experiments are performed (108 + 24 for sensitivity analyses). Each experiment stands for simulation runs of 25 years to make sure the results are statistically significant. From all simulation runs a total number of 3,300 simulation years is obtained. Each simulation experiment starts on January 1, 2000. The metocean data describes the environmental conditions at the position of the OWPP Albatros (54°30'N, 6°24'O) for ten years.[24] The data comprises the significant wave height and the wind speed on an hourly basis for the mentioned location.

MC	Description	Durat.[25] in h	Team size	Resource class	Add. Inspections	Frequency p.a.
CM0	Remote reset	1-2	0	0	-	5.0000
CM1	Inspection, small repair	4	3	1	-	2.3909
CM2	Replacement of small parts (< 2 t)	8	3	2	1	0.7124
CM3	Replacement of small parts (< 2 t)	16	4	2	1	0.7888
CM4	Replacement of large parts (> 2 t)	32	6	3	2	0.1784
CBM1	Replacement of small parts (< 2 t)	8	3	2	-	0.2011
CBM2	Replacement of small parts (< 2 t)	16	4	2	-	0.2284
PM	Replacement of small parts (< 2 t)	24	3	2	-	1.0000

Table 4.2: Maintenance classes
(Hepp 2014, p. 48), (Maples et al. 2013, p. 57, 59, 66)

Different maintenance classes have been defined for maintenance activities (see Table 4.2) according to Hepp (2014, p. 48) and Maples et al. (2013, p. 57, 59, 66). These maintenance classes comprise different activities with similar requirements regarding repair time, vehicles and technicians. Thus, for each maintenance class it is defined, which activities it comprises, how often a failure occurs per year as well as the required resource (vehicle and number of technicians). The range of classes include corrective maintenance (CM0 - CM4), condition-based (CBM1, CBM2) and planned maintenance (PM). Condition-based maintenance is distinguished from corrective maintenance as the WTG will not fail. It is only shut down during the the maintenance activities. The same applies to planned maintenance, which is conducted once per year. The start date for planned maintenance is April 1. Planned maintenance is usually conducted in

[24]The data was provided by the MeteoGroup
[25]Duration

spring when the wind speed is low and the shutdown of WTGs does not result in too big yield losses.

The working time for CM0 varies from 1 to 2 hours (equally distributed) (Maples et al. 2013). For all other classes the working time is fix and can be divided into different missions. The team size indicates the number of technicians required to fulfill the task. The resource class indicates the vehicle needed for this maintenance action:

- Class 0: Remote reset, no physical visit needed
- Class 1: Transport of technicians with little equipment (helicopter, transfer vessel or mother vessel)
- Class 2: Transport of technicians and spare parts up to 2 t (transfer vessel or mother vessel)
- Class 3: Transport of technicians and spare parts heavier than 2 t (jack-up repair vessel)

For CM2, CM3 and CM4 additional inspections are required. These inspections have diagnostics character. They correspond to CM1. The frequency defines the number of failures per class per year. As shown in the theoretical part of this thesis the random distribution of failures can be modeled with a negative exponential distribution. This results in varying mean times between failures, but in the long run the defined and required frequencies per year are met as has been proven in Section 3.4.1. In the experiments the phase of constant failure rates (useful life period) is investigated, higher failure rates in the beginning and the end of the OWPP's life time according to the bath tub curve are not investigated.

	Helicopter[26]	**Transfer vessel**[27]	**Mother vessel**[28]	**Repair vessel**[29]
Max. number of technicians	3	12	51	6
Max. H_s in m	-	1.5	3	2
Max. V_w in m/s	17	12	17	10
Speed in kn	128	20	11	10
Speed in OWPP in kn	64	16	11	10
Annual costs in EUR	2,160,000	900,000	7,500,000	-
Daily costs in EUR	-	1,200	4,000	150,000
Hourly costs in EUR	1,200	-	-	-
Mobilization costs in EUR	-	-	-	400,000

Table 4.3: Vehicle characteristics

[26] Besnard et al. 2013, p. 448; Franken 2010, p. 24; Plato 2014
[27] Besnard et al. 2013, p. 448; Schreiber 2012, p. 10
[28] Siemens 2015a; Claaß 2013; Ampelmann 2009, p. 36
[29] Heavy Lift Specialist 2015; Maples et al. 2013, p. 77

Table 4.3 gives an overview of the assumptions of the vehicle characteristics relating to capacity, weather limits, speed and costs. The costs indicated in this table are based on data from literature validated in practice.

For the offshore-based platform concept a manned and appropriately equipped offshore platform is needed. The annual costs for such a platform are assumed to amount to EUR 5.5 million[30]. Besides the platform, the vessels and the helicopter for maintenance work there are also vehicles to supply offshore-based concepts as described in Section 3.3.1. The assumptions regarding these vehicles are indicated in Table 4.4. The offshore-based concepts require a supply with material and consumables per week. The technicians are replaced every two weeks.

	Offshore supply vessel	**Crew supply helicopter**
Max. number of technicians	-	12
Max. H_s in m	3	-
Max. V_w in m/s	10	17
Speed in kn	12	128
Daily costs in EUR	15,000	-
Hourly costs in EUR	-	3,500
Operation interval	Each week	Each two weeks

Table 4.4: Support vehicle characteristics[31]

The following assumptions have been made with regard to the technicians:

	Assumption
Shift start time	06:00
Latest shift end time	18:00
Minimum working time	5 h
Work week duration	7 d
Salary in EUR p.a.	70,000 per technician
Catering in EUR p.a.	22,000 per technician (offshore-based only)

Table 4.5: Assumptions for technicians

For the experiments it is assumed that the technicians work 7 days per week with one 12 h shift per day. A mission is only executed if the possible working time is greater than 5 h. The total number of technicians in the model always corresponds to the total technician capacity of the deployed fleet. For offshore-based concepts the technicians need catering of approximately EUR 22,000 p.a. and technician. For offshore-based

[30]General industry knowledge
[31]General industry knowledge

concepts twice as many technicians are required (in respect of the total technician capacity of the deployed fleet). Technicians work 14 days offshore and then stay 14 days onshore for recreation.

The WTGs are assumed to have 5 MW capacity. This corresponds to the current offshore projects and is greater than the average of the OWPPs that have already been constructed. The power curve used for the experiments represents the behavior of a Senvion 5M WTG and is illustrated in Figure 2.16 of Section 2.2.2.

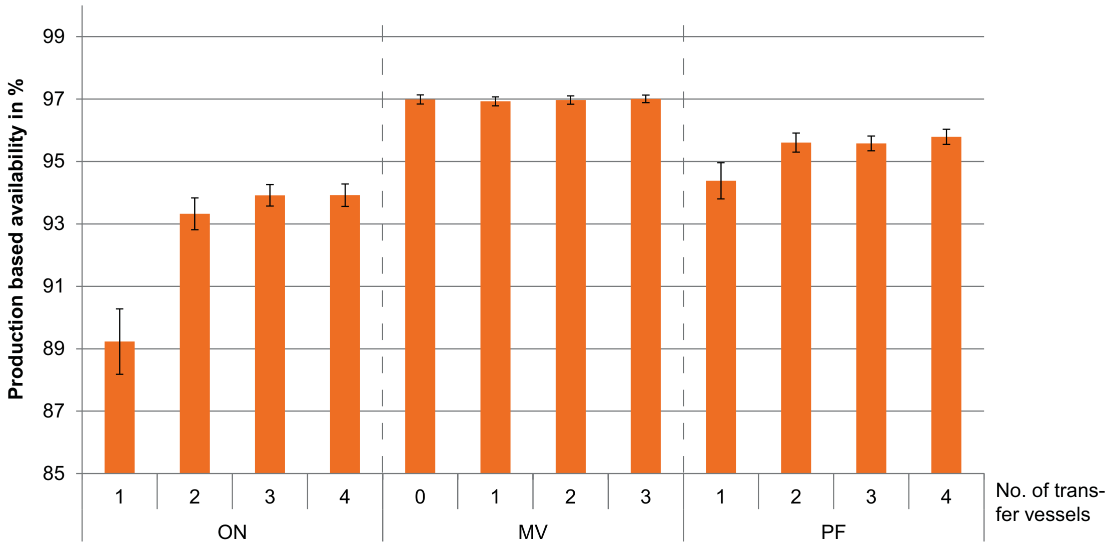


Figure 4.3: Deviation of availability in scenario 9

To guarantee the significance of results a minimum number of simulation runs (years) must be conducted. The aim is to achieve a deviation of less than 1 % for the production-based availability. The maximum deviation based on the 95 % confidence interval[32] has reached 0.58 % for the offshore-based platform concept with one transfer vessel in scenario 9. Figure 4.3 shows the production-based availabilities for scenario 9. The onshore-based concept with one transfer vessel reaches even higher deviations, but only for scenarios in which the onshore-based concept is not sufficient to maintain the OWPP. Apart from that this investigation shows that a sufficient number of simulation runs (25 years) was conducted per simulation experiment to not exceed the maximum aimed derivation of results, which is the above mentioned 1 %.

Another important output of the model is the number of occurred maintenance events and the number of completed maintenance events. These two numbers should be the same. A discrepancy between both numbers (maintenance events are higher than completed maintenance events) indicates that a concept is not sufficient to maintain the

[32] Based on the Student's t-distribution

OWPP because this discrepancy means that the concept has not enough capacity (vehicles and technicians) to fulfill all important maintenance tasks.

	ON				MV				PF			
No. TV[33]	**1**	**2**	**3**	**4**	**0**	**1**	**2**	**3**	**1**	**2**	**3**	**4**
CM0												
Events p.a.	404.0	418.1	423.8	420.1	437.8	432.5	428.4	439.0	429.1	433.2	432.3	429.9
Compl.[34] in %	99.9	99.9	99.9	99.9	100.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0
CM1												
Events p.a.	195.2	201.0	205.1	206.4	206.0	210.3	212.0	210.5	204.0	211.0	206.2	207.4
Compl. in %	99.8	99.8	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9
CM2												
Events p.a.	57.2	60.2	57.8	59.7	59.8	62.0	62.4	58.8	62.6	58.4	59.5	61.7
Compl. in %	98.5	98.6	99.3	98.9	99.8	99.7	99.9	99.9	99.4	99.7	99.5	99.7
CM3												
Events p.a.	65.2	67.0	66.6	66.0	68.6	69.4	66.8	67.6	68.0	66.8	66.2	65.0
Compl. in %	96.2	99.1	99.0	98.7	99.9	99.8	99.9	99.9	98.9	99.0	98.6	98.8
CM4												
Events p.a.	14.4	15.5	16.0	15.6	15.2	16.0	15.3	15.5	14.8	15.4	14.5	14.5
Compl. in %	99.4	98.2	99.3	97.2	98.2	98.5	97.7	98.4	99.2	98.7	97.8	98.6
CBM1												
Events p.a.	17.3	18.8	18.3	18.4	18.4	18.2	19.3	19.0	18.6	18.4	17.9	19.2
Compl. in %	43.4	98.7	98.3	98.3	100.0	100.0	100.0	99.8	99.1	99.8	100.0	99.8
CBM2												
Events p.a.	19.4	19.1	19.5	19.6	19.3	20.1	19.0	19.9	19.2	19.9	19.9	19.1
Compl. in %	16.5	97.7	98.8	99.2	99.8	99.4	100.0	99.4	98.3	99.8	98.4	99.2

Table 4.6: Work orders (events) vs. completed work orders in scenario 9

Usually the number of condition-based maintenance events shows a discrepancy because these events have a lower priority than corrective maintenance events. This check is done for all scenarios and all logistics concepts. As shown in Table 4.6 for the onshore-based logistics concept with one transfer vessel in scenario 9 a relevant discrepancy (indicated in percent) between both values for CBM1 and CBM2 can be seen (red figures). It is the same for the concept in scenario 5, 6 and 8. In all other scenarios, for all other concepts the discrepancy for maintenance events is less than one (event). This small discrepancy results from open work orders at the end of each simulation run. The insufficient logistics concepts will be excluded for the comparison of the results.

[33] Transfer vessel
[34] Completed

5 Comparison and Evaluation of Results

In this chapter the main results of the simulation runs are analyzed and described. This will be done in detail for the scenarios 1, 5 and 9 because all important findings can be derived from these three scenarios. The results of the other scenarios are coherent with these findings. Furthermore, an overview of results is given for all scenarios. This is followed by the results of the sensitivity analyses for failure rates, weather conditions and costs. Subsequently, in-depth results for scenario 9 are presented. Based on the results the logistics concepts are evaluated. Finally, the findings are critically discussed.

5.1 General Scenario Results

Figure 5.1 shows the annual costs of all investigated logistics concepts in scenario 1. The most cost-efficient concept is onshore-based with one transfer vessel (EUR 13.6 million p.a.). With additional transfer vessels the costs for personnel and transfer vessels increase, but the lost revenues are only slightly reduced.

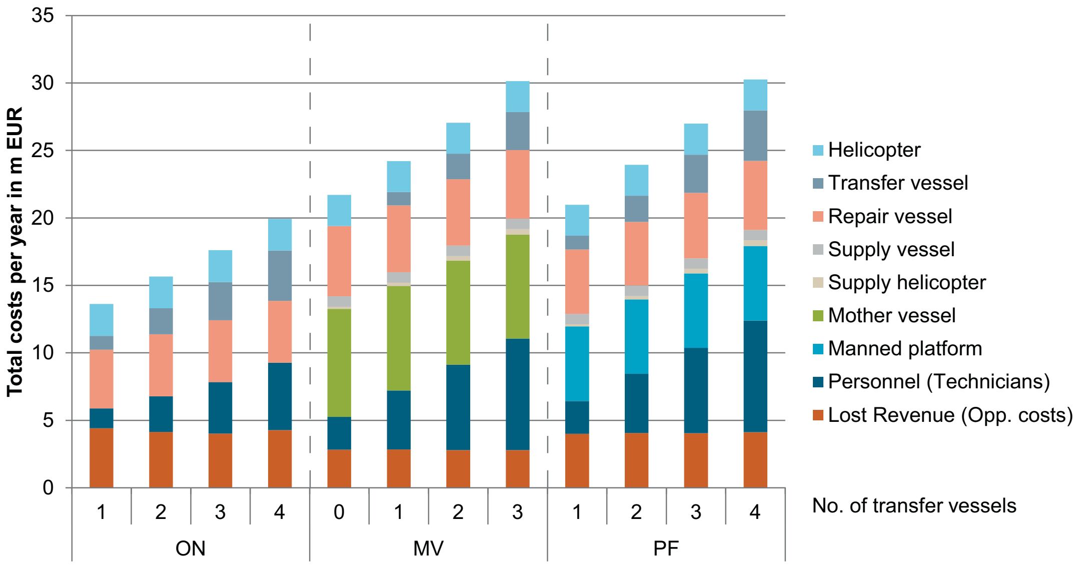


Figure 5.1: Results in scenario 1[35]

[35]Opp. stands for opportunity

The offshore-based concepts have higher costs than the onshore-based one. This is due to the additional vehicles needed to supply the mother vessel or the platform. The lost revenues for the mother vessel concept are lower compared to the other concepts. This is due to the high accessibility of the mother vessel. A transfer of technicians from the mother vessel to a WTG is possible until a significant wave height of 3 m. With each additional transfer vessel the costs increase disproportionately compared to the onshore-based concept. For each additional offshore technician another technician is required who can work when the first (offshore) technician recreates onshore (for 14 days). The costs for the jack-up repair vessel are more or less the same for all concepts (about EUR 5 million p.a.). The same applies to the helicopter with EUR 2.3 million p.a.

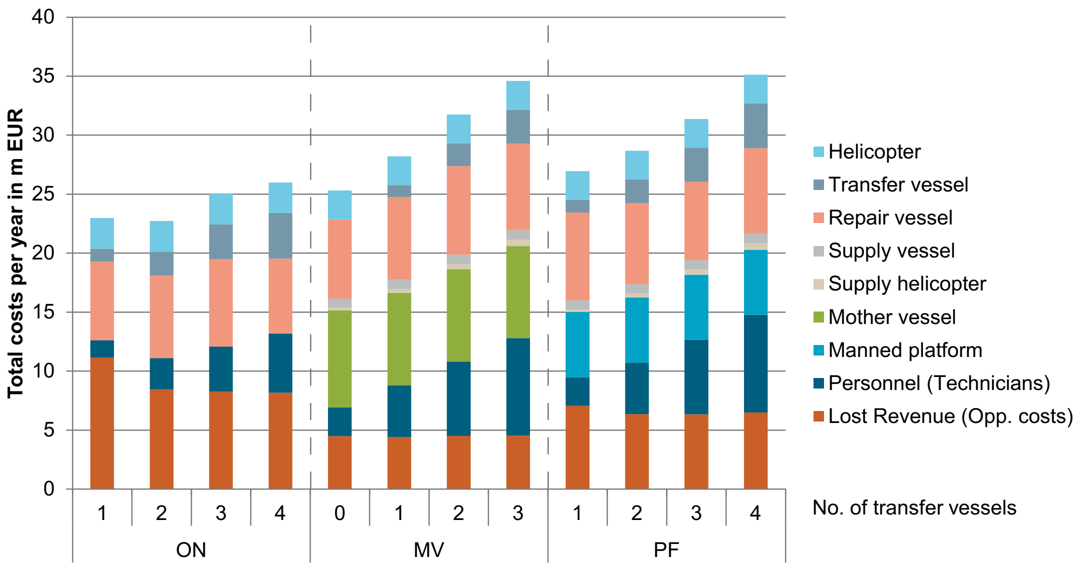


Figure 5.2: Results in scenario 5

In scenario 5, too, the most cost-efficient concept is an onshore-based concept. But this time with two transfer vessels (see Figure 5.2). The additional costs for an additional transfer vessel and additional personnel are compensated by less revenue losses compared to the onshore-based concept with one transfer vessel. Furthermore, the onshore-based concept with one transfer vessel is not sufficient to maintain the OWPP. The total annual costs for the onshore-based concept with two transfer vessels amount to EUR 22.7 million. The onshore-based concept has higher revenue losses than the offshore-based concepts. A difference to the platform concept, though, is the longer travel time of the vessels in the onshore-based concept. Some weather windows cannot be used for work and lead to longer downtimes. Both offshore-based concepts result in higher costs of more than EUR 25 million p.a. due to supply vessels. The annual jack-up repair vessel and helicopter costs amount to EUR 7.0 million respectively EUR 2.5 million.

For scenario 9 the results are different (see Figure 5.3). The most cost-efficient concept is the mother vessel concept without a transfer vessel (EUR 30.2 million). The mother vessel is only supported by a helicopter. A look on the onshore-based concept shows that the concept with one transfer vessel has high revenue losses. Because of the long travel time the available time to do work offshore is reduced. But as mentioned before in Section 4.3 this concept is not considered as it is not sufficient to maintain the OWPP. The most cost-efficient onshore-based concept with two transfer vessels (EUR 31.0 million) has twice the revenue losses (40 % of the total costs) of the mother vessel concept. These high revenue losses for the onshore-based concept justify the deployment of offshore-based concepts with all additional costs. The costs of the platform concept are not competitive, because the only benefit of the concept is the short way to the WTG. However, as the same transfer vessel (like for the onshore-based concept) are used, the accessibility is not improved. Thus, only a little bit more time for carrying out the maintenance work is available. This does not compensate for the additional costs of the platform concept. The most cost-efficient platform concept costs EUR 34.0 million p.a. The costs for jack-up repair vessel and helicopter are EUR 9.0 million to EUR 9.5 million respectively EUR 2.5 million to EUR 3.0 million p.a. for all concepts.

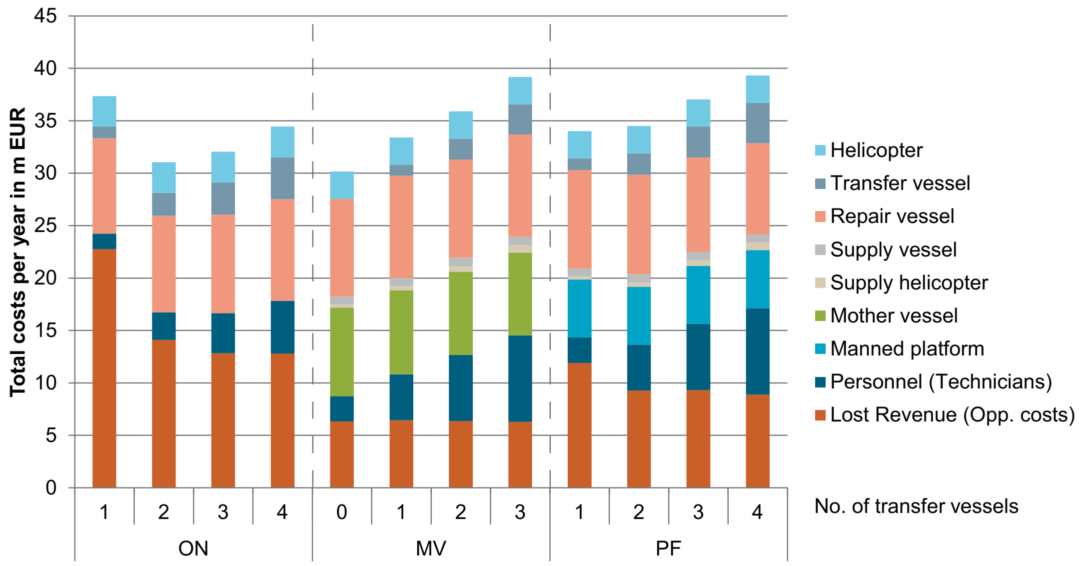


Figure 5.3: Results in scenario 9

Table 5.1 gives an overview of all scenarios and the most cost-efficient concept per scenario. The table indicates that the onshore-based concept is advantageous compared to the offshore-based concepts for almost all scenarios. Only for scenario 9 that is based on an OWPP of 90 WTG which are located 100 km away from shore, an offshore-based mother vessel concept is the most cost-efficient. For scenario 1, 2, 3, 4 and 7 the onshore-based concept with one transfer vessel is the most cost-efficient concept.

Scenario	Best concept	No. of transfer vessels	Costs in m EUR p.a.	Availability in %
1	ON	1	13.6	95.3
2	ON	1	15.4	94.3
3	ON	1	15.2	94.1
4	ON	1	19.9	94.9
5	ON	2	22.7	94.5
6	ON	2	23.5	94.2
7	ON	1	25.7	94.6
8	ON	2	29.0	94.1
9	MV	0	30.2	97.0

Table 5.1: Most cost-efficient concepts

For scenario 5, 6 and 8 the onshore-based concept is again the most cost-efficient, but this time an additional transfer vessel is required. This trend is well illustrated in Figure 5.4. Small OWPPs or near shore OWPPs can be maintained by an onshore-based concept. The further or the bigger the OWPP the more transfer vessels are needed. Moreover, at a certain point offshore-based concepts have an advantage.

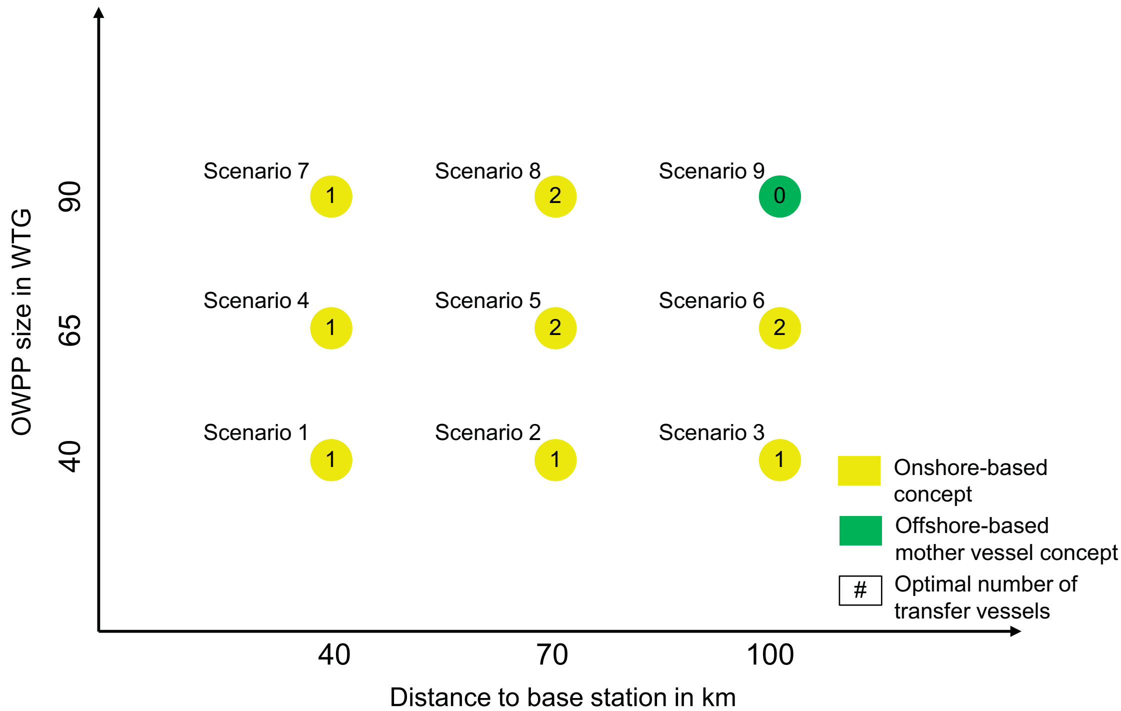


Figure 5.4: Overview of most cost-efficient logistics concepts

5.2 Comparison of Sensitivity Analysis Results

Different sensitivity analyses have been conducted to see how robust the concepts are concerning changes in weather conditions, failure rates and costs parameters. These sensitivity analyses refer to the extreme scenarios 1 and 9. For the sensitivity analyses only the most cost-efficient variants (number of transfer vessels) for each logistics concept are chosen.

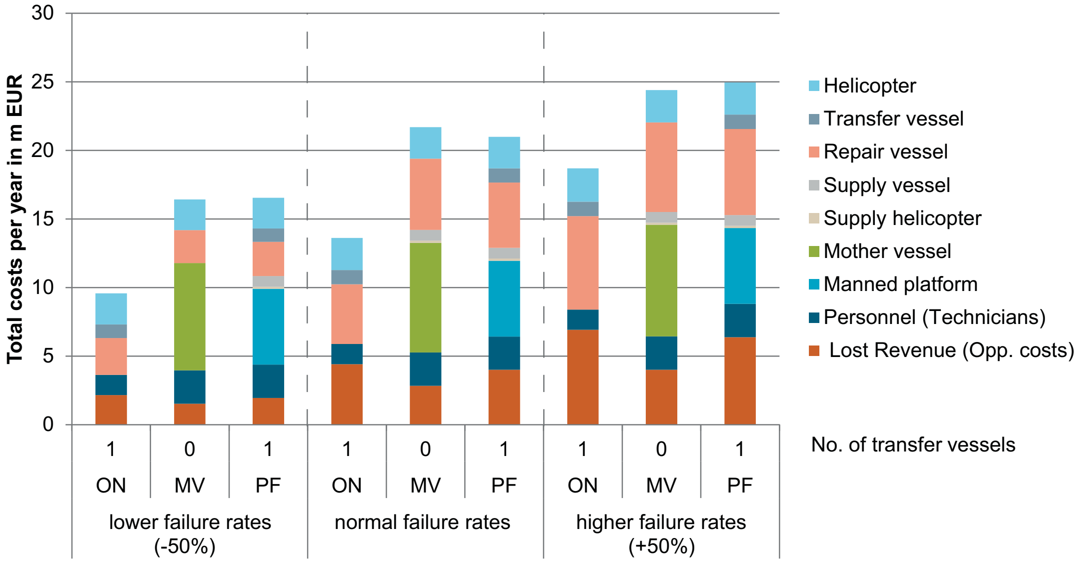


Figure 5.5: Failure rate sensitivity in scenario 1

In Figure 5.5 the sensitivity of failure rates in scenario 1 is shown. The onshore-based concept is more sensitive (absolute) to increased failure rates and less sensitive (absolute) to lower failure rates compared to offshore-based concepts. But the onshore-based concept is still the most cost-efficient one for all failure rate scenarios with costs ranging from EUR 9.5 million p.a. to EUR 18.7 million p.a. Even if revenue losses increase with higher failure rates, the offshore-based concepts will have higher costs and even other additional costs (supply vessel and supply helicopter), so the reduced revenue losses cannot compensate these additional costs. The trend, though, is a smaller difference in the cost efficiency of the concepts the higher the failure rates are. For normal failure rates the mother vessel concept is least cost-efficient, but for higher failure rates it becomes less costly than the platform concept.

Almost the same behavior as to the sensitivity to weather conditions can be identified (see Figure 5.6). The onshore-based concept with one transfer vessel is the most cost-efficient one in all weather scenarios with EUR 12.1 million to EUR 15.9 million p.a. The difference between onshore and offshore-based concepts is around EUR 7 million p.a. In scenario 1 the concepts show a higher sensitivity to failure rates than to weather conditions. This depends on the design of the sensitivity analyses. Considering even worse weather conditions the impact on the logistics concepts might be stronger.

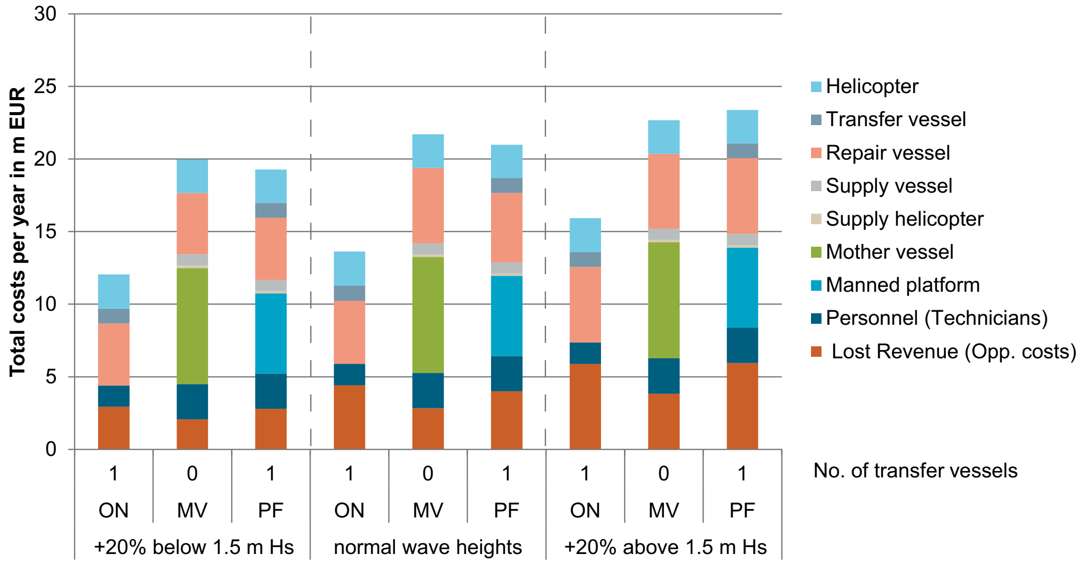


Figure 5.6: Weather sensitivity in scenario 1

In scenario 9 the influence of failure rates on the logistics concepts is significantly different. The mother vessel concept is less sensitive to changes of failure rates compared to the onshore-based and the manned platform concept (see Figure 5.7). For lower failure rates the onshore-based concept with two transfer vessels is most cost-efficient with EUR 20 million p.a. Normal failure rates lead to the mother vessel concept being marginally cheaper than the onshore-based concept.

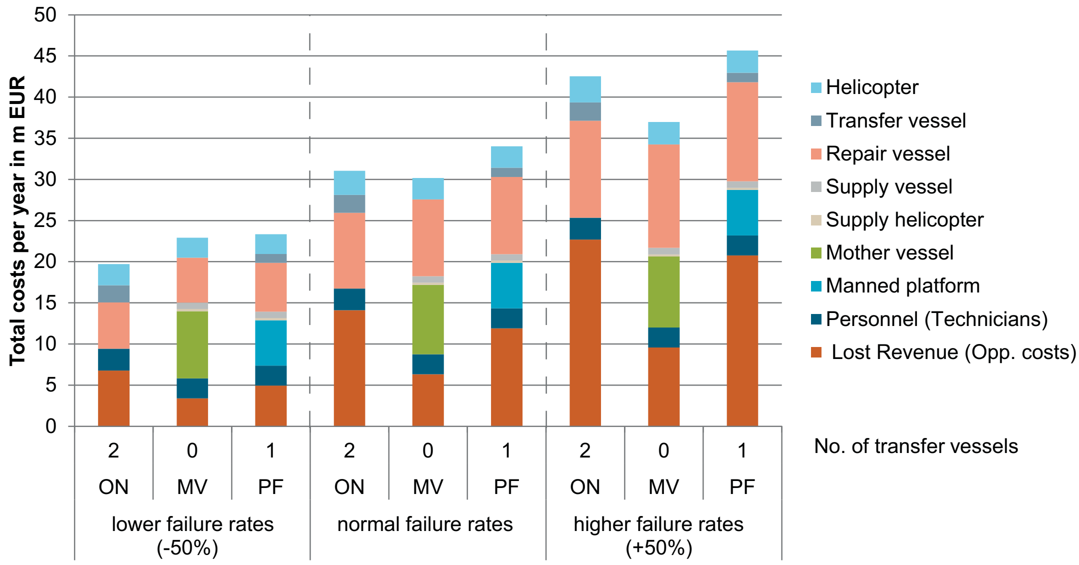


Figure 5.7: Failure rate sensitivity in scenario 9

Higher failure rates result in an increase of the difference between the concepts. The mother vessel concept becomes clearly the most cost-efficient concept with EUR 37 million p.a. The lost revenues increase largely for the onshore-based and offshore-based manned platform concept. This is due to the low significant wave height limit of the deployed transfer vessels. The additional failures cannot be repaired due to restricted accessibility. The mother vessel concept, which can transfer personnel until higher significant wave heights, leads to significantly lower revenue losses. Thus, in total, the mother vessel concept is the most cost-efficient logistics concept for higher failure rates.

The mother vessel concept is also less sensitive to changes of weather conditions in scenario 9 (see Figure 5.8). For good weather conditions the onshore-based concept with two transfer vessels is still most cost-efficient with EUR 20 million p.a. Because of the good weather sufficient work periods are available to execute the work onshore-based. But the worse the weather the more cost-efficient the mother vessel concept becomes. For normal weather conditions it is already most cost-efficient and all the more for worse weather conditions with EUR 32.5 million p.a. In all weather scenarios the platform concept is least cost-efficient with almost EUR 40 million p.a. for worse weather.

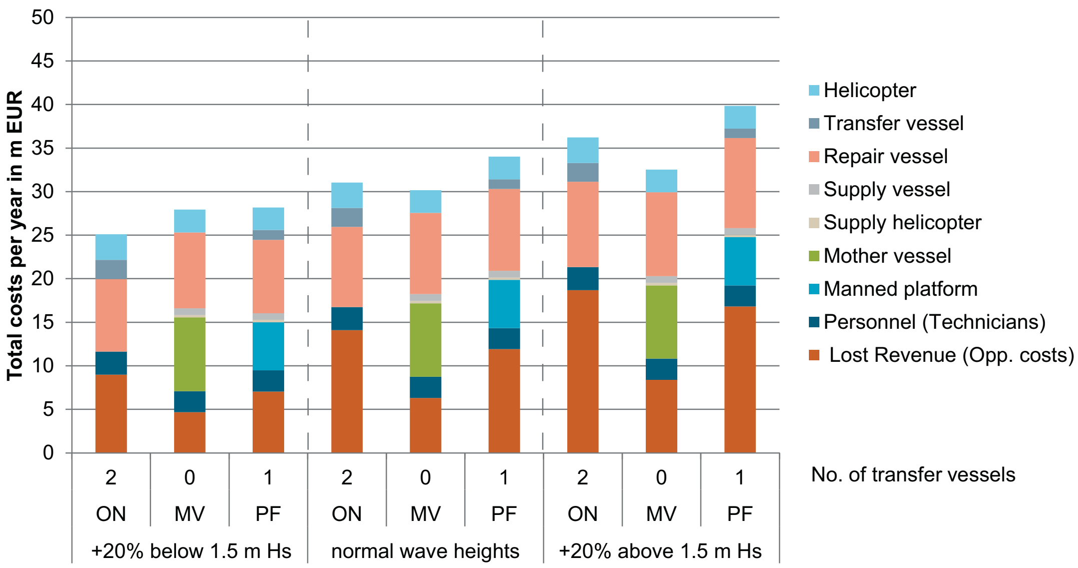


Figure 5.8: Weather sensitivity in scenario 9

In scenario 9, too, the impact of varied failure rates on the logistics concept performance is stronger than the impact of weather conditions. Compared to scenario 1 all concepts react more sensitively in scenario 9 to changes of failure rates and weather conditions.

The results have also been tested for changes of costs. For scenario 1 for the most cost-efficient concept the costs have been varied between -10 % and +10 % (see Figure

5.9). In scenario 1 for the onshore-based concept with one transfer vessel the costs for the transfer vessel (per year and per day) have been varied. Also the most cost-efficient variations of the offshore-based concepts (mother vessel and manned platform) have been tested regarding cost variations. In this case, the most cost-efficient variants are the platform-based concept with one transfer vessel and the mother vessel without transfer vessel. The cost for the unmanned platform and mother vessel have been varied. The costs of the transfer vessel are constant. A comparison within one concept with different numbers of transfer vessels does not lead to any changes because the effect is almost the same for all variations of the concept. The effect of the transfer vessel cost variation for the onshore-based concept is marginal. The total cost change is less than +/-1 %. A change in platform costs for the offshore-based platform concept has a higher effect on the total costs (ca. +/- 2.5 %). This is understandable as the platform costs are six times higher than the annual transfer vessel costs. A change in mother vessel costs for the offshore-based mother vessel concept leads to approximately +/- 3.5 % of the total costs. In total, the changes in costs for scenario 1 do not result in changes of the most cost-efficient concept.

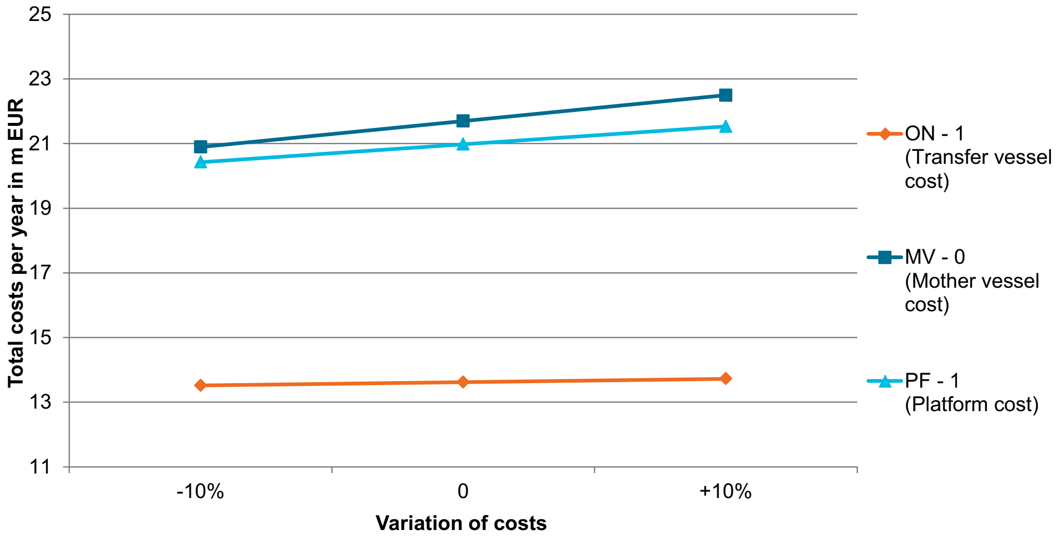


Figure 5.9: Cost sensitivity in scenario 1

In scenario 9 the total costs of the different concepts are similar to each other (see Figure 5.10). But a change in mother vessel costs will not change the total results. Even 10 % higher costs for the mother vessel will not exceed the costs of the onshore-based concept without cost variation. Also in this scenario the offshore-based mother vessel concept is more sensitive to cost changes (ca. +/- 3 % of the total costs) than the onshore-based concept. This is due to eight times higher annual costs for the mother vessel compared to a transfer vessel. The offshore-based platform concept is less cost-efficient than the other concepts in each scenario of cost variation.

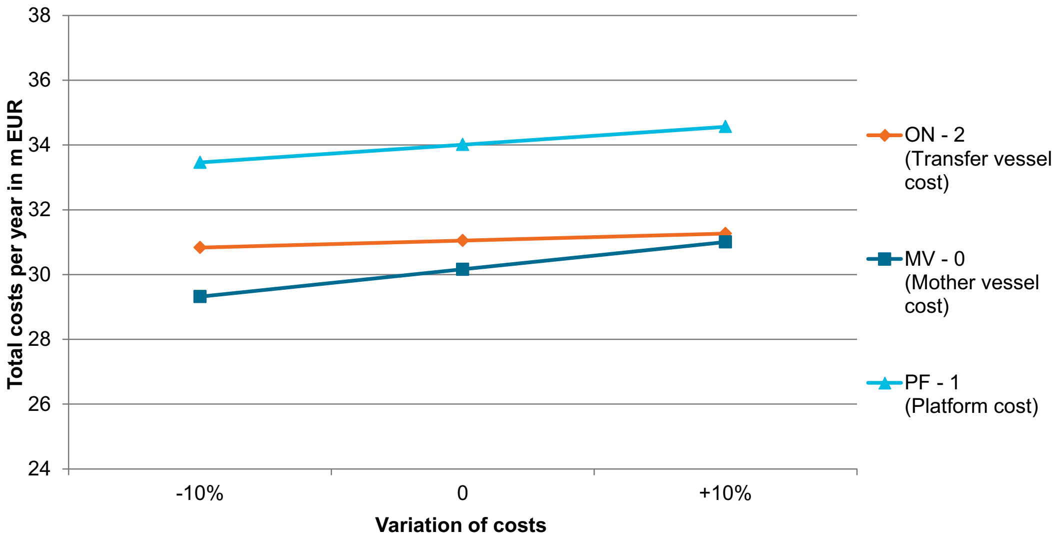


Figure 5.10: Cost sensitivity in scenario 9

5.3 Detailed Analysis of Selected Scenario

In this section detailed results for scenario 9 are given. Costs, availabilities and the capacity factors are shown for all months of the year. At the end of this section the downtime for different maintenance classes as well as its components are analyzed in detail.

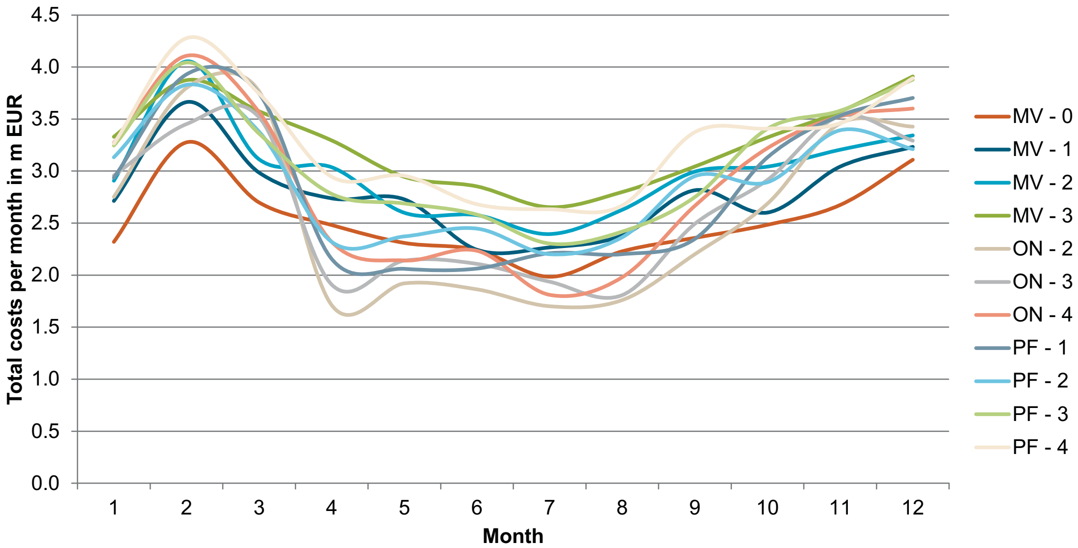


Figure 5.11: Monthly cost trends in scenario 9

A central question is if a concept exists that is the most cost-efficient solution for all months of the year. Figure 5.11 can answer this question. It shows that the offshore-based mother vessel concept without transfer vessel is the most cost-efficient from October to March. From April to September, though, the onshore-based concept with two transfer vessels is more cost-efficient. A combination of both concepts can lead to 8.1 % savings in costs. If the mother vessel concept is deployed all year long it leads to total costs of EUR 30.2 million p.a. The costs of both concepts combined amount to EUR 27.7 million p.a.

Figure 5.12 illustrates the monthly trend of the capacity factor for the different concepts. This factor describes the relation of the electric energy yield to the maximum possible electric energy yield per year (full load at all times of the year). The trend is the same for all concepts. In the winter time the capacity factor is high (almost 50 %) caused by strong winds. This means, that the lower availability in winter can be compensated by the stronger winds. In summer, a high availability for almost all concepts can be observed. But the capacity factor is low because of lower wind speeds in summer.

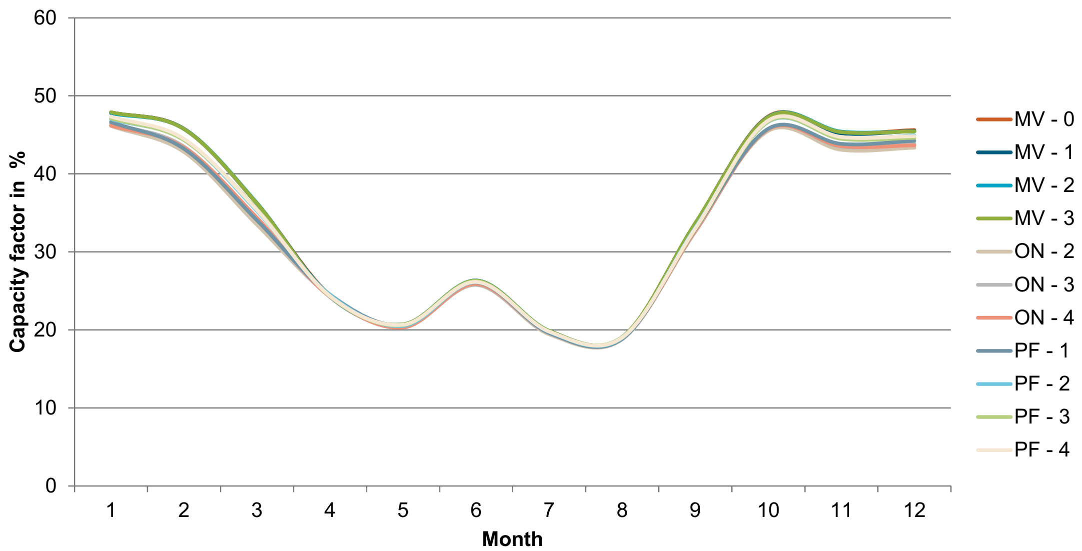


Figure 5.12: Monthly capacity factors in scenario 9

In summer, the curves for all concepts are almost congruent because all concepts have a high availability within a range between 95 to 98 %. In winter the curves fan out as the availabilities of the concepts have a wider range from 90 to 96 %. Thus, the amount of produced electricity varies within a wider range than in summer.

Figure 5.13 shows the trend of availability through the year for the different variants of the onshore-based concept. The onshore-based concept with one transfer vessel is excluded because it is not sufficient to maintain the OWPP. The concept with two transfer vessels has the lowest availability from October to March because in this bad weather season the waiting times between weather windows can be long. So the concept with three or four vessels are able to use the weather windows more effectively. In April, the concept with two transfer vessel outmatches the other concept variants. This can be explained by the fact that the other concept variants are able to conduct all planned maintenance work orders in April, May and June. The WTGs have to stop operation during planned maintenance work. Thus, the downtimes are consequently a bit higher in April and May compared to the concept with just two transfer vessels, which distributes the planned maintenance work on several months (April to August).

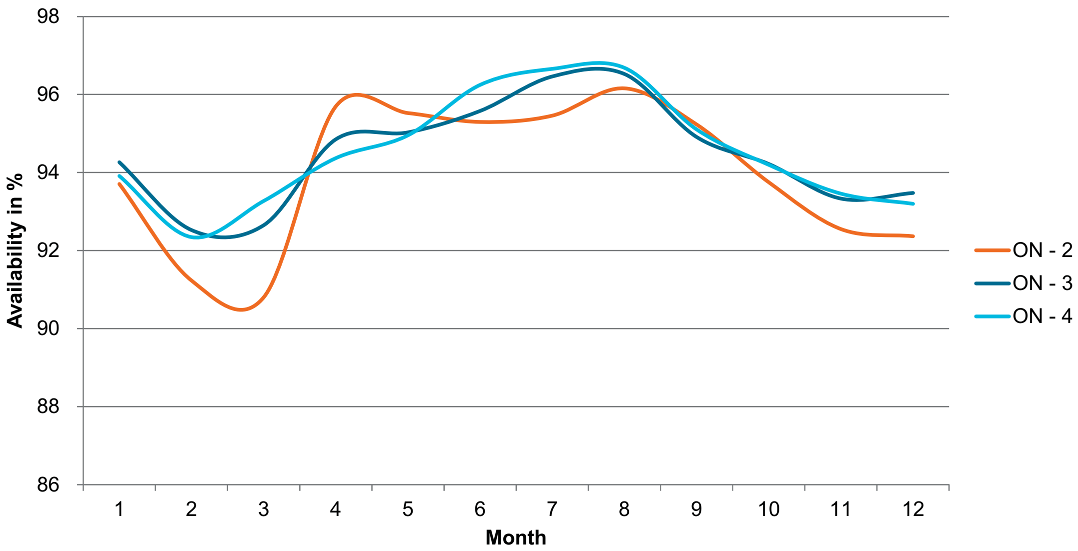


Figure 5.13: Monthly availability of onshore-based concept in scenario 9

The same effect can be seen for the different variants of the mother vessel concept (see Figure 5.14). In April, the concept without transfer vessel support has the highest availability followed by the concept with one transfer vessel. The concept without a transfer vessel cannot accomplish all planned maintenance work orders before July. In comparison the concept with three additional transfer vessels can accomplish all maintenance work orders already in April. Apart from April and May in almost all other months the availability is 97 % or higher. Thus, there is almost no decrease of availability in the winter months. This is due to the capability of the mother vessel to access the WTG until a significant wave height of 3 m.

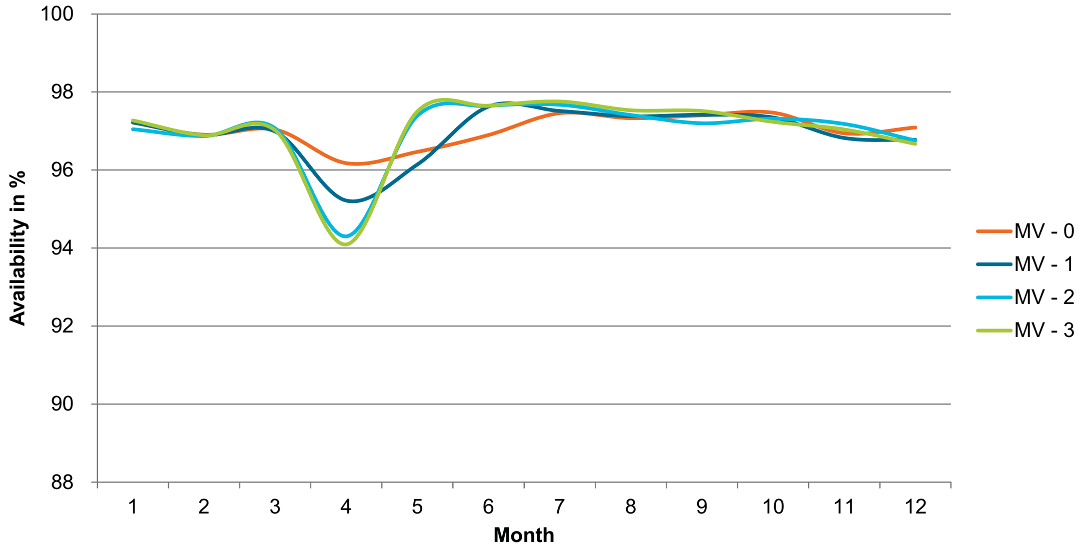


Figure 5.14: Monthly availability of offshore-based mother vessel concept in scenario 9

The planned maintenance effect in April can also be seen for the different variants of the platform concept (see Figure 5.15). The planned maintenance work orders are not accomplished before September for the concept with one transfer vessel. Hence, these downtimes are distributed over six months. The availability also shows a decrease in the winter months like the onshore-based concept. The decrease is not that strong. This can be explained by the shorter distances from the platform to the WTGs (compared to a base station onshore) and thus the better usage of the available weather windows.

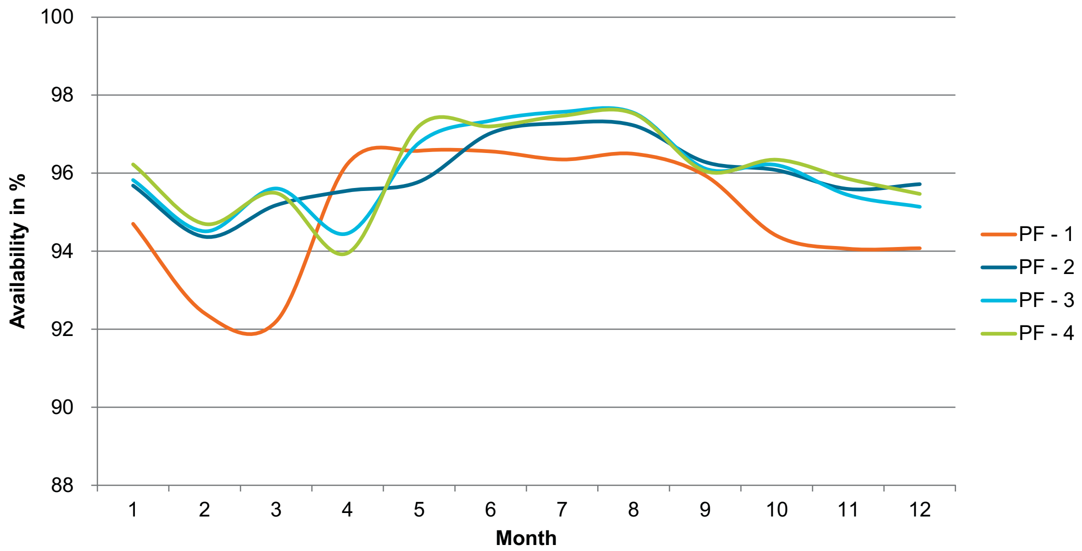


Figure 5.15: Monthly availability of offshore-based platform concept in scenario 9

Another interesting analysis is the distribution of missions over the year. It can be seen if and where overcapacities exist. Figure 5.16 displays the missions for the onshore-based concept with two transfer vessels for scenario 9. It can be seen that the helicopter has the same amount of missions (20) almost every month. The missions of the transfer vessels are heterogeneous during the year. From September to February between 13 and 18 mission days for transfer vessels can be observed. From April to August almost 32 to 47 missions per month for both transfer vessels together are accomplished. From April to July both transfer vessels use almost all possible weather windows. On seven to ten days each month in summer the vessels cannot be deployed because of too high significant waves. In the other months of the year the first transfer vessel uses almost every available weather window for maintenance activities. The second transfer vessel has on average four days per month during these months on which it could work but no work order exists. The transfer vessel could for example be used in other OWPPs. Of course for weather days (work orders cannot be processed due to bad weather), on which the transfer vessels cannot sail to the OWPP other deployment possibilities must be found. Otherwise high overcapacities of vessels occur in winter months.

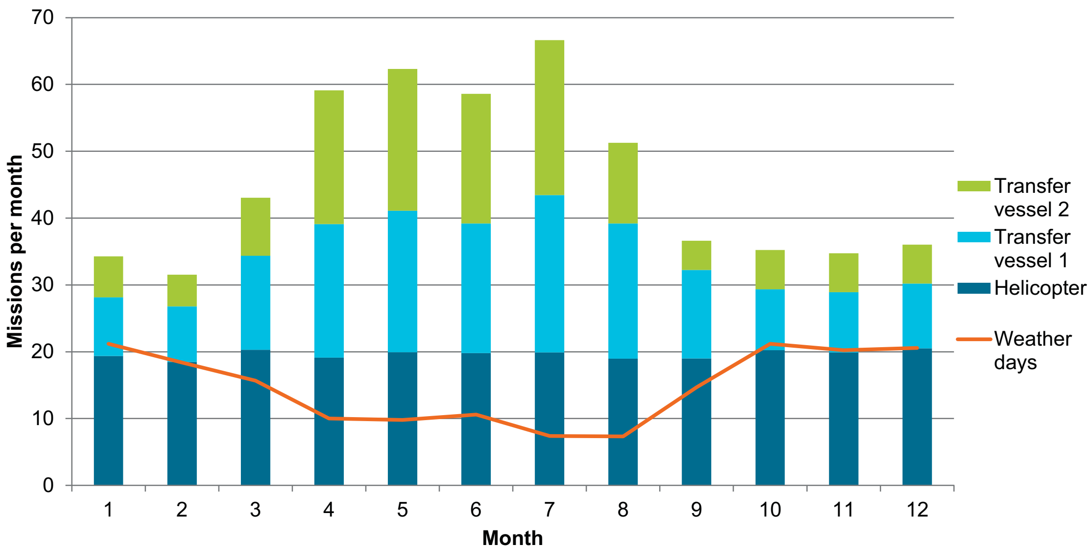


Figure 5.16: Missions per month of onshore-based concept in scenario 9

For the mother vessel concept a heterogeneous distribution of missions during the year can be seen (see Figure 5.17). The helicopter has approximately 20 mission days per month. The weather days of the mother vessel are between zero and five per month. This is below the number of weather days for the onshore-based concept. The mother vessel is deployed 14 to 16 days per month from September to March. From April to August 18 to 31 mission days per month can be observed. From July to March the overcapacity of the mother vessel amounts to more than 10 days per month. This capacity could be used for maintenance works in other OWPPs. Another possibility is to distribute the planned maintenance missions over the year to achieve a more equally spread work load. But this also means that longer downtimes occur in the strong wind period in winter.

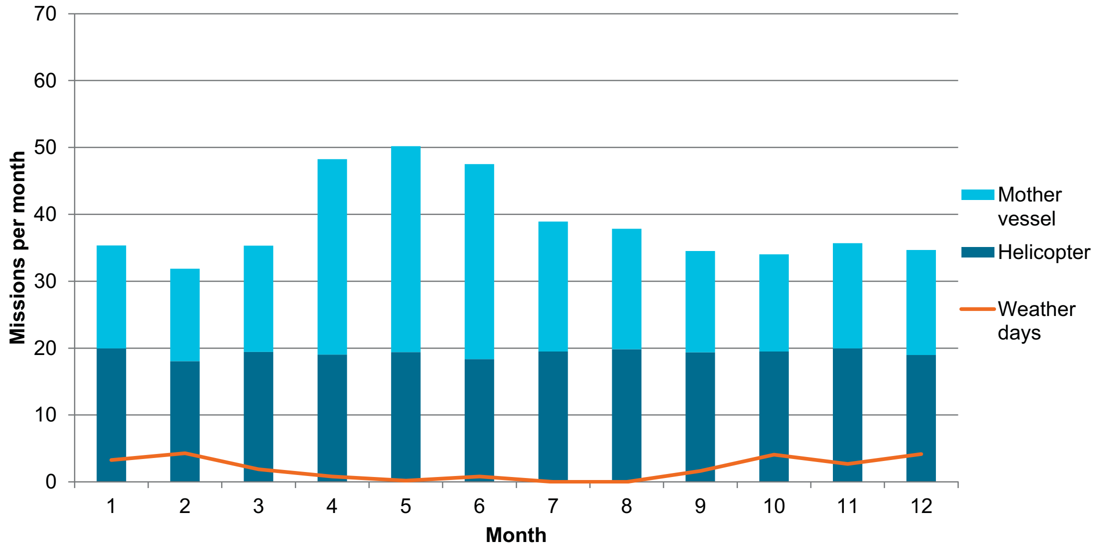


Figure 5.17: Missions per month of offshore-based mother vessel concept in scenario 9

The trend throughout the year for the number of missions per month of the offshore-based platform concept is similar to the onshore-based concept (see Figure 5.18). The helicopter also operates almost constantly 20 days per month.

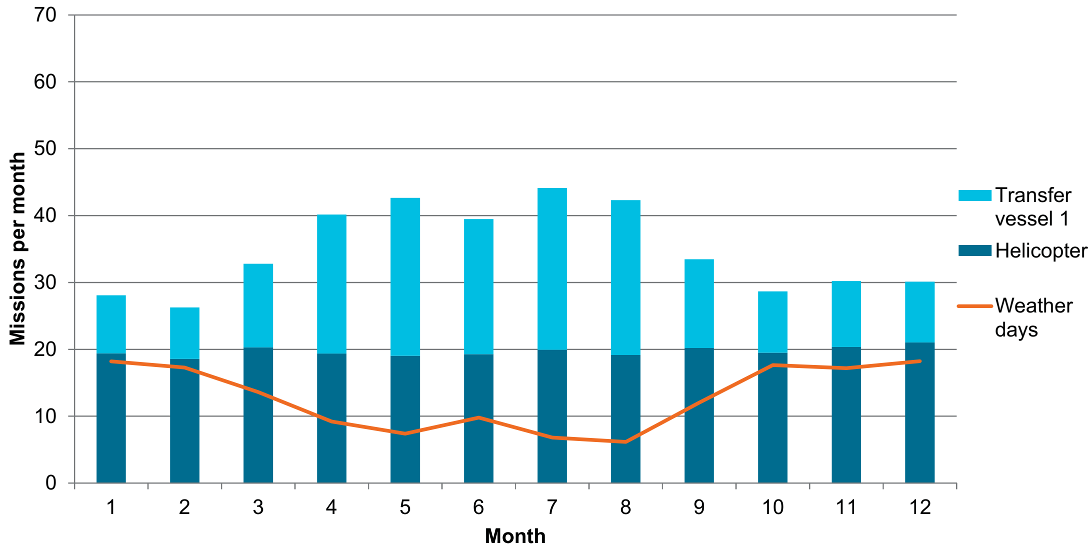


Figure 5.18: Missions per month of offshore-based platform concept in scenario 9

The total number of missions of the transfer vessel is lower compared to the number of missions of the two transfer vessels of the onshore-based concept. This can be explained by the shorter travel distances to the WTGs and thus a longer available working time. From September to February the transfer vessel accomplishes between eight and 13 mission days. From April to August almost 20 to 24 missions per month can be seen for the transfer vessel.

In this period the transfer vessels uses almost all possible weather windows to transfer technicians for planned maintenance work. In the remaining time, on four days the transfer vessel could work but no work order exists. In summer there are six to ten days each month on which the vessels cannot be deployed because of too high significant waves. In winter, the number of weather days increases up to 18. Although the offshore-based platform concept requires the lowest number of missions to maintain the OWPP in scenario 9 it is not the most cost-efficient concept. This is due to higher yield losses and higher initial investments (e.g. for the platform).

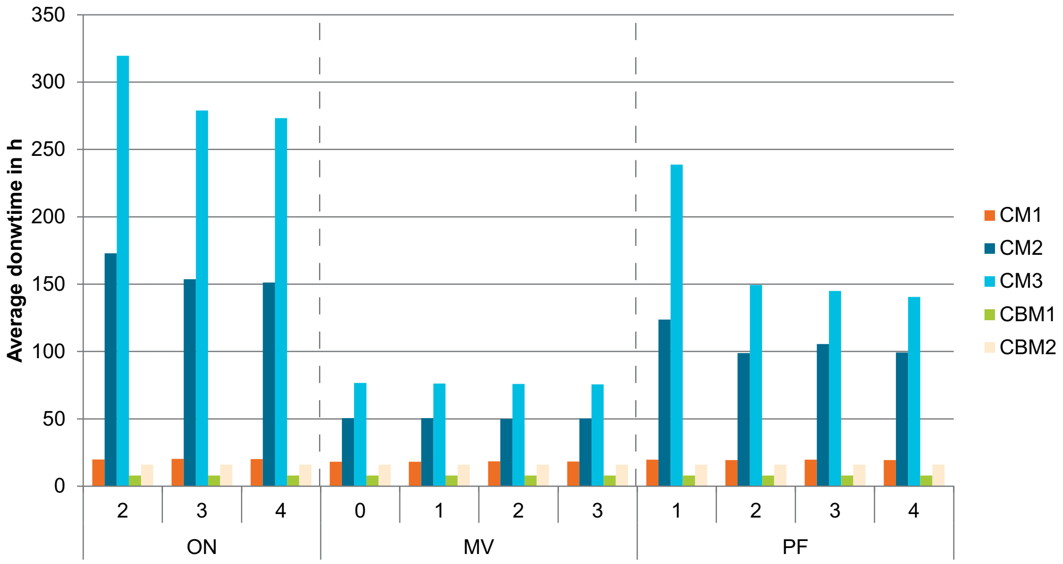


Figure 5.19: Downtime per maintenance class in scenario 9

Figure 5.19 shows a comparison of average downtime per maintenance class and logistics concept (without onshore-based with one transfer vessel). CM0 and CM4 are not shown in the figure, because CM0 represents remote reset and has the same downtime in all concepts. For CM4 a large jack-up repair vessel is required. This vessel is independent of the logistics concepts, thus, CM4 has almost the same downtime for all compared logistics concept. It is noticeable that for condition-based maintenance (CBM1 and CBM2) the downtime is the same for all logistics concepts (8 h and 16 h). This can be explained by the fact that only the working time is downtime for condition-based maintenance.

Particularly, the WTG is only shut down when the technicians are working. Also CM1 has almost the same downtime for all concepts. This is due to the helicopter, which is mainly deployed for CM1 work orders. The mother vessel concept leads to the lowest downtime per maintenance class (CM2: 50 h, CM3: 76 h). These times are almost independent of the number of transfer vessels. The mother vessel alone is already sufficient to maintain the 90 WTGs. Further transfer vessels are not necessary. For the onshore-based concept the situation looks different. The downtime per maintenance class correlates with the number of transfer vessels - the more transfer vessels the lower the downtime. Compared to the mother vessel concept the downtimes are on average three to four times higher (CM2: 160 h, CM3: 290 h). The unmanned platform concept also shows a correlation between downtime and number of transfer vessels. The downtime is more than two times higher (CM2: 107 h, CM3: 168 h) compared to the mother vessel concept.

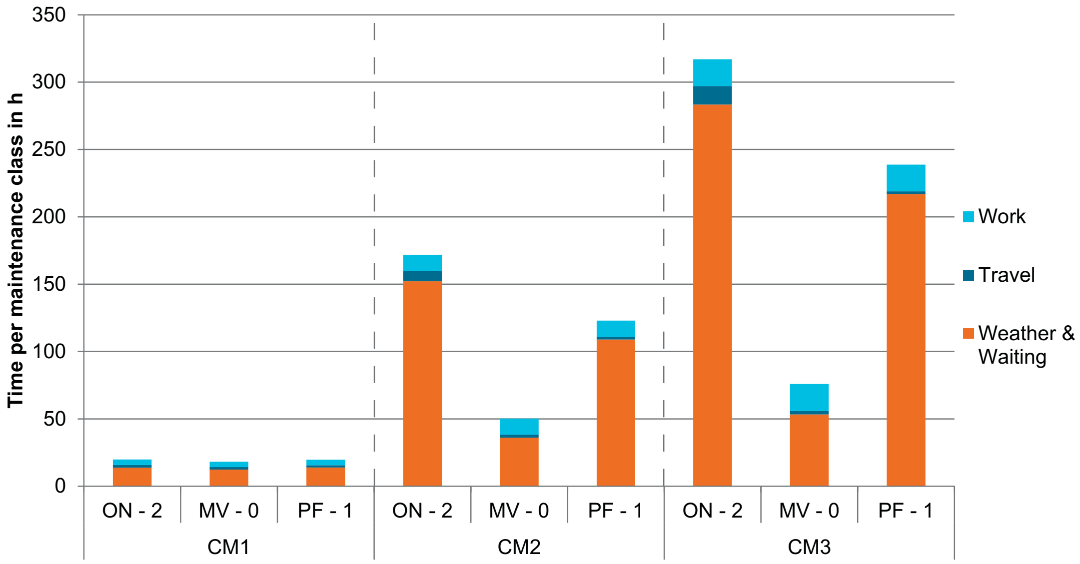


Figure 5.20: Components of downtime in scenario 9

Figure 5.20 shows the distribution of the downtime (only for corrective maintenance classes) for the best variant of the three logistics concepts: onshore-based concept with two transfer vessels, offshore-based mother vessel concept without transfer vessel and offshore-based platform concept with one transfer vessel. It can be seen that the working time is the same for all concepts per maintenance class. For offshore-based concepts the travel time is always less than 2 h. For the onshore-based concept the travel time varies from 2 h to 14 h. The figure emphasizes that working time and travel time have less influence compared to weather and waiting time. Weather and waiting time comprise the time in which a work order cannot be processed because of bad weather or the non-availability of a vessel to complete the work order. For corrective maintenance the weather and waiting time for the mother vessel concept is up to three times higher than travel and working time, for the platform concept it is up to 11 times higher and for onshore-based concept it is up to 14 times higher. This stresses the great influence of weather and waiting time on the downtime and availability, and thus the costs for revenue losses. It explains the benefit of the mother vessel concept.

The curves in Figure 5.21 clarify the relationship between availability and costs for the onshore-based concept in scenario 9. With increasing availability the revenue losses shrink but the O&M costs increase so that a minimum in total costs is achieved somewhere between 94 and 95 % availability. It reveals that a maximization of availability for any price is not reasonable in any case. The total costs always have to be considered (see also Section 2.3.1).

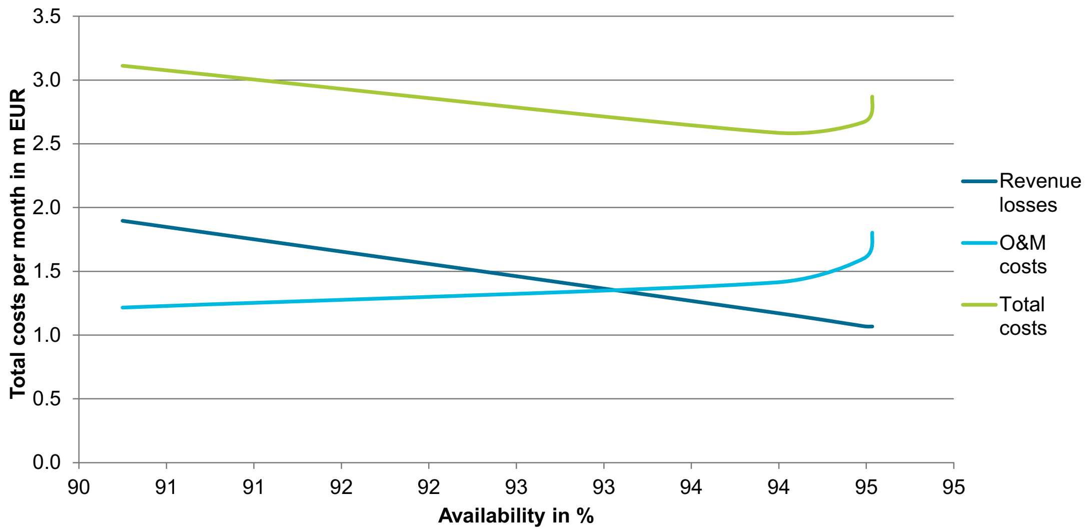


Figure 5.21: Costs vs. availability in scenario 9

5.4 Evaluation of Investigated Logistics Concepts

The previous analyses and results have given a good overview of how the different logistics concepts perform under certain circumstances.

The onshore-based concept can be deployed cost-efficiently for many OWPPs in the German North Sea. Although it always leads to higher revenue losses (which mean lower availability), they are compensated by lower costs for the transfer vessels compared to a mother vessel or a manned platform. Compared to offshore-based vessels not so high costs incur (supply of platform or mother vessel, additional personnel). But the onshore-based concept is only beneficial as long as the WTG capacity is constant (at the current level) and a helicopter is used. Taking into account higher capacities of WTGs the revenue losses become higher and as a result other concepts are more cost-efficient. Also the helicopter support is another key factor to the success of the onshore-based concept. Without helicopter support the revenue losses might be a lot higher. The onshore-based concept, especially for OWPPs that are located far away from shore (100 km), is more sensitive to bad weather and higher failure rates. Thus, a risk-averse OWPP operator should choose an offshore-based concept.

The mother vessel concept has been identified as the most cost-efficient concept for the scenario with the largest OWPP (90 WTGs) 100 km far away from the base station. Going offshore with the base station (mother vessel) leads to multiple costs which have to be compensated by lower revenue losses. Although the mother vessel concept leads almost always to an availability above 97 % the reduction of lost revenues is not always enough to justify the costs for this offshore-based concept. The concept is relatively stable in relation to changes in weather or failure rates. Nevertheless, the high cost of the mother vessel may have a great impact on the total costs if the charter rate changes for example. For all investigated scenarios the mother vessel needs no support by a transfer vessel. Only for safety reasons or to speed up planned maintenance activities an additional transfer vessel might by meaningful.

In no scenario the offshore-based platform concept is the most cost-efficient. But in smaller OWPPs close to the shore it is more cost-efficient than the mother vessel concept. One major advantage of the platform concept is the reduction of travel time. But as shown above the transfer time has less impact on the availability of the OWPP. The weather and waiting time has the most impact but there is not such a big difference to the onshore-based concept. The only difference is that short weather windows can be used for work within the platform concept, but these short windows cannot be used for work starting from shore. So on the one hand there is only a small advantage and on the other hand there are huge costs incurring by deploying a manned platform. There is not only the investment but there are also the costs for the platform supply and the higher number of technicians. So from a pure cost perspective this concept would not be deployed. But there are other soft reasons why this concept might be deployed. For example, seasickness is one factor that should not be underestimated. Staying all day long on a mother vessel or spending hours for the transfer on the transfer vessels can make the technicians seasick. This situation can be prevented by a fix offshore-based platform.

5.5 Discussion of Findings

In this section the main findings are outlined and critically discussed. These findings have been derived from the previous analyses of results.

Main findings

- Most OWPPs in the German North Sea can be maintained by an onshore-based logistics concept supported by a helicopter.

- The deployment of a mother vessel is beneficial for large OWPPs located far from the base station.
- The conducted sensitivity analyses show that the mother vessel concept reveals the lowest sensitivity to weather and failure rate changes.
- No logistics concept is the most cost-efficient one during the whole year. A combination of concepts is meaningful and can save costs.
- The mother vessel concept leads to a high availability almost all over the year.
- The platform concept shows a decrease in availability in the winter months, but not as strong as the onshore-based concept.
- If a concept is not flexible, overcapacities can occur. This overcapacities can be used for pooling concepts. Peaks of overcapacities can be avoided by shifting planned work into months with low work loads.
- Weather and waiting time has the highest impact on downtimes compared to work and travel time. Thus, it is important to use weather windows or try to enlarge weather windows by advanced equipment.
- Higher availability of a logistics concept does not mean that this logistics concept is superior to other concepts.
- The developed model is able to evaluate different logistics concepts and to identify most cost-efficient logistics concepts.

The reason that the onshore-based concept is superior to offshore-based concepts in most scenarios is the high cost for offshore-based concepts and the use of the helicopter. Without a helicopter the onshore-based concept would not have such a good performance. For the investigation it has been assumed that it is always reasonable to sail to the OWPP from the base station (no matter how long it takes). Most likely an OWPP operator would not accept the long travel time of its technicians even if it is most cost-efficient. Aspects of safety and risk aversion have not been considered because the operators have their individual requirements. This might lead to the deployment of an additional vessel or the choice of a concept which is not most cost-efficient but safer.

The cost results are highly dependent on the input parameters in terms of costs and revenues. These parameters can change over the time or if fundamental market changes occur. Especially the costs for jack-up repair vessels strongly depend on the type of charter (spot market vs. long time charter). Thus, sensitivity analyses have been conducted. Nevertheless, it cannot be assured that more significant changes will not occur. Also the revenue per MWh corresponds to the average value at the moment and of the last years. This value, though, might decrease as the subsidy is reduced. This can lead to the deployment of cheaper concepts (in terms of logistics and personnel costs). In contrast, the trend of higher capacities per WTG supports more expensive concepts (in terms of logistics and personnel costs), which ensure higher availabilities throughout the year.

Concepts have to be flexible but as a consequence the contracts of the OWPP operator have to be flexible as well. Sometimes good contract conditions limit the flexibility. It might not be possible to deploy and pay a mother vessel only in winter time and in summer time just deploy two transfer vessels. In addition, if the number of technicians changes throughout the year, the operator must ensure that the number of technicians needed in the high work load period is available. If the flexibility is bought at high expense, the benefit might be gone.

It has also to be pointed out that often the manufacturer and not the owner is responsible for maintenance in the first years of the OWPP operation due to warranty reasons. In this phase the manufacturer can guarantee a minimum availability for the OWPP. Thus, his objectives might not be the overall cost minimization (logistics costs plus opportunity costs) but the maximization of availability. This could lead to the selection of a different logistics concept.

Limits and benefits of the model

Although the model presents operational processes, it is not suitable for operational process planning. The operational processes follow a fixed routine (always shortest path) and these routines cannot be adjusted easily. Another limitation of the model refers to the aspect that in reality the captain of the vessel is the one who decides if the transfer to a WTG is safe and this might not be the case even if the wave height is below the limit.

Failures in the repair processes at the WTGs have also not been considered. These can occur during human work. Cost variations have been considered with sensitivity analyses, but the costs could vary more significantly. An important part that the model does not take into account is related to soft factors, such as safety reasons, buffer functions, ergonomics. These aspects have to be considered when evaluating the results.

Nevertheless, the simulation-based model is able to deliver cost results for different concepts to compare these concepts on a strategic basis. These results can support the selection of a logistics concept in the planning phase or e.g. the investment decision for a vessel. The model is also able to support resource planning in the long run.

A substantial benefit of the simulation model to distinguish it from other approaches, though, is the monthly analysis of results and the transparency of logistics processes. Furthermore, the realistic work order assignment to vehicles is an advantage. This also applies to the realistic connection between availability and electric power production and the exact matching of weather windows and missions.

Usually, building simulation models consumes a considerable amount of time and is not really user-friendly. However, using the developed model user friendliness is increased as it takes only one mouse click to model scenarios and logistics concepts and another one to simulate them.

6 Conclusion

This last chapter of the thesis summarizes the approach and the results. In the second part of this chapter an outlook for further research activities based on the developed model and the findings is given.

6.1 Summary

In Chapter 1 of this thesis an introduction to the topic, the background and the initial problem for offshore wind energy logistics during the operation phase is given. It is shown that offshore wind energy production is too expensive at the moment and that the operation phase with 20 to 30 % of the total project costs has a high potential to be more cost-efficient and make offshore wind energy more competitive. Thus, a need of a method or tool to evaluate logistics concepts for OWPPs is identified.

In Chapter 2, the theoretical background regarding logistics, modeling and simulation is explained. In addition, it is shown that only simulation can be used to build an appropriate evaluation model due to the high complexity and parallel events. Among these basics, specific knowledge about offshore wind energy is presented. Especially the operation phase of OWPPs and the deployed logistics concepts are explained and analyzed. Already existing tools for the evaluation of operation logistics concepts have been described and weaknesses have been identified in this part.

Based on the two former chapters and the findings with regard to the existing tools and the requirements from the initial situation a simulation-based evaluation model has been developed in Chapter 3. The model is implemented using the software *Enterprise Dynamics*. It is a modular model, which can be used for different OWPP scenarios and different logistics concepts. Besides planned and corrective maintenance activities also condition-based maintenance activities are covered by the model. The model is comprehensively described regarding scope, requirements, assumptions and its architecture. A verification of the model is performed as well as a validation with data gathered from literature and real OWPPs. Results are also compared with the output of another existing tool. The comparison shows that the developed model provides valid results.

In Chapter 4 nine scenarios representing the OWPPs in the German North Sea have been defined (regarding number of WTG and distance to base station). Also three different logistics concepts (onshore-based, offshore-based mother vessel and offshore-based platform with four variants each regarding the number of transfer vessels) are defined to conduct the simulation runs. All parameters for the simulation runs in terms of costs, weather and failure rates are specified in this chapter and correspond to realistic data. To test the robustness of the logistics concepts further sensitivity analyses have been defined. 132 simulation runs have been performed with a total number of 3,300 simulated years.

In Chapter 5 the results of the simulation experiments are presented and compared. For most OWPP the onshore-based logistics concept with one or two transfer vessels is the most cost-efficient one. The mother vessel concept only becomes most attractive for the scenario with the largest OWPP (90 WTGs) 100 km away from the base station. The success of the onshore-based concept can be explained by high costs of the offshore-based concepts. The onshore-based concept leads to lower availability and higher revenue losses. But these losses are over-compensated by lower vehicle costs. Also important for the success of the onshore-based concept is the deployment of a helicopter.

Sensitivity analyses regarding weather and failure rates reveal the lower sensitivity of the mother vessel concept especially for large OWPPs far away from the base station. But the concept is prone to higher charter costs of the mother vessel. A detailed monthly cost analysis of all concepts has shown that there is a cost saving potential of almost 8.1 % if different concepts are combined. That means for example that in summer an onshore-based concept is deployed and in winter an offshore-based mother vessel concept could be used.

The analyses of the distribution of maintenance missions (to inspect or repair WTGs) has shown that the peak of missions per month is in the time of planned maintenance missions starting in April and lasting for one or more months (depends on number of vessels). In the other months without planned maintenance actions overcapacities can occur in some cases. These capacities can be used for work in other OWPPs. It might also be possible to use personnel (technicians) from service providers which are only hired for the time of planned maintenance work.

Typical availability trend lines during the year are identified for the different logistics concepts. The mother vessel concept can achieve the highest availabilities followed by the platform concept and the onshore-based concept. This results from the low weather and waiting downtime (WTG has failed but no mission is possible because of bad weather conditions or nighttime) for the mother vessel concept because of the high accessibility until 3 m of significant wave height. This downtime (weather and waiting downtime) has the highest share of the total downtime compared to work and travel downtime. The weather and waiting downtime is higher for the platform concept due to the use of transfer vessels with an accessibility of not more than 1.5 m significant wave height. Concerning the onshore-based concept the weather and waiting downtime is even higher as some weather windows cannot be used for work because the working time would be too short due to the long travel time.

Summarizing this, it can be stated that the model is able to meet the requirements it has been designed for. It is transparent and able to simulate the complex logistics processes in the operating phase of OWPPs. Moreover, it is modular; that means it is adjustable to many existing logistics concepts and OWPP scenarios. The model can be used to:

- Support investment decisions for vehicles
- Develop logistics concepts in the OWPP development phase
- Plan resources (during operation) for a certain future time frame

The developed model differs from other existing tools because it can produce results on a monthly base. It is also a real simulation tool with a modular structure enabling an automated and thus fast model generation. That means the user has all benefits of simulation but not the disadvantages. Usually it takes a significant amount of time to create simulation models. The model is valid and can represent complex situations. Furthermore, the model has a strategic orientation (simulation of many years) but operational processes are represented precisely to achieve a high quality of results.

6.2 Outlook

Many further research questions can be investigated with the developed model. Several questions have been arising during the development relating to the advantage of pooling the equipment or the supply of more than one OWPP with one logistics concept. Another interesting research question refers to the impact on the results if a transfer vessel could carry 24 technicians or the work could be carried out during the nighttime. Furthermore, investigating the influences of higher WTG capacities and lower feed-in tariffs would be very interesting.

Moreover, the model could be developed further. Approaches would be an integration of a weather database to simplify the use of weather data from different locations of the OWPP. In addition, the adaption and extension of maintenance classes could be automated to simplify the creation of new maintenance classes. It might also be possible to integrate different operational strategies on how the vessels are deployed.

Concerning the model's limits, the model could be expanded covering hinterland processes of spare parts supply. A delay in the availability of spare parts could be modeled easily and then investigated. This could have a strong impact on the OWPP KPIs. The integration of maintenance actions for the balance of plant might also be a meaningful complement.

In conclusion, many research questions and ideas for further developments can be derived and approached. Nevertheless, the model developed within this thesis provides a notable contribution to nowadays offshore wind O&M research.

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Electricity production costs of offshore wind power plants are high compared to other energy sources. The costs of offshore wind power have to be reduced to be attractive as a renewable energy source. The operational costs, especially logistics costs, have a great potential for cost reduction. In this thesis a modular simulation model for the operation of offshore wind power plants is developed by using the software Enterprise Dynamics. The model is able to represent offshore-based and onshore-based logistics concepts. The output is logistics and opportunity costs (revenue losses). The model is used to gain new findings on the correlation between different influencing factors (e.g. weather conditions), parameters (e.g. number and type of equipment) and the logistics concept performance (economic viability). Based on the developments in the German North Sea, multiple simulation experiments have been conducted on three different logistics concepts (with four variants each) and nine offshore wind power plant scenarios. The validity of the results has been demonstrated through sensitivity analyses for selected input parameters.

The investigation shows that for most German offshore wind power plants an onshore-based logistics concept is the most cost efficient option. An offshore-based concept only becomes the most cost efficient option for a large offshore wind power plant scenario with 90 wind turbine generators located 100 km away from the base station. The success of onshore-based concepts is related to the high additional equipment and personnel costs of offshore-based concepts. Other important findings are that no logistics concept is superior throughout the whole year, and that a combination of concepts leads to the best cost efficiency. The investigation also identifies that the influence of weather downtime (no mission possible because of bad weather conditions) on the availability of the offshore wind power plant is significantly higher compared to the downtime resulting from travel or repair works. The developed model distinguishes itself from other approaches by the event-discrete simulation character, transparent processes and the ability for monthly analysis.

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