AALBORG UNIVERSITY

Student report

DECISION SUPPORT FOR OPERATION AND MAINTENANCE OF OFFSHORE WIND TURBINES

| Student: Andreea Almasi | Master Thesis | MSc Structural and Civil Engineering |
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School of Engineering and Science
Fibigerstræde 10
9220 Aalborg
http://bsn.aau.dk/

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Participant:

MSc Student Andreea Almasi

Supervisors:

Professor John Dalsgaard Sørensen

PhD Fellow Tomas Gintautas

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Synopsis:

In this thesis, the way in which the energy cost is formed was studied, therefore capital expenditure, operational expenditure, decommissioning expenditure were analyzed for the Horns Rev 2 wind farm. The project presents a detailed analysis of the operation and maintenance activity, therefore two maintenance methods, corrective and preventive, were considered in order to obtain the final operational expenditure. Furthermore the energy production was obtained for each year of the wind farm lifetime and also the cost of energy was calculated.
After the baseline model was established, a sensitivity analysis with different scenarios applied on the baseline model was conducted in order to observe the cost variation of the energy and of the maintenance activity.

The content of the report is freely available and it can be published with source reference only with the author's agreement.

Preface

The project preface is based on the preface from the project "The Excitation and Foundation of Marine Structures" [Andersen et al., 2014]

The current report has been completed by student Andreea Almasi, during the 4th semester of the master program of Structural and Civil Engineering at Aalborg University. The report is realized in the period between 17th of March and 31st of July 2014. The main subject is *Decision support for operation and maintenance of offshore wind turbines.*

The cover pictures are taken from [Ropeworks, 2011] and [Siemens, 2009].

Reading guidelines

The report was realized by using different references which are presented in the bibliography placed in the back of the report. Right after the bibliography, the next are the appendices. Furthermore, a list of digital appendices is presented for an easier understanding of the programs which where used for obtaining the results presented in the report. Harvard method was used for presenting the source references. This means that the sources are listed with surname and the year: [Surname, year]. For the sources references which have more than one author, the remaining authors will be listed as "et al". These references are presented in the bibliography, where books, technical reports or other publications are stated with authors, title, edition, publisher and year. The online pages are stated with authors, title, hyperlink and year.

The source references presented before a period refer to the source of that sentence, while the source references which are placed after a full stop indicates the source of the whole section. For figures, pictures, tables, the source references are listed after or under their caption. If no source references is presented, it means that the figure is created by the student. If at the beginning of a section, a source reference is presented, then it means that the source was used for the entire section.

Figures and tables are numbered after the corresponding chapter or section. Therefore the first figure in Chapter 1 is numbered 1.1 and the second is 1.2 and so on.

Contents

Introduction 1

The renewable wind power energy is a wide research area nowadays and a developing industry. The future wind farms will have an increased number of turbines and higher power capacity compared to existing wind farms. These changes imply more complicated installation, operation and maintenance, activities and implicitly higher costs. The focus is particularly on offshore wind farms, where the installation and the maintenance operations are more difficult to perform than for onshore wind turbines. This is because the access to the offshore wind farm depends on weather conditions and vessels availability. A total capacity of 6562 MW is installed in Europe in 69 offshore wind farms. This capacity is produced by a number of 2080 turbines, from which 75% have monopile foundations. From this total capacity, the offshore wind farms which were installed in 2013 represent 1567 MW and they were placed in North Sea in a percent of 72%, Baltic Sea 22% and Atlantic Ocean 6%. Furthermore, the wind farms were installed in water depth with an average of 20 m and the average distance from shore to their site is 30 km.[Corbetta et al., 2014]

1.1 Reference model

The main aim of this project is to build a baseline model in order to analyze the costs raised by the wind farm operation and maintenance, *O&M*. Furthermore, a sensitivity analysis of this model was performed for obtaining the best solution which could be implement in *O&M* activity. The *O&M* model was created based on Horns Rev 2 using publicly available data. Figure 1.1 shows the wind farm, which was inaugurated in 2009 and it is placed in the North Sea at 31.7 km from shore.

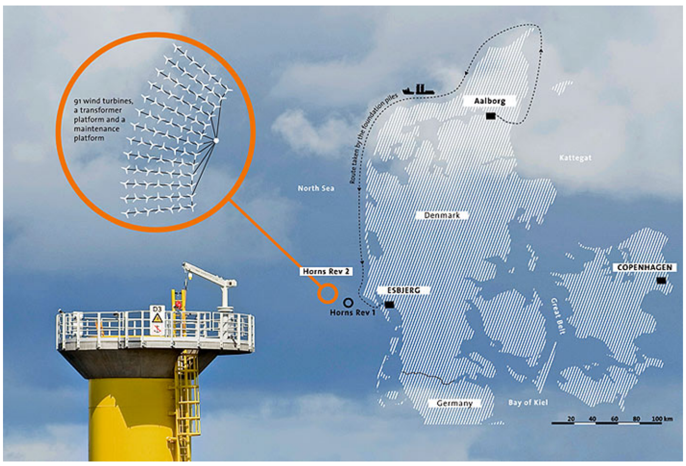

Figure 1.1. Location of Horns Rev 2. [Magazine, 2008]

The Horns Rev 2 wind turbines foundations are monopiles and are placed in water depth between 9 m and 17 m. A number of 91 turbines which are positioned in 13 rows, each consisting in 7 turbines, form the Horns Rev 2 wind farm.

1.2 Maintenance methods used in offshore wind farm industry

Three types of maintenance are considered in offshore wind farm industry. The first type is the scheduled maintenance which is conducted in summer, due to the fact that the access to the wind farm is easier and the energy losses are lower. This type of maintenance is associated with inspections, because the turbine components are visually inspected and they are replaced if considered necessary. The second type of maintenance is the condition based maintenance, which means that the wind farms are permanently monitored by SCADA [1] system. With the help of this system, it can be detected when the components are too damaged, therefore the maintenance activity will be planned for replacing the components before failures occur. The third type is the corrective maintenance, which is performed when an unexpected failure occurs or when it cannot be prevented. [Estate, -]

1.3 Project contents

At the beginning of the model developed in this project, the installation steps of the wind farms were analyzed and their costs calculated.

Further, the cost model in this thesis focuses on the $O\&M$ activity and its costs. Two methods of wind farm maintenance are considered: corrective maintenance, CM, and preventive maintenance, PM.

In the end of the wind farm lifetime, the wind farm must be decommissioned, which implies the removal of the offshore turbines and the restore of the marine environment as it was before the construction of the wind farm. The decommissioning costs for the Horns Rev 2 were also calculated and considered in the baseline model.

The energy production of the wind farm is calculated for each year of lifetime, considering the wind speed measurements and the power curve of the wind turbines. After the capital expenditure, $CAPEX$, operational expenditure, $OPEX$, decommissioning expenditure, $DECEX$, and the annual energy production, AEP of the wind farm are obtained, the levelised cost of energy, $LCOE$, is calculated and used as basis for comparing different $O\&M$ strategies.

A sensitivity analysis with different scenarios was conducted on the baseline model, in order to observe the maintenance costs variation and to decide which should be the best solution of the maintenance activity of a wind farm, which will lead to minimum costs.

[1] Supervisory Control and Data Acquisition

Description of the costs formation 2

The most important aspect that has to be taken into account when building an offshore wind farm is its overall cost. This cost is composed from $CAPEX$, $OPEX$ and $DECEX$. These 3 costs categories play an important role in determining the $LCOE$.

2.1 Cost categories

In this section the formation of each cost category is described.

2.1.1 CAPEX

This category of expenditure was chosen to be divided into 5 subcategories for a better understanding of each part contribution over the cost.

1. **Planning and development** - this element refers to all the processes which are related to the financial aspect of the wind farm construction, environmental surveys, planning actions and legal advice. Furthermore it includes also other activities required for the smooth construction of the wind farm, such as accountancy advices.[Willow and Valpy, 2011]

2. **Turbine** - this subcategory includes the costs which are related with the manufacturing and assembly of wind turbine elements, including the nacelle, hub, blades, tower and electrical system of the turbine. The transportation costs of the turbine components to the construction port are not included in the turbine costs because they are assumed to be ex-works [1]. Furthermore the installation costs are also not included. [Willow and Valpy, 2011]

3. **Foundation** - the costs which are included in this element are the manufacturing costs of the foundations. As for the turbine element, the foundation subcategory does not include the costs regarding the installation and transportation activities. [Willow and Valpy, 2011]

4. **Installation** - in these costs are included the expenditure with the transportation which are not ex-works, preparation and installation of the turbine components which are made onshore and offshore.[Willow and Valpy, 2011]

[1] It implies that the seller has to transport the goods to the construction site.

5. **Electrical infrastructure** - this element includes all the electrical part of the wind farm, more exactly the offshore substations, the export cables which are making the connection between onshore and offshore wind farm and array cables. [Willow and Valpy, 2011]

2.1.2 OPEX

This part of expenditure includes the operation and maintenance costs of a wind farm. Preventive and corrective maintenance, monitoring of the wind farm and inspections regarding the condition of the turbines contribute to OPEX. These actions bring up the costs of the personnel salaries, needed vessels and equipment, spare parts of the turbine. Furthermore, also fees for port berthing, insurance, audit, sea bed lease are included in OPEX. [Willow and Valpy, 2011]

2.1.3 DECEX

In order for the wind farm building to be approved, its owner is obliged to make some provisions for the decommissioning and dismantling of the wind farm, which will take place at the end of wind farm lifetime. The generator, blades, nacelle and tower have to be dismantled and the piles have to be cut off from the seabed. In the end, the steel which cannot be used anymore is sold as steel scrap, therefore the dismantling costs are slightly reduced by these revenue. [Hobohm et al., 2013]

2.1.4 LCOE

The levelised cost of energy of a wind farm depends on its CAPEX, OPEX, DECEX and AEP. A simple definition of LCOE, can be stated as the lifetime costs of the wind farm per energy unit produced. Based on [Hobohm et al., 2013], LCOE can be calculated by equation (2.1)

$$LCOE = \frac{CAPEX + DECEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+WACC)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+WACC)^t}} \tag{2.1}$$

$CAPEX$	Capital expenditure [€]
$DECEX$	Decommissioning expenditure [€]
$OPEX_t$	Operational expenditure in year t [€]
AEP_t	Annual energy production in year t [MWh]
$WACC$	Interest rate = 8.6% [Nielsen et al., 2010]
n	Operational lifetime of the wind farm [n=20 years]
t	Lifetime individual year [n=1,2,3,...]

2.2 Factors with influence on costs

The $CAPEX$, $OPEX$, $DECEX$ and $LCOE$ are influenced by different factors which contribute in different percentages to the final cost of a wind turbine. If these factors are optimized, it may lead to a significant reduction of the costs. Some of the main parameters which have an impact on overall costs are: significant wave height, wind speed, size and capacity of vessels, water depth, size of the supply markets, distance to shore, duration of weather forecast.

A. Significant wave height

Significant wave height, H_s, is an important factor which is taken into consideration for the construction of a wind farm. It is combined with other factors, such as wind speed and duration of the weather forecast, in order to determine the workable and non-workable days. Furthermore, the wave heights and wind speeds are important factors which have to be considered also in the design process of the wind turbines components. Currently, H_s working range is around 1.4 m and it is desired to increase H_s above 2 m, which will lower the weather downtime and the support structure installation cost [The Crown Estate, 2012].

B. Size and capacity of vessels

The vessels which are used in the building process of a wind farm are inappropriate because they are from oil and gas industry. The vessels suitable for offshore wind farms industry should have a convenient length for the storage of the wind turbines components which have to be transferred offshore. Furthermore, the vessels should be capable of heavy lift operations. Even if longer vessels imply high cost of their construction and their fuel consumption, there are also advantages, such as: they could operate in bad sea conditions and will reduce the downtime for installation, $O\&M$ activities of wind turbines, which will lead to a cost decrease. [The Crown Estate, 2012]

C. Water depth

The water depth is directly related to the wind turbine foundation. Together with the increasing water depth, the size of the wind turbine foundation is increasing too. In recent years, the wind farms have been installed in greater depths, due to the fact that wind speed increases with distance from the shore. Between the years 2000-2005, the wind farms were installed in water depths between 5 m to 15 m, and starting with 2006, the depth increased slowly in the range from 20 m to 35 m [The Crown Estate, 2012].

D. Wind speed

Wind speed is one of the most important factors which have to be taken into consideration when building a wind farm, because is the direct parameter which influences the wind turbine to produce more energy.

E. Size of the supply markets

Currently, the offshore wind turbines industry does not have a fully developed supply market and it typically operates only on a project by project basis. Many components that are used in order to build an offshore wind turbine are adapted from onshore turbines or they are designed partly after the standards from oil and gas industry. Some of the measures that could reduce costs are the maturity of the supply chain and the design of components tailored for the needs of the wind turbine industry. Together with the maturity of the market, the competition in the suppliers field will increase and will drive to cost reduction. The entry of the suppliers from countries such as China, India, South Korea will also lead to a cost reduction, due to cheap labor and low cost of the raw materials in these countries [The Crown Estate, 2012].

F. Distance from the shore

The existing wind farms are situated relatively close to the shore, which limits personnel transportation time to the turbines to maximum two hours. There are both advantages and disadvantages of the distance increase from the shore. On the one side, the advantages are that the energy production will increase, due to high wind speeds. Another advantage is that the wind farms will contain a higher number of turbines than the current wind farms which are placed close to the shore. On the other side, the disadvantage is that the transport of personnel from port to the wind farm will take more time. [C.L.Cockburn et al., -]

G. Duration of weather forecast

The downtime is directly influenced by the weather forecast which leads to higher installation costs, simply because the installation process can only be performed under favorable weather conditions. The support structure of a wind turbine, except the tower, is the first component which is installed. After the support structure installation, the array cable and the turbine, including also the tower can be placed. The array cable and the turbine installation can typically take place between the months March and October, when the sea does not present unfavorable weather conditions.

2.3 Current installation process

This section is mainly based on [BVG Associates, 2013]

The installation process of a wind turbine can be divided into 6 main parts: installation ports, foundation installation, turbine installation, cables installation, scour protection installation and substation installation.

1. **Installation ports**

   Before being transported to the offshore site, the main components of a wind turbine can be pre-assembled in ports which are close to the site. For example, the nacelle, hub and two of the blades can be put together onshore, in order to reduce the amount of work needed to be done offshore. Therefore, just one blade has to be installed offshore, as can be seen in the Figure 2.1.

Figure 2.1. Onshore pre-assembled components. [Siemens, 2013]

Figure 2.2 shows that even all the three blades can be assembled to the rotor onshore and installed to the nacelle offshore.

Figure 2.2. Installation process with onshore pre-assembled components. [Guillen et al., 2011]

The decision if the components should be pre-assembled onshore and in which way, belongs to the wind farm contractors. Based on [Guillen et al., 2011],a port should have 3 main characteristics: 1000 tons capacity crane on tracks, enough linear footage and at least 200 acres for assembly and storage.

2. **Foundation installation**

   The main used vessels for the installation of a steel foundation are the jack-up vessel and the floating vessel. By taking into account the mass of the foundation, it can be decided whether or not the crane capacity of an installation vessel is enough to lift the foundation.

	Foundation types		
	Monopile	**XL Monopile**	**Jackets/Tripods (Space Frames)**
Jack-up vessels	It is chosen by taking into account the mass of the foundation The most used crane capacity is up to 500 t It is used more often in shallow waters	It is chosen by taking into account the mass of the foundation The crane capacity has to be above 1000 t Not many jack-up vessels can handle these weights	The optimal one is with the crane capacity of 1000 t or higher It can carry at least five foundations
Floating vessels	It is used in deep waters It leads to faster installation because it can operate at H_s up to 2.5 m which implies a low downtime	It is used in deep waters It leads to faster installation because it can operate at H_s up to 2.5 m which implies a low downtime	The foundations are installed using sheerlag cranes vessels, but they are not optimal for installation because of their sensitivity to weather conditions (maximum H_s is 0.75 m)
Current capacity for installation vessels	There are 15 suitable vessels for foundation installation They can also be used for turbine installation	A number of 4 vessels which have enough crane capacity are used for foundation installation One new build vessel is under construction They can also be used for turbine installation	13 vessels are capable of foundation installation 2 vessels are under construction Only 2 out of 13 vessels fulfill the criteria to carry at least 5 space frames Several companies developed a vessel design which will be capable to carry between 5 to 7 space frames

Table 2.1. Vessels description for foundation installation.[BVG Associates, 2013]

3. **Turbine installation**

   All existing wind farms until 2013 have been operated with jack-up vessels for the turbine installation. In the latest offshore projects, vessels such as self-propelled jack-ups, leg-suspended and jack-up barges were used. These types of vessels can operate in water depths up to 25 m and they can transport only a small number of turbine components. The development of the ports and the longer transit distance will lead to larger vessels. The vessels will have higher speed (maximum 12 knots)[2] and the vessels will be capable to transport 6 or more turbines of size 6MW or even larger. A number of 4 of this type of vessel are operating on the market and 2 more are under construction. Furthermore, future investments are expected in relation to vessels suitable for turbine and foundation installation with a mass grater than 1200 t. In the recent years, the new vessels introduced in the offshore industry can operate in water depths of about 45 m, because they are equipped with longer legs. [BVG Associates, 2013]

4. **Cables installation**

   There are two methods for cable installation: the first one is by using a single lay and burial process with a plough and the second one implies that the cable is on the sea bed and it is buried using a jetting tool operated from a remote vehicle. The cables can be classified as inner array cables and export cables. The inner cables connect together the turbines and the offshore substation, if there is one, and the export cables make the connection between the wind farm and the transmission system placed onshore [Kaised and Snyder, 2012]. For this activity there are enough vessels and the selection criteria is based on their cost and their availability.

5. **Scour protection installation**

   The formation of scour is because of the sediment transport produced around the turbines foundations. If the area where the turbines are installed is exposed to strong currents and an erodible seabed, the foundations stability can be threatened and scour protection is a necessity. This protection implies that stones are placed around the support structures.[Kaised and Snyder, 2012]

6. **Substation installation**

   The main role of the substation is to collect all the produced energy from the turbines before it is transported to the shore through the export cables.

2.4 Current maintenance process

The maintenance process can be divided in corrective maintenance and preventive maintenance. The direct costs required for the maintenance process are those related to the spare parts, vessels and technicians. To these costs are added the indirect costs composed by the revenue losses raised from the energy which could be produced in the time that the failures are repaired.

Corrective maintenance - the turbine will be stopped from the moment the failure occurs until it is repaired. The time to repair is composed by the logistic time, waiting time, travel time and operation time.

[2] 1 knot = 0.514 m/s

- Logistic time is for purchasing the spare parts needed for fixing the failed component. Some of the spare parts can be stored in the port deposit, therefore they do not require logistic time.
- Waiting time is due to the bad weather such that the technicians can not reach the wind farm and they have to wait for the weather window which is suitable for each type of vessel. This weather window implies that the wind speed and the significant wave height have to be below the maximum limits which are required in order to repair the failure.
- Travel time is when the weather conditions are favorable for the maintenance and the technicians are transported from the port to the wind farm in order to repair the failure.
- Operation time is when the failure is repaired.

Figure 2.3 shows a graphic representation of these periods of time.

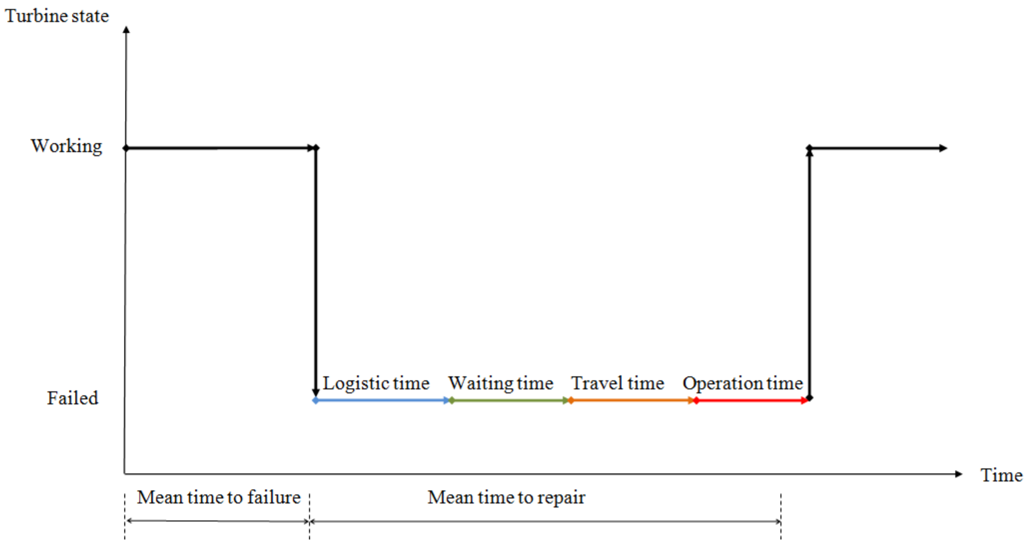

Figure 2.3. Graphic representation of a component repair.

Preventive maintenance - the turbine is stopped just when the maintenance is performed, therefore there is a low level of energy loss.

The vessels types which are in general used for the maintenance process are:

- **Personnel transfer vessels**

  These vessels have a size between 14 and 24 m, a carrying capacity of maximum 12 technicians and the necessary equipment, and their main aim is to perform daily visits to the wind farm. [BVG Associates, 2013]
- **Offshore support vessels**

  Usually, offshore support vessels are floating dynamic positioning vessels which are equipped with cranes, helideck, workshops and their maximum capacity of personnel accommodation is 50 technicians. These type of maintenance vessels are partially stationed offshore in order to respond immediately to turbines problems.[BVG Associates, 2013]

- **Mother ships**

  These are the larger vessels which can accommodate up to 100 people and they have also different types of facilities such as offices, workshop areas or recreational areas. Furthermore, mother ships can launch and recover 2 or even more personnel transfer vessels.[BVG Associates, 2013]

The last two presented types of vessels are capable to operate in much more unfavorable sea conditions than the first type of vessel.

Horns Rev 2 model 3

This chapter analyzes the steps which generally have to be followed in the installation, operation and maintenance of a wind farm such as Horns Rev 2, which serves as example in this project. The following cost models are based on engineering judgment and information from the literature, because the real numbers used in industry are not publicly available.

The main characteristics of the considered wind farm are presented in Table 3.1.

Project capacity [MW]	209.3
Turbine model	SWT-2.3-9.3
Turbine capacity [MW]	2.3
No. of turbines	91
Hub height [m]	68
Rotor diameter [m]	93
Type of foundation	Monopile
Depth range [m]	9-17
Distance from shore [km]	31.7
Distance from port [km]	32.6

Table 3.1. Horns Rev 2 characteristics.[4COffshore, 2014a]

3.1 Capital expenditure

In the analysis of Horns Rev 2 $CAPEX$, two main costs categories were considered: technology costs and installation costs. In this report, the installation costs of the wind farm are studied for each main step of the installation procedure of the wind farm and the results are presented further.

3.1.1 Foundations installation costs

The type of the vessel for installing the foundations of the wind farm is considered to be monohull floating sheerleg crane - Matador 3. [4COffshore, 2014b] Based on [Kaised and Snyder, 2012] its dayrate is considered to be 94.000 € and the spread dayrate is 7.500 €. Therefore the total daily cost of the vessel is 101.500 €.

The final cost of the foundations installation and the factors which contribute to it are shown in Table 3.2

Installation time [hours/trip]	202
Weather adjusted time [hours/trip]	224
Number of trips	23
Total installation time of operation [hours]	5152
Total cost [€]	21.789.000

Table 3.2. Foundations installation costs.

3.1.2 Turbines installation costs

The most proper type of vessel for the turbines installation is the self propelled installation vessel. Based on [Kaised and Snyder, 2012], the vessel dayrate was assumed the same as in the case of foundations installation. Table 3.3 shows the total cost of installation with its contributing factors.

Installation time [hours/trip]	423
Weather adjusted time [hours/trip]	498
Number of trips	12
Total installation time of operation [hours]	5976
Total cost [€]	25.273.500

Table 3.3. Turbines installation costs.

3.1.3 Cables installation costs

The installation procedure of the cables will be performed in two parts: inner array cables and export cables installation. The vessels dayrates were considered based on [Kaised and Snyder, 2012]. For the export cables installation was considered a different vessel than the one used for inner array cables installation, due to the fact that the export cables are heavier than the inner ones, which require a vessel with a high capacity turntable [Kaised and Snyder, 2012]. The final costs of them are presented in Table 3.4.

	Inner array cables	**Export cables**
Vessel dayrate [€]	36.000	90.000
Cable rate [km/day]	0.3	0.7
Cable length [km]	70	42
Required installation time [days]	233	60
Cable installation costs [€]	8.388.000	5.400.000

Table 3.4. Cables installation costs.

3.1.4 Scour protection installation costs

The following assumptions made for scour protection installation are based on [Kaised and Snyder, 2012]. An amount of 1,250 tons of scour protection is required for each turbine. The vessels needed are a tug and a hopper barge which has the capacity of 1,250 tons. Their dayrate is 6.000 €. The loading time per trip is assumed 12 hours, dumping time 4 hours and travel time from port to the wind farm is 9 hours. After the calculations were performed, a total cost of 568.750 € was obtained for the scour protection operation.

3.1.5 Substation installation costs

Based on [Kaised and Snyder, 2012], it is assumed that just one substation is required for the wind farm. The installation of the substation foundation is assumed to last 2 days and the substation topside installation 3 days. The vessel required is considered to be a heavy lift vessel with a dayrate of 58.000 € and beside that 3 tugs, a barge and a crew boat, with a dayrate of 14.000 €. Therefore the total cost of the substation installation is 360.000 €.

3.1.6 Labor costs

The labor costs required for the installation procedure were calculated for each main step by assuming a number of technicians that are needed and by considering that the cost of a worked hour is 140 €/hour. The final costs are presented in Table 3.5.

	Number technicians	**Required hours**	**Costs [euro]**
Foundations	5	5152	3.606.400
Turbines	5	5976	4.183.200
Inner Cables	2	5592	1.565.760
Export Cables	2	1440	403.200
Scour protection	2	2275	637.000
Substation	4	120	67.200
Total labor costs [€]		10.462.760	

Table 3.5. Labor costs.

The total investment costs used for Horns Rev 2 are 3.3 billion DKK [Energy, 2009] which is approximated 442.147.200 €. From these costs, the installation costs presented above are 72.242.010 € and the rest of 369.905.190 € are considered technology costs.

Figure 3.1 presents the percentage assigned for these 2 costs categories. Based on [IRENA, 2012], the wind farms installed until 2010 allocated 13% from their CAPEX to installation part and the rest of 87% to the technology part. It can be observed that the percent obtained for the installation of the Horns Rev 2 wind farm is slightly higher than one based on [IRENA, 2012]. One of the reasons for this difference could be that the vessels dayrates considered in this project do not correspond with those used in reality.

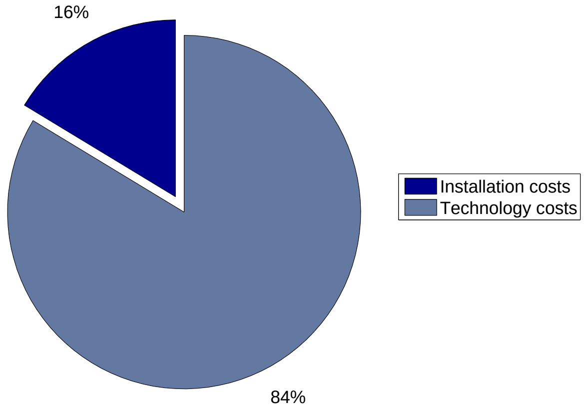

Figure 3.1. Percentages for installation and technology costs.

The total installation costs are composed of the considered costs for each main phase of the wind farm installation. Figure 3.2 shows the percentages allocated for each of these phases.

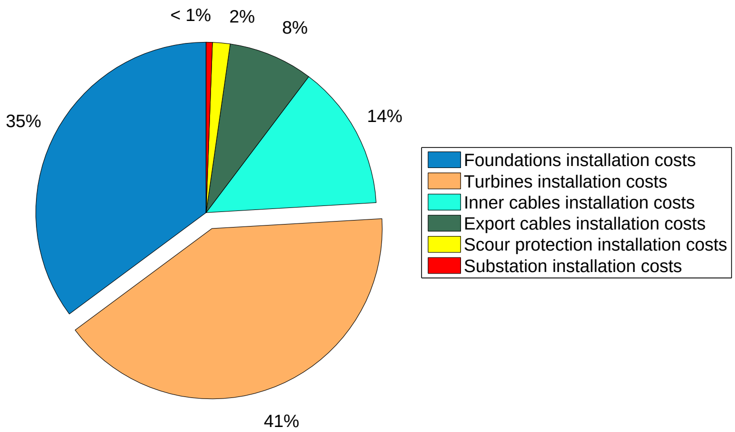

Figure 3.2. Obtained costs percentages of each installation phase.

For a comparison between the obtained percentages in this project and those used in industry, Figure 3.3, which is based on [IRENA, 2012], is presented and it shows the costs percentages used in offshore wind farm industry for each installation phase.

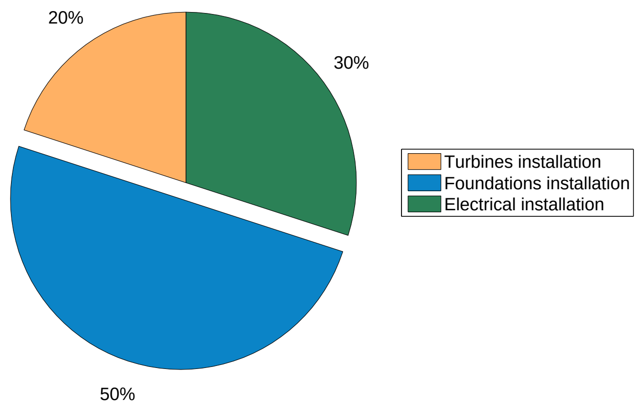

Figure 3.3. Theoretical costs percentages of each installation phase.

By comparing Figure 3.2 with Figure 3.3, it can be noticed that there is a difference between the percentages. It can be concluded that this difference is obtained due to the fact that for installation costs calculations from this project were not used weather data and just a weather adjustment factor in order to take into account the bad weather conditions. Therefore the installation time obtained for each phase can be over− or underestimated. Furthermore, the assumed vessels dayrates could differ from the real ones since the real vessels dayrates are not available.

Furthermore, the technology costs are composed of the expenditure regarding the turbines manufacturing, foundations manufacturing, electrical infrastructure manufacturing, planning and development. [IRENA, 2012] Figure 3.4 shows the percentage of each of these categories. The percentages are considered based on [IRENA, 2012] and [Willow and Valpy, 2011].

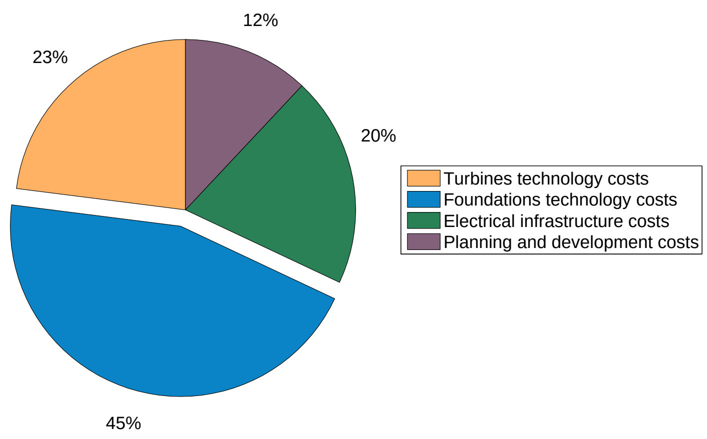

Figure 3.4. Costs percentages for each of the technology cost category.

The used algorithm for the installation costs and its formulas can be found in Appendix A.1 and the calculations in Digital Appendix B.1.1.

3.2 Wind data analysis of the wind farm site

For the Horns Rev 2 wind farm, the wind and wave data were received from this thesis supervisors. The measurements are from 30 to 30 minutes for a period of 9 years. In order to have measurements for 20 years, which is the considered wind farm lifetime in this thesis, the 9 provided years were repeated with small changes: years from 10 to 18 are the measurements from the years 1 to 9 multiplied with 1.1 and years 19 and 20 are the measurements from the years 1 and 2 multiplied with 0.9. Alternatively wind speed and wave height measurements for the years 10 to 20 could have been obtained by a random selection from the 9 years data. This alternatively choice for obtaining the 20 years of measurements is analyzed further in this thesis, in chapter 4.

The data presents the wind speed at 10 m height and they are recalculated by equation (3.1) in order to generate the wind speeds at the hub height of the wind turbines.

$$U = U_{ref} \cdot \left[\frac{H}{H_{ref}} \right]^{\alpha} \tag{3.1}$$

U	Wind speed at the hub height [m/s]
U_{ref}	Wind speed at 10 m height [m/s]
H	Height where wind speed is desired to be calculated [m]
H_{ref}	Height where wind speed is measured [m]
α	Shear exponent [-]

The coefficient α was calculated by using the wind measurements from 2 different heights. Due to lack of these data from Horns Rev 2, wind measurements from the FINO research platform were used to estimate α. The considered heights were $H1 = 52$ m and $H2 = 62$ m and the shear exponent is given by equation (3.2).

$$\alpha = \frac{ln\frac{U_{H2}}{U_{H1}}}{ln\frac{H2}{H1}} \tag{3.2}$$

U_{H1}	Wind speed at 52 m height [m/s]
U_{H2}	Wind speed at 62 m height [m/s]

A value of 0.15 was obtained for α and the calculations can be seen in Digital Appendix B.1.2.

A two parameters Weibull distribution is used to describe the wind speed variations, therefore the probability density function, PDF, is given by equation (3.3).

$$F(U) = \frac{k}{\lambda} \cdot \left(\frac{U}{\lambda}\right)^{k-1} \cdot e^{\left[-\left(\frac{U}{\lambda}\right)^{k}\right]} \tag{3.3}$$

k	Shape parameter [-]
λ	Scale parameter [m/s]

Figure 3.5 shows the distribution of the 20 years wind speed data at the hub height and the values of the two parameters which describe the distribution are k = 2.12 and λ = 11.67 m/s.

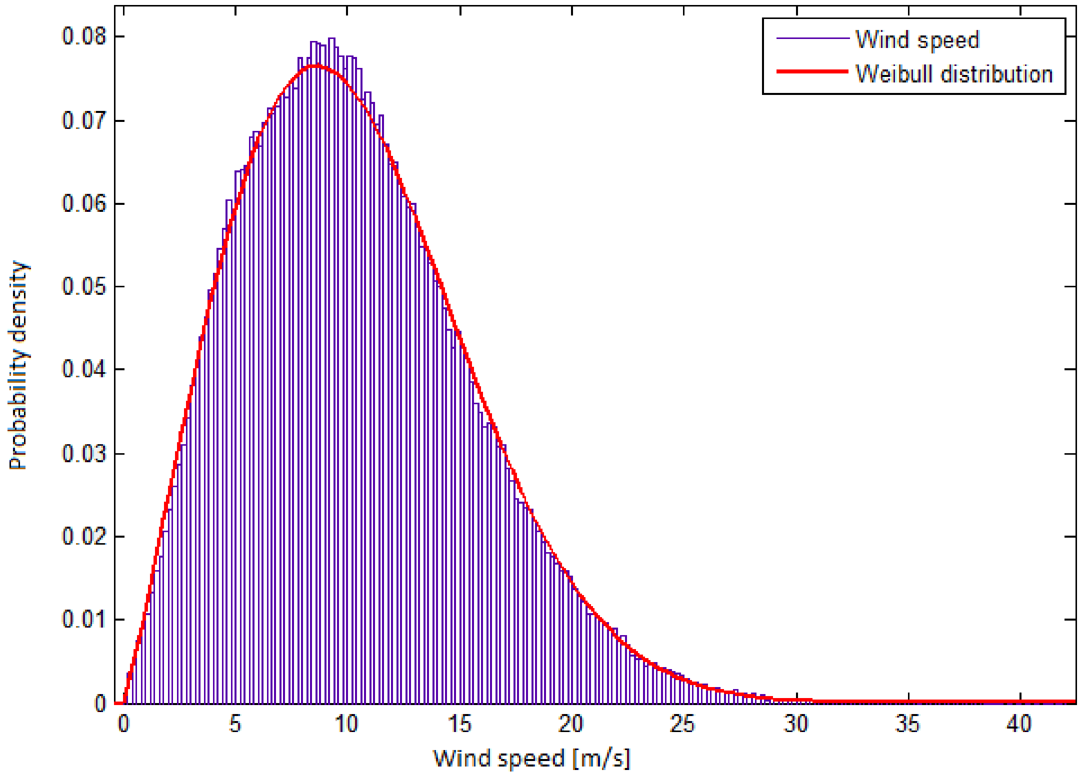

Figure 3.5. Probability and Weibull distribution of the wind speed.

The mean wind speed in the 20 years lifetime of the wind farm Horns Rev 2 resulted as being 10.33 m/s.

The calculations can be found in Digital Appendix B.1.2.

3.2.1 Annual energy production

Annual energy production of a wind turbine depends on the turbine power curve and the wind speed distribution at the hub height.

Power curve

The power curve of a wind turbine can be defined as the electrical power output versus wind speed. [Hau, 2006] The main characteristics that define the power curves are:

- Cut in velocity, v_i - the wind speed value when the wind turbine starts to produce power.
- Rated wind velocity, v_r - the value of the wind speed when the rated generated power is produced.
- Cut out velocity, v_o - the maximum value of the wind speed at which the power is produced by the turbine.

For Horns Rev 2 wind farm, the characteristics of the power curve are presented in Table 3.6

v_i	4 m/s
v_r	13.5 m/s
v_o	25 m/s

Table 3.6. Power curve characteristics.[LORC, 2014]

The graphic representation of the power curve is shown in Figure 3.6 and it was realized with the power curve data taken from [LORC, 2014] .

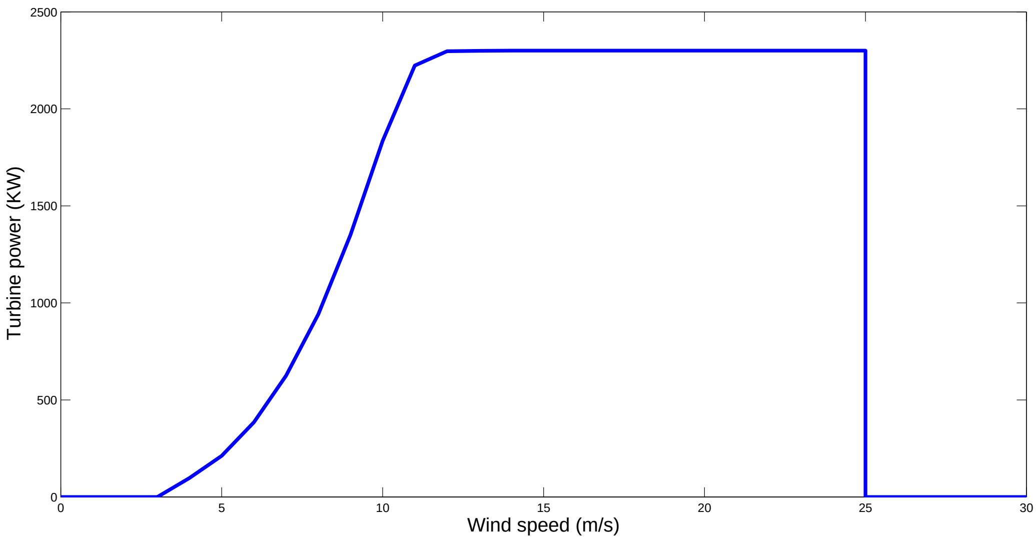

Figure 3.6. Power curve of a wind turbine Siemens SWT-2.3-93.

The calculations can be seen in Digital Appendix B.1.2.

The annual energy production, AEP, is given by equation (3.4). Weibull probability of wind speed, $P_w(u)$, is multiplied with the power curve of the wind turbine, $F(u)$, and integrated over the wind speed range, du.

$$AEP = \int_0^{\infty} P_w(u) \cdot F(u) \cdot du \tag{3.4}$$

Table 3.7 shows the AEP for each year of the wind farm lifetime when it is assumed that no maintenance activity is performed, therefore the wind farm availability is assumed to be 100%.

Year	**AEP without energy loss -100 % availability [GW/h]**
1^{st}	953.40
2^{nd}	1028.20
3^{rd}	918.01
4^{th}	1089.20
5^{th}	1123.20
6^{th}	1277.20
7^{th}	1219.60
8^{th}	1240.20
9^{th}	1168.20
10^{th}	1052.80
11^{th}	1131.70
12^{th}	1032.70
13^{th}	1187.80
14^{th}	1212.10
15^{th}	1364.20
16^{th}	1286.50
17^{th}	1298.90
18^{th}	1262.40
19^{th}	832.58
20^{th}	899.41

Table 3.7. Annual energy production at 100% availability of the wind farm.

The calculations of AEP without performing the maintenance activities can be seen in Digital Appendix B.1.2.

3.3 Operational expenditure

$O\&M$ costs are composed by the CM costs and PM costs.

3.3.1 Corrective maintenance

The corrective maintenance is performed every time when a failure occurs. It is assumed that failures can be divided in two groups, minor and major failures, depending on the time the failure is required to be repaired. It is considered that minor failures require a repair time of 12 hours and major failures require a repair time of 30 hours. The category of failure in which each component belongs, can be seen in Table 3.8.

Minor failures	Major failures
Mechanical brakes	Blades
Sensors	Drive train
Hydraulics	Yaw system
Control system	Hub
Electrical system	Pitch
Structure cracks	Gears
Generator	

Table 3.8. Failures categories.

Each component has a failure frequency, based on which the calculations were performed.

Failure component	Annual expected number of failures	Percentage for contribution of each component to annual failures of a turbine [%]
Blades	0.1307	3.38
Drive train	0.2888	7.47
Yaw system	0.5076	13.13
Hub	0.001	0.03
Pitch	0.9778	25.29
Gears	0.045	1.16
Mechanical brakes	0.005	0.13
Sensors	0.054	1.40
Hydraulics	0.0536	1.39
Control system	0.8616	22.28
Electrical system	0.4651	12.03
Structure cracks	0.1512	3.91
Generator	0.3246	8.40
Total annual number of failures for a wind turbine	3.866	100

Table 3.9. Annual failure frequencies for the components of a wind turbine.

In this thesis, failure frequencies presented in Table 3.9 are used, based on [Ribrant and Bertling, 2007] and [B.Maples et al., 2013].

Minor corrective maintenance

For this maintenance category, the following assumptions were made: the crew responsible for the failures repair is composed of 3 technicians who are working 12 hours per day. For each worked hour, the cost is assumed to be 140 €. The logistic time is considered to be 0 hours, because the spare parts are stored in the port deposit. The vessel required for minor CM is assumed to be a crew transfer vessel and the travel limits for port-wind farm-port travel and the operation limits can be seen in Table 3.10.

	Minor maintenance
	Crew transfer vessel
Vessel dayrate [€/day]	5.000
Travel wave limit [m]	1.5
Travel wind limit [m/s]	20
Travel time [hours]	1.76
Operation wave limit [m]	4
Operation wind limit [m/s]	10
Operation time [hours]	12

Table 3.10. Vessel and maintenance operation limitations.

Major corrective maintenance

The assumptions made for the major CM category are as follows: 2 crews are responsible for failures repair and each crew is composed by 3 technicians. The crews are working in shifts of 12 hours and the cost of each worked hour is assumed to be 140 €. The logistic time is considered to be 168 hours, time in which the spare parts are brought in port. The vessel required for major CM is assumed to be a jack up vessel and the travel limits for port-wind farm-port travel and the operation limits can be seen in Table 3.11.

	Major maintenance
	Jack up vessel
Vessel dayrate [€/day]	60.000
Travel wave limit [m]	1.5
Travel wind limit [m/s]	15
Travel time [hours]	4.40
Operation wave limit [m]	5
Operation wind limit [m/s]	10
Operation time [hours]	30

Table 3.11. Vessel and maintenance operation limitations.

The wind speed limit for access the wind turbines for both categories is 10 m/s, which is taken from Appendix Table A.2. In order to calculate the travel time of the vessel for both failures categories, equation (A.1) is used. The vessels dayrates were considered based on [Kaised and Snyder, 2012] and the travel and operation wind speed and wave height limitations are considered based on [Dowell et al., 2013].

3.3.2 Description of the simulation model

For estimating the CM costs, a simulation model is used and Monte Carlo simulation is performed to estimate the expected values of CM costs. The mean time to failure, MTTF, of each wind turbine component can be predicted, by using the failures frequencies from Table 3.9. Therefore, MTTF can be calculated by equation (3.5).

$$MTTF = \frac{1}{\lambda_f} \tag{3.5}$$

λ_f | failure frequency of each component

The exponential distribution, represented by equation (3.6), is used to model the distribution function of the time to failure.

$$F(t) = 1 - e^{\frac{-t}{MTTF}} \tag{3.6}$$

Realizations of time to failure are obtained by simulation where realizations of random numbers, R, uniformly distributed between 0 and 1 are used. If $F(t)$ is replaced by R, the random numbers required for Monte Carlo simulations can be provided with equation (3.7).

$$t = -MTTF \cdot \ln(R) \tag{3.7}$$

Monte Carlo method is generally used for performing a risk analysis by computing models which use a probability distribution for each variable which presents uncertainty and it is considered in the model. After the model is computed, it is simulated for thousands of times before the calculations are finished. For each model simulation, there are used different random numbers generated by the distribution function. One of the main advantage of Monte Carlo simulation is that by performing a sensitivity analysis, it can be observed the impact of different variables on the obtained results. [Corporation, 2014] One of the disadvantages is that Monte Carlo simulation can take a long time to perform the calculations. The results depend on the number of simulations and the higher the simulations number, the more precise are the results.

3.3.3 Corrective maintenance results

The model was simulated 1000 times and the final results obtained for Horns Rev 2 wind farm are presented in this subsection.

Number of failures of the wind turbines components

By using equation (3.7), the failures of each component of each turbine were generated. Figure 3.7 shows the failure percentage in one year of each component from the minor category.

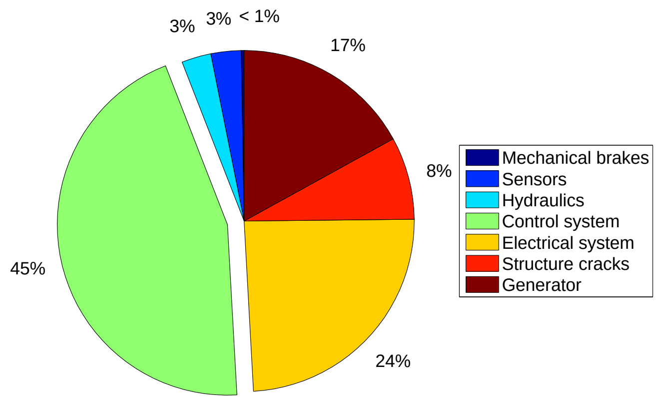

Figure 3.7. Annual failures percentages for minor components category.

It can be seen that the control system of a wind turbine is the component which fails most often in a year from those 7 components which compose the minor category of failures. In Figure 3.8 are presented the failure percentages of the components from the major category.

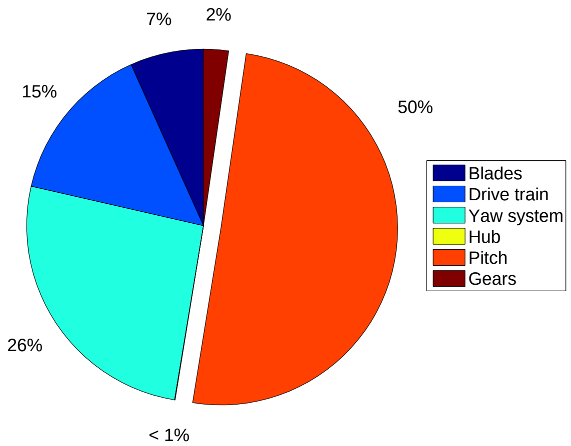

Figure 3.8. Annual failures percentages for major components category.

For an overview of all components failures, Figure 3.9 describes the distribution of failure numbers for all components of a wind turbine.

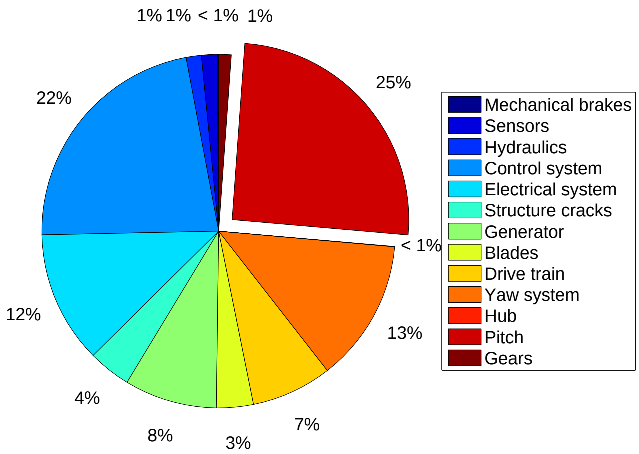

Figure 3.9. Annual failures percentages for the components of a wind turbine.

From Figure 3.9, it can be stated that the wind turbine pitch system is the component which fails more often in a year. The obtained annual failures rates with the simulation model agree with the failure frequencies from Table 3.9 showing that the simulation model is performed correct.

Energy loss

When a failure is repaired, the wind turbine is not working, therefore it is not producing energy. This non produced energy is named in this project the energy loss. Figure 3.10 shows how much energy could be produced in the downtime allocated for each minor failure component using the cost model in section 3.3.2.

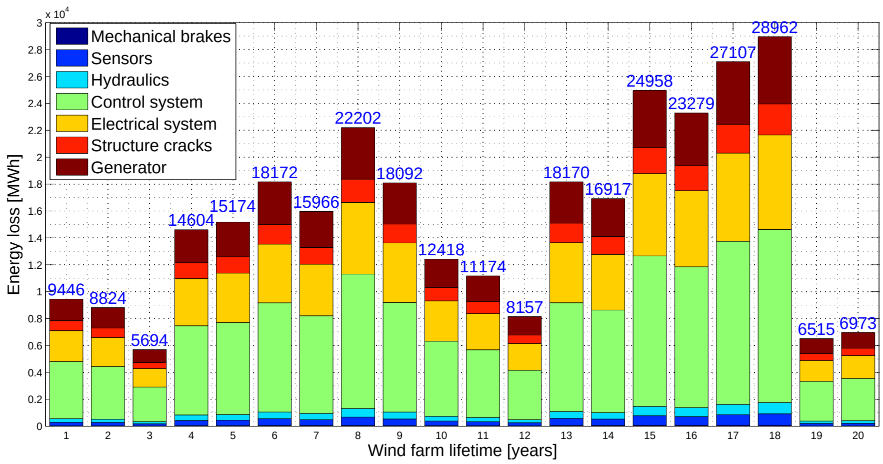

Figure 3.10. Wind farm annual energy loss influenced by each component from minor failures category.

Figure 3.11 represents the energy loss for major failures components.

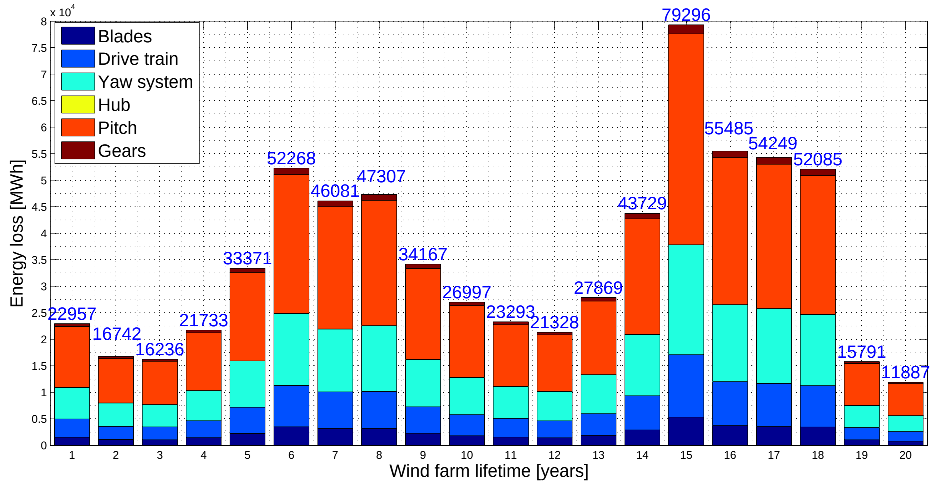

Figure 3.11. Wind farm annual energy loss influenced by each component from major failures category.

It can be noticed that the decreasing and increasing trend of the energy loss for the first 9 years is the same as for the following years. The reason for this is that the wind speed and wave height measurements from the first 9 years are correlated with the measurements from the following years. As presented in section 3.2, the wind speed and wave height measurements were provided just for a period of 9 years. Therefore to obtain a 20 years of measurements, the first 9 years were repeated for the following 9 years, but the measurements were multiplied with 1.1. For the last 2 years of lifetime, the measurements from the 1^{st} and 2^{nd} year were considered, but they were multiplied with 0.9. Furthermore, the differences between years can be also influenced by the low number of run simulations. A higher number of simulations was not applied because it would have increased the computation time, and it would have made it very difficult to run all the calculations. It should be noted that a higher number of the simulations would provide more stable results.

3.3.4 Corrective maintenance costs

The total costs required for the CM procedure are composed by the spare parts costs, vessel dayrate costs, crew costs and revenue losses.

- **Spare parts costs** - for each spare part of each component was allocated a price, in order to calculate the final costs with the spare parts. Table 3.12 shows the prices for the components which were considered in the CM. The prices were considered based on [M.Martin-Tretton et al., 2011] and [Rademakers and Braam, 2002], but they were converted from USD to EURO. By multiplying the spare part price for each component with how many times a component fails, the final costs with the spare parts are obtained.

Component	Price [€/component]	No. of failures /year/ wind farm	Spare parts costs [€/year]
Blades	5000	12	60.000
Drive train	10.000	26	260.000
Yaw system	4000	45	180.000
Hub	50.000	0.1	5.000
Pitch	4.000	88	352.000
Gears	70.000	4	280.000
Mechanical brakes	1.000	0.5	500
Sensors	500	5	2.500
Hydraulics	1.000	5	5.000
Control systems	3.000	78	234.000
Electrical systems	3.000	42	126.000
Structure cracks	5.000	14	70.000
Generator	15.000	29	435.000
Total annual number of failures per wind farm		349	
Total annual number of failures per turbine		3.84	
Total annual costs with spare parts [€/wind farm]			2.010.000

Table 3.12. Annual costs with spare parts and failures number.

- **Vessel dayrate costs** - for the maintenance activity of the wind farm, the vessels are rented just for the time period composed by travel time and operation time. The waiting time and logistic time are not considered, because the vessels are not used in that period. For minor CM, the costs with the vessel are approximately 350.000 €/year and for major CM are approximately 8.000.000 €/year.
- **Crew costs** - in the crew costs calculations, the same time period was used as for vessel costs calculations. The reason is that the crew is working only in the travel and operation time. Therefore, the expenditure with the crews required for minor CM are approximately 700.000 €/year and for major CM are approximately 1.300.000 €/year.
- **Revenue losses** - depend on the energy loss and the cost of energy. By multiplying the energy loss presented in Figures 3.10 and 3.11 with the assumed cost of energy of 130 €/MWh, the revenue losses are obtained. Figure 3.12 shows the revenue losses for minor failures category.

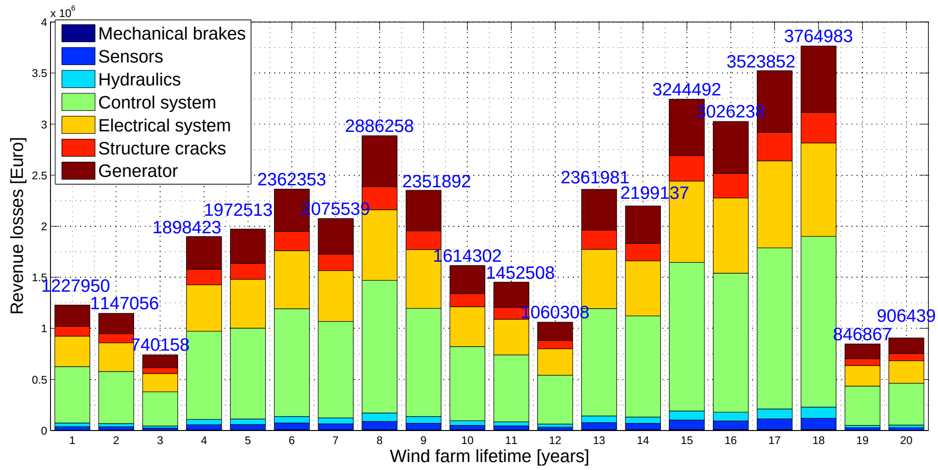

Figure 3.12. Wind farm annual revenue losses for minor failures components.

Figure 3.13 presents the revenue losses for major failures category.

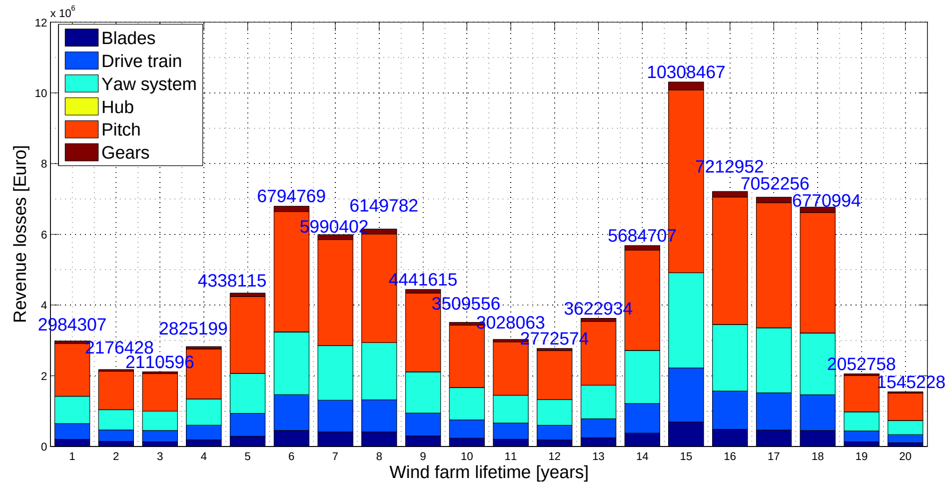

Figure 3.13. Wind farm annual revenue losses for major failures category.

- **Total costs for corrective maintenance** - are composed by summing up the costs with the spare parts, vessels dayrate costs, crew costs and revenue losses. Figure 3.14 presents the total costs for each category of CM and also their total.

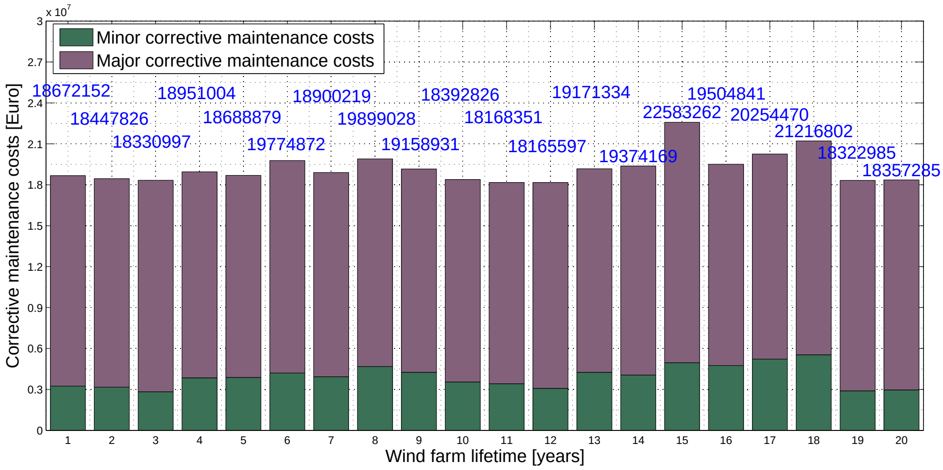

Figure 3.14. Wind farm annual corrective maintenance costs.

All the calculations performed for corrective maintenance can be seen in Digital Appendix B.1.3.

3.3.5 Preventive maintenance

Preventive maintenance is performed before a failure occur and the purpose of carry out this type of maintenance is to avoid an actual failure. PM can be classified in scheduled maintenance and condition based maintenance. In the following, condition based maintenance is considered. This implies that the maintenance is performed by considering the real condition of a component. Therefore, each component of a wind turbine is monitored by a system which shows the components health condition. As in the case of CM, the components are divided in 2 failures categories: major and minor. These types of failures are presented in Table 3.8. The number of technicians and all the limitations required for PM are the same as for CM and they are presented in subsection 3.3.1.

Description of the preventive maintenance model

The model theory is based on [Nielsen and Sørensen, 2010].

Due to the fact that the condition based maintenance is performed by taking into account the health condition of each component, a damage accumulation model was defined for each component of each turbine from the wind farm, using equation (3.8).

$$D_{t+\Delta t} = D_t + \frac{dD}{dt} \cdot \Delta t \tag{3.8}$$

D_t	Damage size at time step t
$\frac{dD}{dt}$	Damage accumulation rate
Δt	Time step

The time step is considered 30 minutes and the damage accumulation rate is given by equation (3.9).

$$\frac{dD}{dt} = \frac{dN}{dt} \cdot C \cdot \Delta K^m \tag{3.9}$$

$\frac{dN}{dt}$	Number of cycles per hour
C	Damage coefficient
ΔK	Change in damage accumulation
m	Damage exponent.

Coefficient C is assumed to follow a Lognormal distribution and it is calibrated to the failure rates from Table 3.9 for each component individually and the mean values of each component are presented in Table 3.13.

Component	**Mean value**
Blades	$5.67 \cdot 10^{-10}$
Drive train	$1.09 \cdot 10^{-9}$
Yaw system	$1.89 \cdot 10^{-9}$
Hub	$7.60 \cdot 10^{-11}$
Pitch	$2.85 \cdot 10^{-9}$
Gears	$7.60 \cdot 10^{-11}$
Mechanical brakes	$7.60 \cdot 10^{-11}$
Sensors	$1.65 \cdot 10^{-10}$
Hydraulics	$1.65 \cdot 10^{-10}$
Control systems	$2.84 \cdot 10^{-9}$
Electrical systems	$1.60 \cdot 10^{-9}$
Structure cracks	$5.36 \cdot 10^{-10}$
Generator	$1.18 \cdot 10^{-9}$

Table 3.13. Mean values of damage coefficients.

Based on [Nielsen and Sørensen, 2010], the number of load cycles per hour was assumed to be $360/h$ and the damage exponent was assumed to be 2. These 2 parameters were assumed to be constant for all the wind turbine components considered in the model. Change in damage accumulation is assumed to depend on the wind speed, therefore ΔK is given by equation (3.10).

$$\Delta K = \beta \cdot \Delta s \cdot \sqrt{\pi \cdot D} \tag{3.10}$$

β	Geometry factor
Δs	Wind speed measurements

The geometry factor is considered to be 1 and the wind speed measurements from the wind farm lifetime were used.

The followed steps in the condition based maintenance model are applied:

- The initial condition for the damage accumulation model is $D(t=0) = D_0$.
- When the turbine is operating, the damage is accumulated for all the components and when 1 is reached, the turbine stops producing energy.
- The damage level requiring maintenance is set to 0.8, meaning that maintenance of the component is planned in the moment the component damage reached 0.8. This implies that the spare part is ordered, the good weather window is searched and the crew and vessel are prepared.
- If the component is repaired before damage level will reach 1, then the rest of the components for the same turbine will continue to operate and to accumulate damage in the waiting time and logistic time and it will not accumulate damage in the time that the turbine is repaired, because the turbine is stopped during the repair time. The damage starts to be accumulated again to the rest of the components of that turbine, after the turbine will be fixed and turned on again.
- If the component is repaired just after the damage level reached 1, that means that the component failed and the entire turbine stops. Therefore the damage accumulation was stopped for the rest of the components from that certain turbine in the moment that the component failed and the components will start to accumulate damage again after the failed component was repaired.
- For the repaired components the damage accumulation will start again with an initial damage of $D_0 = 0.01$.

In order to illustrate the damage accumulation process, Figure 3.15 shows the damage accumulation progress for the pitch component of a wind turbine.

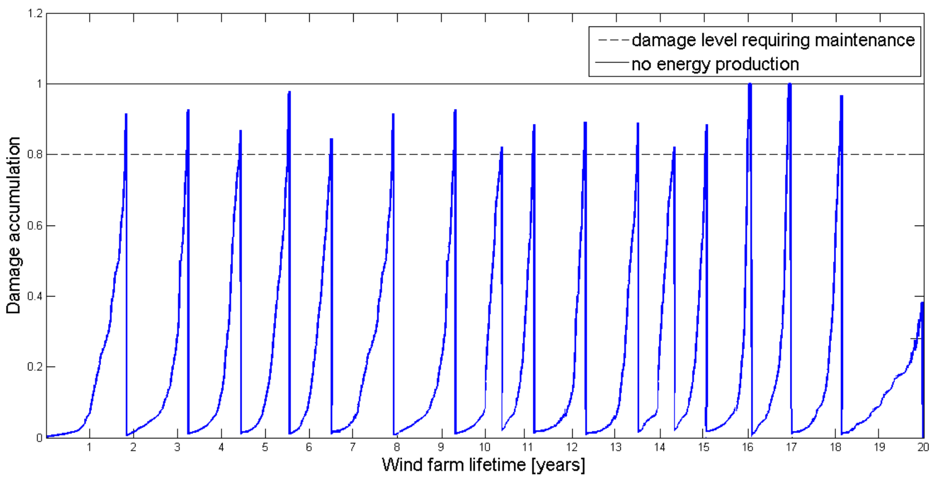

Figure 3.15. Graphic representation of the damage accumulation process for pitch component.

Figure 3.15 illustrates that when a component accumulates a damage of 0.8, then the maintenance is planned and performed. The damage continues to accumulate until the moment when the repair is performed. During the repair, the turbine is stopped and it is not producing energy. After the component is replaced, the damage accumulation process will start again from 0.01, which it is the assumed initial damage of a replaced component. If the damaged component could not be replaced before the damage reaches level 1, then the failure occurs and it will lead to corrective repairs.

3.3.6 Preventive maintenance results

For obtaining the final results and costs resulting from the PM activity, the model was simulated 120 times.

Number of failures of the wind turbines components

The time when a failure occurs to a component is related to the failure frequency of each component based on Table 3.9 and implicitly to the MTTF. Table 3.14 shows MTTF of each component and the number of failures per wind farm during 20 years.

Component	**MTTF [years]**	**No. of failures/ lifetime/ wind farm**
Blades	7.65	258
Drive train	3.46	530
Yaw system	1.97	947
Hub	1000	0
Pitch	1.02	1436
Gears	22.22	0
Mechanical brakes	200	0
Sensors	18.51	49
Hydraulics	18.65	50
Control systems	1.16	1478
Electrical systems	2.15	819
Structure cracks	6.61	247
Generator	3.08	593
Total number of failures/wind farm/lifetime		6407
Total number of failures/turbine/year		3.52

Table 3.14. Components mean time to failure and their failures number.

The obtained number of failures which occur in the wind farm lifetime fits with the annual failures frequencies from Table 3.9.

Energy loss

There are two cases when the energy is lost during the condition based maintenance. The first case is when the component is repaired before the actual failure of the component, therefore the energy is lost just in the repair time. The second case is when the component could not be repaired before the failure. Therefore, the energy is lost from the moment the failure occurred and until the component was repaired. Figure 3.16 shows the energy loss from the minor components failures and in Figure 3.17 is presented the energy loss from the major components failures.

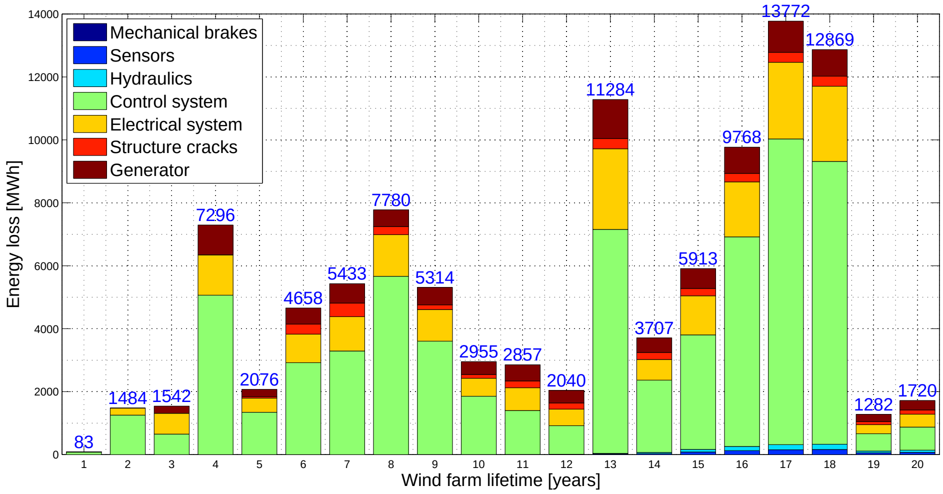

Figure 3.16. Wind farm annual energy loss due to minor components failures.

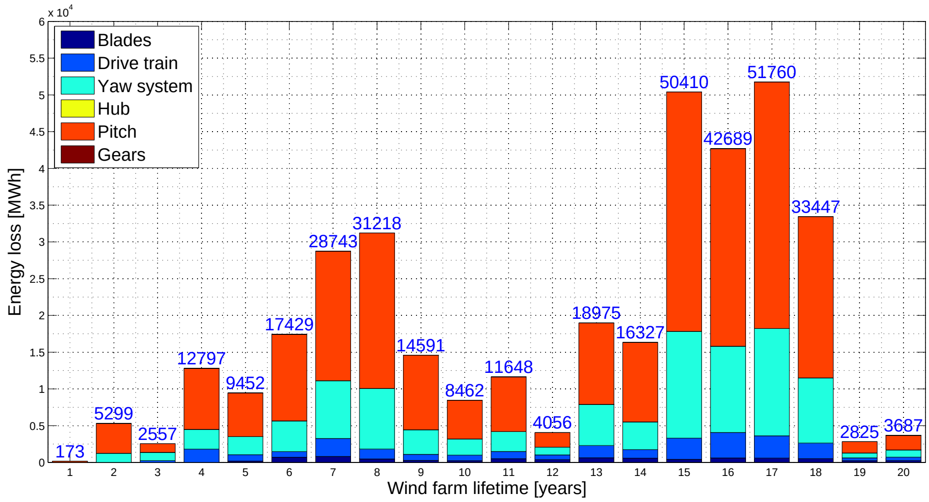

Figure 3.17. Wind farm annual energy loss due to major components failures.

The difference between years occurs because in certain years there are more components which accumulated enough damage in order to be replaced than in other years.

Comparing Figures 3.10 and 3.11 from corrective maintenance cost model with Figures 3.16 and 3.17 from preventive maintenance cost model, it can be concluded that the loss of energy is significantly higher in case of corrective repairs than for preventive ones. This high difference is due to the fact that a failure repair leads to higher energy loss than preventing the failure.

3.3.7 Preventive maintenance costs

The total PM costs include the costs with the spare parts, vessels, crews and revenue losses.

- **Spare parts costs** - the spare parts prices used in calculating the spare parts expenditures are considered the same as in case of corrective maintenance and they are presented in Table 3.12. The final spare parts costs were obtained by multiplying the component price with the number of failures of each component during lifetime. A cost of 33.235.600 € was obtained for the spare parts needed for 20 years of PM.
- **Vessel dayrate costs** - the vessels are rented just for a period of time composed by travel time and operation time. Waiting time and logistic time are disregarded. Therefore, an approximately total vessel cost of 220.000 €/year is needed for minor PM and 6.000.000 €/year for major PM.
- **Crew costs** - for calculating the final crew costs, it was considered that the technicians are paid in travel and operation time and not in waiting and logistic time. The crew expenditures are 430.000 €/year for minor PM and 1.000.000 €/year for major PM.
- **Revenue losses** - are obtained by multiplying the energy loss presented in Figures 3.16 and 3.17 with the cost of energy which is considered 130€/MWh. The revenue losses resulted from minor PM are shown in Figure 3.18.

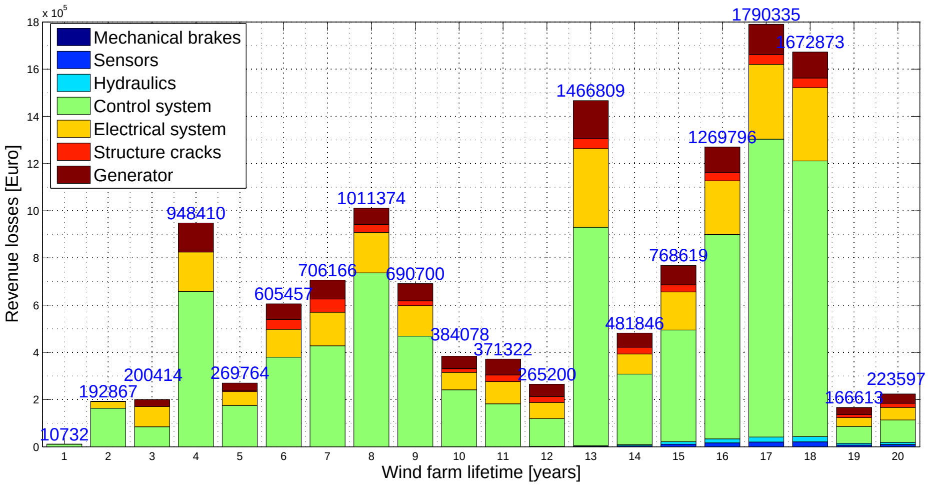

Figure 3.18. Wind farm annual revenue losses for minor failures category.

For major failures category, the revenue losses are presented in Figure 3.19.

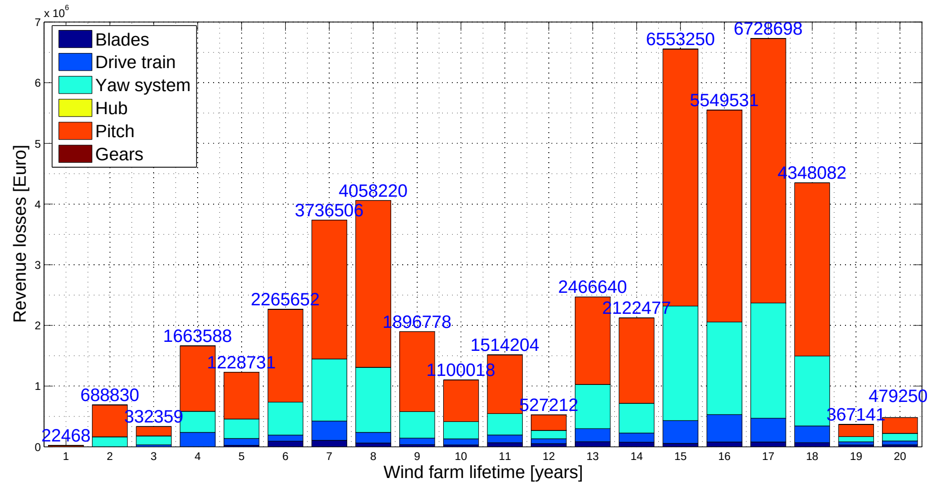

Figure 3.19. Wind farm annual revenue losses for major failures category.

- **Total costs for preventive maintenance** - represents the costs composed of spare parts costs, vessel dayrates costs, crew costs, revenue losses and they are presented in Figure 3.20.

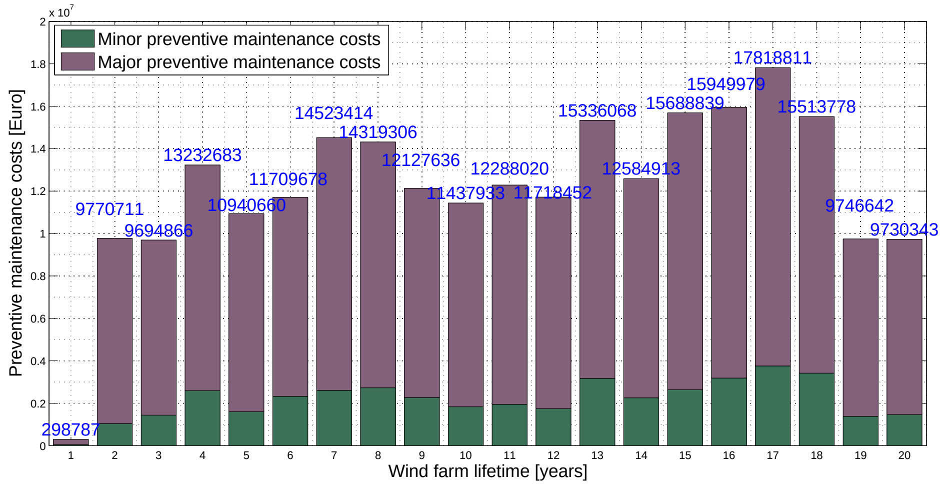

Figure 3.20. Wind farm annual preventive maintenance costs.

The energy loss due to maintenance activities leads to revenue losses, which contributes to the total maintenance costs. Therefore it can be concluded based on the results presented above that the corrective maintenance generates higher costs than the preventive one.

All the calculations performed for PM can be seen in Digital Appendix B.1.3.

3.3.8 Annual energy production including maintenance activity

During maintenance activity of the wind farm, there is some loss of energy. Table 3.15 shows AEP of Horns Rev 2 after performing only CM and after both CM and PM are conducted.

Year	**AEP with CM energy loss [GW/h]**	**AEP with PM energy loss [GW/h]**
1^{st}	920.99	953.14
2^{nd}	1002.60	1021.40
3^{rd}	896.08	913.91
4^{th}	1052.90	1069.10
5^{th}	1074.70	1111.70
6^{th}	1206.80	1255.10
7^{th}	1157.50	1185.40
8^{th}	1170.70	1201.20
9^{th}	1116.00	1148.30
10^{th}	1013.40	1041.30
11^{th}	1097.20	1117.20
12^{th}	1003.20	1026.60
13^{th}	1141.70	1157.50
14^{th}	1151.40	1192.00
15^{th}	1260.00	1307.90
16^{th}	1207.80	1234.10
17^{th}	1217.60	1233.40
18^{th}	1181.30	1216.10
19^{th}	810.28	828.48
20^{th}	880.55	894.00

Table 3.15. Annual energy production after performing wind farm maintenance.

It can be observed in Table 3.15 that if corrective maintenance is implemented as a maintenance strategy, then the energy production level of the wind farm is lower than if preventive maintenance would be implemented. The reason for this is that in case of corrective maintenance, the repairs are performed only after the components failed. Therefore the energy loss due to corrective maintenance is higher, because the wind turbines downtime is longer than in case of preventive maintenance. During preventive maintenance the wind turbine components are monitored and when it is considered that the components are too damaged, they are generally replaced before the failures occur.

3.4 Decommissioning expenditure

At the end of the wind farm lifetime, the operation of decommissioning has to be performed. The activities of the wind farm decommissioning are taking place in the approximate reverse order than the installation activities.

3.4.1 Turbines decommissioning costs

The method used is the self-transport model, which means that after the turbines are removed, they have to be transported back to shore by the vessel which performs the removal. The factors which contributes to the final costs of the turbines decommissioning are presented in Table 3.16.

Decommissioning time [hours/trip]	383
Weather adjusted time [hours/trip]	451
Number of trips	12
Total decommissioning time of operation [hours]	5412
Total cost [€]	22.888.250

Table 3.16. Turbines decommissioning costs.

3.4.2 Foundations decommissioning costs

The operations for the foundations removal are based on a single vessel model, which means that the removal time is calculated per one single foundation and in the end it is multiplied with the number of the foundations to obtain the final removal time of the entire wind farm. The final costs for foundations decommissioning can be seen in Table 3.17.

Removal time [days/foundation]	3
Total removal time of foundations [days/wind farm]	273
Total cost [€]	27.709.500

Table 3.17. Foundations decommissioning costs.

3.4.3 Cables decommissioning costs

The vessels needed for cables removal are less expensive than those for the cables installation. There are two possibilities for cables decommissioning: the first possibility is that the cables are removed entirely and the second possibility is that there is no need for cables removal. For the baseline model, it was assumed that the cables are removed and the final costs are shown in Table 3.18.

	Inner array cables	Export cables
Vessel dayrate [€]	24.000	35.000
Cable removal rate [km/day]	0.6	1.4
Cable length [km]	70	42
Required decommissioning time [days]	117	30
Cable decommissioning costs [€]	2.808.000	1.050.000

Table 3.18. Cables decommissioning costs.

3.4.4 Substation decommissioning costs

The topside of the substation is first removed by a heavy lift vessel and will be placed on a barge and after that the operation will be repeated for the foundation part after its cutting. The final costs for the substation removal is 280.000 € and it is obtained by multiplying the number of days required for the substation removal and the day rate of the vessel needed for the operation.

3.4.5 Scour protection decommissioning costs

As in the case of the cables removal, the scour protection may or may not be removed. Baseline model was computed with the assumption that the scour protection is not necessary to be removed.

3.4.6 Site clearance costs

For this procedure, the area where the wind farm was situated has to be verified in order to see if the decommissioning was performed in a proper way. The area where each foundation was installed should be verified, therefore the final cost is given by multiplying the number of foundations with the site clearance costs per foundation. A cost of 1.116.000€ is needed for this operation.

3.4.7 Scrap revenues

With the purpose of decreasing decommissioning costs, the scrap obtained from wind farm removal can be sold. Due to the fact that these revenues have a minor influence on the final decommissioning cost, they were not taken into account in the baseline model.

3.4.8 Labor costs

The labor costs required for the decommissioning of the wind farm were calculated for each main step by assuming the technicians number and considering that a technician is paid with 140 €/hour. Table 3.19 presents the final labor costs.

	Number technicians	Required hours	Costs [euro]
Foundations	5	6552	4.586.400
Turbines	5	5412	3.788.400
Inner Cables	2	2808	786.240
Export Cables	2	720	201.600
Substation	4	168	94.080
Site clearance	4	144	80.640
Total labor costs [€]		9.537.360	

Table 3.19. Labor costs for wind farm decommissioning.

The decommissioning of the wind farm is estimated to 65.389.110 € and the percentages of each decommissioning operation are presented in Figure 3.21.

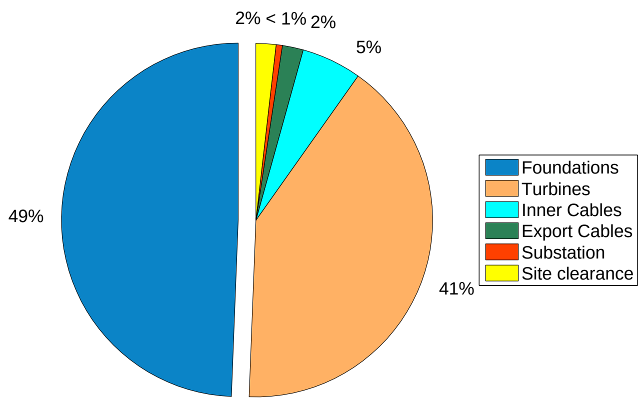

Figure 3.21. Percentages of different decommissioning costs.

The algorithm used in order to calculate the decommissioning costs is presented in Appendix A.1 and the calculations can be seen in Digital Appendix B.1.4.

3.5 Levelised cost of energy

In order to calculate LCOE, equation (2.1) is used. The calculations were performed by considering AEP which was obtained after the maintenance of the wind farm was performed. For the corrective maintenance cost model a LCOE of 68.69 €/MWh is obtained and for preventive maintenance cost model a LCOE of 59.80/MWh. Therefore, based on the obtained results, it can be concluded that the preventive maintenance strategy is more profitable for the wind farm.

3.5.1 Comparison of LCOE

Based on [S.Tegen et al., 2012], LCOE for offshore wind farms is between 118$/MWh and 292$/MWh, which are approximately 87 €/MWh and 216 €/MWh respectively.

It can be observed that the obtained LCOE from the model developed in this project is lower than the LCOE based on [S.Tegen et al., 2012]. The reason for this is that LCOE is sensitive to various factors, such as capital costs, O&M costs, wind farm energy production. Furthermore, it has to be taken into account that the baseline model was developed based on the assumptions made in this thesis and on costs which were considered based on different references. Due to the fact that the exact costs and prices used in offshore wind farm industry are not available for public, the prices of spare parts or vessels dayrate, used in this thesis could be over− or underestimated and the CAPEX of the wind farm could differ from the one used in reality for Horns Rev 2 wind farm. Therefore, the obtained costs in this project could differ from the real ones.

3.5.2 Contribution of cost categories to LCOE

Figure 3.22 illustrates the contribution of each of the three types of costs to LCOE in the case of corrective maintenance.

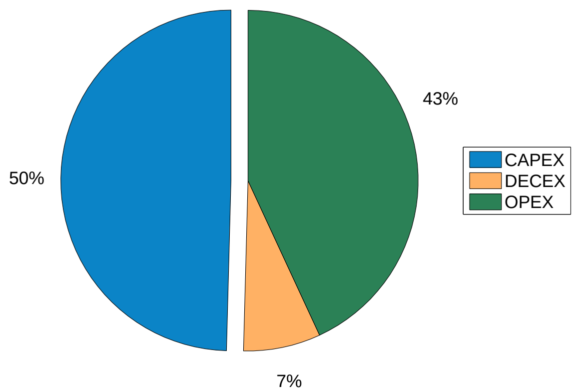

Figure 3.22. Contribution of cost categories to LCOE as a result of CM.

For preventive maintenance, the contribution of CAPEX, OPEX and DECEX to LCOE is shown in Figure 3.23.

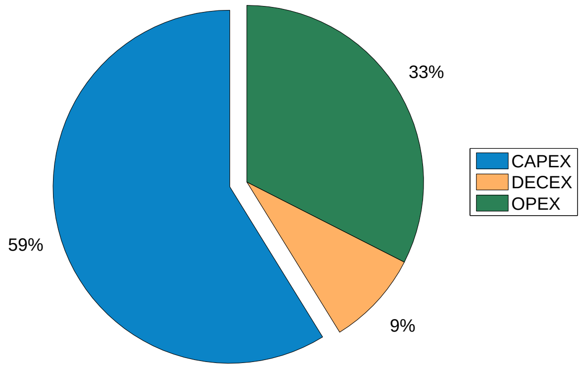

Figure 3.23. Contribution of cost categories to LCOE as a result of PM.

Based on [Stark et al., 2013], CAPEX represents between 70-80% of LCOE, OPEX represents between 20-30% and DECEX a much lower share between 0-5%. Comparing Figures 3.22 and 3.23, it can be observed that the contribution of OPEX to LCOE in the case of corrective maintenance is higher than in the case of preventive maintenance. The reason is the fact that the corrective maintenance is generally more expansive to perform than the preventive maintenance.

Sensitivity analysis 4

This chapter presents the analysis of various changes applied to the baseline model. Different scenarios were studied in order to observe the variation of the final $OPEX$ and $LCOE$.

4.1 Scenarios analysis

The scenarios from 1 to 7 are analyzed to observe the costs variation in both CM and PM and the scenarios from 8 to 10 are analyzed in order to observe the changes only in PM costs. The LCOE variation for each scenario will be presented.

4.1.1 Scenarios description

Scenario 1

It is assumed that the wind farm is placed offshore at a distance of 15 km from port instead of 32.6 km, which represents a decrease in distance by approximately 50%.

Scenario 2

It is considered that the wind farm is placed offshore at a distance of 50 km from port instead of 32.6 km, which represents an increase in distance by approximately 50%.

Scenario 3

The values of measured wind speed are increased by 10%.

Scenario 4

The values of measured wave height are increased by 10%.

Scenario 5

Both values of measured wind speed and wave height are increased by 10%.

Scenario 6

Both values of measured wind speed and wave height are decreased by 10%.

Scenario 7

Measurement values for wind speed and wave height for years 10 to 20 are obtained by a random selection from the measurements of the first 9 years.

Scenario 8

The maintenance level is considered first to be 0.7 and next to be 0.9 instead of 0.8 as in baseline model.

Scenario 9

The initial damage, D_0, after a component is repaired is considered 0.02 instead of 0.01.

Scenario 10

The impact of damage exponent, m, over the final costs will be studied. The coefficient m will be considered at first 1 and after that 3 instead of 2.

4.1.2 Obtained results

For calculating the capacity factor of the wind farm, the potential energy production if the turbines will operate at their maximum capacity was calculated and an output of 36399 GWh was obtained for the wind farm lifetime and the calculation can be seen in Digital Appendix B.2.1.

Scenario 1 - it is assumed that the wind farm is placed offshore at a distance of 15 km from port instead of 32.6 km, which represents a decrease in distance by approximately 50%

It can be observed in Table 4.1, that if the distance from shore to the wind farm site is decreased by 50%, the energy loss due to maintenance activity and the generated costs are lower both for CM and for PM. One of the reasons for decreased costs is that the maintenance crew can reach the wind farm in a short period of time, therefore the failures can be repaired faster. Furthermore, the favorable weather window required for the maintenance operation will be shorter and easier to find. It can be noticed that LCOE is decreased by 2.81% for CM and 1.55% for PM.

	Baseline Model		**Scenario 1**	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	286.57	617.09
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.496.000	22.531.440
Crew costs [€/lifetime]	13.750.000	27.584.000	12.261.000	25.188.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	6.082.100	149.925.776
Total costs [€/lifetime]	78.690.000	305.650.000	73.094.000	277.870.000
LCOE [€/MWh]	68.69		66.76	
LCOE variation percent	2.81% ↘			
Energy production [GWh]	21563		21675	
Capacity factor [%]	59.23 %		59.54 %	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	95.56	328.34
Spare parts costs [€/lifetime]	17.110.000	16.125.600	17.099.200	16.195.080
Crew costs [€/lifetime]	8.592.400	19.734.000	7.678.200	18.135.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	3.808.600	107.949.350
Total costs [€/lifetime]	43.461.100	200.969.800	41.008.800	184.963.630
LCOE [€/MWh]	59.80		58.87	
LCOE variation percent	1.55% ↘			
Energy production [GWh]	22108		22154	
Capacity factor [%]	60.73 %		60.86 %	

Table 4.1. Influence of the offshore distance on the maintenance and energy cost.

Scenario 2 - it is considered that the wind farm is placed offshore at a distance of 50 km from port instead of 32.6 km, which represents an increase in distance by approximately 50%

In Table 4.2 are presented the raised new costs of wind farm maintenance generated when the offshore distance is increased by 50%. It can be observed that LCOE is increased by 2.39% for CM and by 1.19% for PM.

	Baseline Model		**Scenario 2**	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	337.10	787.16
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.420.000	22.471.000
Crew costs [€/lifetime]	13.750.000	27.584.000	15.086.000	29.520.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	7.483.200	175.712.463
Total costs [€/lifetime]	78.690.000	305.650.000	83.812.000	330.030.000
LCOE [€/MWh]	68.69		70.33	
LCOE variation percent	2.39% ↗			
Energy production [GWh]	21563		21454	
Capacity factor [%]	59.23 %		58.94 %	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	107.55	422.38
Spare parts costs [€/lifetime]	17.110.000	16.125.600	17.090.530	16.039.580
Crew costs [€/lifetime]	8.592.400	19.734.000	9.339.000	20.816.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.632.400	123.907.130
Total costs [€/lifetime]	43.461.100	200.969.800	45.043.430	215.672.110
LCOE [€/MWh]	59.80		60.51	
LCOE variation percent	1.19% ↗			
Energy production [GWh]	22108		22048	
Capacity factor [%]	60.73 %		60.57%	

Table 4.2. Influence of the offshore distance on maintenance and energy cost.

By analyzing the results from Scenario 1 and Scenario 2, it can be concluded that the costs are influenced by the distance from the shore. It can be noticed that the maintenance costs increase as the distance from the shore is increased. A larger distance implies a larger downtime of the wind turbines due to failures occurrence, which generates higher energy loss. It can be observed that a relative large change in LCOE is obtained by decreasing the distance by 50% compared to an increase in distance by 50%. This is because the energy loss is generally lower if the wind farm is placed closer to the shore.

It should be noticed that in this thesis for both scenario 1 and scenario 2 were used the same wind speed measurement values as the baseline model. In many cases the wind speed increases as the distance from the shore increases, therefore the energy production of a wind farm placed further from shore will be generally higher than for a wind farm situated closer to shore.

Scenario 3 - the values of measured wind speed are increased by 10%

Table 4.3 presents the costs variation for a higher wind speed at the wind farm location. It can be observed a higher energy loss for both maintenance strategies. Even if the costs for corrective and preventive maintenance increased due to this higher energy loss, the LCOE decreased by 6.65% for corrective maintenance and by 3.38% for the preventive one. This decrease is due to 6.17% increased energy production generated by higher wind speed. Furthermore, the damage growth is accelerated by the increased wind speed, therefore the lifetime of the components will be shorter and will lead to higher spare parts costs.

	Baseline Model		**Scenario 3**	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	347.46	824.73
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.454.200	22.445.825
Crew costs [€/lifetime]	13.750.000	27.584.000	13.237.000	25.430.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	6.566.200	151.367.045
Total costs [€/lifetime]	78.690.000	305.650.000	82.428.000	306.460.000
LCOE [€/MWh]	68.69		64.12	
LCOE variation percent	6.65% ↘			
Energy production [GWh]	21563		23043	
Capacity factor [%]	59.23 %		63.30 %	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	151.06	591.76
Spare parts costs [€/lifetime]	17.110.000	16.125.600	20.846.310	19.412.320
Crew costs [€/lifetime]	8.592.400	19.734.000	9.537.300	20.061.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.730.800	119.412.820
Total costs [€/lifetime]	43.461.100	200.969.800	52.002.000	235.820.000
LCOE [€/MWh]	59.80		57.78	
LCOE variation percent	3.38% ↘			
Energy production [GWh]	22108		23472	
Capacity factor [%]	60.73 %		64.48 %	

Table 4.3. Influence of the wind speed on the maintenance and energy cost.

Scenario 4 - the values of measured wave height are increased by 10%

It can be noticed in Table 4.4 that the energy loss is increasing for both corrective and preventive maintenance if the values for the wave height are considered higher at the wind farm site. The reason for this increase is the difficulty to find a weather window with favorable wave height when the vessels with the crews can go offshore to perform the maintenance of the wind turbines. This leads to higher downtime of the wind turbines which imply both energy and revenue losses.

	Baseline Model		**Scenario 4**	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	372.75	799.34
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.415.000	22.362.160
Crew costs [€/lifetime]	13.750.000	27.584.000	12.983.000	25.937.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	6.440.000	154.384.715
Total costs [€/lifetime]	78.690.000	305.650.000	85.296.000	306.600.000
LCOE [€/MWh]	68.69		69.40	
LCOE variation percent	1.03% ↗			
Energy production [GWh]	21563		21406	
Capacity factor [%]	59.23 %		58.81 %	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	111.27	423.87
Spare parts costs [€/lifetime]	17.110.000	16.125.600	17.076.450	16.053.580
Crew costs [€/lifetime]	8.592.400	19.734.000	7.922.300	18.416.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	3.929.700	109.619.700
Total costs [€/lifetime]	43.461.100	200.969.800	43.393.550	199.192.380
LCOE [€/MWh]	59.80		59.78	
LCOE variation percent	0.03% ↘			
Energy production [GWh]	22108		22043	
Capacity factor [%]	60.73 %		60.56 %	

Table 4.4. Influence of the wave height on the maintenance and energy cost.

Scenario 5 - both values of measured wind speed and wave height are increased by 10%

Table 4.5 shows the results of the maintenance cost models obtained after the 10% increase in both wind speed and wave height. Comparing Tables 4.5 and 4.3, it can be observed an increase in the energy loss and total maintenance costs obtained in Scenario 5. Therefore it can be concluded that the increase in energy loss was generated by the the fact that the value for wave height was increased and it is more difficult to find a favorable weather window in which the crews can be transferred to the wind farm and repair the failures.

	Baseline Model		**Scenario 5**	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	403.31	929.57
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.424.000	22.371.175
Crew costs [€/lifetime]	13.750.000	27.584.000	12.611.000	24.211.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	6.255.500	144.110.475
Total costs [€/lifetime]	78.690.000	305.650.000	88.722.000	311.540.000
LCOE [€/MWh]	68.69		64.88	
LCOE variation percent	5.54% ↘			
Energy production [GWh]	21563		22882	
Capacity factor [%]	59.23 %		62.86%	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	172.78	697.48
Spare parts costs [€/lifetime]	17.110.000	16.125.600	20.807.320	19.284.080
Crew costs [€/lifetime]	8.592.400	19.734.000	8.526.500	19.006.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.229.400	113.133.040
Total costs [€/lifetime]	43.461.100	200.969.800	56.025.000	242.100.000
LCOE [€/MWh]	59.80		58.13	
LCOE variation percent	2.79% ↘			
Energy production [GWh]	22108		23345	
Capacity factor [%]	60.73 %		64.14%	

Table 4.5. Influence of the wind speed and wave height on the maintenance and energy cost.

Scenario 6 - both values of measured wind speed and wave height are decreased by 10%

For a decreased wind speed and wave height by 10%, it can be noticed in Table 4.6 that the costs generated by corrective maintenance of the wind farm decreased by 2.24%, while the LCOE increased by 10.13%. In the case of preventive maintenance, the total costs decreased by 14.93%, while the LCOE increased by 7.88%. Furthermore, it can be observed that the costs of the spare parts decreased for preventive maintenance, because the turbine components can be replaced more rarely due to a slower damage accumulation and implicitly longer components lifetime.

	Baseline Model		**Scenario 6**	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	226.56	500.32
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.520.000	22.653.545
Crew costs [€/lifetime]	13.750.000	27.584.000	14.800.000	31.486.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	7.341.500	187.418.550
Total costs [€/lifetime]	78.690.000	305.650.000	69.115.000	306.600.000
LCOE [€/MWh]	68.69		75.65	
LCOE variation percent	10.13 ↗			
Energy production [GWh]	21563		19607	
Capacity factor [%]	59.23 %		53.86 %	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	56.49	184.31
Spare parts costs [€/lifetime]	17.110.000	16.125.600	13.680.310	13.071.700
Crew costs [€/lifetime]	8.592.400	19.734.000	8.264.700	19.778.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.099.500	117.728.900
Total costs [€/lifetime]	43.461.100	200.969.800	33.389.000	174.540.000
LCOE [€/MWh]	59.80		64.51	
LCOE variation percent	7.88 ↗			
Energy production [GWh]	22108		20093	
Capacity factor [%]	60.73 %		55.20 %	

Table 4.6. Influence of the wind speed and wave height on the maintenance and energy cost.

Scenario 7 - measurement values for wind speed and wave height for years 10 to 20 are obtained by a random selection from the measurements of the first 9 years

Analyzing the results from Table 4.7, it can be concluded that if the values for wind speed and wave height for the years 10 to 20 would be obtained by a random selection from the measured values during the first 9 years, the energy production of the wind farm would have been lower by 1.82% for CM and by 1.71%. Furthermore, the energy loss decreased by 10.87% for corrective maintenance and by 26.4% for preventive maintenance. It can be observed that LCOE for both maintenance strategies are highly similar.

	Baseline Model		Scenario 7	
	Corrective Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	312.79	702.86	278.31	626.97
Spare parts costs [€/lifetime]	17.456.619	22.502.511	17.485.335	22.548.570
Crew costs [€/lifetime]	13.750.000	27.584.000	14.148.000	28.632.000
Vessels costs [€/lifetime]	6.820.500	164.187.729	7.018.100	170.429.970
Total costs [€/lifetime]	78.690.000	305.650.000	74.833.000	303.120.000
LCOE [€/MWh]	68.69		69.22	
LCOE variation percent	0.77 ↗			
Energy production [GWh]	21563		21170	
Capacity factor [%]	59.23 %		58.16 %	
	Preventive Maintenance			
Energy loss [GWh/lifetime]	103.82	366.54	76.90	269.10
Spare parts costs [€/lifetime]	17.110.000	16.125.600	15.808.990	15.041.860
Crew costs [€/lifetime]	8.592.400	19.734.000	8.724.400	20.203.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.327.600	120.258.660
Total costs [€/lifetime]	43.461.100	200.969.800	38.858.000	190.490.000
LCOE [€/MWh]	59.80		59.90	
LCOE variation percent	0.17 ↗			
Energy production [GWh]	22108		21730	
Capacity factor [%]	60.73 %		59.69 %	

Table 4.7. Influence of the random selection of the wind speed and wave height values for the years 10 to 20 on maintenance and energy cost.

Scenario 8 - the maintenance level is considered first to be 0.7 and next to be 0.9 instead of 0.8 as in baseline model

Table 4.8 shows the results for the preventive maintenance when the level of the accumulated damage of the components which requires maintenance is considered 0.7. It can be seen that the energy loss and the total costs decreased. The reason for this decrease is that the maintenance is performed at a smaller level of damage, therefore more failures of the wind turbines components are prevented and there would be a lower number of failures which would require corrective repairs.

	Baseline Model		**Scenario 8**	
	Preventive Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	103.82	366.54	71.32	228.54
Spare parts costs [€/lifetime]	17.110.000	16.125.600	17.638.700	16.707.220
Crew costs [€/lifetime]	8.592.400	19.734.000	8.763.300	20.082.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.346.900	119.540.000
Total costs [€/lifetime]	43.461.100	200.969.800	40.020.500	186.039.420
LCOE [€/MWh]	59.80		58.77	
LCOE variation percent	1.72% ↘			
Energy production [GWh]	22108		22278	
Capacity factor [%]	60.73 %		61.21 %	

Table 4.8. Influence of the damage level which requires maintenance on maintenance and energy cost.

Table 4.9 presents the results when the level of accumulated damage of the components which requires maintenance is considered 0.9. It can be observed an increase in energy loss and in total costs of the maintenance. This is due to late identification of the damaged components at a point where it is typically too late to apply preventive maintenance. Therefore failures which need corrective maintenance occur more often.

	Baseline Model		Scenario 8	
	Preventive Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	103.82	366.54	180.07	653.70
Spare parts costs [€/lifetime]	17.110.000	16.125.600	16.597.450	15.530.880
Crew costs [€/lifetime]	8.592.400	19.734.000	8.435.100	19.390.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.184.100	115.414.480
Total costs [€/lifetime]	43.461.100	200.969.800	52.625.750	235.316.360
LCOE [€/MWh]	59.80		62.35	
LCOE variation percent	4.26% ↗			
Energy production [GWh]	22108		21744	
Capacity factor [%]	60.73 %		59.74 %	

Table 4.9. Influence of the damage level which requires maintenance on maintenance and energy cost.

Scenario 9 - the initial damage, D_0, after a component is repaired is considered 0.02 instead of 0.01

In Table 4.10 are presented the results when the initial damage is considered 0.02. It can be observed that there was an increase in the total costs of the maintenance. The reason for this increase, is that the damage will accumulate in a shorter time if the damage accumulation process starts from 0.02, therefore more repairs will be required, which lead to higher maintenance costs.

	Baseline Model		Scenario 9	
	Preventive Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	103.82	366.54	120.41	429.65
Spare parts costs [€/lifetime]	17.110.000	16.125.600	20.063.000	18.943.000
Crew costs [€/lifetime]	8.592.400	19.734.000	9.416.100	21.604.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	4.670.700	128.600.000
Total costs [€/lifetime]	43.461.100	200.969.800	49.803.100	225.001.500
LCOE [€/MWh]	59.80		61.34	
LCOE variation percent	2.57% ↗			
Energy production [GWh]	22108		22028	
Capacity factor [%]	60.73 %		60.52 %	

Table 4.10. Influence of the initial damage, D_0, on the maintenance and energy cost.

Scenario 10 - the impact of damage exponent, m, over the final costs will be studied. The coefficient m will be considered at first 1 and after that 3 instead of 2

Table 4.11 shows the results when m from PM model is considered 1. The damage exponent, m, has an impact on the damage accumulation process, therefore if m has a low value, the damage accumulates slower than if m has a high value. Due to this reason, the damage coefficient, C, was calibrated again, in order to obtain the correct failure time of the wind turbine components.

	Baseline Model		**Scenario 10**	
	Preventive Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	103.82	366.54	57.83	139.55
Spare parts costs [€/lifetime]	17.110.000	16.125.600	21.703.060	20.220.080
Crew costs [€/lifetime]	8.592.400	19.734.000	10.897.000	22.612.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	5.405.400	134.597.200
Total costs [€/lifetime]	43.461.100	200.969.800	45.523.360	195.570.780
LCOE [€/MWh]	59.80		59.00	
LCOE variation percent	1.34% ↘			
Energy production [GWh]	22108		22381	
Capacity factor [%]	60.73 %		61.49 %	

Table 4.11. Influence of the damage exponent, m, on the maintenance and energy cost.

The results with the damage exponent, m, equal to 3 are presented in Table 4.12.

	Baseline Model		**Scenario 10**	
	Preventive Maintenance			
	Minor	**Major**	**Minor**	**Major**
Energy loss [GWh/lifetime]	103.82	366.54	317.13	925.19
Spare parts costs [€/lifetime]	17.110.000	16.125.600	14.467.000	12.432.240
Crew costs [€/lifetime]	8.592.400	19.734.000	6.428.400	15.045.000
Vessels costs [€/lifetime]	4.262.100	117.460.000	3.188.700	89.556.220
Total costs [€/lifetime]	43.461.100	200.969.800	65.311.000	237.308.160
LCOE [€/MWh]	59.80		64.15	
LCOE variation percent	7.27% ↗			
Energy production [GWh]	22108		21336	
Capacity factor [%]	60.73 %		58.62 %	

Table 4.12. Influence of the damage exponent, m, on the maintenance and energy cost.

Analyzing both cases for Scenario 10, it can be concluded that the energy loss and total costs increase with a higher value of m. The reason for this is that the damage accumulation process occurs faster through the increase of the damage exponent, therefore the failures are more difficult to detect and more corrective repairs will be required.

The calculations for all scenarios can be found in Digital Appendix B.2.1.

4.1.3 Comparison of scenarios

Figure 4.1 shows how the capacity factor for corrective maintenance varies for all scenarios in comparison with the capacity factor obtained in the baseline model.

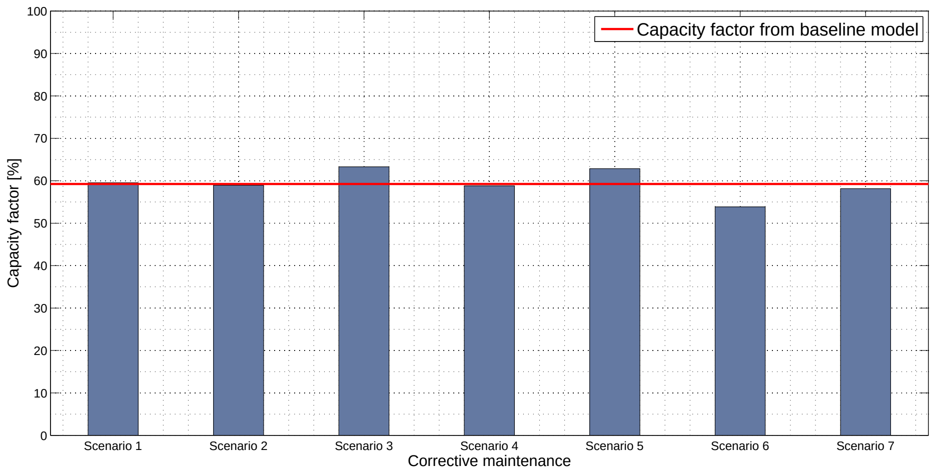

Figure 4.1. Capacity factor of scenarios considering the corrective maintenance.

For the preventive maintenance strategy, the variation of capacity factor is presented in Figure 4.2.

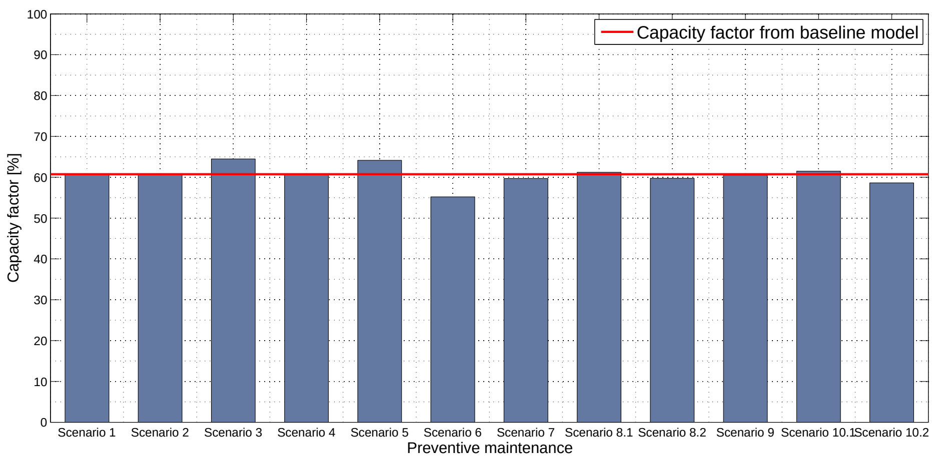

Figure 4.2. Capacity factor of scenarios considering the preventive maintenance.

Comparing Figures 4.1 and 4.2, it can be observed that in all the scenarios from 1 to 7, where both corrective and preventive maintenance were considered, the capacity factor of the wind farm is higher when the preventive maintenance is implemented. It can be noticed that in scenario 3 was obtained the highest capacity factor, therefore it can be concluded that generally the wind farms generate high energy production in areas with high wind speed either the corrective or preventive maintenance is considered.

5 Conclusion

The main objective of this thesis was to create a baseline model regarding the required costs of Horns Rev 2 wind farm installation, operation and maintenance and decommissioning and to compare different scenarios of O&M considering different environmental conditions and model parameters.

The installation costs are part of capital expenditure and a fraction of 16% was found to be allocated for them from the total CAPEX of the wind farm.

A more detailed analysis was made for O&M costs, therefore two maintenance types were considered and implemented: corrective maintenance and preventive maintenance. After the calculations were performed, it can be stated that the CM method requires higher costs than the PM method. One of the main reasons is that the corrective repairs require a larger amount of time than the preventive repairs, therefore also the time when the wind farm is not producing energy is longer in the case of CM than of PM. The energy loss leads to revenue losses, which contribute to total costs of the maintenance.

Due to the fact that the construction of the wind farm is not approved if the decommissioning activity from the end of its lifetime is not planned, the decommissioning costs were also considered in the baseline model.

A sensitivity analysis was performed for observing the variation of the final costs required for the maintenance activity and the variation of LCOE. It can be concluded that the maintenance costs increase as the distance from the shore is increased, due to the fact that the longer the distance, the higher will be the costs with the vessels and the crews. If the wind farm site is placed in an area with high wind speed, the energy production is increased, but the maintenance is more expensive to perform. Even so, it is favorable to place wind farms in areas with high wind speed, because higher energy production leads to a decrease in LCOE.

The accumulated damage level of the components which requires preventive maintenance influences the final maintenance costs. The costs will increase as the level is increased, because the failures will be harder to prevent and will imply corrective repairs. With a considered initial damage for the PM model higher than 0.01, the costs are increased due to the fact that the damage of the components is accumulated faster, therefore more repairs are required. A high value of the damage exponent, m, will lead to an accelerated damage accumulation process, therefore more failures will occur and implicitly higher costs will be generated.

It can be concluded based on the model developed in this project that in order for a wind farm to be profitable, it is better to place it in an area with high wind speed. Furthermore, it is favorable that corrective repairs are avoided, therefore the preventive maintenance should be performed when a low level of accumulated damage of the components was detected.

Future work

The models developed and presented in this project can be extended and analyzed into more detail by considering many other scenarios in order to observe the variation of maintenance and energy costs. Besides corrective and condition based maintenance, the scheduled maintenance can be also considered as an option. Furthermore, the maintenance operation which makes use of either a vessel and a helicopter could be analyzed in order to identify the conditions in which is more favorable to use a helicopter instead of a vessel. Further research could focus on the development of a more detailed model for condition based maintenance, where the damage exponent and the number of cycles could be considered different for each component of the wind turbine.

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Appendix A

A.1 Horns Rev 2 model

Capital expenditure

The algorithm used for calculating the installation costs is based on [Kaised and Snyder, 2012].

Foundation and Turbine installation

The costs of the foundation and turbine installation were calculated using the same formulas but adapted for each situation.

The vessel travel time, TT [hours], from the port to the wind farm can be calculated by equation (A.1).

$$TT = 2 \cdot \frac{D}{S} \tag{A.1}$$

D	Distance from port to the wind farm [nm]
S	Vessel speed[kn]

The installation time required by one trip, TrT [hours], is given by equation (A.2).

$$TrT = TT + L + I + M \tag{A.2}$$

$L = VC \cdot l$	Loading time [hours/trip]
VC	Vessel capacity [units/trip]
l	Loading time [hours/turbine]
$I = VC \cdot i$	Installation time [hours/trip]]
i	Installation time [hours/turbine]
$M = VC \cdot m$	Vessel movement inside the wind farm [hours/trip]]
m	Vessel movement inside the wind farm [hours/turbine]

The weather adjustment factor, W, is applied to TrT in order to indicate the time proportion in which the vessel can perform the installation operations. Based on [Kaised and Snyder, 2012],W is assumed 0.9 for foundation installation and 0.85 for turbine installation. Therefore the weather adjusted time for one trip, AT [hours], is give by (A.3):

$$AT = TrT \cdot \frac{1}{W} \tag{A.3}$$

In order to established the number of trips, NT, required for the installation the equation (A.4) can be used.

$$NT = \frac{NU}{VC} \tag{A.4}$$

NU	Number of the wind farm turbines = 91

The total installation time, IT [hours], is given by equation (A.5).

$$IT = AT \cdot NT \tag{A.5}$$

The total cost of the vessel per day, TCV [€], is calculated by equation (A.6).

$$TCV = SDR + VDR \tag{A.6}$$

SDR	Spread dayrate [€]
VDR	Vessel dayrate [€]

In the end, the final cost of the installation is given by equation (A.7).

$$COST = \frac{IT}{24} \cdot TCV \tag{A.7}$$

Cables installation

The calculation algorithm for the installation costs of the inner array cables and the export cables is the same but it was applied individually for each of them.

The time required for the cables installation, TC [days] is given by equation (A.8).

$$TC = \frac{CL}{RC} \tag{A.8}$$

CL	Cable length [km]
RC	Cable rate [km/day]

The values for CL and RC are presented in TableA.1.

	Length [km]	Rate [km/day]
Inner array cable	70	0.3
Export cable	42	0.7

Table A.1. Cables features. [4COffshore, 2014a]

The cable installation cost, $COST$ [€] is given by equation (A.9).

$$COST = VDR \cdot TC \tag{A.9}$$

Scour protection installation

The total amount of scour, TS [tons] needed for the entire wind farm is calculated by equation (A.10)

$$TS = SU \cdot NU \tag{A.10}$$

SU	Amount of scour per unit - 1.250 [tons]

The trips number needed for the scour protection installation, ST, is given by equation (A.11).

$$ST = \frac{TS}{SVC} \tag{A.11}$$

SVC	Vessel capacity used for scour protection installation - 1.250 [tons]

In order to calculate the total travel time of the vessel required for scour protection, STT, the equation (A.1) is used. To this equation, the time required for loading and dumping is added.

The final cost of the scour protection installation, $COST$ [€],is given by equation (A.12).

$$COST = \frac{STT}{24} \cdot VDR \tag{A.12}$$

Substation installation

The final cost of the substation installation is given by equation (A.13).

$$COST = VDR1 \cdot SD + VDR2 \cdot SD \tag{A.13}$$

$VDR1$	Vessel dayrate for the foundation and lifting [€/day]
$VDR2$	Vessels dayrate for the other required vessels (tugs, barge, crew boat) [€/day]
SD	Substation installation days

Decommissioning expenditure

Turbines decommissioning

The vessel travel time, TT [hours], from the wind farm to the port can be calculated by equation (A.14).

$$TT = 2 \cdot \frac{D}{S} \tag{A.14}$$

D	Distance from port to the wind farm [nm]
S	Vessel speed[kn]

The removal time required by one trip, ReT [hours], is given by equation (A.15).

$$ReT = TT + L + Remove + M \tag{A.15}$$

$L= VC \cdot l$	Off-loading time [hours/trip]
l	Off-loading time [hours/turbine]
$Remove= VC \cdot i$	Removal time [hours/trip]]
r	Removal time [hours/turbine]
$M = VC \cdot m$	Vessel movement inside the wind farm [hours/trip]
m	Vessel movement inside the wind farm [hours/turbine]

The weather adjustment factor, W, is applied to ReT in order to indicate the time proportion in which the vessel can perform the decommissioning operations. Based on [Kaised and Snyder, 2012],W is assumed 0.85 for turbine decommissioning. Therefore the weather adjusted time for one trip, AT [hours], is give by (A.16):

$$AT = ReT \cdot \frac{1}{W} \tag{A.16}$$

In order to established the number of trips, NT, required for the decommissioning operation, the equation (A.17) can be used.

$$NT = \frac{NU}{VC} \tag{A.17}$$

The total decommissioning time, De [hours], is given by equation (A.18).

$$De = AT \cdot NT \tag{A.18}$$

The total cost of the vessel per day, TCV [€], is calculated by equation (A.19).

$$TCV = SDR + VDR \tag{A.19}$$

In the end, the final cost of the decommissioning of the wind farm is given by equation (A.20).

$$COST_{turbines} = \frac{De}{24} \cdot TCV \tag{A.20}$$

Foundation decommissioning

The required time to remove a single foundation is given by equation (A.21).

$$RemovalTime = S + P + (C \cdot d) + L + M \tag{A.21}$$

S	Stabilizing time of the vessel [hours]
P	Pumping time of the foundation mud [hours]
C	Cutting time of the foundation [hours/m]
d	Pile diameter [m]
L	Lifting and placing time of the foundations on the vessel [hours]
M	Moving time to the next foundation [hours]

In the end, the final cost for the foundations decommissioning is given by equation (A.22):

$$COST_{foundations} = (VDR + SDR) \cdot NU \cdot RemovalTime \tag{A.22}$$

Cables decommissioning

The algorithm is applied for inner array cables and export cable.

The removal time of the cables is given by equation (A.23).

$$RemovalTime = \frac{CL}{RemovalRate} \tag{A.23}$$

The final cost is calculated by equation (A.24)

$$COST_{cables} = RemovalTime \cdot (VDR + SDR) \tag{A.24}$$

Operations and maintenance costs

Corrective maintenance

The wind speed limitations for the wind turbine maintenance are presented in Table A.2.

Wind speed [m/s]	**Access restriction**
>30	No site access
>20	No climbing turbines
>18	No operating roof doors
>15	No work on nacelle roof
>12	No access to hub
>10	**No lifting nacelle roof**
>7	No rotor blade removal
>5	No climbing meteorology mast

Table A.2. The constraints for the wind turbine maintenance.[McMillan and Ault, -]

Digital Appendix B

B.1 Horns Rev 2 model

B.1.1 Capital expenditure

Maple file: ”Estimation of installation costs.mw”
The program is used in order to establish the installation costs for the foundation, turbine, cables, substation, scour protection.

B.1.2 Wind data analysis of the wind farm site

Matlab program: ”ShearExponent.m”
In the program, the shear exponent was calculated.
Matlab programs: ”WindSpeedAtHubHeight.m”, ”WindSpeedWeibullDistribution.dfit”
The matlab programs are used to calculate the wind speed at the hub height and the Weibull distribution for the wind speed.

Annual energy production

Matlab program: ”PowerCurve.m”
The file presents the power curve values and its graphic representation.
Matlab program: ”AEP100percentAvailability.m”
The file shows AEP calculated without performing the maintenance activities.

B.1.3 Operation expenditure

Corrective maintenance

Matlab file: ”CorrectiveMaintenanceCode.m”
The program shows the simulation model for corrective maintenance.
Matlab formatted data:”CorrectiveMaintenance.mat”
In this file are all the stored results obtained after the simulation model was run.
Matlab file: ”InterpretingCMResultsFigures.m”
The program shows the interpreted results with their figures.

Preventive maintenance

Matlab file: ”PreventiveMaintenanceCode.m”
The program shows the simulation model for preventive maintenance.
Matlab formatted data:”PreventiveMaintenance.mat”

In this file are all the stored results obtained after the simulation model was run.
Matlab file: "InterpretingPMResultsFigures.m"
The program shows the interpreted results with their figures.

B.1.4 Decommissioning expenditure

Maple file: "Decommissioning cost estimation.mw"
In the program can be seen the calculations of the decommissioning wind farm: turbines, foundations, cables, substation, site clearance.

B.2 Sensitivity analysis

B.2.1 Obtained results

Matlab file "Capacityfactor.m", "calc_energy_capacity_factor.m"
The file calculates the potential energy production if the turbines operate at maximum capacity.

B.2.2 Baseline Model

Matlab file: "ResultsBaselineModel"
The programs show the results obtained by interpreting the values obtained in the baseline model.
Matlab formatted data: "CorrectiveMaintenance.mat","PreventiveMaintenance.mat"
In the files are all the stored results obtained after the baseline model simulation program was run.

Scenario 1

Matlab file: "CMScenario1.m", "PMScenario1.m"
The programs show the simulation model for CM and PM with the changes required for Scenario 1.
Matlab formatted data: "CMScenario1.mat", "PMScenario1.mat"
In the files are all the stored results obtained after scenario 1 was run.
Matlab file: "ResultsScenario1.m"
In this file are interpreted the results obtained in scenario 1.

Scenario 2

Matlab file: "CMScenario2.m", "PMScenario2.m"
The programs show the simulation model for CM and PM with the changes required for Scenario 2.
Matlab formatted data: "CMScenario2.mat", "PMScenario2.mat"
In the files are all the stored results obtained after scenario 2 was run.

Matlab file: ”ResultsScenario2.m”
In this file are interpreted the results obtained in scenario 2.

Scenario 3

Matlab file: ”CMScenario3.m”, ”PMScenario3.m”
The programs show the simulation model for CM and PM with the changes required for Scenario 3.
Matlab formatted data: ”CMScenario3.mat”, ”PMScenario3.mat”
In the files are all the stored results obtained after scenario 3 was run.
Matlab file: ”ResultsScenario3.m”
In this file are interpreted the results obtained in scenario 3.

Scenario 4

Matlab file: ”CMScenario4.m”, ”PMScenario4.m”
The programs show the simulation model for CM and PM with the changes required for Scenario 4.
Matlab formatted data: ”CMScenario4.mat”, ”PMScenario4.mat”
In the files are all the stored results obtained after scenario 4 was run.
Matlab file: ”ResultsScenario4.m”
In this file are interpreted the results obtained in scenario 4.

Scenario 5

Matlab file: ”CMScenario5.m”, ”PMScenario5.m”
The programs show the simulation model for CM and PM with the changes required for Scenario 5.
Matlab formatted data: ”CMScenario5.mat”, ”PMScenario5.mat”
In the files are all the stored results obtained after scenario 5 was run.
Matlab file: ”ResultsScenario5.m”
In this file are interpreted the results obtained in scenario 5.

Scenario 6

Matlab file: ”CMScenario6.m”, ”PMScenario6.m”
The programs show the simulation model for CM and PM with the changes required for Scenario 6.
Matlab formatted data: ”CMScenario6.mat”, ”PMScenario6.mat”
In the files are all the stored results obtained after scenario 6 was run.
Matlab file: ”ResultsScenario6.m”
In this file are interpreted the results obtained in scenario 6.

Scenario 7

Matlab file: ”CMScenario7.m”, ”PMScenario7.m”
The programs show the simulation model for CM and PM with the changes required for Scenario 7.
Matlab formatted data: ”CMScenario7.mat”, ”PMScenario7.mat”

In the files are all the stored results obtained after scenario 7 was run.
Matlab file: ”ResultsScenario7.m”
In this file are interpreted the results obtained in scenario 7.

Scenario 8

Matlab file: ”PMScenario8a.m”
The program shows the simulation model for PM with the damage accumulation requiring maintenance considered to be 0.7.
Matlab file: ”PMScenario8b.m”
The program shows the simulation model for PM with the damage accumulation requiring maintenance considered to be 0.9.
Matlab formatted data: ”PMScenario8a.mat”, ”PMScenario8b.mat”
In the files are all the stored results obtained after scenario 8 was run.
Matlab file: ”ResultsScenario8a.m”,”ResultsScenario8b.m”
In this file are interpreted the results obtained in scenario 8.

Scenario 9

Matlab file: ”’PMScenario9.m”
The program shows the simulation model for PM with the changes required for Scenario 9.
Matlab formatted data: ”PMScenario9.mat”
In the files are all the stored results obtained after scenario 9 was run.
Matlab file: ”ResultsScenario9.m”
In this file are interpreted the results obtained in scenario 9.

Scenario 10

Matlab file: ”PMScenario10a.m”
The program shows the simulation model for PM with the damage exponent considered to be 1.
Matlab file: ”PMScenario10b.m”
The program shows the simulation model for PM with the damage exponent considered to be 3.
Matlab formatted data: ”PMScenario10a.mat”, ”PMScenario10b.mat”
In the files are all the stored results obtained after scenario 10 was run.
Matlab file: ”ResultsScenario10a.m”,”ResultsScenario10b.m”
In this file are interpreted the results obtained in scenario 10.