Erasmus School of Economics

Department of Econometrics and Management Science

MSc Graduation Project:

Opportunistic Maintenance in Offshore Wind Farms

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Preface and Acknowledgments

This report is for my Master Thesis for the Degree of Master of Science in Econometrics and Management Science, Specialization Operation Research and Quantitative Logistics at Erasmus University of Rotterdam, the Netherlands.

I would like to thank my Professor Rommert Dekker for supervising this project. I would also like to thank my family and friends for their support and patience throughout my studies.

Dimitra Gianniki

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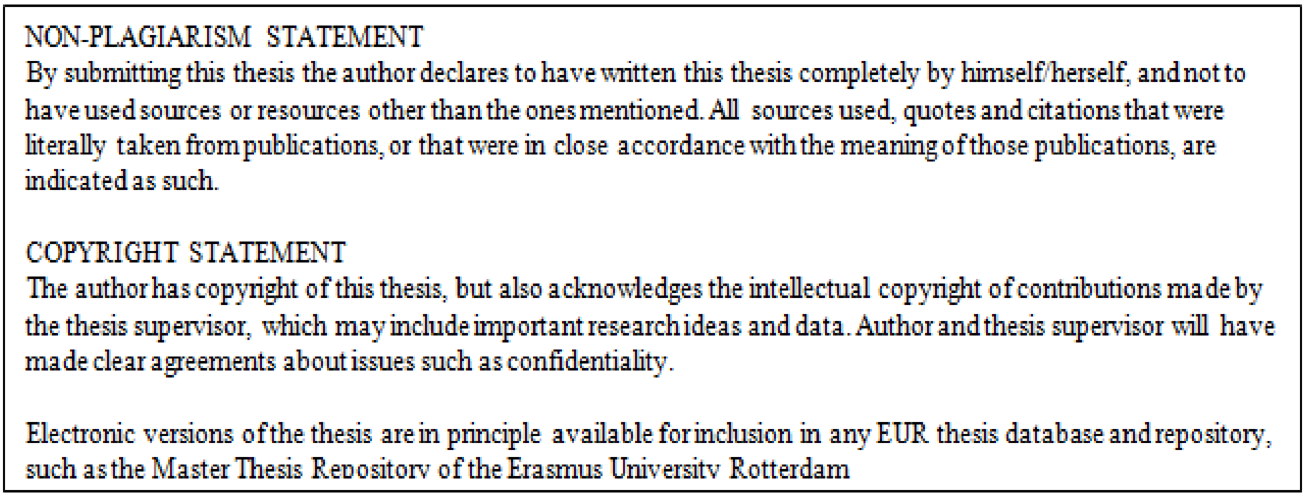

Abstract

Harvesting offshore wind energy will grow significantly in the future as investments in large scale wind farms will take place. Already in early 90's wind energy industry has stepped offshore due to a number of interesting characteristics compared to onshore wind yield. In early cases the offshore farms were installed in low water depths and small distance to shore. Future wind farms will be installed further from shore where the wind speed is higher thus the energy production. This new approach will lead to higher Operations & maintenance costs are functioning under a harsh maritime environment and thus their accessibility for maintenance is influenced by sea-state (i.e. waves) and weather conditions(i.e. wind). What is more, visiting an offshore wind farm is more costly as their distance from shore creates problems in their accessibility.

In this Master Thesis, a way to optimize maintenance strategies in an integrated manner will be attempted. For that reason, parameters such as environmental conditions which influence the accessibility of an offshore wind farms will be taken into account. The main cost savings are related to the production losses and logistic costs including fuel and mobilization costs. The proposed model is trying to minimize the maintenance costs by decreasing production losses and transportation costs. Wind speed and Wave heights of the period 1993 until 2012 are used to simulate the wind and wave pattern. A cost comparison is made for the different locations and for different weather scenarios in order to prove the importance of both elements. The results showed that savings can be achieved with the proposed model even in harsh weather conditions.

Keywords:

[Offshore, wind farms, optimization, opportunistic maintenance, weather restrictions]

Content

List of Symbols

WT: Wind Turbine

PM: Preventive Maintenance

CM: Corrective Maintenance

CBM: Conditioned-based Maintenance

TBM: Time Based Maintenance

O&M: Operations and Maintenance

H_S: Significant wave height

MILP: Mixed Integer Linear Programming

$\mathrm{u_{cut-in}}$: Cut-in wind speed

$\mathrm{u_{nominal}}$: Nominal wind speed

$\mathrm{u_{cut-out}}$: Cut-out wind

KNMI: Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meterological Institute)

OTMC: Optimized Total Maintenance Costs

BTMC: Basic Total Maintenance Costs

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Chapter 1

1. Introduction

Harvesting offshore wind energy will grow significantly in the future as investments in large scale wind farms will take place. By the end of the decade, it is expected that in the European seas wind farms with total capacity of thousands of megawatts will be installed. The challenges for their installation will be considerable, including the problems that will need to be faced related to their operation and maintenance (O&M) process and costs. Particularly, the turbines and their support structure need inspection and maintenance in order to remain reliable so as to produce energy to a satisfactory percentage. O&M costs for offshore wind structures are far more expensive compared to the onshore one as the transportation to the farms are more challenging due to the harsh weather conditions in the sea.

In order to keep the offshore wind plant reliable and operational there are two types of visits, the 'planned c.q. regular' and the 'unplanned c.q. unavailability' service visits. The maintainability of the wind farms are firm dependent on the access system used, as the wind farms are at least twenty km offshore, consisting of forty turbines or more with an average of two or three failures per year for each turbine. The amount of visits is substantial and so are the maintenance, repair and operations (MRO) costs associated. Thus, in order to reduce total costs of ownership (TCO) of offshore wind farms there is a need to execute an integrated and optimized O&M plan.

As presented by Musial and Butterfield (2006), the O&M costs are more difficult and expensive for offshore farms compared to the equivalent onshore. If one considers also the fact that they are a significant part (15%-25%) of their total costs of energy (COE) then it is easy to ascertain that is of major concern. The current reliability and failure modes of commercial offshore wind turbines are such that "no maintenance" is not a viable option. For offshore wind turbines it is of great importance the optimal planning of O&M which should include inspections and monitoring results in order to minimize their expected costs through lifetime of the structures. Their accessibility is dependent on the good weather windows which make the O&M planning procedure harder. Therefore, improving their accessibility and reliability are key factors for their availability.

In the below figure, the future improvement of the offshore wind industry is illustrated. Studies have assessed that there is a sharp increase of the wind speed as the distance from shore is longer. But, as the water depth increases the cost of offshore foundations will also increase because of the extra resources and complexity added under the waterline.

Figure 1.1: Technology progression for offshore wind turbines, Musial and Butterfield (2006)

Currently, all offshore wind farms are installed in swallow water of maximum 18 meters depth. The wind-turbines used are land-based which were adapted to the marine environment. This was done by upgraded electrical and corrosion systems placed on concrete gravity bases or steel monopole foundations. Unfortunately, the monopoles are depth-limited due to their inherent flexibility. As the depth is increasing the same happens to the length, diameter and thickness of the monopile. What is more, the equipment needed for the installation is becoming more specialized and thus more expensive.

Another type of offshore wind turbine is the gravity based, which can work as an alternative to the monopile option as it can overcome the flexibility restrictions of the latter. Its costs can grow rapidly especially as the water depth is growing. Extensive preparation of the seabed is required in order to ensure 20mm of substrate.

Figure 1.2: Current options of shallow water foundations, Musial and Butterfield (2006)

Lastly, the suction bucket foundations are not yet used neither to swallow or deep water. They are considered a significant development as the large monopoles currently used can be avoided.

It is easily recognized that there is still area of development in the substructures and foundations of an offshore wind farm as the current European installations are extensions of land-based turbine technology. The same stands for the operation strategies which are not yet optimized.

For all the aforementioned reasons the optimization of O&M strategies of offshore wind farms, although are difficult and expensive, are important due to increased future installations. In this Master Thesis, a way to optimize maintenance strategies in an integrated manner will be attempted. For that reason, parameters such as environmental conditions which influence the accessibility of an offshore wind farms will be taken into account. Specifically, every offshore wind turbine can be accessed by vessel or helicopter. Each vessel has a specific max wind speed and (significant) wave height that can sail. The periods when an offshore site can be visited is called good weather window, in which both wind speed and wave height need to be within an acceptable range.

Except from the weather conditions another challenging parameter that needs to be considered is the maintenance strategy followed. Often, unpredictable failures of component in a system result to high corrective maintenance costs. For that reason, preventive maintenance is used in order to avoid expensive maintenance activities. But, preventive maintenance can also be expensive if it is done too frequently. Opportunistic maintenance has shown in many cases that can increase in an effective way system's reliability and decrease the frequency of random failures in a system. This is happening because this type of maintenance takes into account unexpected opportunities to perform preventive maintenance.

This thesis focusses on determining the optimal maintenance strategy for offshore wind farms build the in the Dutch part of the North Sea. Taking into account weather conditions, turbine specific information on power output, average failures per year which result to corrective maintenance activities and required annual preventive maintenance tasks an integrated model will be implemented in order to help improving the current and future maintenance challenge of offshore wind farms. More specifically, the research questions worked on this report are:

- Combining corrective with preventive maintenance will drive to a reduction of total maintenance costs?
- Is the impact of weather conditions considerable?
- Location of offshore wind turbine influences the total annual maintenance costs?

The remainder of this report is structured as follows. In Chapter 2 a summary of the existing European situation of the offshore wind farms and especially on the Dutch one is presented. Furthermore a literature review was conducted on the farms' current O&M costs and strategies. A description of maintenance categories and strategies as well as issues and terms involved in the whole process is given in Chapter 3. In Chapter 4 the different parameters related to an offshore wind farm are being analyzed thoroughly. Chapter 5 outlines in details the methodology used to develop the optimization model for maintenance activities while in Chapter 6 the proposed model is being implemented for different locations and the results are presented. A discussion on the assumptions made in this report can be found in Chapter 7 and finally in Chapter 8 the questions of this thesis are answered.

Chapter 2

2. Literature Review

In the below chapter a synopsis of the existing European situation of the offshore wind farms and especially on the Dutch one is presented. Furthermore a literature review was conducted on the farms' current O&M costs and strategies.

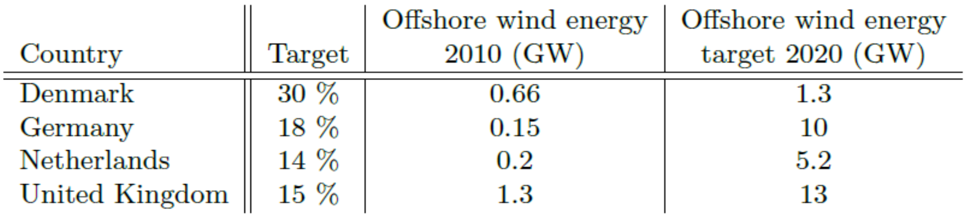
2.1 A review of offshore wind farms and current O&M practices

2.1.1 Current situation in Europe

As presented by the European Parliament and Council (2009), an attempt to convert Europe in a low carbon and high energy efficiency economy was initiated. The European Union Heads of State and Government as a part of the project "Climate and Energy Package" has set the target of 20-20-20, which is:

- 20% reduction of the predicted 2020 energy consumption by upgrading energy efficiency.
- 20% reduction compared to the gas emission levels of the 1990 greenhouse.
- 20% of the energy consumption in the European Union to be derived from renewable resources.

The plan to achieve this goal is to prepare a renewable plan which includes a breakdown of different types of renewable energy. One mean will be to build offshore wind farms. Thus, it is expected that in the European seas wind farms with total capacity of thousands of megawatts will be installed. In the below table, an overview of the installed offshore wind energy in 2010 and the targeted capacity of 2020 for various countries are shown:



Country	Target	Offshore wind energy 2010 (GW)	Offshore wind energy target 2020 (GW)
Denmark	30 %	0.66	1.3
Germany	18 %	0.15	10
Netherlands	14 %	0.2	5.2
United Kingdom	15 %	1.3	13

Table 2.1: Targets of Renewable energy by 2020, Beurskens et al (2011)

As the European Wind Energy Association has stated, Europe has high potentials in offshore wind energy and if is able to meet her demand seven times over. The anticipation is that by 2020 the offshore wind energy should and can increase by 30-40 times and by 2030 by 100 times compared to the installed capacity today. By 2012, 5GW were installed, which means 10% of EU's annual wind energy installations. By 2020 the expectation is that 40GW will be installed, which is equal to 4% of EU electricity demand or 148TWh production. Finally, by 2030, the total capacity installed is estimated to be 150GW or in other words, EU's electricity demand of 564TWh (14%).

Specifically in the Netherlands, in the Dutch Exclusive Economic Zone there are already operational as well as licensed offshore wind farms. Currently, only two wind farms are in use: "Prinses Amalia" and "Egmond aan Zee", which will be considered in the analysis. There are also twelve farms that are licensed but thanks to changes of the subsidy rules, it is not yet known if and when are planned to be built. But, from these twelve existing licensed offshore farms, only three have received subsidy from the Dutch ministry of Economic Affairs in order to be built. These farms are: “Enino” “ZeeEnergie” and “Buitengaas”.

For 2020, the Dutch government has set a goal of 5.2GW of offshore wind energy which cannot be met with the existing farms. Thus, two more offshore projects are assigned one in “Borsele” area for 1GW ($344km^2$) and the second one in “Ijmuiden” for 5GW ($1170km^2$).

2.2 Study of the practices for offshore wind farms

O&M costs for offshore wind farms are consisting of about 23% on the project’s total costs (figure 2.1). For an equivalent onshore farm these costs of energy are estimated to be a lot lower with a percentage of 5-10% (Andrawus, Watson and Kishk (2007)). The reason of this difference can be attributed to the fact that offshore wind turbines are functioning under a harsh maritime environment and thus their accessibility for maintenance is influenced by sea-state (i.e. waves) and weather conditions(i.e. wind). What is more, visiting an offshore wind farm is more costly as their distance from shore creates problems in their accessibility.

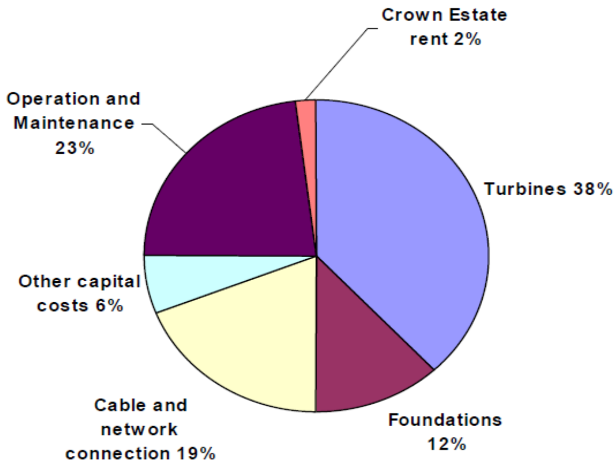


Figure 2.1: Average Cost breakdown. Musial and Butterfield (2006)

Current O&M practices applied in existing offshore farms are reactive. Specifically, when a part failure takes place the wind turbine becomes non-operational. Then, at the first opportunity a maintenance “mission” is launched in order to repair it. However, this visit is an extra one to the planned routine preventive maintenance. To fix the failed parts the repair is made in situ or by exchange and so the wind turbine becomes fully operational again. Corrective maintenance has been adopted as reliability based optimization in order to increase energy harness.

The maintenance strategy used for prototypes first offshore wind farms was the corrective. That happened because, as being the first ones that were built, they had to be tested for their efficiency in high energy production, in order to attract more future funding. That’s why they were small in size and located close to the shore. But, even if it’s a costly approach leading to high maintenance costs, it has been applied for all existing offshore wind farms.

This aforementioned strategy is suitable for onshore wind farms as their accessibility is unaffected by their remoteness, weather conditions and availability of ways to transport, for example helicopters and/or vessels. On the contrary, for offshore wind farms, as concluded from the literature review is effective in terms of keeping high levels of the turbines’ availability, but is expensive as most the failures combined with the weather conditions are unpredictable. Scheduling in these cases repairs at short notice is costly and sometimes even impractical.

As it is also easily noticeable from figure 2.1 O&M costs are “blamed” for a large percentage in the costs of energy produced by them, optimizing their maintenance costs would lead to higher competitiveness in the energy market as the electricity production by offshore wind farms will be less costly.

A literature review for this reason has been conducted as previous strategies have to be identified and evaluated in order to specify the challenges of future remote wind farms. The following surveys have shown that there is truly a need for re-evaluation and modification of O & M strategies in order to become effective and less expensive.

Musial and Butterfield (2006) made a review of the current situation in offshore wind industry and highlighted the most critical parameters that affect their future development. As, most of the recent turbines used in offshore wind farms are extension of the land-based technology, they must be re-engineered to adapt to environmental and logistical factors. The reliability of onshore wind farms can be kept in an acceptable level, fact that made them successful, as it is combined with reduced capital costs. Their accessibility is also in high levels and thus corrective maintenance can be applied to ensure maximum profit. For this reason, the additional capital investment for O & M costs was neglected. This study, explain that this case for offshore wind farms is not a solution as working at the sea is time consuming and difficult and thus costly. Therefore, corrective maintenance is not proved to be an economical solution and there is a need for development of new maintenance strategies taking into consideration the marine environment and its effects.

Van Bussel (1997) assess the O&M process for large offshore wind farms concluding that finding ways to reduce them is significant as their costs may end-up to 30%. This study also concludes that maintenance costs for offshore farms are higher than onshore projects and the approach of no maintenance is not a viable option. Currently, the existing strategy is reactive response with regular care when the permits a visit to the offshore site. That is why the reliability of offshore wind farms is much affected by the marine environment, indicating the necessity to a different approach as in future larger projects will take place. Technical re-design offshore wind turbines, is also suggested by the study in order to achieve a financially effective project.

In further research, van Bussel and Henderson (2001) keep discussing on the need to diverge the maintenance strategy for offshore wind from the onshore one. Problems of accessibility and wind and wave conditions result in higher costs especially when it comes to corrective maintenance. As O&M costs are higher compared to onshore, optimizing accessing methods and transportation modes in combination with optimized maintenance strategies is suggested as essential by the authors.

McMillan, Gowan and Rogers (2002), studied the impact of the reliability levels of offshore wind turbines on the investment payback period and on maintenance methods. Specifically the key indicator used to identify parameters that affect offshore wind farms was the capacity factor. Operational requirements of an offshore wind farm are different from power the ones in power plants as are coupled with weather conditions and distance from shore which result in accessibility difficulties. Adding up the number of wind turbines and the challenging maintenance expenditures, O&M costs in offshore projects are not only costly but also unique. As future project are expected to attract higher wind speeds by larger distance from shore, the current maintenance practices, such as the corrective one will no longer be effective. A cost-optimal time-based strategy, as suggested in this study, may be more efficient as the time interval between maintenance will be defined by the cost reduction in energy produced.

Sorensen (2009) describes how the risk-based inspection planning can be used for the maintenance of offshore wind farms. This paper presents how risk and pre-posterior Bayesian theory could be applied for optimal O&M planning. The costs of corrective maintenance of offshore wind farms are important and in the future as more remote parks will take place, they are going to be increased. Therefore, the author suggest the a change to proactive maintenance strategy would reduce the maintenance costs of existing and future offshore wind farms as time between visits to them will be based on inspections and the failure rates of the components. What was not taken into account in this study is the accessibility due to weather and wave (sea) conditions. These are important factors and could limit the number of regular inspections/visits and maintenance tasks on the critical parts of the wind turbines and affect the on-time tasks that should take place in specific time of the year when they are more effective. What was concluded from this study was the need to change maintenance strategies from corrective to proactive or even to their combination.

Andrawus, Watson and Kishk (2007), find imperative to improve the maintenance strategies of offshore wind farm as the current ones will be inadequate for future installations. For that reason, the authors attempt to analyze the current practices, investigating corrective maintenance and modeling the failure rates of the wind turbines. This study, suggests that attention has to be given to critical areas, fact that will cause to implement effective maintenance and will reduce the overall cost of O&M strategies. With this, root causes of wind turbine failures will be gradually eliminated and the overall return on investment will be maximized. Moreover, this paper suggests that even if frequent maintenance activities will be carried out and direct costs will be increased, this will result eventually in decreasing the exposure risk or consequences of not performing the required maintenance. However, less frequent maintenance results to less costs and higher exposure risk. Thus, for optimizing the maintenance activities for offshore wind farms, an interaction between the above should take place aiming in determining the optimum level. Concluding, this study suggests an optimization of the existing maintenance policies by considering the failure rates of the wind turbines' components together with the maintenance expeditions, aiming to energy production in competitive prices.

Lastly, as proposed by Besnard et al (2009), planning of maintenance activities is a way to save costs. Specifically, scheduled maintenance activities can be optimized by taking advantage low wind forecasts and corrective maintenance at failures. Specifically, a model that combines corrective maintenance with preventive was applied in order to save costs. In other words, opportunistic maintenance can be applied, but the maintenance schedule should be flexible.

As concluded from the above literature review on the different maintenance strategies and their associated costs there is room for improvement. By optimizing the maintenance policy used for the offshore wind farms not only the overall return on the investment will be maximized but also the reliability which means that the availability will be higher. In this thesis an attempt to optimize and combine two different maintenance strategies, corrective and preventive, will be assessed.

Chapter 3

3. Maintenance strategies review

In this chapter, maintenance categories and strategies are described, as well as issues and terms involved in the whole process. From the first day of operation of a wind farm it is mandatory to keep it in operation mode and reliable by maintaining its wind turbines.

3.1 Introduction to Maintenance Strategies

The definition of maintenance as presented in Budai, Dekker and Nicolai, (2008) is given as: “Maintenance is the set of activities carried out to keep a system into a condition where it can perform its function”. There are two types of maintenance strategies that are widely used: corrective and preventive maintenance.

Corrective maintenance (CM) takes place after a failure has occurred in order to restore an item to a state in which it can perform its required function, as noted by IEEE (2000). This type of maintenance is carried out when there is no effective way to detect and prevent a failure.

Preventive maintenance (PM) is applied in specific predetermined time internals in order to reduce the failure probability or to avoid system degradation (IEEE,2000). Preventive maintenance is divided in two main approaches:

- *Condition Based Maintenance (CBM)* is based on estimating/measuring the condition of the equipment and assessing if it will fail during some future period. The assessment involves inspections or Condition Monitoring Systems (CMS) so as to decide the maintenance actions to be taken. CBM can be used for non-age related failures.
  Often, instead of the terminology (CBM) the terms “On-Condition Maintenance: and “Predictive Maintenance” can be used interchangeably. [7]
- *Time Based Maintenance (TBM)* is carried out according to pre-specified time intervals or number of units of use. It’s a preventive maintenance but it is applied without previous investigation. It is more suitable for age-related failures as they can be defined with probability distributions.

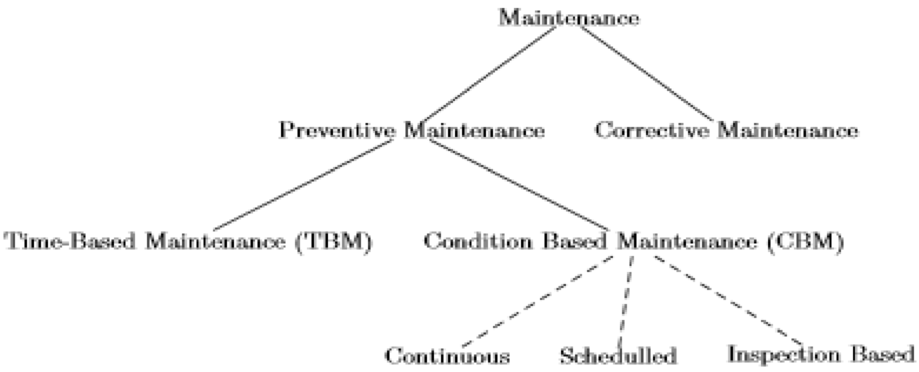


Figure 3.1: Type of maintenance strategies, Svensk Standard (2000)

3.2 Models of Maintenance Optimization

Often, unpredictable failures of component in a system result to high corrective maintenance costs. For that reason, preventive maintenance is used in order to avoid expensive maintenance activities. But, preventive maintenance can also be expensive if it is done too frequently.

The best path forward is to balance corrective and preventive maintenance in order to minimize total associated cost.

This type of optimization is associated with the utilization of mathematical models in order to define the best decision from a set of alternatives for a maintenance problem. There are various interconnected maintenance decision problems:

- Manage and optimize spare parts, i.e. optimize the stock of spare parts in the size, variety, etc.
- Optimize the workforce, i.e define the optimal size of the service crew for the maintenance and the related equipment.
- Planning of the maintenance activities, e.g. set-up and arrange the maintenance tasks concerning the available maintenance workforce, spare parts and the suitable equipment.
- Comparison of the maintenance methods with reference to reliability, costs and risk criteria
- Capital investment analysis, e.g. analysis of the value of transportation, maintenance equipment etc.
- Maintenance planning optimization (e.g. on-line condition monitoring, age replacement etc.)

The evaluation of different decisions is executed based on optimization principles such as availability, safety and costs towards specific constraints (workforce, weather environment, costs, available working hours).

Below some examples of models will be described and the references will be provided.

3.2.1 *Age Replacement models*

A variety of models were introduced regarding the age replacement of a component. In those models, a component is being replaced either on at the end of a stated interval or when a failure occurs. The decision depends on which one occurs first. This approach is only preferable if preventive maintenance costs less than the corrective one and the failure rate is increasing with time.

A basic mode was represented from Barlow and Proschan, (1965). Another model introduced by Bagai and Jain (1994) a proposal of minimal repair was recommended, meaning that when a component fails it has to be repaired in order to return to the same condition as before the occurred failure. Fox (1966) introduced a discount policy, in which the value loss of a replaced component is decreasing with its age.

What is more, in Rangan et al (2006) described a block/age replacement model in which failures were occurred from shocks. Failures of two categories can follow after a shock: a minor one which will treat with minor repairs and a major for which a replacement is needed. Those shocks are following a non-homogenous Poisson distribution.

3.2.2 *Condition based Maintenance*

This type of maintenance was proposed by Park (1988) so as to avoid unneeded maintenance and limit initial failures. CBM is applied to specific parts of a wind turbine such as the blades, gear box etc. A question that needs to be answered is to determine relevant variables and their relation failures and probabilities. This procedure needs to be done before the optimization step.

What needs to be identified is the optimal limits for the tracked variables mentioned above which are needed in order to perform maintenance. Park (1988) is introducing a model to define the optimal wear-limit for preventively replace a component and in Park (1993) the model is extended to take into account various monitoring variables.

One must decide at each decision step, if the component that is under inspection when it should be maintained and when the next inspection will take place. Mohamed (1995) argues that preventive maintenance will be executed depending on the condition of a component at inspection. Inspections happen at fixed time.

3.2.3 *Block replacement strategies*

As mentioned previously in 3.2.1 section, Barlow et al (1965) represents a basic model of block replacement. In that model, the components are being replaced at a failure or at pre specified times kT (k= 1,2,..). In order to prevent double replacement of an already replaced component an adjusted model was recommended from Berg and Epstein (1976). A scheduled replacement is taking place only when a component reach a specific age T.

This model was modified by M. Berg and B. Eipstein (1979) to include the operational costs of a unit when the unit's age is increasing. Lastly, the block replacement policy described by Barg and Eipsten was extended in 1979 to include multi-component systems with any discrete lifetime distributions.

3.2.4 *Opportunistic maintenance policies*

Opportunistic maintenance has shown in many cases that are an effective way to improve system's reliability and decrease the frequency of random failures in a system. This is happening because this type of maintenance takes into account unexpected opportunities to perform preventive maintenance. This policy could be effective for an offshore wind farm. The main reason is that reaching a wind farm by vessel or helicopter is costly and grouping maintenance activities could save money.

Dekker and Dijkstra (1992) presented an opportunity-based components replacement model. In that model, preventive maintenance can be performed only at maintenance opportunities which occur based on a Poisson process.

Wildeman, Dekker and Smit (1997) are introducing a model that takes into account short term information. It's a rolling horizon dynamic algorithm which can be applied to many maintenance optimization models.

A model was presented by Haurie and L'Ecuyer (1982) which is focused to m identical components that are in the same condition to one group of preventive maintenance. This model was also enhanced in order to in include m non-identical components (Haurie and L'Ecuyer, 1983).

To sum up, in this chapter a definition of maintenance provided together with the different categories. There are two main types of maintenance, corrective and preventive. The latter one has two sub categories which are split further to more specialized types of maintenance. Various optimization maintenance models were designed in order to tackle different maintenance problems.

3.3 Challenges to select the appropriate maintenance strategy and parameters

In this section a brief overview will be presented regarding the issues and terms involved in the whole process of selecting the appropriate maintenance strategy and the related parameters in order to increase the offshore farm availability.

3.3.1 Parameters selection

The definition given by van Bussel and Anderson (2001) for the availability of a wind farm is the percentage of time that is able to produce electricity. Availability is a function of maintainability, reliability and serviceability of the hard- and software in the entire system. Specifically, for offshore wind farms the importance of its accessibility for O&M of hardware equipment is equal to the maintenance strategy selected.

Vestas points out a comparison between availability rates for the Fjaldene onshore wind farm and Tuno Knob offshore wind farm. The average availability for Fjaldene is reported to be at 99.3% mainly due to the proximity of this wind farm to Vestas' Central Service Department. Tuno Knob average availability is calculated to be at 97.9%, 98.1%, and 95.2% for the years 1996 to 1998.

It is readily concluded that deciding between the different types of maintenance will be critical not only on cost perspective but also on the wind farm availability. The main parameters influencing the offshore wind farm availability is the wind speed and wave height as above a certain level vessels cannot sail to the offshore area to perform maintenance.

On the below table an example of the accessibility of offshore wind farm is illustrated for winter, summer and for the total year for the locations that will be examined in this thesis. As expected the accessibility during the winter is much lower compared to the summer while the total year accessibility is not higher than 67%. Thus, using as a decision variable the weather parameter is important due to its high influence on the total maintenance costs as due to fluctuating environments.

In order to calculate the accessibility percentage of the different location the shape and scale parameters of the Weibull distribution calculated in Chapter 4 below, (section 4.1 and 4.2) were used to generate the wind and wave data for the different seasons and for the total year. The data were generated using the function "wblrnd" in MATLAB.

	Accessibility		
Location	Winter	Summer	Year
Ijmuiden (225)/Ij-geul munitiestortplaats	33%	74%	53%
Lauwersoog (277)/ Wadden Schiermonnikoog	49%	91%	67%
Valkenburg (210)/ Europlatform	40%	78%	52%
De Kooy (235)/ K13 Alpha 3	56%	74%	68%
Average for 4 Locations	44%	79%	60%

Table 3.3.1 Examples of offshore wind farm accessibility subject to weather constraints

As concluded, it is important to decide the proper maintenance activity or combination of maintenance activities in order to achieve cost reduction. In this thesis an attempt will be made to combine corrective maintenance with preventive and low wind speeds in order to optimize the maintenance costs. As mentioned earlier, weather is a significant component impacting the costs. Fluctuating marine environment will be tested by running various scenarios with different wind speeds and wave heights in order to assess whether the proposed model can optimize the maintenance costs in a volatile environment.

In the present report, wind turbine availability for a specified time interval (usually one calendar year) will be calculated. Availability expresses the percentage of time a wind turbine is able to function, independently of wind conditions, and excluding grid faults or human interventions such as manual shutdowns. For the complete wind farm, availability is the average of the availability values of all wind turbines for the same period of time. This definition specifies clearly that availability does not include the amount of time a wind turbine is not operating because wind speed is below cut-in or above cut-out values. Availability in this document is the time the wind turbine has no kind of failure nor is it under any type of maintenance, scheduled and unscheduled.

More details on the scenarios applied as well as the results will be presented in Chapter 6.

Chapter 4

4 Parameters affecting the offshore wind farms performance and maintenance-Analysis

Gaining access to an offshore wind farms is highly dependent of the wave height of the sea level. Maintenance can be difficult even impossible in harsh weather conditions due to wave heights, wind speeds and poor visibility. In this chapter all these factors influencing an offshore wind farm are being analyzed thoroughly. Give more refs.

4.1 Wind speed

Wind speed is one of the major parameters that affect not only the energy production of a wind farm, but also its downtime and accessibility. As expected, wind speed is fluctuating over location and time. The speed is higher above sea level in comparison with wind speed above land. An example on the variation of the wind speed over location is demonstrated in the figure below:

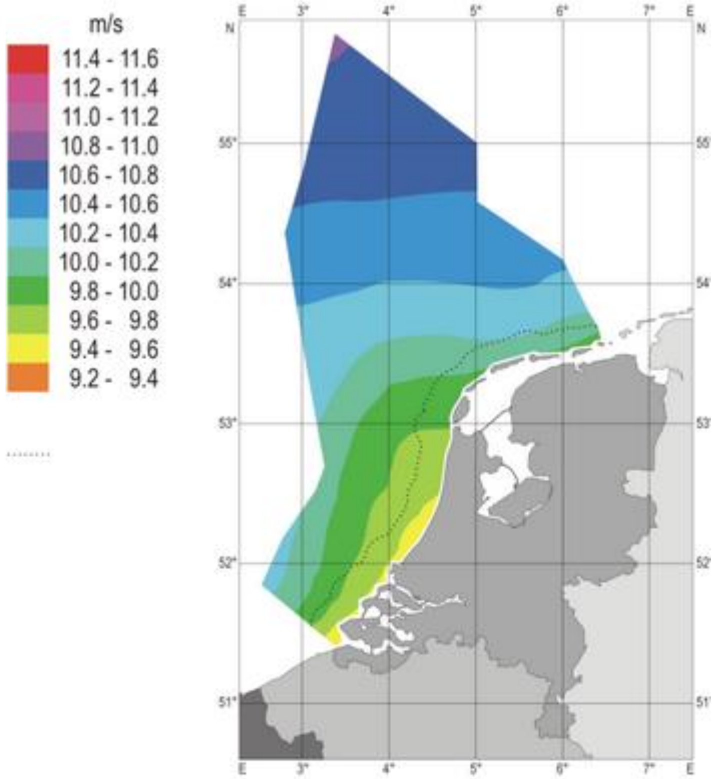


Figure 4.1: Mean wind speed for the period of 1997-2002, at a height of 90m in the North Sea, reported by ECN newsletter of March 2010.

The above graph demonstrates that wind speed is increasing proportionally to the distance from the shore.

In order to evaluate the difference of the wind speeds between the locations and seasons, 1-hour average wind data were gathered for different locations in the North Sea (see below table 4.1). Specifically, data of the daily average wind speed published from the Royal Dutch Meteorological

Institution (KNMI) has been analyzed for a 20-year period (1993-2012). Wind speed data were given at a height that varies from -0,20m to 12,50m above sea level. In order to model the frequency of wind speeds a probability distribution function fitted to the observed data is used.

Location number	Longtidute (east)	Latitude (north)	Altitude (m)	Location name
210	4,419	52,165	-0,20	Valkenburg
225	4,575	52,463	4,44	Ijmuiden
235	4,785	52,924	0,50	De Kooy
270	5,755	53,225	1,50	Leeuwarden
277	6,196	53,409	3,00	Lauwersoog
286	7,150	53,196	0,20	Nieuw Beerta
323	3,884	51,527	1,40	Wilhelminadorp
330	4,124	51,993	12,50	Hoek van Holland

Table 4.1 Wind data obtained for different locations, Royal Netherlands Meteorological Institute.

Figure 4.2: Map of KNMI measuring network in the North Sea, Royal Netherlands Meteorological Institute

Specifically, the data of the below locations were used. One of the reasons is that for the wave height there were limited data available for only 4 out of the above 8 locations.

1. Ijmuiden (225)
2. Lauwersoog (277).
3. Valkenburg (210)
4. De Kooy (235)

The reason that for choosing those areas is that they are located in different spots in the North Sea from the northern part (Lauwersoog) to the southern part (Valkenburg). Expectation is that depending on the location of the wind turbine, the maintenance costs will be different as a consequence of the different weather conditions.

The *Weibull distribution* was applied as it can model the variance of the wind speed well. This is due to its greater flexibility and simplicity along with the good agreements with the experimental data.

The Weibull distribution is a continuous probability distribution with parameters α and β (α>0, β>0), where β is the shape parameter and α is the scale parameter. The probability density function of a Weibull random variable x is:

$$f(x,\beta,\alpha) = \frac{\beta}{\alpha}\ (\frac{x}{\alpha})^{\alpha-1}e^{(\frac{x}{\alpha})^{\beta}}, \quad x\geq 0$$

The distribution function for $x\geq 0$ is given by:

$$F_X(x,\beta,\alpha) = 1 - e^{-(\frac{x}{\alpha})^{\beta}}, \ \ x\geq 0$$

The shape value α is approximately 2 in the northern Europe and the scale parameter β depends on the location because the mean wind speed also depends on the location.

In appendix A more details about Weibull distribution can be found.

Using MATLAB, a Weibull fit of the data was made using max likelihood. The fit was made for 1 year data, as well as for the below four different season's separately:

- Winter: December, January, February
- Autumn: September, October, November
- Spring: March, April, May
- Summer: June, July, August

In the below table 4.2 the corresponding shape and scale parameters can be found as well as the mean wind speed for all locations and the different seasons. The average wind speed is somewhat lower compared to the wind speed showed in the above figure (3.1). The reason is the difference in height, as the wind speed varies as a power of height. Give units for the scale m/s.

Location and Number	Weibull Parameters for Wind data	Winter	Autumn	Spring	Summer	Year
210-Valkenburg	Scale parameter (α) (m/s)	5.68	5.30	5.50	4.95	5.54
	Shape parameter (β)	2.17	2.19	2.45	2.66	2.26
	Mean wind speed (m/s)	6.41	5.12	4.87	4.40	4.91
225-Ijmuiden	Scale parameter (α) (m/s)	9.47	7.62	6.97	6.70	8.37
	Shape parameter (β)	2.46	2.44	2.61	2.64	2.46
	Mean wind speed (m/s)	8.40	8.59	7.84	7.54	7.42
235-De Kooy	Scale parameter (α) (m/s)	7.43	6.34	6.22	5.55	6.39
	Shape parameter (β)	2.32	2.41	2.64	2.81	2.40
	Mean wind speed (m/s)	9.11	5.62	5.52	4.95	5.67
277-Lauwersoog	Scale parameter (α) (m/s)	6.33	5.20	5.46	4.54	5.35
	Shape parameter (β)	2.33	2.45	2.55	2.88	2.54
	Mean wind speed (m/s)	5.61	4.61	4.85	4.04	4.74

Table 4.2 Wind speed distribution for different locations: Weibull parameters of daily mean wind speed

According to the above table, for every location the highest mean wind speed is recorded during the winter, while the lowest daily mean wind speed is reported during the summer. Between the different locations, Ijmuiden is the one with the highest values whereas Valkenburg and Lauwersoog have similar annual average wind speeds.

The highest mean wind speed is recorded during the winter, with the highest value to be 9.11m/sec (De Kooy) and the lowest during the summer with the lowest reported value to be 4.04m/sec (Lauwersoog and Wilhelminadrop).

These data will be used as an input in the proposed model in order to define the weather condition and consequently define the ability to access the offshore wind farm. As there is not much difference on the scale, shape and mean wind speeds between location Valkenburg and Lauwersoog, the proposed model in this thesis can be applied in the first three locations (210,225,235). Running the model for the Lauwersoog location will give similar results as in Valkenburg.

In appendix C the graphical results can be found for the different seasons and for the total year.

Furthermore, in order to define how often the wind data gathered had good fit with the Weibull distribution, Q-Q plots were used. These plots can be extremely useful when highlighting distribution asymmetry, heavy tails, multi-modality, outliers, or other data anomalies.

Below the QQ plots of the wind data for 20-year period (1993-2012) for the locations of Valkenburg and Ijmuiden are illustrated. The x-axis plots the theoretical quartiles for a statistical population from Weibull distribution, while the y-axis plots the data. For locations De Kooy and Lauwersoog the results of the QQ Plots are similar to the below graphs confirming that for all locations the use of Weibull distribution was the appropriate distribution.

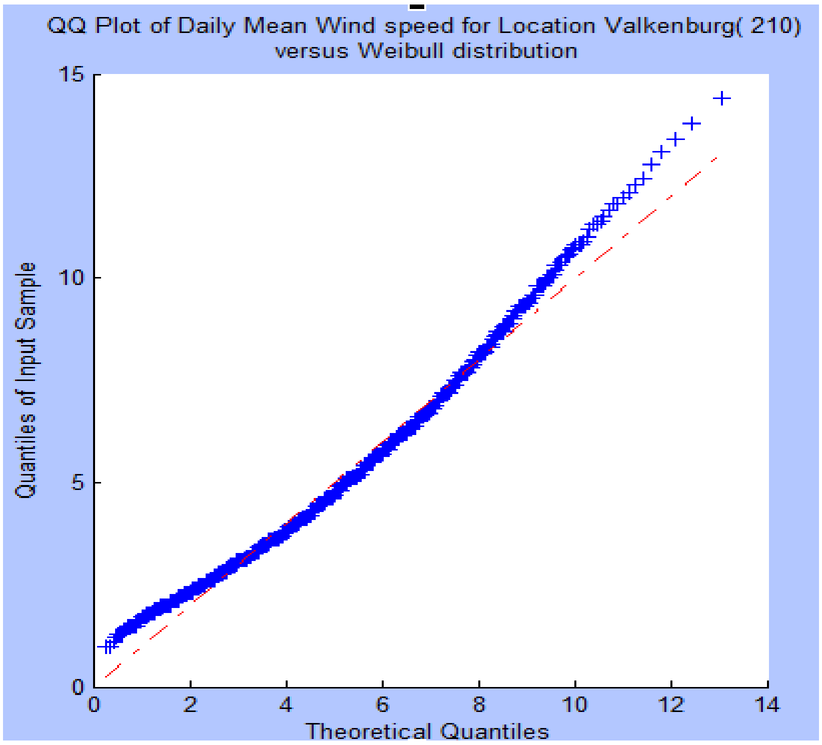


Figure 4.3: QQ plot for Weibull distribution for Location 3 Valkenburg

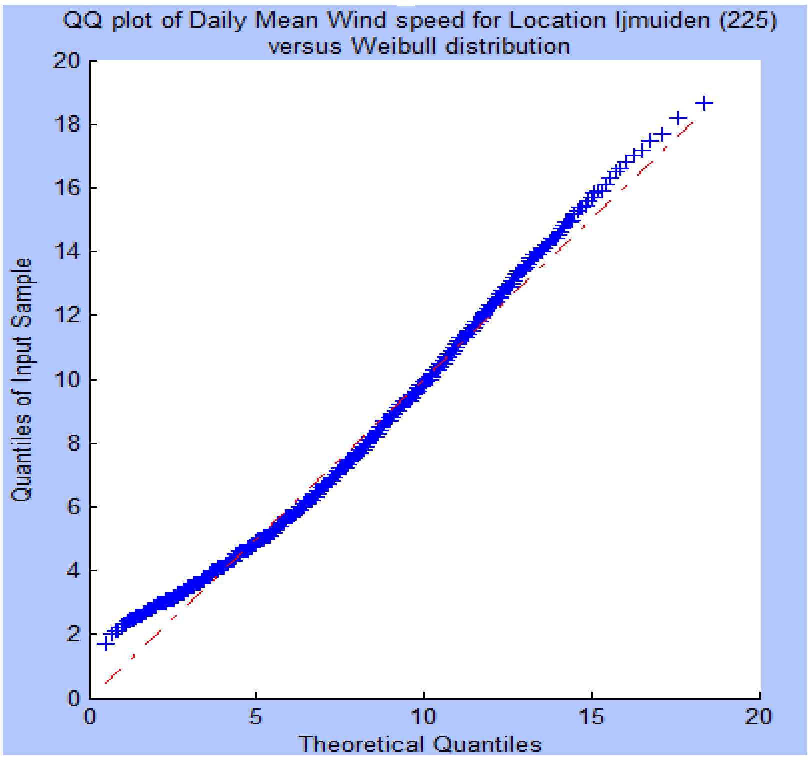


Figure 4.4: QQ plot for Weibull distribution for Location 1 Ijmuiden

It can be concluded for the above QQ plots that the set of data are modeled well with the Weibull distribution as both lines are close to a straight line of y=x .There are not extraordinary anomalies or asymmetries which are confirming that using the Weibull distribution to validate the data was a good decision.

4.2 Wave height

One of the common ways to transport personnel and light equipment for executing maintenance in the offshore WT is small boats or helicopters. As this mode of transport is limited to relative benign sea states of up to 2 meters wave height (Rademakers et al,2003) the wave height is an important parameter that influences the total waiting time due to bad weather conditions and as a result the total downtime of the WT.

The mean wave height or as it is called **Significant Wave Height (H_S),** is defined as the highest one third of the waves. Initially it was used to mathematically express the height measured by a “trained observer” but nowadays is widely used to calculate ocean waves’ height. As observed by Rijkswaterstaat, the location for which the significant wave data is measured can be found in the below picture. The locations for which inputs were retrieved are marked in red boxes. Likewise with the wind speed data, the input used for the wave height was the daily average for the same time period of 20 years (1993-2012).

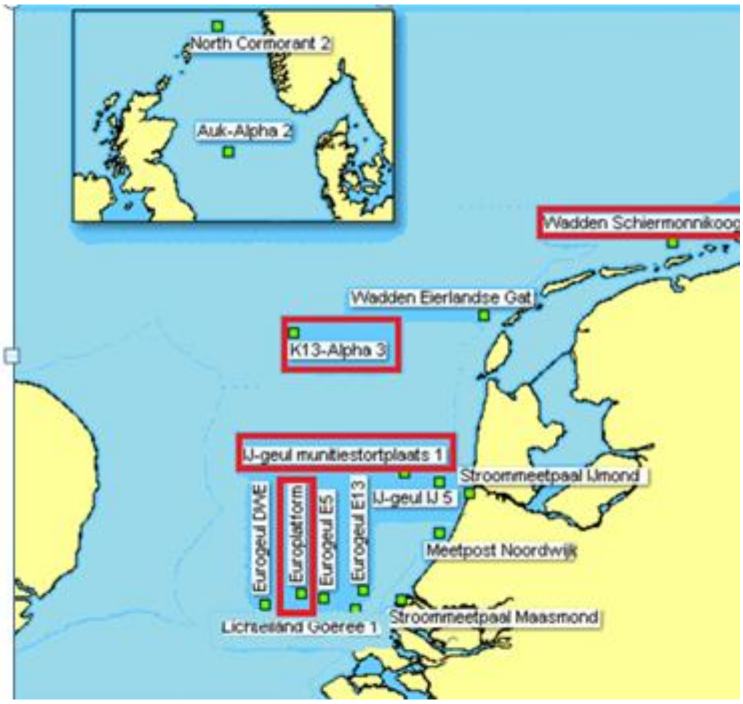


Figure 4.5 Map of the wave height stations in the North Sea, Rijkswaterstaat-Ministry of Infrastructure and the Environment

In the below table the shape and scale parameters of the daily average of Significant Wave Height for 4 locations can be found as well as the mean height for the total year and for the different seasons. The input data were daily and for a total period of 20 years. Using MATLAB, a max likelihood fit of the Weibull distribution was applied.

In appendix D the graphical results can be found for the different seasons and for the total year.

Location	Weibull Parameters for Wave data	Winter	Autumn	Spring	Summer	Year
Europlatform	Scale parameter (α) (m)	1.93	1.74	1.53	1.39	1.65
	Shape parameter (β)	2.37	2.27	2.21	2.24	2.19
	Mean wave height (m)	1.71	1.54	1.36	1.23	1.46
Ijmuiden	Scale parameter (α) (m)	1.87	1.67	1.24	1.14	1.47
	Shape parameter (β)	2.00	2.01	1.86	1.87	1.81
	Mean wave height (m)	1.65	1.48	1.10	1.01	1.31
K13 platform	Scale parameter (α) (m)	1.62	1.25	1.39	1.17	1.37
	Shape parameter (β)	4.22	5.15	5.12	4.27	3.95
	Mean wave height (m)	1.47	1.15	1.28	1.06	1.24
Wadden Schiermonnikoog	Scale parameter (α) (m)	1.63	1.47	1.20	1.12	1.35
	Shape parameter (β)	1.84	1.79	1.86	1.77	1.75
	Mean wave height (m)	1.45	1.31	1.06	0.99	1.20

Table 4.3 Wave height distribution for different locations: Weibull parameters of daily average wave height

As for the wind data (section 4.3), QQ Plots for Weibull distribution were run in order to assess whether the data set has a good fit with the theoretical distribution used. Both graphs below have slightly thin positive tail. The tail divergence for line y=x is slight which means that the data are still making a fit with Weibull distribution.

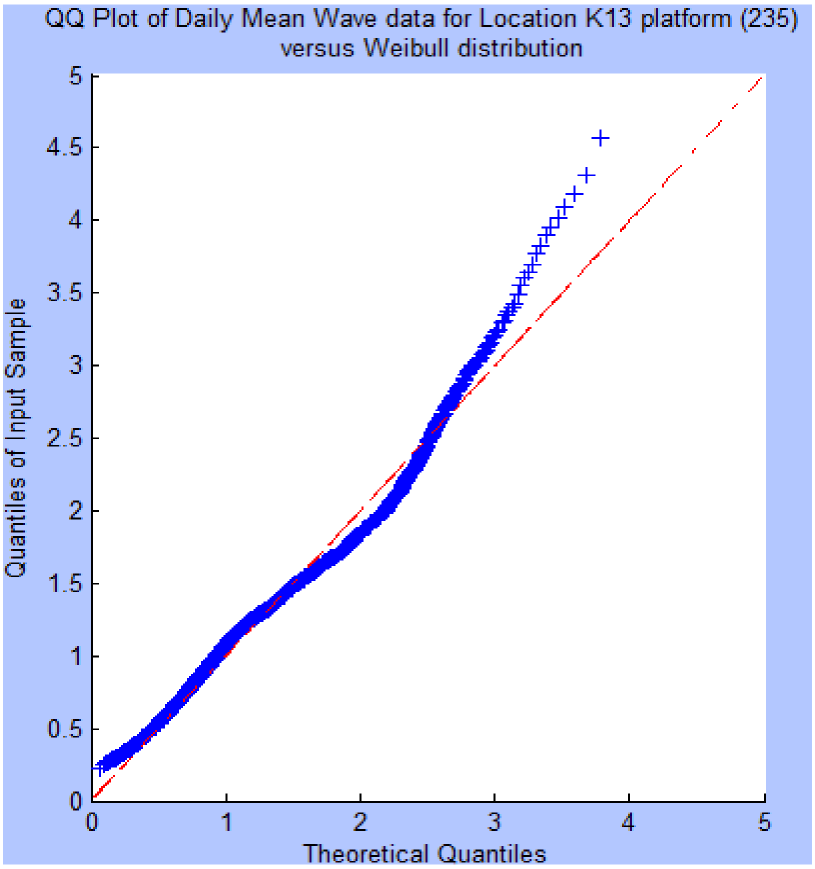


Figure 4.6: QQ plot for Daily Mean Wave data versus Weibull distribution for Location K13 platform

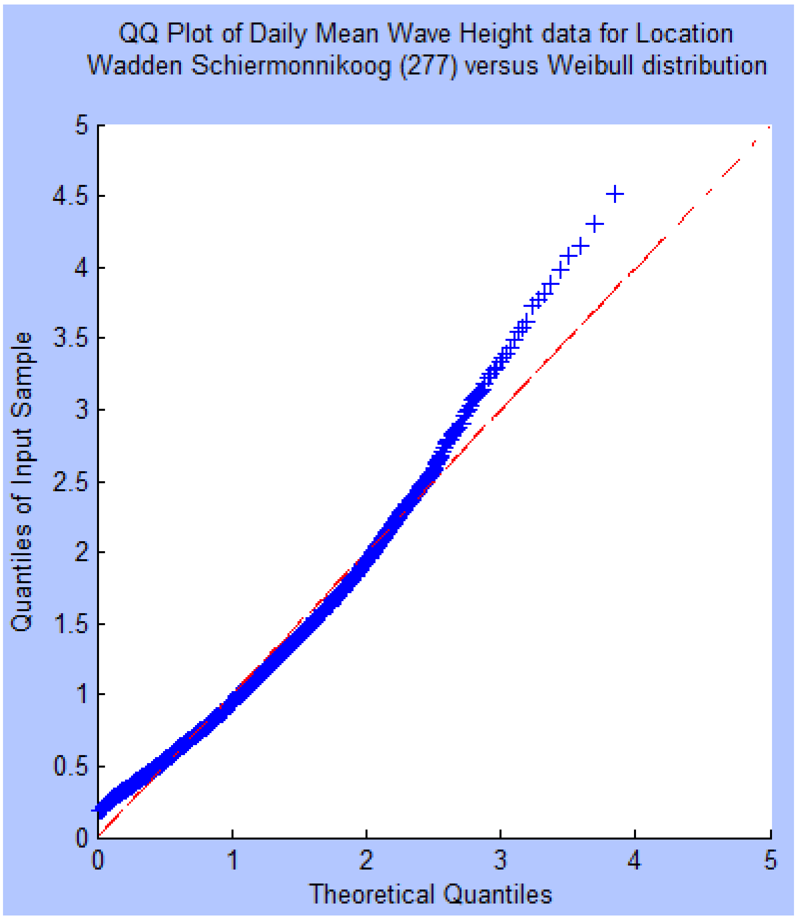


Figure 4.7: QQ plot for Daily Mean Wave Height data versus Weibull distribution for Location Wadden Schiermonnikoog (277)

Similar graphs were generated for the locations of Europlatform and Ijmuiden which means that also these have slightly thin positive tail which means flatter distribution of data points.

4.3 Accessibility of an offshore wind farm

Both wind speed and wave height (described in section 3.1 and 3.2) are influencing the accessibility of an offshore wind farm, which is an important factor when maintenance should be performed. Offshore wind turbines can be accessed by vessel or helicopter. Each vessel has a specific max wind speed and (significant) wave height that can sail. The periods when an offshore site can be visited are called good weather window, in which both wind speed and wave height need to be within an acceptable range.

In order to define the good weather widows for accessing an offshore farm and to validate whether its location in the sea area affects its accessibility, two locations in the North Sea were used. Specifically, location Ijmuiden and Valkenburg were used.

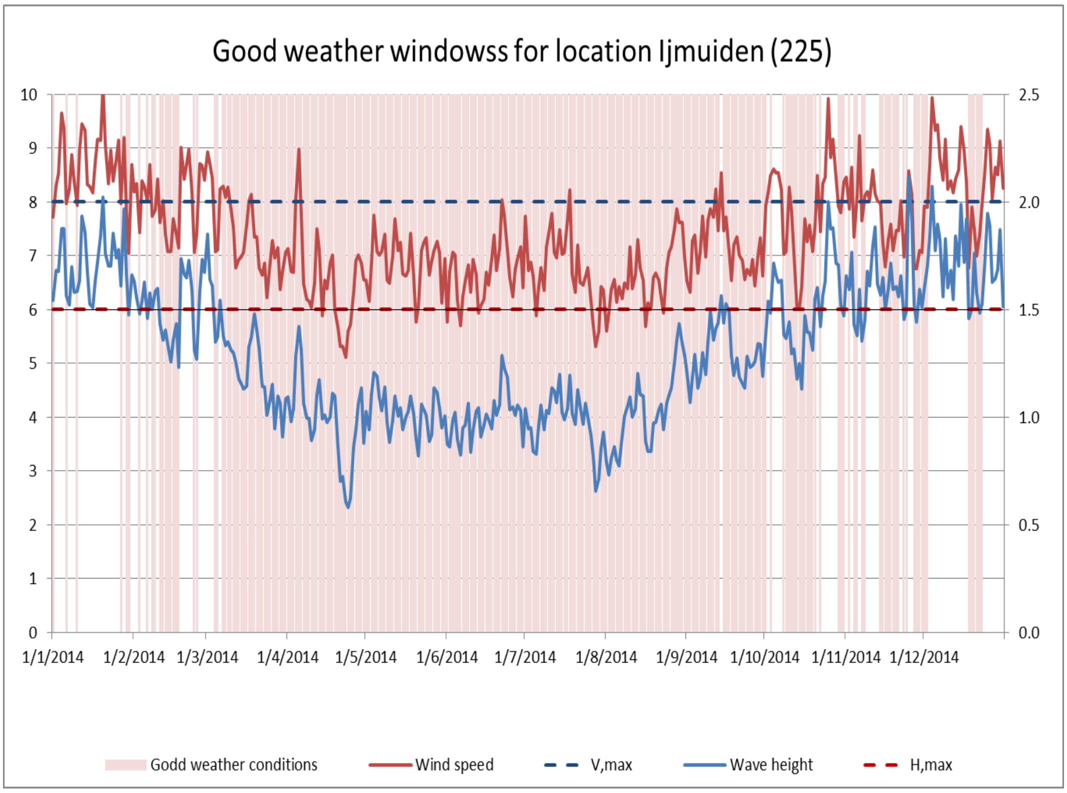


Figure 4.8: Example of good weather windows for the location Ijmuiden

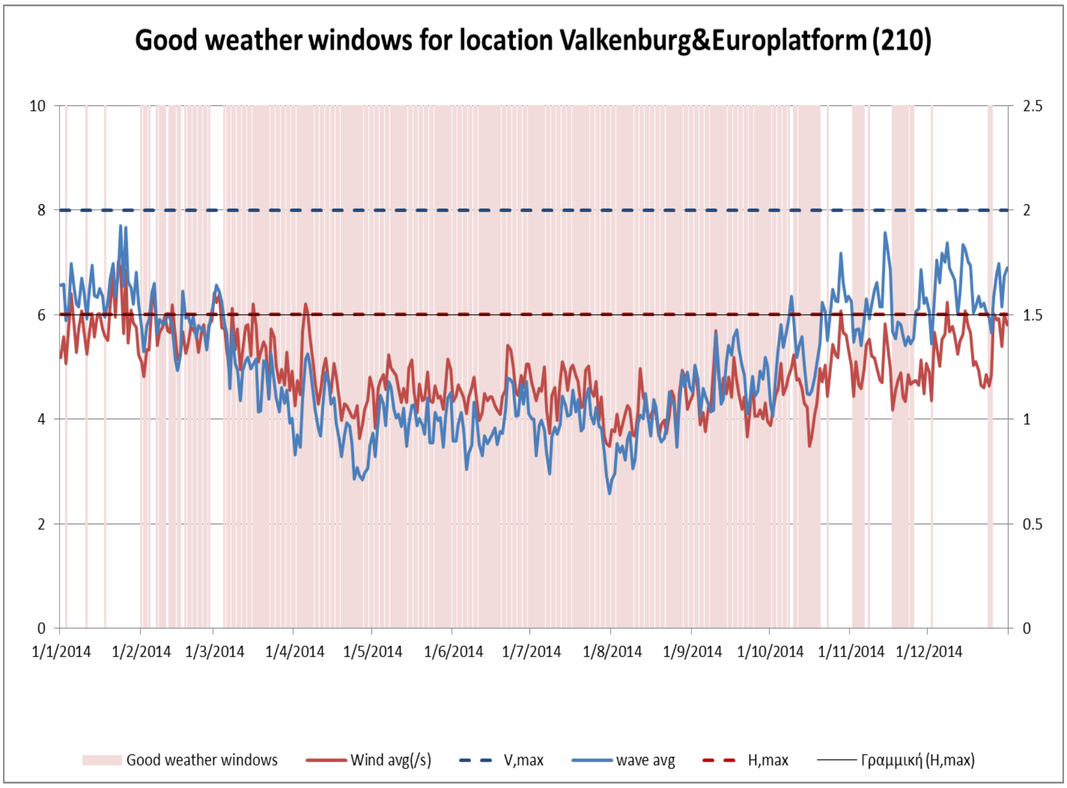


Figure 4.9: Example of good weather windows for the location Valkenburg

To generate the above graph the daily average of 20-years data set for both wind speed and wave data were manipulated in order to get a final data set of one year (365 days). For every day of the year 20 data points are available from 1993 until and including 2012. The average of these 20 data was calculated for every single day and the resulted number was saved in a new column in order to be used for the weather scenarios calculation. This exercise was applied for every group of 20 data for every single day and for both wind speed and wave height. The new data set of 365 values for each of the wind speed and wave height was used in order to create the above graphs.

The constraints used to define the good weather conditions were defined as the maximum significant wave height at 1.5m and the maximum wind speed at 8m/sec. The pink shaded blocks represent the wind speed and wave height that satisfies the criteria in order for a vessel to sail to the offshore wind farm.

The total number of days per year with good weather conditions for the location of Ijmuiden is 220 which correspond to 60% of accessibility for the total year. On the other hand, the good weather windows location Valkenburg are 275 days which corresponds to a total of 75% of accessibility to the offshore wind farm for the total year.

Using the shape and scale parameter calculated in section 4.1 and 4.2 for the wind and wave data, the same exercise applied. The constraints of maximum significant wave height at 1.5m and the maximum wind speed at 8m/sec remained the same at 1.5m for wave height and at 8m/sec for wind speed. In this case, the accessibility of the offshore wind farm for Ijmuiden was calculated to be 53% (versus 60% calculated above) while for Valkenburg was reported at 52% (versus 75% calculated as described above).

Depending on the location of the wind farm in the sea area, there are different weather conditions thus different numbers of good weather windows. In order to compare the results and the validity of the assumption that weather affect the total maintenance costs, the model will be run taking into account both options of including or not the weather conditions.

Both wind speed and wave height data will be used to define the good weather windows when a maintenance activity can take place. In chapter 6 more detail analysis on how the data will be implemented is presented. Please note that the weather conditions were not created according to visibility but based on average wind speed and/or significant wave height.

4.4 Introduction to Wind Energy

Before building an offshore wind farm, it is important to measure its performance. Specifically, the performance of a wind turbine and following of a wind farm is influenced by the wind speed of the region, the power and the failure rate of the wind turbine.

4.4.1. Wind Turbine- Power calculation

In general, wind turbines convert the kinetic energy in the wind initially into rotational kinetic energy in the turbine and then electrical energy. The wind speed and swept area of the wind turbine are defining the available energy which will be converted. In order to calculate the economic viability of a wind farm, the estimated power and energy output of the wind turbine needs to be calculated.

Before introducing the formula, some basic notation and their explanation shall be provided.

Wind energy: As noted by Manwell J.F et al. (2002), the power of an air mass that flows into through an area A is given by:

$$P_{air} = \frac{1}{2}\, \rho A u^3$$

Where, ρ is the Air density in kg/m^3, *u* is the wind speed in m/s.

When flowing into the area of a wind turbine rotor part of the wind power is converted into mechanical power. There is a theoretical limit on the total amount of power that can be produced by a wind turbine so as to prevent the air mass from stopping. It is called the Betz limit and the maximum value is 59%.

Power coefficient: The ratio between the powers extracted from the blade area and flowing into that area is called power coefficient C_p. The value depends on the angle of attack (angle between wind direction and the blade) and tip speed ratio (ratio between blade tip speed and wind speed). For a good wind turbine design C_p is around 0.35.

In order to calculate the power output curve of a wind turbine as a function of the wind speed the following formula can be applied:

$$P_{avail} = C_p \cdot v_t \cdot \frac{1}{2} \rho A u^3$$

Where, v_t is the efficiency coefficient of the components in the wind turbine (up to 0.8).

4.4.2 Power curve of a Wind Turbine

As mentioned above, (Manwell J.F et al, 2002), the energy output of a wind turbine is a good mean to access its performance. Energy from the wind is only converted to electricity from the wind turbines when the wind speed is within a certain range, which is determined by the power curve of the wind turbine. There are 3 important characteristics of a power curve:

1. ***Cut-in wind speed*** *(u_{cut-in}):* is the wind speed at which the wind turbine starts to generate power. For most of the wind turbines that speed is between 3-5m/s. (point A n the below figure)
2. ***Nominal or rated wind speed*** ($u_{nominal}$)**::** at that speed the full power is reached, which is reached usually at 12-15 m/sec. (point B in the figure)
3. ***Cut-out wind speed*** ($u_{cut-out}$)***:*** the wind turbine is turned off for safety reasons. Usually, at wind speeds of 25m/sec or more. (point C)

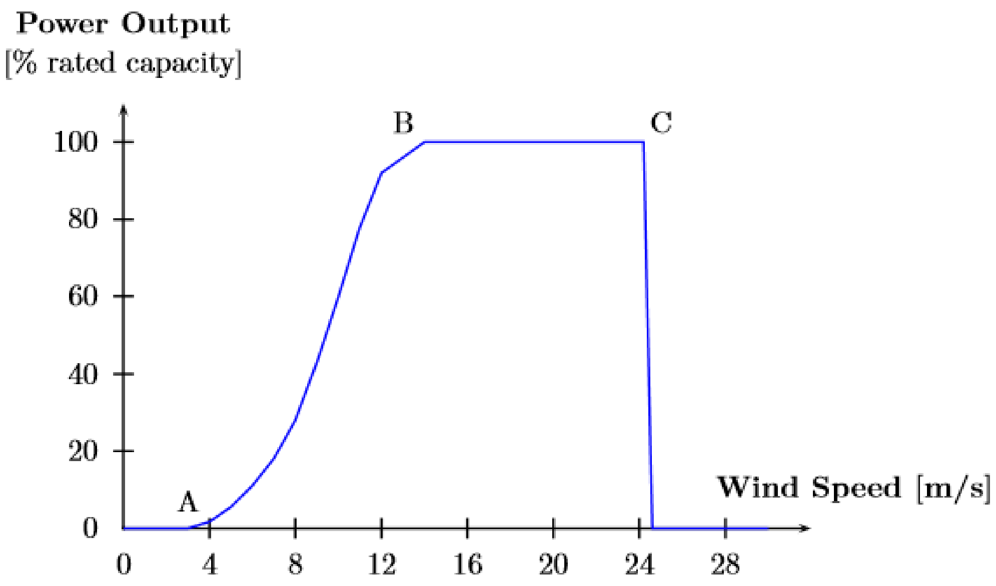


Figure 4.10: Power curve of a wind turbine. Point A: cut-in wind speed, Point B: rated wind speed, Point C: cut-out wind speed

This chapter is introducing and describing all the related items and terminology around wind farms and specifically the offshore ones. Particularly concepts such as wind speed, wave height, good weather windows, and wind energy and power curve were defined.

Wind speed and wave height are influencing the capability of the maintenance crew to visit the offshore farm especially during the winter months when their values are higher. Depending on the type of maintenance or vessel needed to sail to the offshore structure, there are different upper limit that above them it is not possible to visit the wind farm. When the rate of the wind speed and wave height is inside the allowed values in a specific day or period are considered good weather windows. What is more, the introduction to wind energy and how it can be calculated according to the power curve of the wind turbine was also explained in this chapter.

As weather forecast is not available for more than 10 days ahead as it is difficult to predict. In order to test the model, an assumption will be made that the average wind speed and wave height calculated for every day of the simulation will be constant throughout the day. Moreover, by creating different weather scenarios an attempt will be made to test the weather impact on the maintenance cost optimization even with no short term weather forecast available.

In summary, Chapter 4 attempts to explain the critical elements related to the offshore wind farm and its optimization. The reason is that the data presented in this chapter will be the inputs in the proposed model on chapter 5 below of this thesis in order to optimize the maintenance costs.

Chapter 5

5 Methodology

In this chapter the methodology used to develop the optimization model for maintenance activities is described in detail. As stated in Chapter 1, the aim of this report is to test whether combining corrective with preventive maintenance will minimize the total maintenance costs. This will be tested in conjunction with the weather impact on different locations in the North Sea. Besnard et al (2009) argues that combining CM with PM tasks and taking low wind speed into consideration maintenance costs will decrease. The model proposed was a good base to build the model of this report as the weather conditions were not included in the proposed model by Besnard et al (2009). Using wind data from the Royal Netherlands Meteorological Institute and wave data from Rijkswaterstaat the model proposed by Besnard et al (2009) will be enhanced and tested.

5.1. Introduction

As proposed in Besnard et al (2009), planning of maintenance activities is a way to save costs. Specifically, scheduled maintenance activities can be optimized by taking advantage of low wind forecasts and corrective maintenance at failures.

Usually, maintenance activities are scheduled to be performed under fixed period of times without taking into account power production as well as losses of production when the WT in down for maintenance. Cost savings could be achieved if the maintenance activities are performed during low wind speeds which mean low energy production. Every WT is subject to failure which can be considered as an opportunity to implement part of the scheduled maintenance tasks. By considering a failure as an opportunity for maintenance it would help to avoid the necessity to re-visit and access the WT again, and might cut down work and transportation costs.

For the above mentioned reasons, the model applied in this thesis is trying to optimize maintenance tasks by combing CM with PM as well as taking into account low energy output. In order to achieve this, a mixed integer linear optimization problem (MILP) is applied.

To solve the below described model every single constraint was written in MATLAB as well as the objective function that will be optimized. The model will not be solved using a specific method but using author’s own method. More information on the optimization theory can be found on Appendix B.

5.2 Problem formulation

The proposed model in this thesis is based on the mathematical formulation presented by Besnard et al (2009). The recommended model was run only for 60 days during the summer period when the weather constraint was not relevant as summer is considered to be the season with the mildest weather conditions. In this report, the model will be run for a full year (365 days) and the weather constraint will be added. During the winter, weather conditions have to be taken into account in order to represent a real life situation. As it was concluded from chapter 4, weather conditions are the most important factor influencing the accessibility of the offshore wind farm and thus its availability of producing energy. Thus, weather restriction will be added in the below model.

In the model proposed the time periods are divided into Short Horizon (SH) periods and Long Horizon (LH) periods. On the SH, the code is checking on a daily basis whether a failure has occurred as it is assumed that a CM is only known once it has occurred and can be identified during the SH model run. During the SH, the model will try to minimize costs by combining CM tasks with PM. On the LH, using statistical wind data forecasts the model will identify for every week, the best time periods that PM can be scheduled. Those time periods are defined based on the forecasted wind speed.

Time Framework

The SH is discretized into $N_{T_{short}}$ time periods each one consisting of ***one day***. The set of the total time periods in the SH interval is represented as $\mathrm{T_{short}}$= {1… $N_{T_{short}}$}.

The average power production during one time period t is P_t, $t \in T_{short}$.

The LH is discretized into $N_{T_{long}}$ time periods each one consisting of ***one week***. The set of the total time periods in the SH interval is represented as $\mathrm{T_{short}}$= { $N_{T_{short}} + 1, \dots, N_{T_{short}} + N_{T_{long}}$}.

Expected power production P_k^{LH} is estimated by using Weibull distribution. More details on the Weibull distribution and probability function is given in Appendix A.

System Description

Both preventive and corrective maintenance tasks within the time horizons have to be defined. Specifically, the model assumption is that on average 2 failures per WT per year are occurring and that 3 PM tasks per WT and per year need to be scheduled and performed.

The set PM of preventive maintenance works will be defined and subtasks of at least one hour will be included. For each task j ∈ PM the time to execute PM is τ_j^{PM} hours. The optimization is starting by forcing the PM task j in wind turbine i to be performed within the next w_{ij0} time steps.

A subset CM ⊂ WT of corrective maintenance tasks required for the wind turbines is determined. CM is forced to be performed during the SH time intervals and it is assumed that at most one corrective maintenance task can be performed in one day. Estimated time for the maintenance activity is τ_i^{CM}. Costs associated due to production losses during maintenance at each period t are defined as P_t^{CM}.

Costs and time Constraints

Transportation costs and production losses due to maintenance are assumed to be the costs in this model. In order to calculate the energy losses when performing preventive maintenance, the electricity market price C_{el} will be used multiplied by the electricity output, i.e P_t (in kWh) for the SH and P_K (in kWh) for the LH. The same will apply for the losses P_t^{CM} when performing corrective maintenance at time period t ∈ T . There are also the transportation costs C_{tr} which are considered fixed each day and usually include sailing crew, fuel, boat and/or helicopter location costs. The type of those costs is dependent on the type of service contracted with the transport company.

The number of working hours per day for the short horizon for the maintenance crews is defined as h. In those hours we should take into account τ_ω which is the time to access the nacelle of a wind turbine. For the long horizon h_{kt} is the total amount of maintenance hours.

As noted by Besnard et al (2009) the below assumptions made also in this thesis for the L*ong Horizon:*

- On average **2** preventive maintenance tasks can be performed at each period t.
- Maintenance crew can work for h-2 τ_{ω}hours each time the wind park is visited.

In the beginning, let us introduce the following notation:

<u>Decision variables:</u>

$$w_{it} = \begin{cases} 1, \text{if the weather allows to visit the WT i at step t} \\ \quad 0, \ \text{otherwise} \end{cases}$$

$t \in \mathrm{T_{short}},\ \mathrm{i}\ \in$ CM

$$x_{ijt} = \begin{cases} 1, \text{if PM task j in WT i is performed at step t} \\ 0, \text{otherwise} \end{cases}$$

$t \in \mathrm{T_{short}}$, j ∈ PM, i ∈ CM

$$v_{ijt} = \begin{cases} 1, \text{if PM task j in WT i is performed at step t} \\ 0, \text{otherwise} \end{cases}$$

$t \in \mathrm{T_{long}}, i$, j ∈ PM

$$y_{it} = \begin{cases} \ 1, \text{if CM task in WT i is performed at step t} \\ 0, \text{otherwise} \end{cases}$$ [1]

t ∈ T, i ∈ WT

<u>Auxiliary binary variables</u>

$$z_t = \begin{cases} 1, \text{if the wind park is visited at step t} \\ 0, \text{otherwise} \end{cases}$$

$t \in \mathrm{T_{short}}$

$$u_{it} = \begin{cases} 1, \text{if the WT i is visited at step t} \\ 0, \text{otherwise} \end{cases}$$

$t \in \mathrm{T_{short}},\ \mathrm{i}\ \in$ WT

Parameters:

<u>Set and Indexes:</u>

$\mathrm{T} = \mathrm{T_{short}} \cup \mathrm{T_{long}}$ Set of time periods

$\mathrm{t} \in \mathrm{T}$ Index of time periods

$\mathrm{i}\ \in \mathrm{WT}$ Index of the wind turbines

CM ⊂ WT Set of wind turbines requiring corrective maintenance

---

PM: set of preventive maintenance

$j \in \mathrm{PM}$ Preventive maintenance tasks index

$k \in \{1, \dots, L\}$ Index of power loss levels for LH

Costs and production parameters

C_{pen}: Penalty for supplementary maintenance hours [€/h]

C_{el}: Electricity cost [€/kWh]

C_{tr}: Site transportation costs (maybe split for vessels and helicopters)

P_k^{LH}: Power loss for LH, $k \in \{1, \dots, L\}$

P_t^{CM}: Power loss if corrective maintenance task is done at step t, $t \in T_{short}$

Time parameters

ω_{ij0}: Number of time steps before preventive maintenance task j in wind turbine i should be performed, $t \in T$, $i \in WT$, $j \in PM$

τ_i^{CM}: Time to do corrective maintenance in WT i, $i \in CM$

τ_j^{PM}: Time to do preventive maintenance task j, $j \in PM$

τ_ω: Time to access the nacelle of a wind turbine

h: available maintenance hours during the SH

h_{tk} : Total working hours at day t, $t \in T_{long}$

Next to that, the formulation of the problem consists of the objective function. The aim is to minimize the total CM costs, PM loss costs and Long horizon PM loss and transport costs.

$$\boldsymbol{Min} \sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt} \tau_j^{PM} P_t]\, C_{el} + z_t C_{tr} + e_t C_{pen}]$$

$$+ \sum_{t \in T_{long}} [\sum_i \sum_j \sum_k h_{tk}[\,[v_{ijt} P_k^{LH}]\ C_{el} + \frac{C_{tr}}{h - 2\tau_\omega}]]$$

The *first part* of the objective function is minimizing corrective maintenance costs and preventive maintenance costs when performed combined, the transportation costs to the wind farm and the penalty occurred when the maintenance crew is working more than the agreed daily working hours. In other words, this part of the equation is trying to optimize the costs incurred during then SH when opportunistic maintenance strategy is applied.

The *second part* of the objective function is minimizing preventive maintenance costs. These preventive maintenance tasks are being scheduled based on weather forecasts and low wind speed is chosen in order to minimize the energy losses and thus the maintenance costs. This part of the objective function is connected to the LH model.

Subject to:

$z_t \geq u_{it},\ i\ \in WT, t\ \in\ T_{short}$: ensures that costs for visiting the WT are incurred if any preventive or corrective maintenance is performed.

$u_{it} \geq\ x_{ijt},\ \ i\ \in WT, \qquad j \in PM, \qquad t\ \in\ T_{short}$

$\mathrm{u_{it}} \geq\ \mathrm{v_{ijt}},\ \ \mathrm{i}\ \in \mathrm{WT}, \qquad \mathrm{j} \in \mathrm{PM}, \qquad \mathrm{t}\ \in\ \mathrm{T_{long}}$

$u_{it} \geq\ y_{it}, \qquad\qquad\qquad i\ \in WT,\ \ t\ \in\ T_{short}$

The above constraints ensure that a maintenance work is performed in the wind turbine i if any corrective or preventive maintenance is performed in that turbine

$\sum_{t \in \mathrm{T_{Long}}} y_{it} = 0, i \in CM$: Corrective maintenance is forced to be executed during the short horizon. By adding this constraint it’s ensured that no CM is performed on the long horizon.

$\sum_{t-=1}^{\omega ij0} x_{ijt} * v_{ijt} = 1, i \in WT, j\ \in PM$: Every preventive maintenance is performed during the remaining days allowed.

A penalty is paid during the short horizon in case the maintenance working hours are more than the available number of hours.

$\sum_{ij} x_{ijt} * \tau_i^{PM} + y_{ij} * \tau_i^{CM} + u_{it} * \tau_\omega \leq h + e_t, t\ \in\ T_{short}$

$\sum_{ij} v_{ijt}[\tau_j^{PM} + \tau_\omega/2] \leq \sum_{tk} h_{tk}, t\ \in\ T_{long}$

$h_{tk} \leq h\ , \quad t\ \in\ T_{long}, k \in \{1,2, \dots, L\}$

As the offshore wind energy will be growing fast in the coming years it will become necessary to explore ways to minimize as much as possible the operational costs and maximize the energy production. The purpose of the above model is to try to assess whether combining corrective with preventive tasks and schedule PM on low wind speed based on wind forecasts does save maintenance costs. For that reason, the above described model will be implemented and the results will be analyzed. The model will be implemented in MATLAB and in the next chapters more details on the assumptions made, running time, restrictions and results will be presented.

Based on the input variables of the proposed mathematical formulation the conclusion carried out is that the weather variable $\mathrm{w_{it}}$ will play a significant role on the maintenance costs as it is related to the capability of the maintenance crew to visit and perform CM tasks in order for the WT to be operational and thus produce energy. In other words, when the decision variable has the value 0, meaning that the weather does not allow visiting the wind farm while $\mathrm{x_{ijt}}$ variable is 1 meaning that a failure occurred and CM has to be performed, energy losses will follow. What is more, energy losses when PM task is scheduled will be also generated as well extra transportation costs when PM task is not scheduled with CM. To wrap up, weather constraint, energy losses and transportation costs will be the main contributors to the total maintenance costs.

To summarize, the proposed model is consisting of three types of decision variables, weather conditions, two types of corrective maintenance tasks and three types of preventive maintenance tasks. The model will be run for 365 days which means that the number of the weather decision variables is 365, for CM it is 730 and for PM it is 1095. This model as described above is a Mixed Integer Linear Programming problem which involves the optimization of a linear objective function, subject to linear equality and inequality constraints. Mixed integer programming problems are in general much more difficult to solve than linear programming problems.

Below a flowchart of how the model will be run is presented:

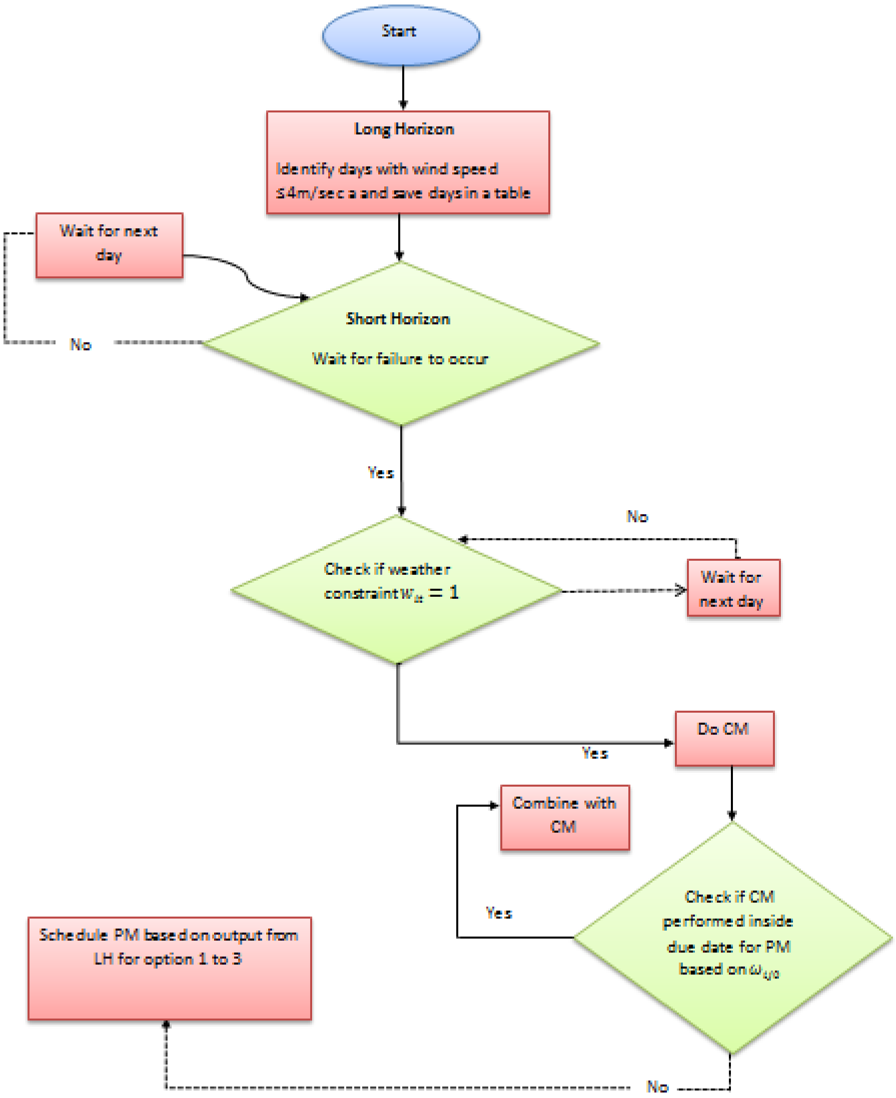


Figure 5.1: Flowchart of the proposed maintenance model

Chapter 6

6 Implementation and Results

6.1 Weather Scenarios for different locations

The above described model will be implemented for 4 different locations in various combinations of average wind speed and significant wave height. In order to define the wind and wave pairs the criteria used was the proximity of the various locations of which the wind and wave data were gathered. Below the different combinations of wind speed and wave height can be found:

1. Ijmuiden (225)- Ij-geul munitiestortplaats 1→ Location 1
2. Lauwersoog (277)- Wadden Schiermonnikoog→ Location 2
3. Valkenburg (210)-Europlatform→ Location 3
4. De Kooy (235) –K13 Alpha 3→ Location 4

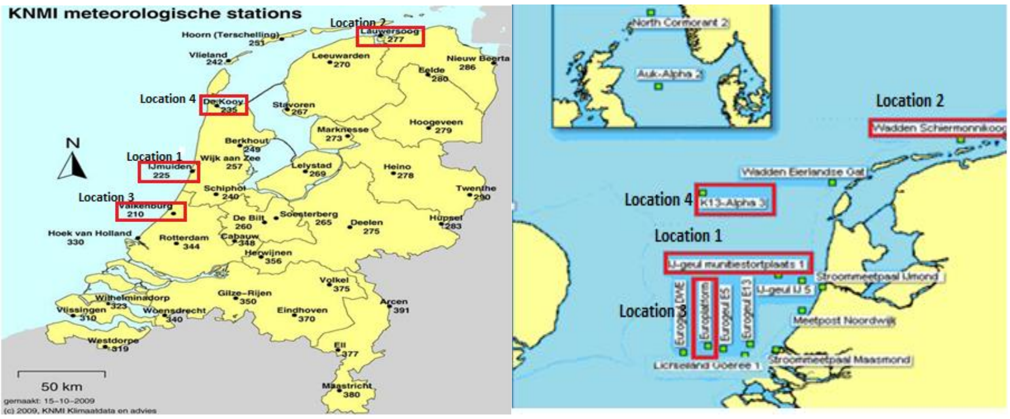


Figure 6.1: Combinations of Different Locations

The weather is the most important parameter which determines if an offshore wind farm can be accessed or not. A great attention shall be given in order to capture the diverse and fuzzy weather conditions in the sea. For that reason, in order to test the model in different weather conditions and compare whether the diversity of the weather conditions affect the results, weather scenarios were developed. Below, a few exampled examples of different combinations of weather scenarios which will be applied to the proposed model on this report are presented below:

- **Scenario 1:** *Low* wind speed and wave height throughout the year (L-L-L-L)
- **Scenario 2:** *High* wind speed and wave height during the year (H-H-H-H)
- **Scenario 3:** *High* wind speed and wave height during the winter, *Medium* wind speed and wave height during the spring, *Low* wind speed and wave height during the summer and *Medium* wind speed and wave height during autumn. (H-M-L-M)
- **Scenario 4:** *Low* wind speed and wave height during the winter *Medium* wind speed and wave height during the spring, *High* wind speed and wave height during the summer and *Medium* wind speed and wave height during autumn. (L-M-H-M)

The term High (H), Medium (M) and Low (L) was defined as follows by the author:

Low: From the 20-years data set of the average daily wind speeds retrieved from the website of KNMI and from the 20-years data set of the significant wave height gathered from the Rijkswaterstraat website, the minimum value of the each day is selected for each season in order to create a total data set of a full year (365 values). For example, out of the 20 values for the 2nd of January starting in 1993 until 2002 (both years included) the minimum daily average wind speed is selected. The same procedure is followed for each day of the year for both wind speed and wave height values from the input data obtained for each location.

Medium: As described above, the same procedure was applied for each season. This time the average value of the 20 measurements for each day of the year for 20 years was calculated and retrieved. This method was applied for both average daily average wind speed and significant wave height values.

High: Again the same method was implemented to capture the maximum values for each day of the year from a data pool of 20 years. The high values were obtained for both daily average wind speed and wave height value.

In every model run, according to user's wish the weather scenarios can change. The scenarios are predefined prior running the MATLAB code. Specifically, before the model is run the user can select location (225, 277, 210, 235) and for every season (winter, spring, summer, autumn) can type "H" for high, "L" for Low and "M" for medium wind and wave data. Moreover, constraints on maximum wind speed and wave height which below them a vessel can sail to the wind farm are defined prior the algorithm's run.

By constructing different weather conditions and thus scenarios the uncertainty of the future weather will be accounted for and the flexibility of the model will be validated.

6.1.1 Vertical wind profile

The wind speed differs with the height above the ground. When the wind speed distribution is known at height $\mathrm{z_r}$, it can be also evaluated at height z using the vertical profile of wind speed. The logarithmic wind profile is a simple model used in this thesis:

$$\frac{\mathrm{u(z)}}{\mathrm{u(z)_r}} = \ln\left(\frac{\mathrm{z}}{\mathrm{z_o}}\right)/\ln\frac{z_r}{z_o},$$

Where in is the standard logarithmic function and $\mathrm{z_o}$ is a surface roughness which depends on the landscape type. For instance, as presented by Manwell et al (2001), for calm open sea $\mathrm{z_o}$ can be 0.2, 8 for lawn grass and 500 for forests. For offshore wind value the value of $\mathrm{z_o}$ is low which means that low heights the power production and low turbulences.

The wind turbine was for this thesis is Vestas V80 (see below section 6.1.2) which has a height of 80m, which is representing z variable on the above formula. In chapter 4, table 4.1, the height on which the wind speed was calculated can be found which corresponds to $\mathrm{z_r}$.

6.1.2 Selection of Wind turbines

In order to calculate the wind speed on the desired height using the formula described in section 6.1.1 the type of wind turbine used is Vestas V 80 with the below characteristics:

Turbine Type	Height (m)	Cut-in wind speed (m/s)	Cut-in wind speed (m/s)	Cut-out wind speed (m/s)	Dutch Offshore Wind Farm in Use
Vestas V 80	80	4	16	25	Prinses Amalia

Table 6.1: Vestas V80 Wind Turbine Specifications

The energy curve of this turbine is the following:

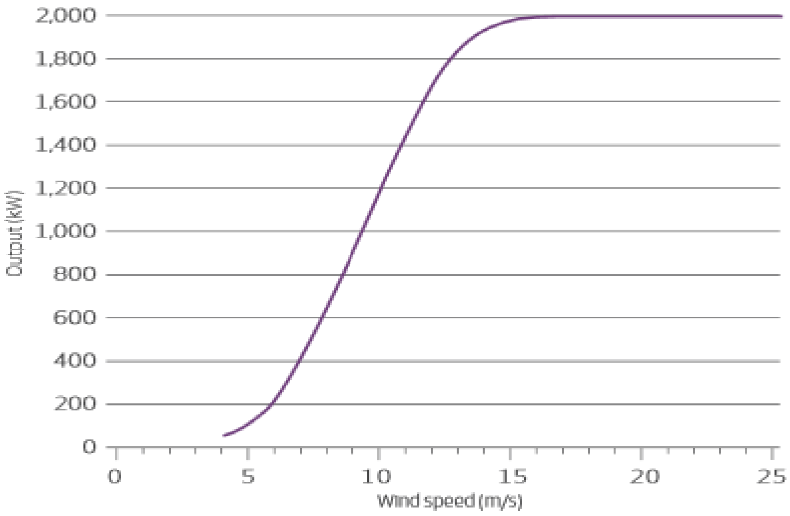


Figure 6.2: Vestas V80, 2MW Turbine

The reason for choosing this type of WT is because it's already operational in the Dutch Exclusive Economic Zone (EZZ) and specifically on the offshore wind farm "Prinsess Amalia" in the area of Ijmuiden.

6.1.3 Weather constraints according to the type of maintenance activity

As reported by van Bussel et al (2003), there is different maintenance actions (corrective or preventive) which are categorized according to the type of failure occurred and the required repair tools needed. In order to define the weather restrictions (max wind speed and wave height) that needs to be taken into account the below maintenance categories were used. Below, 4 different categories were defined and the associated restrictions on the weather conditions are indicated.

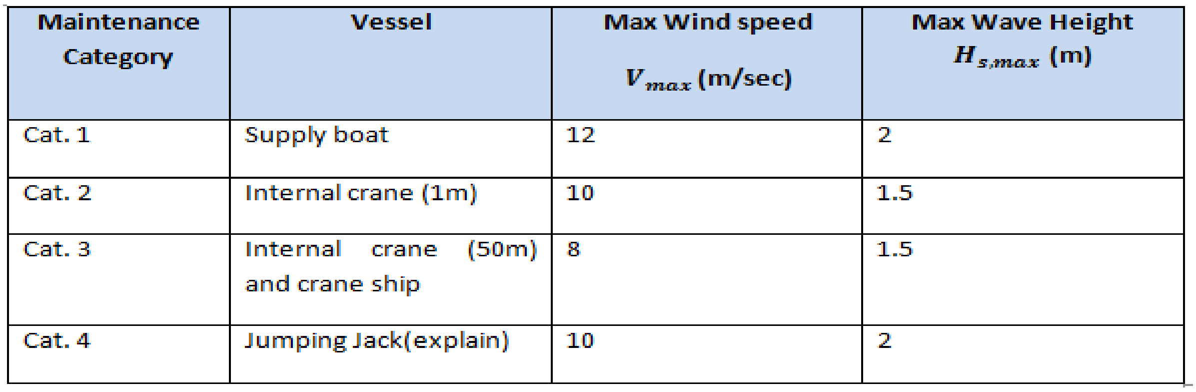
Category 1 (Cat.1): Repair time of less than 1 day in order to perform small repairs such as replacement of carbon brushes or cleaning the blades. Only personnel and tools are needed.

Category 2(Cat.2): Small parts are repaired e.g. replacement of pitch motor, internal crane hoisting outside. The repair time is around 1 day.

Category 3 (Cat.3): 1 or 2 days needed in order to replace large components, e.g. replacement of generator, gearbox. Large internal crane needed.

Category 4 (Cat.4): Replacement of heavy components (e.g. replacement of hub, nacelle, and yaw system) which requires large external crane. Typically this maintenance category demands approximately 2 days.

For each of the described above maintenance categories the required vessel with maximum wind and wave specifications are illustrated below:



Maintenance Category	Vessel	Max Wind speed V_{max} (m/sec)	Max Wave Height $H_{s,max}$ (m)
Cat. 1	Supply boat	12	2
Cat. 2	Internal crane (1m)	10	1.5
Cat. 3	Internal crane (50m) and crane ship	8	1.5
Cat. 4	Jumping Jack(explain)	10	2

Table 6.2: Examples of different maintenance categories

For this thesis, the values used to define the good weather conditions in order to access the offshore wind farm will be of maintenance category 3. The weather decision variable will be generated based on the constraints on maintenance category 3. When the wind speed is above 8m/sec and wave height is above 1.5m the vessels cannot sail to the offshore wind farm in order to perform maintenance tasks. The wave height is an important parameter that influences the total waiting time due to bad weather conditions and as a result the total downtime of the WT and its availability.

6.2 Define Corrective and Preventive Maintenance

Offshore wind farms are new sector of wind energy technology under development. For that reason, there is limited number of data on the failure rates of different offshore wind turbines. Hence, a failure and consequently a CM are defined randomly throughout the year for the model run. Calling the “randi” function of MATLAB which is using a discrete uniform distribution, CM needed will be generated randomly for a period of n days, which in this thesis was 365 days. All CM activities are assumed to be known only at a short notice and hence forced to be performed during the short horizon interval. The expected time for CM to be performed is τ_i^{CM}. The expected time to perform corrective maintenance is known and predefined before the model run. For this report it was assumed that 4 hours are needed to perform CM.

All the scheduled PM tasks within the time horizon need to be defined. A set of preventive maintenance tasks j ∈ PM that must be performed within the horizon is defined and the time to be performed is τ_j^{PM}. At the beginning of the optimization, the PM task j in wind turbine i has to be executed within the next ω_{ij0} time steps, where ω_{ij0} is a preset threshold. The time steps that the PM has to be performed will be defined before the model run for every PM needed. In this thesis, it was assumed that three PM tasks will need to be performed during the year. In section 6.3 ω_{ij0} per PM is defined.

When running the optimization model, both CM tasks and days with low wind speed are considered as an opportunity to perform PM. The resulting total annual maintenance costs from the model proposed will be referred as “Optimized Total Maintenance Costs (OTMC)”. In order to calculate the savings achieved by applying the suggested model in this thesis, the maintenance costs of the base case will be calculated. In order to calculate the base case, the maintenance schedule and thus the associated costs will need to be defined. Therefore, in the base case CM tasks will not be seen as an opportunity to combine PM tasks thus CM tasks will be performed separately from PM. What is more, on the base case low wind speed is not taken into account in order to schedule PM tasks. Only the restriction ω_{ij0} of time steps needed before the PM has to be executed will be considered. Those costs will be described as "Base Total Maintenance Costs (BTMC)". Based on the output of OTMC and BTMC a comparison will be made in order to check whether the proposed model achieved savings. Every scenario of the model will be run for a full year, which means that both the optimized and base maintenance costs are annual.

6.3 Predefine of model inputs and costs

Initially, before the model was run, PM maintenance tasks have to be pre-determined. Particularly in these model 3 different PM will need to be performed. The first PM needs 3 hours to be executed and the remaining two tasks need 3 hours each. In chapter 6, section 6.2 the process of defining the CM works was described. It was assumed that there are at most 2 corrective activities per year per wind turbine and that they can be executed in at most a day.

In order to define the maintenance costs in € the below *assumptions* were made:

- Number of wind turbines (WT): different scenarios of min 1 and max 5 WT
- Number of corrective maintenance tasks in a year: 2 for every WT
- Number of preventive maintenance tasks in a year: 3 for every WT.
    - The first PM activity has to be performed before the first 100 days of operation of the WT, $\boldsymbol{\omega_{i10}}$ **=100 days**
    - The second PM activity has to be performed after day 100 but before the 255 days of operation of the WT, $\boldsymbol{\omega_{i20}}$ **=255 days**
    - The third PM activity has to be performed after day 255 but before the 340 days of operation of the WT, $\boldsymbol{\omega_{i30}}$**=340 days**

The above predefined days of performing PM was an assumption made for the model and can be changed according to the user's needs.

- Electricity price $\boldsymbol{C_{el} = 0.05€/kWh}$
- Transportation costs including fuel and possible daily crew costs $\boldsymbol{C_{tr}}$**: 500€**
- Penalty for extra working hours for a team of two maintenance technicians $\boldsymbol{C_{pen}}$**: 500€/hour**
- Working hours per team **h: 7 hours**
- Time to access the WT $\boldsymbol{\tau_{\omega} = 0.5}$ **hours**
- Time for CM to be performed $\boldsymbol{\tau_i^{CM}}$**: 4 hours**
- Time for PM to be performed: $\boldsymbol{\tau_j^{PM}}$**= 3 for j=1 and** $\boldsymbol{\tau_j^{PM}}$**=4 for j= 2,3**
- Maintenance category performed is 2 (table 6.2), meaning the max wind speed will be 8m/sec and max wave height will be 1.5m Above these value no vessel can sail to the offshore wind farm.
- Spare parts and personnel and vessels are always available

On the below table a summary of the input data is presented:

Number of Wind Turbines	Number of CM/year	Number of PM/year	Electricity price in €/kWh	Transportation costs including fuel and possible daily crew costs in €	Penalty for extra working hours/ Team of two maintenance technicians in €/hr	Working hours per team	Time to access the WT τ_ω
5	2	3	0.05	500	500	7	0.5

Table 6.3: Summary of input data for the proposed model

The model will be run firstly for a base case of 1 WT and afterwards it will be run for different locations for 5 WT. The program applied in all cases is MATLAB. The objective function and all constrains were written in MATLAB and the model was applied.

6.4 Description of model

The model was run for 365 days, which means that 365 optimizations are performed using the model previously described. Each time the short horizon is optimized, with full information on the weather conditions and then advanced with a day. The short horizon is divided in days and Long Horizon in weeks each consisting of 7 days, thus 52 weeks.

The algorithm starts by running first the LH part of the model. Using the Weibull distribution, random wind data are generated which are considered to be the wind forecasts. Every week, the LH model is trying to define the best opportunity or opportunities that PM task(s) can be scheduled. In other words the code is checking weekly and saving in a table the days that the wind speed based on the wind forecast is 4m/sec or below. Wind speed of 4m/sec was chosen as the upper limit of min wind speed, as the wind turbine Vestas V80 used for this model has a cut in speed of 4m/sec. When the simulation on the LH is done, a table is prepared with the days of the year that wind speed is low and thus it is beneficial to schedule PM tasks as the energy losses will be low. The days listed in a table as opportunities will be used on the SH part of the model. This is the main function of the LH model.

As soon as the LH part of the model has run, the weekly divided LH has to be split in days giving the SH part of the model. We will assume that the wind values determined in the LH model are known for every day in the SH model. On every optimization step of the SH corresponding to one day the algorithm runs until a failure occurs. Failures are not known before the SH part of the model start to run but only generated randomly using the “randi” command in MATLAB. As soon as a failure occurs, the code will first check whether the weather variable w_{it} on the day of the failure is 1 or 0. If the value is 0 meaning that the wind farm is not accessible, then no maintenance task can be performed and energy losses need to be calculated. The algorithm will keep running until the day that the wind farm can be visited will be identified (w_{it} is 1). Until that day the model will need to calculate the energy losses for the WT(s) that are not operational. As soon as w_{it} is 1 the CM task will be performed on that day and PM task will be combined if possible. Below the assumptions made for the PM tasks and the criteria based on which a PM task will be combined with PM or scheduled based on the LH data is described.

For PM tasks, as stated in section 6.3, they have to be performed based on predefined requirements. A short summary is described below:

- PM1: low limit is day 1 upper limit is 100 days
- PM2: low limit is day 101 and upper limit 255
- PM3: low limit is day 256 and upper limit 340

The above days are predefined by the user and can be changed based on the requirements on when the PM has to be performed. Note that formulating the PM requirements in this way; one will always take the first opportunity to combine PM with CM. Yet the time between two consecutive PM executions may be 254, in case on day 1 and on day 255 PM is combined with CM. An alternative modeling is to require that PM is done with maximal intervals of say 120 days. In that case it makes sense to delay the combination of PM and CM to a moment as close as possible to the upper limit. In that case one typically uses a threshold interval δt and do the combination only if the CM occurs within δt time units from the day where PM is really due. Optimizing δt is complex and one can develop a heuristic by comparing the savings by combining the PM with CM versus the lost life of PM by doing it earlier than the last possible moment. That is one compares P (CM falls in δt time units) x saving of combining PM with CM versus PM costs x δt/PM time interval.

Although such an approach is interesting, we will not consider it in this thesis.

Before explaining the different options that the model was tested on, the assumption regarding the calendar year should be explained. As described in section 6.1, in order to test the proposed model in different weather conditions weather scenarios will be generated. Specifically, for every season of the year three different types of weather can be selected, low, medium and high. This input is manually defined by the user before the model runs. As the input of the weather is defined per season with the sequence Winter-Spring-Summer-Autumn, the year starts on the 1st of December and ends on the 30th of November. Thus, when the model output is day 110 (meaning 20th of April based on the assumption of the model), in the graphs it will be depicted on day 79 (31 days earlier-20th of March) in order to be aligned with the actual month based on a calendar year starting from the 1st of January until 31st of December.

The model output will be checked based on the below options:

<u>Option 1 – “due date at min wind speed”</u>

As described above, during the LH, the days with low wind speed will be identified and saved in order to be used during the for the SH model. On the SH, the model will start checking when the first failure occurs in order to combine the PM task with CM. If the first CM will not take place before the day that was identified in the LH as the day with the lowest wind speed then the model will schedule PM on that day. If a failure occurs before that day then CM will be combined with PM. The below example will try to describe the model:

The third PM has to be performed before day 340 but after day 255. During the LH the below days were identified as opportunities to perform PM:

Day of the year	260	262	263	276	277	285	288	293	297	313	334
Wind speed in m/sec	1.4	3.6	3.2	3.3	3.5	3.3	3.9	3.5	1.8	1.9	1.6

Table 6.4.1: Example of days of LH when PM can be performed for option 1

Based on the above output of the LH, if no failure occurs until day 259, then the model will schedule PM on day 260 as is the day with the lowest wind speed from the suitable days identified during the time period of day 256 until and including day 340.

Option 2- “due date 14 days before last day of PM”

As described above, during the LH, the appropriate days (low wind speed) will be identified and saved for the SH model. On the SH, the model will start checking when the first failure occurs in order to the PM task with CM. If the first CM will take place not later than 14 days before the due date of the PM then the model will combine CM with PM. If not, then the model will check the output of the LH, and will identify which of the 14 days the wind farm can be visited based on the list of days with wind speed below 4m/sec and will schedule PM on the day with the lowest wind speed. The below example will try to describe the model:

The first PM has to be performed before day 100. If no failure occurred until day 85, then the model will check the values from day 86 until 100 (both days included) in order to identify which days were selected as opportunities to perform PM and will schedule the PM maintenance task.

Day of the year	86	90	95	99
Wind speed in m/sec	2.3	3.8	1.7	3.6

Table 6.4.2: Example of days of LH when PM can be performed for option 2

In this case, the first PM will be scheduled to be performed on day 95 as is the day with the lowest wind speed.

Option 3- “due date the last week for PM”

As described above, during the LH, the appropriate days (low wind speed) will be identified and saved for the SH model. On the SH, the model will start checking when the first failure occurs in order to the PM task with CM. The model will wait until the last week before the PM is due before scheduling it without combining with CM. If the first CM will be performed the last week before the week of PM is due then the model will combine CM with PM. If not, then the model will check the wind speed values of the days identified on the LH and will schedule PM on the day with lowest wind speed. If such day does not exist, then PM will be scheduled on the day with the lowest wind speed of the available days. The below example will try to describe this option:

The second PM has to be performed before day 255 and not earlier than day 101. If no failure occurred until day 252, then the model will check the values from days 253, 254 and 255 in order to identify which day is suitable to perform PM.

week 36	Day 246	Day 247	Day 248	Day 249	Day 250	Day 251	Day 252
Wind speed in m/sec	13.8	6.0	6.6	8.2	9.9	4.62	3.9
week 37	Day 253	Day 254	Day 255	Day 256	Day 257	Day 258	Day 259
Wind speed in m/sec	7.3	15.2	10.3	7.0	4.1	5.3	5.2

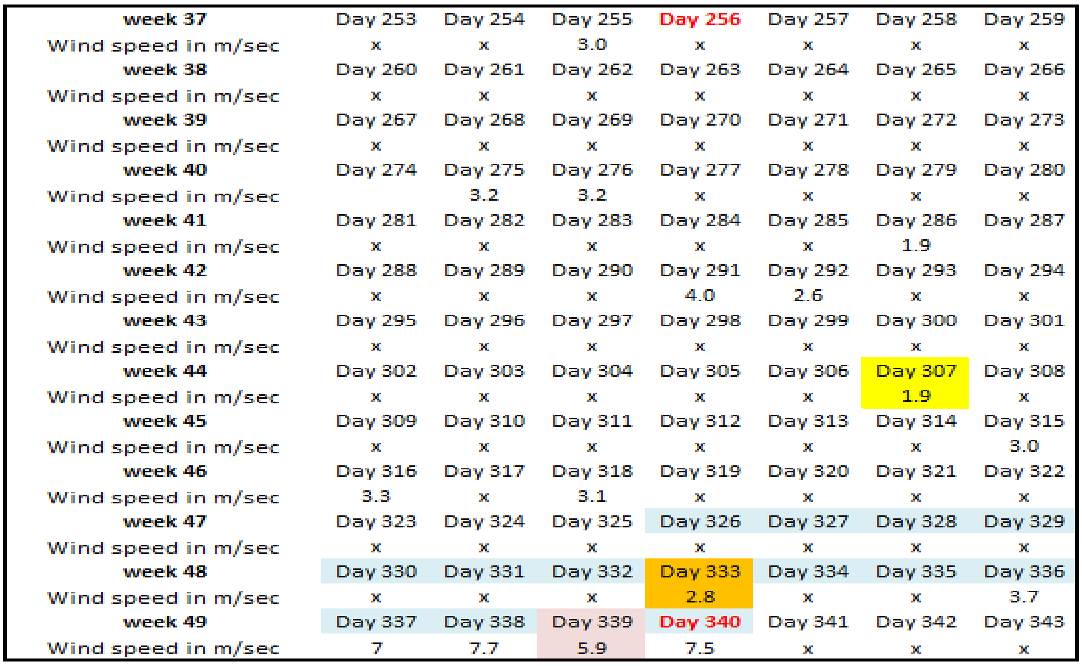
Table 6.4.3: Example of identifying PM for option 3 for LH model

As presented in the above table, the last week before the second PM is due is week 36. In case no failure occurred until and including day 252 the model will check first if days 253,254 and 255 are included in the days identified in the LH. If yes then the model will schedule PM on the day with the min wind speed, in case more than 1 day is in that list. If not, as in this example above, then the PM task will be scheduled on day 253 as is the day that the wind farm can be

In both options, the CM will only be performed if the weather conditions allow the vessel to sail to the wind farm. In the occasion that on the day that CM has to be performed and weather does not allow the farm to be visited, then the WT will remain out of operation and the availability of the wind farm will be affected. The model will be run for both options described above and for 2 cases:

1. Weather constraint is included thus wind farm is not always accessible
2. No weather constraint thus wind farm is always accessible

To summarize, the difference between the three options is the threshold on which a decision should be taken on timing to perform PM. For every option there is a different due date when a decision should be made on whether the PM can be combined with CM or has to be scheduled based on the LH wind data. As described in the beginning of this section, during the LH model the days with wind speed of 4m/sec or below are identified and saved in a table. In the below table an example is given to understand the difference on the three options and. In this example PM has to be scheduled between day 256 to day 340 (highlighted in red). According to option 1 "**due date at min wind speed"** if no failure occurs until day 306, then PM will be scheduled for day 307 (in yellow) as this is the day with the minimum wind speed from the days identified on the LH. For option 2 **"due date 14 days before last day of PM"**, if no failure occurs until day 325, then the model will check the range of days between 326 to 340 (highlighted in blew) and PM will scheduled on day 333 (in orange). Finally, for option 3 **"due date the last week for PM"**, if no failure occurs until day 336,which is the last week before the week that PM is due, then PM will be scheduled on the day with min wind speed. Based on this example, the day to perform PM, based on the LH output will be day 339 (in pink). It can be concluded that the method used to define the timing of the PM is crucial as the wind speed can vary a lot in each option. As the wind is influencing the energy production it will also affect the energy losses during the maintenance.



week 37	Day 253	Day 254	Day 255	Day 256	Day 257	Day 258	Day 259
Wind speed in m/sec	x	x	3.0	x	x	x	x
week 38	Day 260	Day 261	Day 262	Day 263	Day 264	Day 265	Day 266
Wind speed in m/sec	x	x	x	x	x	x	x
week 39	Day 267	Day 268	Day 269	Day 270	Day 271	Day 272	Day 273
Wind speed in m/sec	x	x	x	x	x	x	x
week 40	Day 274	Day 275	Day 276	Day 277	Day 278	Day 279	Day 280
Wind speed in m/sec		3.2	3.2	x	x	x	x
week 41	Day 281	Day 282	Day 283	Day 284	Day 285	Day 286	Day 287
Wind speed in m/sec	x	x	x	x	x	1.9	x
week 42	Day 288	Day 289	Day 290	Day 291	Day 292	Day 293	Day 294
Wind speed in m/sec	x	x	x	4.0	2.6	x	x
week 43	Day 295	Day 296	Day 297	Day 298	Day 299	Day 300	Day 301
Wind speed in m/sec	x	x	x	x	x	x	x
week 44	Day 302	Day 303	Day 304	Day 305	Day 306	Day 307	Day 308
Wind speed in m/sec	x	x	x	x	x	1.9	x
week 45	Day 309	Day 310	Day 311	Day 312	Day 313	Day 314	Day 315
Wind speed in m/sec	x	x	x	x	x	x	3.0
week 46	Day 316	Day 317	Day 318	Day 319	Day 320	Day 321	Day 322
Wind speed in m/sec	3.3	x	3.1	x	x	x	x
week 47	Day 323	Day 324	Day 325	Day 326	Day 327	Day 328	Day 329
Wind speed in m/sec	x	x	x	x	x	x	x
week 48	Day 330	Day 331	Day 332	Day 333	Day 334	Day 335	Day 336
Wind speed in m/sec	x	x	x	2.8	x	x	3.7
week 49	Day 337	Day 338	Day 339	Day 340	Day 341	Day 342	Day 343
Wind speed in m/sec	7	7.7	5.9	7.5	x	x	x

Table 6.4.4: Example of identifying PM for 3 different options

6.5 Location 1- Ijmuiden (225) - Ij-geul munitiestortplaats 1

In this section, the results of the model for location 1 will be presented for the base case of one wind turbine and then extended for five. The model will be run for the three different options described above, for different weather scenarios and for the scenario of no weather restriction and the results will be compared. In order to compare the cost difference between these 3 options, CM task were performed the same day for all 3 options.

Before presenting the results, some explanation of the above used below is given:

- CM: Corrective maintenance
- SH PM: Preventive maintenance performed using the information from SH model. This PM is combined with CM.
- LH PM: Is the PM scheduled to be performed based on the data from the LH model
- Base PM: PM performed based on data from SH and taking into account only the restriction on when the PM has to be performed. These PM tasks are not combined with CM and low wind speed opportunities are not taken into account.

6.5.1 Scenario 1: One Wind Turbine

In this simulation the computational time was short; it took 2:15 minutes to run in an Intel i7 Core. The results of the model can be found below.

LH output:

Wind data for 1 year were generated in MATLAB using the Weibull distribution which is used as LH data. Based on the output the below days identified as opportunities to schedule and perform the 3 PM. These days can be found on the below table:

PM 1		PM 2		PM 3	
Day of the year	Wind speed in m/sec	Day of the year	Wind speed in m/sec	Day of the year	Wind speed in m/sec
5	2.0	106	3.7	258	2.7
6	3.8	127	2.4	261	1.5
36	2.2	128	2.8	262	2.6
43	2.8	144	3.4	264	1.4
80	3.5	148	2.4	281	0.9
86	3.1	163	3.0	283	2.0
92	1.4	165	2.8	285	3.5
99	1.6	167	3.0	296	3.0
		185	4.0	311	2.8
		188	2.5	317	3.4
		191	3.8	327	3.3
		194	0.8	334	0.7
		209	2.3	337	3.4
		211	3.0	340	2.9
		224	3.2	341	3.1
		237	1.5	345	2.8
		242	1.3	355	1.7
		244	2.7	364	1.9
		249	3.6		
		250	3.4		

Table 6.5.1: Days on LH that PM can be scheduled-Scenario 1 for one WT

As concluded from the above table, 46 days (12% of total year) of the year are identified as opportunities to schedule PM based on the restriction of 4m/sec as the lowest wind speed to perform PM. As already mentioned, the value of min wind speed was based on the characteristics of the wind turbine as at a wind speed of 4m/sec and above the full power is reached.

Based on the table 6.5.1, the due date before a PM has to be scheduled without CM on the same day are presented in table 6.5.2 for all the three options studied in this thesis.

Due date per PM for 3 options	***Option 1***	***Option 2***	***Option 3***
PM 1 (day 1-100)	92	194	334
PM-2 (day 101-255)	92	242	334
PM-3 (day 256-340)	99	250	340

Table 6.5.2: Due dates for scheduling PM, for 3 options studied in this report

Wind (Weibull) profile:

Figure 6.5.1 below is graphically representing the wind data generated using the Weibull distribution. The red dots are the days that are identified as opportunities to perform PM.

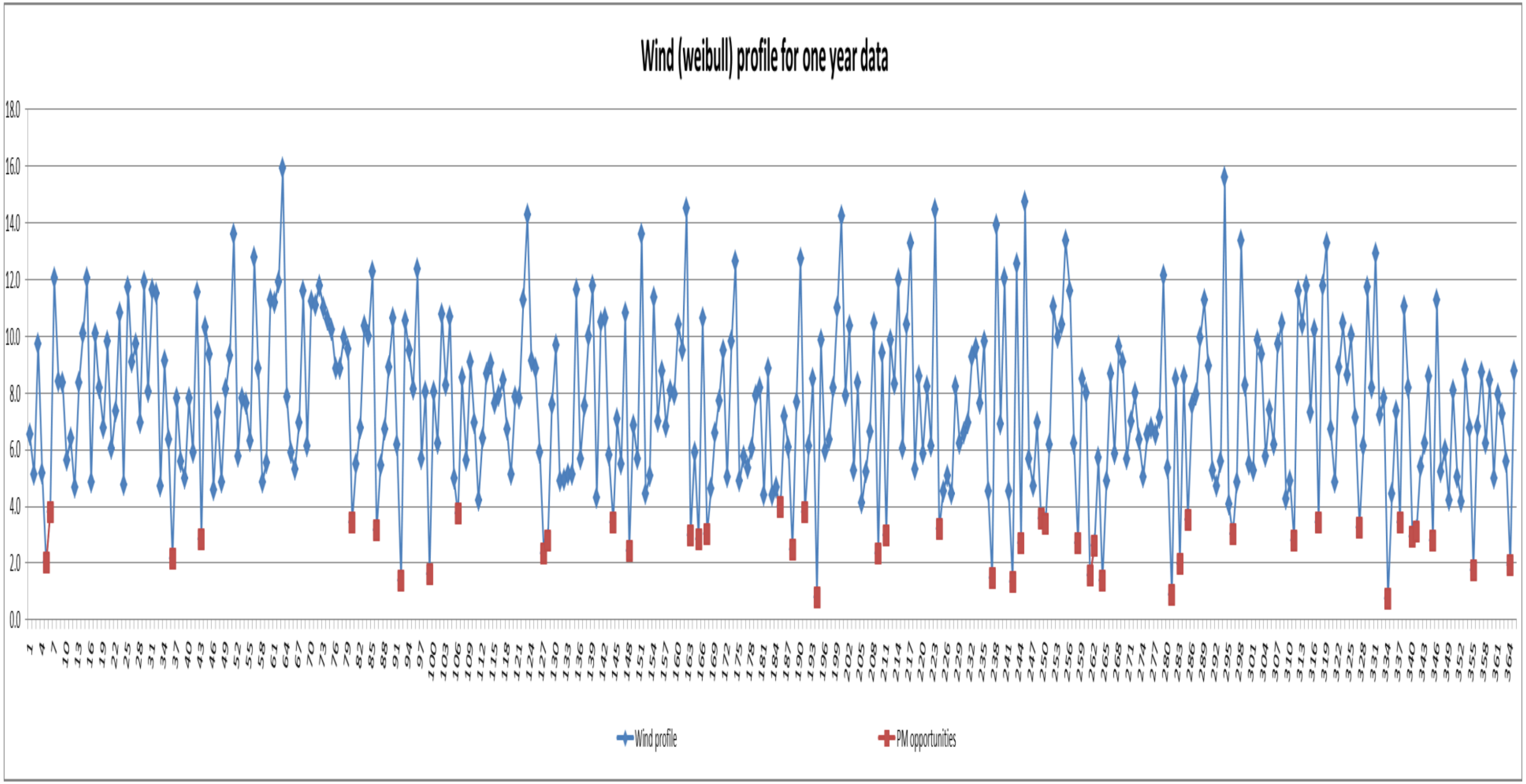


Figure 6.5.1 Wind profile for 1 year. Red dots are representing days with low wind speed when PM can be schedule

Weather restrictions included

- ***Option 1***

Maintenance schedule for 1 year:

Based on the table 6.5.2, the due dates to schedule PM1, PM2 and PM3 before a failure to occur are days 92, 194, 334 respectively.

In option 1, first failure occurred on day 153 thus the first PM had to be scheduled on 92 which was identified for option 1 the day with minimum wind speed. The due date for the second PM to be scheduled was day 194 but the second failure took place in day 153 therefore the second PM was combined with CM task. The third PM had to be scheduled based on the opportunities identified from the wind Weibull data on day 334 but the second failure occurred on day 303 thus the third PM was performed together with CM in order to save the transportation costs.

The detailed maintenance schedule is presented below:

	CM		
Day in the year		153	303
	SH PM		
Day in the year		153	303
	LH PM		
Day in the year	92		
	Base PM		
Day in the year	96	203	279

Table 6.5.3: Proposed maintenance schedule for Location 1, Scenario 1 for 1 Wind Turbine, option 1, weather restriction included

The below figure is a snapshot of the wind profile for the first 100 days. It can be readily noticed that day 92 is the day with the minimum wind speed.

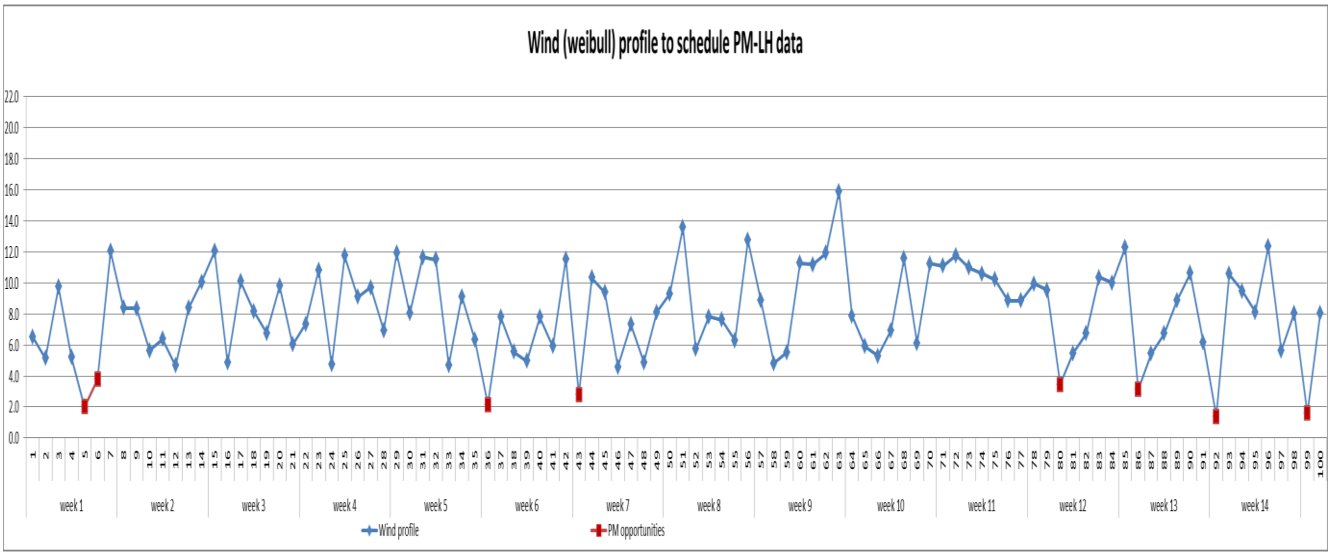


Figure 6.5.2: Wind profile for the first 100 days of the year. Red dots represent opportunities to perform PM when wind speed is low. Yellow and light blue dot represents days when a PM was actually scheduled.

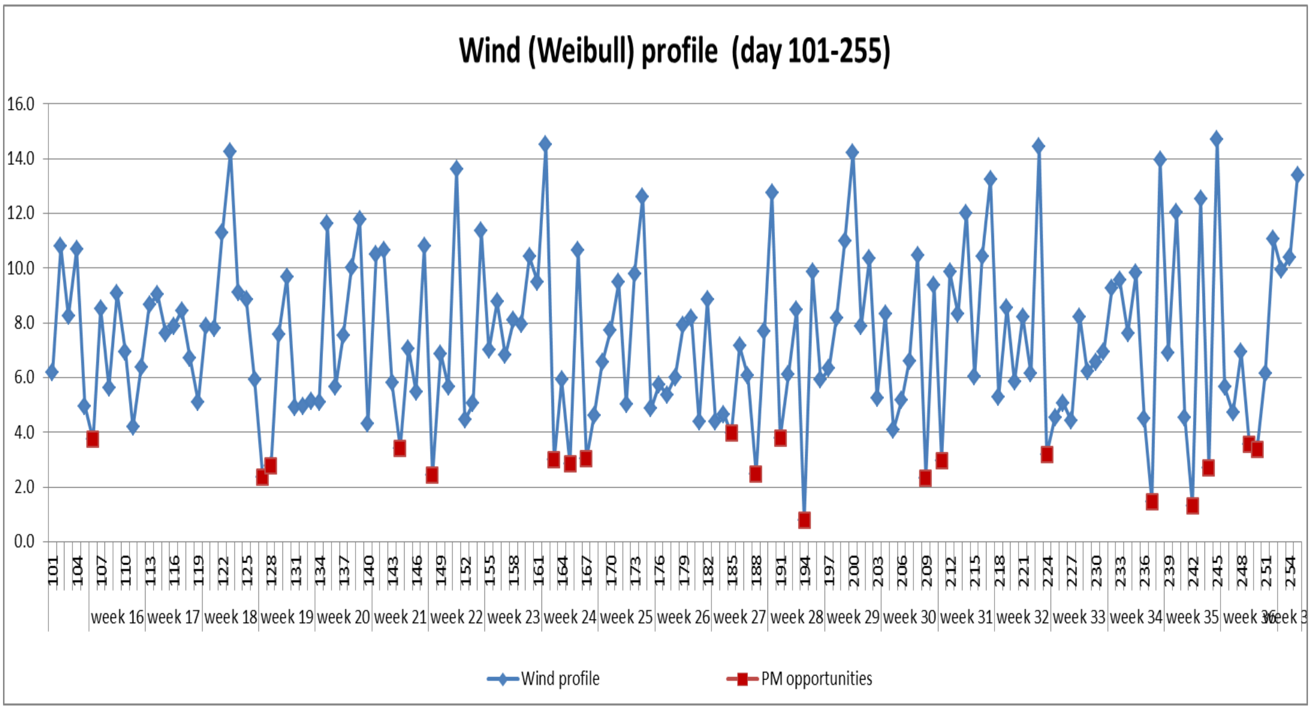


Figure 6.5.3: Wind profile for days 101-255 of the year. Red dots represent opportunities to perform PM when wind speed is low. Yellow and light blue dot represents days when a PM was actually scheduled.

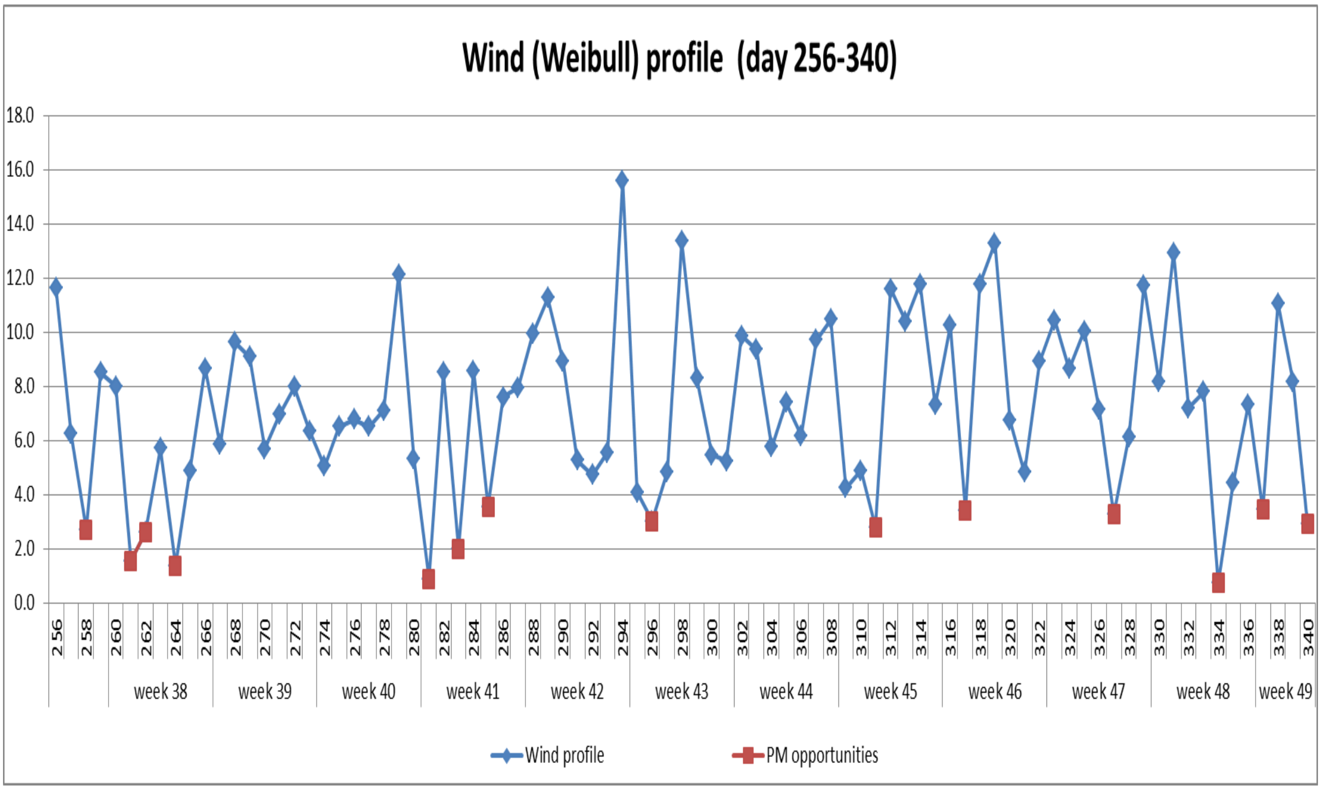


Figure 6.5.4: Wind profile for days 256-340 of the year. Red dots represent opportunities to perform PM when wind speed is low. Yellow and light blue dot represents days when a PM was actually scheduled.

The maintenance costs can be found below in details:

Short Horizon:

The first part of the objective function is related to SH cost minimization.

$$\textit{Min} \sum_{t\,\in\, T_{short}}[[\sum_{i\in CM} y_{it}\tau_i^{CM}P_t^{CM} + \sum_i\sum_j x_{ijt}\,\tau_j^{PM}P_t]\, C_{el} + z_tC_{tr} + e_tC_{pen}]$$

- $\sum_{t\,\in\, T_{short}}[[\sum_{i\in CM} y_{it}\tau_i^{CM}P_t^{CM} + \sum_i\sum_j x_{ijt}\,\tau_j^{PM}P_t]\, C_{el}$:

The CM costs are 834€ and the optimized PM costs are 521€.

- z_tC_{tr}

The transportation costs for SH are 1000€.

- e_tC_{pen}

Penalty costs for extra working hours are 200€ as the total working hours h are constantly 7 and the total hours needed for both CM and PM was 8. For days 153 and 303 a total of 2 hours of penalty has to be paid as the total hours needed to perform CM and PM on the same day was 8.

Long Horizon:

The second part of the objective function is related to LH cost minimization.

$$\textit{Min} \sum_{t\in T_{long}}[\sum_k h_{tk}[P_{kt}C_{el} + \frac{C_{tr}}{h-2\tau_{\omega}}]]$$

The maintenance costs during the LH for the PM task performed are 168€.

Thus, the **OTMC are 2420 €** and the total energy production is 1770kWh. WT availability is 99.17%.

Non-optimized Case

In the base case, when PM is not combined with CM and low wind speed is not taken into account to schedule the PM tasks, the **BTMC are 6853 €** which means that the total savings achieved with the proposed model is 60%. The proposed maintenance scheduled of this case is presented in table 6.5.3.

Power production

The below figure present the monthly energy production during using the SH data for wind speed. The peaks on the wind speed are observed during the winter and autumn while the lowest during the summer.

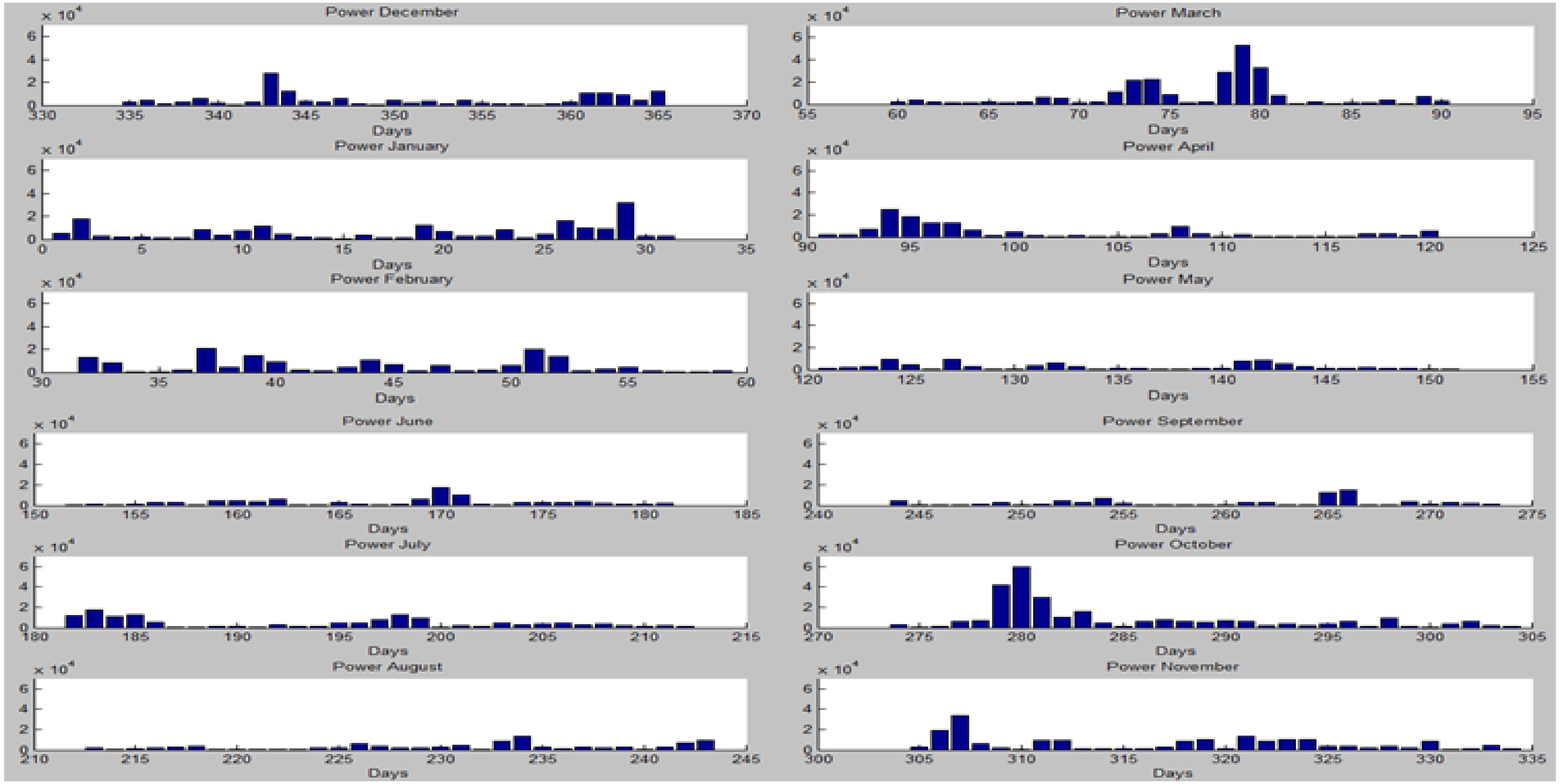


Figure 6.5.5: Monthly energy production for one wind turbine for 1 year, scenario 1, option 1

Maintenance Schedule

On the below graphs, the proposed optimized maintenance schedule for 1 WT for option 1 as resulted from the proposed model is presented. On day 122 (mode output is 153 as the model starts on 1st of December) a failure occurred and CM had to be performed which was combined with PM, as illustrated in figure 6.5.6. On day 272 (model output 303) the second failure occurred and thus the CM had to be performed (figure 6.5.7).

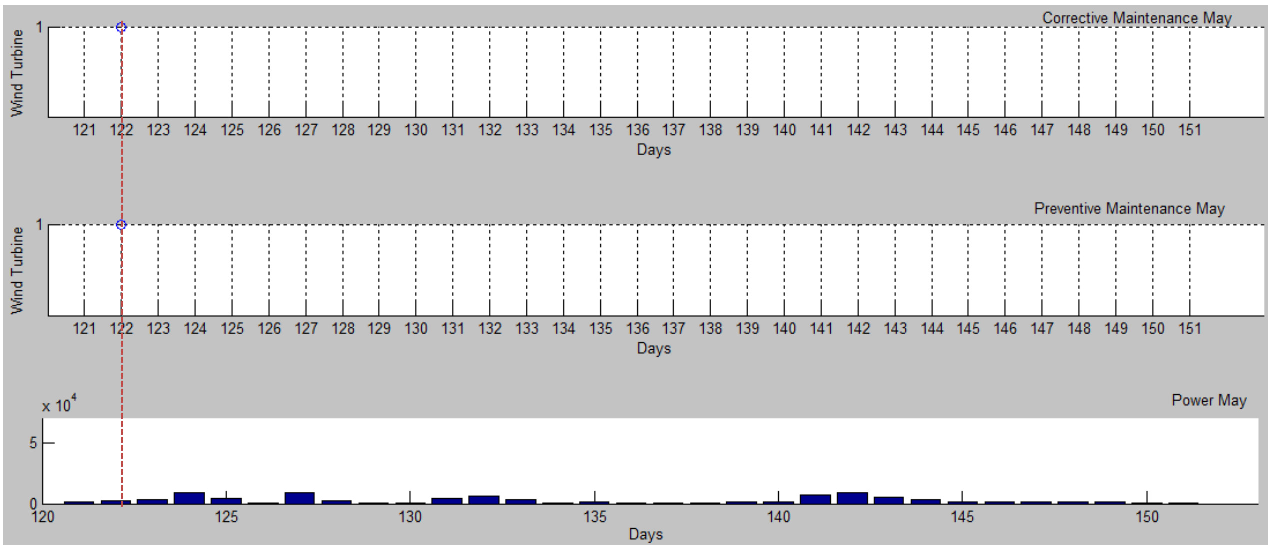


Figure 6.5.6: Failure, power production and Maintenance tasks for SH for *Location 1, Scenario 1, for 1 WT in May. The dashed line presents the advised maintenance schedule for day 122 (day 153).*

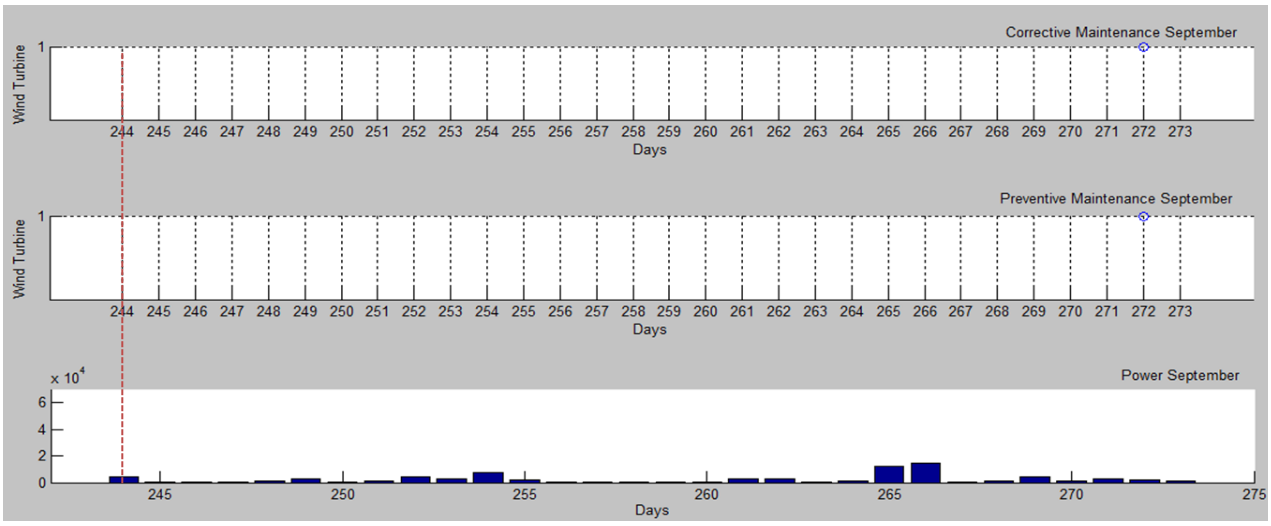


Figure 6.5.7: Failure, Power production and Maintenance tasks based for SH for *Location 1, Scenario 1, for 1 WT in September. The dashed line presents the advised maintenance schedule for day 244.*

On day 61 (mode output is 92 as the model starts on 1st of December) the first PM was scheduled to be performed as proposed by the LH model due to the low wind speed.

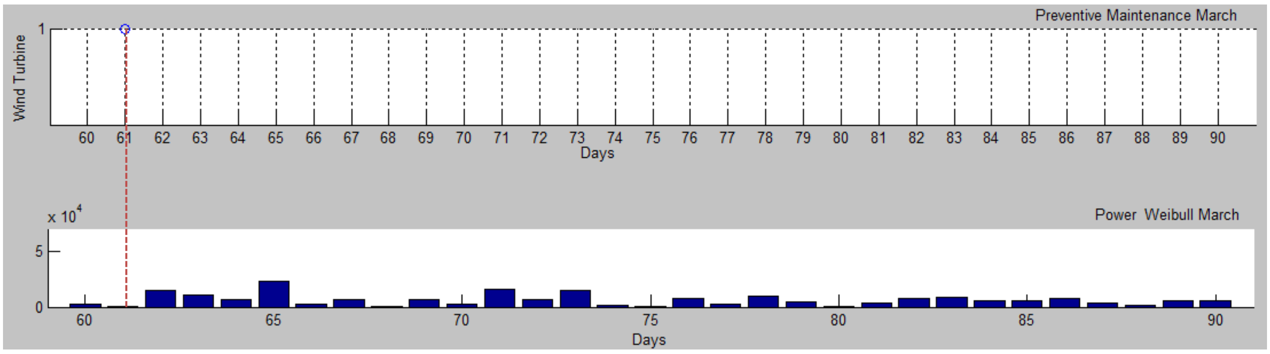


Figure 6.5.8: Power production and Maintenance task for LH for *Location 1, Scenario 1, option 1 for 1 WT in March. The dashed line presents the advised maintenance schedule for day 61.*

- ***Option 2***

The below table is a part of table 6.5.4 represents the days which PM can be scheduled for Option 2:

PM 1

Day of the year	86	92	99
Wind speed in m/sec	3.1	1.4	1.6

PM2

Day of the year	242	244	249	250
Wind speed in m/sec	1.3	2.7	3.6	3.4

PM3

Day of the year	327	334	337	340
Wind speed in m/sec	3.3	0.7	3.4	2.9

Table 6.5.4: Days on LH that PM can be scheduled-Scenario1 for one WT option 2- weather restriction included

Maintenance schedule for 1 year:

Similarly to Option 1, in option 2 the first PM was scheduled based on the results of the LH as the first failure didn't occur before day 84. The first PM was scheduled on day 92 as it was the day with the min wind speed from the day range 84-100. For the second PM, the deadline to be scheduled if no failure had occurred was day 242 and for the third PM the identified due date based on the LH output was day 334. Both failures occurred before the due date to schedule PM without CM combined thus both PM2 and PM3 were performed combined with CM on day 153 and 303

The detailed maintenance schedule is presented below:

	CM		
Day in the year		153	303
	SH PM		
Day in the year		153	303
	LH PM		
Day in the year	92		
	Base PM		
Day in the year	72	233	279

Table 6.5.5: Proposed maintenance schedule for Location 1, Scenario 1 for 1 Wind Turbine, option 2, weather restriction included

The maintenance costs can be found below in details:

Short Horizon:

The first part of the objective function is related to SH cost minimization.

Min $\sum_{t \in T_{short}}[[\sum_{i \in CM} y_{it}\tau_i^{CM}P_t^{CM} + \sum_i \sum_j x_{ijt}\,\tau_j^{PM}P_t]\,C_{el} + z_tC_{tr} + e_tC_{pen}]$

- $\sum_{t \in T_{short}}[[\sum_{i \in CM} y_{it}\tau_i^{CM}P_t^{CM} + \sum_i \sum_j x_{ijt}\,\tau_j^{PM}P_t]\,C_{el}$:

The CM costs are 834€ and the optimized PM costs are 521€.

- z_tC_{tr}

The transportation costs for SH are 1000€.

- e_tC_{pen}

Penalty costs for extra working hours are 200€ as the total working hours h are constantly 7 and the total hours needed for both CM and PM was 8. For days 153 and 303 a total of 2 hours of penalty has to be paid as the total hours needed to perform CM and PM on the same day was 8.

Long Horizon:

The second part of the objective function is related to LH cost minimization.

Min $\sum_{t \in T_{long}}[\sum_k h_{tk}[P_{kt}C_{el} + \frac{C_{tr}}{h-2\tau_\omega}]]$

The maintenance costs during the LH for the 1 PM task performed are168€.

Thus, the **OTMC are 2723€** and the total energy production is 1762kWh. Total availability of the WT is 99.17% for the full year.

Non-optimized Case

In the base case, when PM is not combined with CM and low wind speed is not taken into account to schedule the PM tasks, the **BTMC are 8014€** which means that the total savings achieved with the proposed model is 66%. The proposed maintenance scheduled of this case is presented in table 6.5.4.

In this model run option 1 and option 2 were identical as the due date for both options to schedule the first PM based on the output of the LH model was day 92.

Option 3

Maintenance schedule for 1 year:

In this option, the due date to schedule the first PM was day 99 and was scheduled for that day as no failure occurred until that day and the due date to perform the first PM was day 100. The second and third PM was combined with CM (which saved transportation costs and energy loss) as both failures took place before the due dates of 334 and 340 for PM2 and PM3 respectively.

The detailed maintenance schedule is presented below:

	CM		
Day in the year		153	303
	SH PM		
Day in the year		153	303
	LH PM		
Day in the year	99		
	Base PM		
Day in the year	49	236	285

Table 6.5.5: Proposed maintenance schedule for Location 1, Scenario 1 for 1 Wind Turbine, option 3, weather restriction included

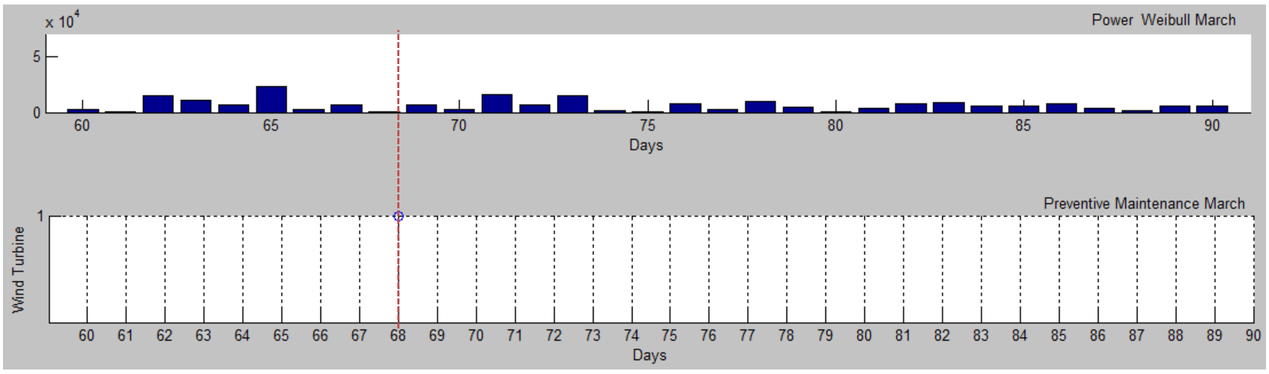


Figure 6.5.9: Power production and PM task based on LH data for *Location 1, Scenario 1, and option 3 for 1 WT in March. The red dashed line presents the advised maintenance schedule for day 68.*

The maintenance costs can be found below in details:

Short Horizon:

The first part of the objective function is related to SH cost minimization.

$$\boldsymbol{Min} \sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt}\, \tau_j^{PM} P_t]\, C_{el} + z_t C_{tr} + e_t C_{pen}]$$

- $\sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt}\, \tau_j^{PM} P_t]\, C_{el}$:

The CM costs are 834€ and the optimized PM costs are 521€.

- $z_t C_{tr}$

The transportation costs for SH are 1000€.

- $e_t C_{pen}$

Penalty costs for extra working hours are 200€ as the total working hours h are constantly 7 and the total hours needed for both CM and PM was 8. For days 153 and 303 a total of 2 hours of penalty has to be paid as the total hours needed to perform CM and PM on the same day was 8.

<u>*Long Horizon:*</u>

The second part of the objective function is related to LH cost minimization.

$$\boldsymbol{Min} \sum_{t\in T_{long}} [\sum_k h_{tk}[P_{kt}C_{el} + \frac{C_{tr}}{h-2\tau_{\omega}}]]$$

The maintenance costs during the LH for the 1 PM task performed are 171€.

Thus, the **OTMC are 2726€** and the total energy production is 1759kWh. Total availability of the WT is 99.17% for the full year.

<u>*Non-optimized Case*</u>

In the base case, when PM is not combined with CM and low wind speed is not taken into account to schedule the PM tasks, the **BTMC are 6,779€** which means that the total savings achieved with the proposed model is 59.78%. The proposed maintenance scheduled of this case is presented in table 6.5.5.

Without Weather Restriction

The model was run for one wind turbine, for the three different options described in section 6.4 without thee weather restriction. A summary of the maintenance schedule is given below:

Option 1- for 1 WT			
	CM		
Day in the year		114	278
	SH PM		
Day in the year		114	278
	LH PM		
Day in the year	92		
	Base PM		
Day in the year	67	107	284

Option 2- for 1 WT			
	CM		
Day in the year		114	278
	SH PM		
Day in the year		114	278
	LH PM		
Day in the year	92		
	Base PM		
Day in the year	84	121	305

Option 3- for 1 WT			
	CM		
Day in the year		114	278
	SH PM		
Day in the year		114	278
	LH PM		
Day in the year	99		
	Base PM		
Day in the year	5	251	271

Table 6.5.6: Proposed maintenance schedule for Location 1, Scenario 1 for 1 Wind Turbine, options 1,2 and 3, without weather restriction

In this case first PM was scheduled to be performed based on the output of the LH model as no failure occurred before the predefined due date. The second and third PM was scheduled with CM as the failures on the WT took place before the due date that the PM tasks had to be scheduled based on the LH model output. Specifically, the failures occurred on days 114 and 278 which are before the due dates presented in table 6.5.2.

As summary of the maintenance costs for 1 WT for three different options with and without weather restrictions can be found below:

Option number	**Scenario number**	**Scenario Description (winter-spring-summer-autumn)**	**Annual OTMC in €**	**Annual BTMC in €**	**Annual CM costs in €**	**Annual Total optimized PM costs in €**	**Transportation costs in €**	**Penalty costs in €**	**Annual non-Optimized PM Costs in €**	**Savings in %**	**Availability in %**	**Energy Output in MW**
Option 1	**Scenario 1 with weather constraint**	`L-L-L-L`	€ 2,723	€ 6,853	€ 834	€ 521	€ 1,000	€ 200	€ 168	60.3%	99.17%	1,770
option 2			€ 2,723	€ 8,014	€ 834	€ 521	€ 1,000	€ 200	€ 168	66.0%	99.17%	1,762
option 3			€ 2,729	€ 6,779	€ 834	€ 521	€ 1,000	€ 200	€ 174	59.8%	99.17%	1,759
Option 1	**Scenario 1 without weather constraint**	`L-L-L-L`	€ 2,420	€ 5,514	€ 563	€ 489	€ 1,000	€ 200	€ 168	56.1%	99.17%	1,763
option 2			€ 2,420	€ 5,678	€ 563	€ 489	€ 1,000	€ 200	€ 168	57.4%	99.17%	1,763
option 3			€ 2,423	€ 5,302	€ 563	€ 489	€ 1,000	€ 200	€ 174	54.3%	99.17%	1,760

Table 6.5.7: Summary of the maintenance costs for Scenario 1 for 1 WT with and without weather restrictions

It can be concluded that more savings can be achieved when weather the restriction is applied. The reason is that on the case that weather restriction is not taken into account, CM or PM can be performed on days with high wind speed and thus the energy losses will be higher.

6.5.2 Scenario 1- Five Wind Turbines

In this simulation the computational time was short; it took 3:15 minutes to run in an Intel i7 Core. The results of the model can be found below.

LH output:

The days identified as opportunities to schedule and perform the 3 PM are the below. Days 344 until 364 are highlighted in light grey, as the last PM has to be performed the latest on day 340, thus these results are not relevant for this model run.

PM 1																					
Day of the year	8	10	15	32	44	45	51	53	59	63	64	73	82	85	86	90	98	99			
Wind speed in m/sec	2.4	2.7	3.4	3.6	2.8	3.9	1.3	3.9	2.5	3.1	1.1	3.6	1.8	2.6	3.4	3.8	2.1	3.7			
PM 2																					
Day of the year	112	115	117	126	136	143	148	151	152	158	166	169	176	194	197	201	221	227	234	248	255
Wind speed in m/sec	1.5	3.2	4.0	1.3	4.0	3.7	2.3	3.2	3.5	2.5	3.0	2.6	1.8	3.8	3.3	3.5	1.1	2.5	2.9	1.4	3.8
PM3																					
Day of the year	257	268	269	275	280	286	293	296	306	313	323	328	337	*344*	*345*	*350*	*355*	*364*			
Wind speed in m/sec	2.1	2.6	3.7	1.8	3.0	2.5	1.8	3.1	0.9	3.6	3.9	2.4	3.3	*1.7*	*3.9*	*1.5*	*3.3*	*3.9*			

Table 6.5.8: Days on LH that PM can be scheduled-Scenario 1 for five WT

As concluded from the above table, 57 days (16% of total year) of the year are identified as opportunities to schedule PM based on the restriction of 4m/sec as the lowest wind speed to perform PM. As already mentioned, the value of min wind speed was based on the characteristics of the wind turbine as of this speed the full power is reached.

Weather restrictions included

- ***Option 1***

Maintenance schedule for 1 year:

WT1: The first failure occurred on day 147 but the first PM had to be performed before day 100. On this option, day 64 was the day determined on the LH with the minimum wind speed. As no failure occurred before this day, the first PM was scheduled on day 15. The other 2 PM were combined with CM as a failure occurred before the due date determined on the LH. For PM2 due date was day 221 and for PM3 was day 306.

WT2: The first failure occurred on day 52 thus PM was combined with CM as the due date before scheduling PM based on the LH data was day 64. The second PM was combined with CM on day 220, one day before the last day that PM could be performed at the minimum wind speed as identified on the LH (table 6.5.8). The third PM was schedule on day 306 as is the day with the lowest wind speed.

Similarly, the maintenance schedule for WT4 and WT5 was determined: The detailed maintenance schedule is presented below:

WT 1

	CM		
Day in the year	147	298	
	SH PM		
Day in the year	147	298	
	LH PM		
Day in the year	64		
	Base PM		
Day in the year	49	184	263

WT 2

	CM		
Day in the year	52	220	
	SH PM		
Day in the year	52	220	
	LH PM		
Day in the year	306		
	Base PM		
Day in the year	7	227	321

WT 3

	CM		
Day in the year	61	203	
	SH PM		
Day in the year	61	203	
	LH PM		
Day in the year	306		
	Base PM		
Day in the year	20	239	340

WT 4

	CM		
Day in the year	30	317	
	SH PM		
Day in the year	30	317	
	LH PM		
Day in the year	221		
	Base PM		
Day in the year	4	166	305

WT 5

	CM		
Day in the year	122	305	
	SH PM		
Day in the year	122	305	
	LH PM		
Day in the year	64		
	Base PM		
Day in the year	67	108	302

Table 6.5.9: Proposed maintenance schedule for Location 1, Scenario 1 for 5 WT, option 1, weather restriction included

On WT3, failure occurred on day 60 but due to weather restrictions CM was performed on day 61. On the same WT the second failure occurred on day 202 but the CM was only performed on day 203 due to weather conditions. On WT4, failure occurred on day 28 but the CM was executed by 2 days delay.

The maintenance costs can be found below in details:

<u>*Short Horizon:*</u>

The first part of the objective function is related to SH cost minimization.

$$\textbf{Min} \sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it}\tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt}\, \tau_j^{PM} P_t]\, C_{el} + z_t C_{tr} + e_t C_{pen}]$$

- $\sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it}\tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt}\, \tau_j^{PM} P_t]\, C_{el}$:

The CM costs are 21,888€ and the optimized PM costs are 14,093€.

- $z_t C_{tr}$

The transportation costs for SH are 5000€.

- $e_t C_{pen}$

Penalty costs for extra working hours are 700€ as the total working hours h are constantly 7 and the total hours needed for both CM and PM was 8. Except from maintenance tasks performed on days 30, 52, 61 for the remaining maintenance tasks combined with PM, the total maintenance hours exceeded the available working hours by 1.

<u>*Long Horizon:*</u>

The second part of the objective function is related to LH cost minimization.

$$\textbf{Min} \sum_{t \in T_{long}} [\sum_k h_{tk} [P_{kt} C_{el} + \frac{C_{tr}}{h - 2\tau_\omega}]]$$

The maintenance costs during the LH for the PM task performed are 1030€.

Thus, the **OTMC are 42,711€** and the total energy production is 8,754kWh. Total availability of the WT is 98.79% for the full year.

Non-optimized Case

In the base case, when PM is not combined with CM and low wind speed is not taken into account to schedule the PM tasks, the **BTMC are 118,855€** which means that the total savings achieved with the proposed model is 64%. The proposed maintenance scheduled of this case is presented in table 6.5.9.

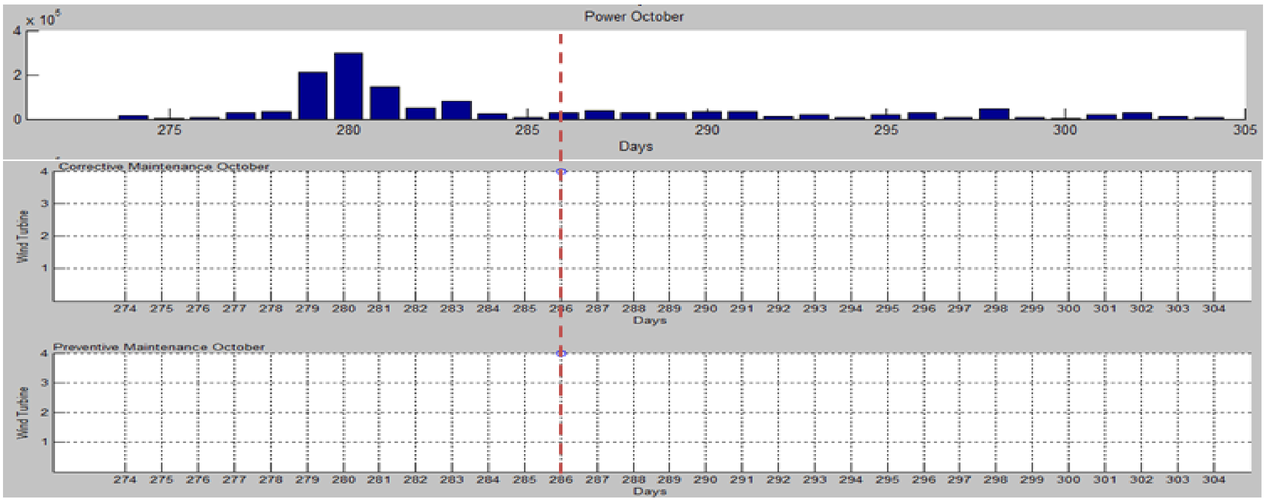


Figure 6.5.10: Failure, power production and Maintenance tasks for SH for *Location 1, Scenario 1, option 1 for 5 WT in October. The dashed line presents the advised maintenance schedule for day 286*

- ***Option 2***

Maintenance schedule for 1 year:

On this option, if no failure occurs before day 84 for PM1, day 241 for PM2 and day 236 for PM then based on the LH data the model will choose from the below time ranges the day with the min wind speed:

PM1: day 85 until 100 (both days included) - day with min wind speed is day 98

PM2: day 241 until 255 (both days included) - day with min wind speed is day 248

PM1: day 326 until 340 (both days included) - day with min wind speed is day 328

WT1: The first failure occurred on day 147 but the first PM had to be performed before day 100. Thus PM1 was scheduled to be executed on day 98. PM3 was combined with CM as failure occurred on day 298.

WT2: The first 2 PM tasks were performed combined with PM, while the third PM was scheduled on day 328 as was the day with min wind speed.

WT3: The third PM task was executed according to the LH data on day 328 as was the day with min wind speed. The other 2 PM tasks were combined with CM.

WT4: The second PM was performed on the day 248 with min wind speed. No failure had occurred before day 241, thus the second PM was scheduled to be performed based on the data from LH.

WT5: Similarly to WT1, the first PM was performed on day 98, as no failure occurred before day 84 thus PM as schedule to be executed the day with the minimum wind speed as the energy loss would be low.

The detailed maintenance schedule is presented below:

WT 1

	CM		
Day in the year	147	298	
	SH PM		
Day in the year	147	298	
	LH PM		
Day in the year	98		
	Base PM		
Day in the year	24	115	288

WT 2

	CM		
Day in the year	52	220	
	SH PM		
Day in the year	52	220	
	LH PM		
Day in the year	328		
	Base PM		
Day in the year	98	176	289

WT 3

	CM		
Day in the year	61	203	
	SH PM		
Day in the year	61	203	
	LH PM		
Day in the year	328		
	Base PM		
Day in the year	100	140	280

WT 4

	CM		
Day in the year	30	317	
	SH PM		
Day in the year	30	317	
	LH PM		
Day in the year	248		
	Base PM		
Day in the year	54	100	331

WT 5

	CM		
Day in the year	122	305	
	SH PM		
Day in the year	122	305	
	LH PM		
Day in the year	98		
	Base PM		
Day in the year	96	171	279

Table 6.5.10: Proposed maintenance schedule for Location 1, Scenario 1 for 5 WT, option 2, weather restriction included

On WT3, failure occurred on day 60 but due to weather restrictions CM was performed on day 61. On the same WT the second failure occurred on day 202 but the CM was only performed on day 203 due to weather conditions. On WT4, failure occurred on day 28 but the CM was executed by 2 days delay.

Short Horizon:

The first part of the objective function is related to SH cost minimization.

$$\boldsymbol{Min} \sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt} \tau_j^{PM} P_t] C_{el} + z_t C_{tr} + e_t C_{pen}]$$

- $\sum_{t \in T_{short}} [[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt} \tau_j^{PM} P_t] C_{el}$:

The CM costs are 21,888€ and the optimized PM costs are 14,093€.

- $z_t C_{tr}$

The transportation costs for SH are 5000€.

- $e_t C_{pen}$

Penalty costs for extra working hours are 700€ as the total working hours h are constantly 7 and the total hours needed for both CM and PM was 8. Except from maintenance tasks performed on days 30, 52, 61 for the remaining maintenance tasks combined with PM, the total maintenance hours exceeded the available working hours by 1.

<u>*Long Horizon:*</u>

The second part of the objective function is related to LH cost minimization.

$$\boldsymbol{Min} \sum_{t\in T_{long}} [\sum_k h_{tk}[\, P_{kt}C_{el} + \frac{C_{tr}}{h-2\tau_{\omega}}]]$$

The maintenance costs during the LH for the PM task performed are 1957€.

Thus, the **OTMC are 43,639€** and the total energy production is 8,757kWh. Total availability of the WT is 98.79% for the full year.

<u>*Non-optimized Case*</u>

In the base case, when PM is not combined with CM and low wind speed is not taken into account to schedule the PM tasks, the **BTMC are 134,981€** which means that the total savings achieved with the proposed model is 68%. The proposed maintenance scheduled of this case is presented in table 6.5.10.

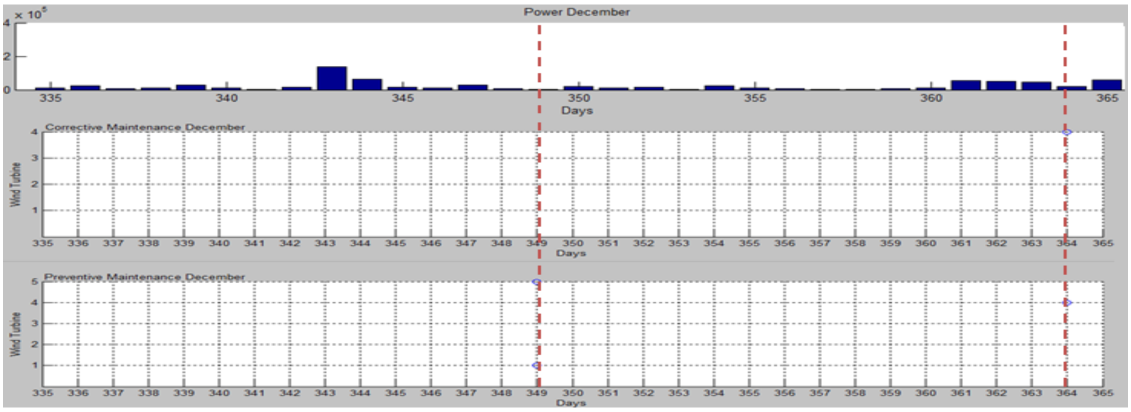


Figure 6.5.11: Failure, power production and Maintenance tasks for SH and LH for Location 1, Scenario 1, option 2 for 1 WT in December. The dashed line presents the advised maintenance schedule for day 349 and 364.

- ***Option 3***

  Maintenance schedule for 1 year:

On this option, if no failure occurs before the last week of the due date of PM then it will be scheduled based on the LH data. The model will choose from the below time ranges the day with the min wind speed:

PM1: week 15(day 99 to 105) - day with min wind speed is day 99

PM2: week 37 (day 253 to 259) - day with min wind speed is day 255

PM1: week 49 (day 337-343) - day with min wind speed is day 337

WT1: The first failure occurred on day 147 but the first PM had to be performed before day 100. Thus PM1 was scheduled to be executed on day 99. PM3 was combined with CM as failure occurred on day 298.

WT2: The first 2 PM tasks were performed combined with PM, while the third PM was scheduled on day 337 as was the day with min wind speed.

WT3: The third PM task was executed according to the LH data on day 337 as was the day with min wind speed during the week of the due date of the PM task. The other 2 PM tasks were combined with CM.

WT4: The second PM was performed on the day 255 with the lowest wind speed. No failure had occurred before day 252, thus the second PM was scheduled to be performed based on the data from LH.

WT5: Similarly to WT1, the first PM was performed on day 99, as no failure occurred before day 98.

The maintenance costs can be found below in details:

WT 1

	CM		
Day in the year	147	298	
	SH PM		
Day in the year	147	298	
	LH PM		
Day in the year	99		
	Base PM		
Day in the year	66	185	276

WT 2

	CM		
Day in the year	52	220	
	SH PM		
Day in the year	52	220	
	LH PM		
Day in the year	337		
	Base PM		
Day in the year	5	136	286

WT 3

	CM		
Day in the year	61	203	
	SH PM		
Day in the year	61	203	
	LH PM		
Day in the year	337		
	Base PM		
Day in the year	21	218	331

WT 4

	CM		
Day in the year	30	317	
	SH PM		
Day in the year	30	317	
	LH PM		
Day in the year	255		
	Base PM		
Day in the year	48	124	324

WT 5

	CM		
Day in the year	122	305	
	SH PM		
Day in the year	122	305	
	LH PM		
Day in the year	99		
	Base PM		
Day in the year	48	118	330

Table 6.5.11: Proposed maintenance schedule for Location 1, Scenario 1 for 5 WT, option 3, weather restriction included

Short Horizon:

The first part of the objective function is related to SH cost minimization.

$$\textbf{Min} \sum_{t \in T_{short}} \left[\left[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt} \tau_j^{PM} P_t \right] C_{el} + z_t C_{tr} + e_t C_{pen} \right]$$

- $\sum_{t \in T_{short}} \left[\left[\sum_{i \in CM} y_{it} \tau_i^{CM} P_t^{CM} + \sum_i \sum_j x_{ijt} \tau_j^{PM} P_t \right] C_{el}$:

The CM costs are 21,888€ and the optimized PM costs are 14,093€.

- $z_t C_{tr}$

The transportation costs for SH are 5000€.

- $e_t C_{pen}$

Penalty costs for extra working hours are 700€ as the total working hours h are constantly 7 and the total hours needed for both CM and PM was 8. Except from maintenance tasks performed on days 30, 52, 61 for the remaining maintenance tasks combined with PM, the total maintenance hours exceeded the available working hours by 1.

Long Horizon:

The second part of the objective function is related to LH cost minimization.

$$\textbf{Min} \sum_{t \in T_{long}} \left[\sum_k h_{tk} \left[P_{kt} C_{el} + \frac{C_{tr}}{h - 2\tau_\omega} \right] \right]$$

The maintenance costs during the LH for the 1 PM task performed are 3,728.

Thus, the **OTMC are 45,409€** and the total energy production is 8,713kWh. Total availability of the WT is 98.79% for the full year.

Non-optimized Case

In the base case, when PM is not combined with CM and low wind speed is not taken into account to schedule the PM tasks, the **BTMC are 90,907€** which means that the total savings achieved with the proposed model is 50%. The proposed maintenance scheduled of this case is presented in table 6.5.11.

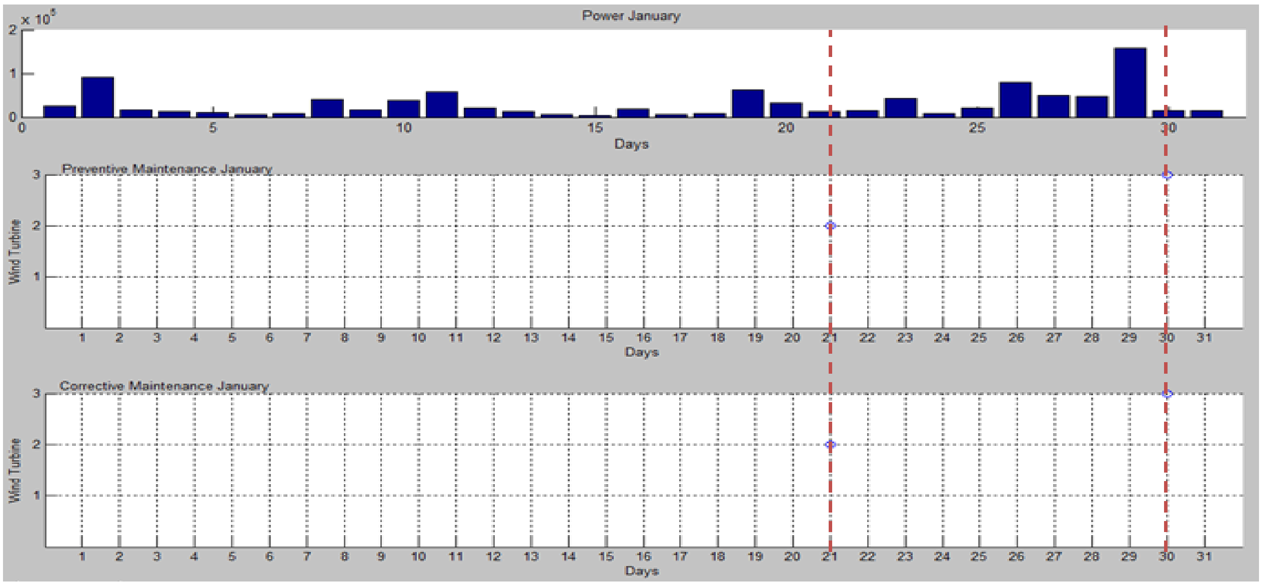


Figure 6.5.12: Failure, power production and Maintenance tasks for SH for Location 1, Scenario 1, option 3 for 5 WT in January. The dashed line presents the advised maintenance schedule for day 21 and 30.

As summary of the costs presented in section 6.51 are shown on the below table:

Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in %	Availability in %	Energy Output in MW
Scenario 1 with weather restriction	`L-L-L-L`	€ 42,711	€ 118,855	€ 21,888	€ 15,123	€ 5,000	€ 700	64%	98.79%	8,754
		€ 43,639	€ 134,981	€ 21,888	€ 16,050	€ 5,000	€ 700	68%	98.79%	8,757
		€ 45,409	€ 90,907	€ 21,888	€ 17,821	€ 5,000	€ 700	50%	98.79%	8,713

Table 6.5.12: Summary of the maintenance costs for Scenario 1 for 5 WT with and with weather restrictions

The corrective maintenance costs are the same for every option as failures occurred on the same day. The difference on the costs is on the PM tasks as based on the option run, the PM was scheduled on a different day thus the energy losses were different. Average savings achieved on those 3 options was 61%.

Without Weather restrictions

The model was run for five wind turbines, for scenario 1 (low wind speed and wave height during the year) but without the weather restriction. As summary of the maintenance for the three different options can be found below:

Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in %	Availability in %	Energy Output in MW
Scenario 1 without weather restriction	L-L-L-L	€ 99,406	€ 183,485	€ 69,150	€ 24,556	€ 5,000	€ 700	46%	99.07%	8,767
		€ 100,658	€ 209,413	€ 69,150	€ 25,808	€ 5,000	€ 700	52%	99.07%	8,768
		€ 103,118	€ 270,602	€ 69,150	€ 23,174	€ 5,000	€ 700	62%	99.07%	8,714

Table 6.5.13: Summary of the maintenance costs for Scenario 1 for 5WT with and without weather restrictions

It is noticeable that the annual “OTMC” are higher compared to the model run including weather condition due to higher energy losses. When a failure occurs on a day with high wind speed the maintenance crew will sail to the wind farm to perform maintenance as there is no restriction on max wind speed and wave height. This will result to high energy losses due to higher wind speed. The percentage of the savings is high but lower compared to the savings achieved for the same weather conditions but including the restriction on maximum wind speed and wave height which allows a vessel can sail to the wind farm.

The corrective maintenance costs are the same for every option as failures occurred on the same day. The difference on the costs is on the PM tasks as based on the option run, the PM was scheduled on a different day thus the energy losses were different. Average savings achieved on those 3 options was 53% which is lower by 8% compared to the model run with weather restriction. On the other hand, the average annual availability is higher in this case (99.07% vs. 98.79%) as the total downtime of the WTs is lower. The reason is that when a failure occurs the maintenance crew can directly sail to the wind farm to perform maintenance, while on the case that weather might prohibit the vessel to sail, there might be days that a WT is not operational due to failure but no vessel can sail to the wind farm.

6.5.3 Review and Comparison of Results for Location 1 and different scenarios

In this section, the results for location 1, for 5 wind turbines and for different weather scenarios will be compared and discussed. The model was run for 2 cases meaning with weather restriction and without.

Weather restrictions included

From the below table, it is noticeable that the difference on the costs is driven by the difference on the timing of scheduling the PM tasks. For every option 1, 2, or 3 there is a difference constraint or deadline before scheduling PM based on LH data without waiting for a failure to occur. On scenario 1, the delta between the lowest PM costs and highest is 2,698€, on scenario 2 the delta is 3,848€, on scenario 3 the delta 7,988€ and on scenario 4 the delta is 5,372€. The conclusion that can be drawn based on those differences on the maintenance costs of PM is that selecting the proper path to identify the opportunity to perform PM is critical to the total maintenance costs. The savings achieved when weather restriction is included vary from 68% to 21%. The differences are due to the weather condition differences. When the weather is flat and same during the year (low or high wind speed and wave height during the year without fluctuations) then the savings achieved are on average at 61%. When the weather is fluctuating during the year from high values to medium or low then the savings on the maintenance costs are ranging from 33% to 46%.

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % with weather constraint	Availability in %	Energy Output in MW
Option 1	**Scenario 1 with weather constraint**	L-L-L-L	€ 42,711	€ 118,855	€ 21,888	€ 15,123	€ 5,000	€ 700	64%	98.79%	8,754
option 2			€ 43,639	€ 134,981	€ 21,888	€ 16,050	€ 5,000	€ 700	68%	98.79%	8,757
option 3			€ 45,409	€ 90,907	€ 21,888	€ 17,821	€ 5,000	€ 700	50%	98.79%	8,713
Option 1	**Scenario 2 with weather constraint**	H-H-H-H	€ 58,827	€ 165,360	€ 31,449	€ 21,578	€ 5,000	€ 800	64%	98.30%	21,319
option 2			€ 58,315	€ 158,470	€ 31,449	€ 21,165	€ 5,000	€ 700	63%	98.25%	21,356
option 3			€ 62,262	€ 138,674	€ 31,449	€ 25,013	€ 5,000	€ 600	55%	98.25%	21,352
Option 1	**Scenario 3 with weather constraint**	H-M-L-M	€ 105,043	€ 202,806	€ 54,770	€ 44,573	€ 5,000	€ 700	48%	98.03%	15,406
option 2			€ 106,812	€ 193,518	€ 54,770	€ 46,642	€ 5,000	€ 400	45%	98.03%	15,401
option 3			€ 113,031	€ 208,422	€ 31,449	€ 52,561	€ 5,000	€ 700	46%	98.03%	15,413
Option 1	**Scenario 4 with weather constraint**	L-L-H-H	€ 83,860	€ 105,792	€ 42,627	€ 35,533	€ 5,000	€ 700	21%	98.68%	13,464
option 2			€ 88,181	€ 188,424	€ 42,627	€ 39,854	€ 5,000	€ 700	53%	98.68%	13,543
option 3			€ 103,950	€ 136,709	€ 42,627	€ 34,483	€ 5,000	€ 700	24%	98.68%	13,434
Option 1	**Scenario 5 with weather constraint**	M-H-H-M	€ 59,699	€ 203,142	€ 32,699	€ 21,500	€ 5,000	€ 500	71%	98.68%	16,940
option 2			€ 54,330	€ 163,303	€ 32,699	€ 91,668	€ 5,000	€ 400	67%	98.52%	16,955
option 3			€ 64,781	€ 125,086	€ 32,699	€ 72,099	€ 5,000	€ 500	48%	98.63%	16,888
Option 1	**Scenario 6 with weather constraint**	M-M-M-M	€ 84,590	€ 149,637	€ 47,686	€ 31,404	€ 5,000	€ 500	43%	98.30%	13,719
option 2			€ 87,207	€ 178,324	€ 47,686	€ 34,122	€ 5,000	€ 400	51%	98.25%	13,731
option 3			€ 88,279	€ 191,018	€ 47,686	€ 35,093	€ 5,000	€ 500	54%	98.25%	13,715
Option 1	**Scenario 7 with weather constraint**	H-L-M-L	€ 55,283	€ 146,806	€ 29,084	€ 20,700	€ 5,000	€ 500	62%	98.36%	15,039
option 2			€ 51,763	€ 102,911	€ 29,084	€ 17,379	€ 5,000	€ 300	50%	98.19%	15,031
option 3			€ 58,559	€ 112,671	€ 29,084	€ 23,976	€ 5,000	€ 500	48%	98.30%	14,963
Option 1	**Scenario 8 with weather constraint**	L-M-M-L	€ 93,717	€ 215,994	€ 49,537	€ 38,480	€ 5,000	€ 700	57%	99.01%	10,351
option 2			€ 92,076	€ 192,619	€ 49,537	€ 36,939	€ 5,000	€ 600	52%	98.90%	10,260
option 3			€ 100,987	€ 173,385	€ 49,537	€ 45,750	€ 5,000	€ 700	42%	99.01%	10,306

Table 6.5.14: Summary of maintenance costs, for Location 1, 5WT, for 8different scenarios, weather restriction included

On the below table 6.5.15, a summary of the maintenance costs when the weather restriction is not take into account is presented. The savings achieved are remarkably higher from the corresponding outcome when the weather is taken into account as a restriction. The reason is that in case a failure occurs on a day when wind speed is above 8m/sec (which is the restriction on the model proposed) then the maintenance crew will perform CM task. This results to high energy losses due to high wind speed. To schedule PM when it has to be performed without CM task, then the model also in this case takes into account low wind speeds. The main reason driving the total annual optimized is the high CM costs. Thus the savings of this case is lower ranging from only 2% (when wind speed is high during the year) to 62% (when wind speed is low during the year).

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % without weather constraint	Availability in %	Energy Output in MW
Option 1	**Scenario 1 without weather constraint**	`L-L-L-L`	€ 99,406	€ 183,485	€ 69,150	€ 24,556	€ 5,000	€ 700	46%	99.07%	8,767
option 2			€ 100,658	€ 209,413	€ 69,150	€ 25,808	€ 5,000	€ 700	52%	99.07%	8,768
option 3			€ 103,118	€ 270,602	€ 69,150	€ 23,174	€ 5,000	€ 700	62%	99.07%	8,714
Option 1	**Scenario 2 without weather constraint**	`H-H-H-H`	€ 204,903	€ 229,819	€ 110,421	€ 88,882	€ 5,000	€ 600	11%	98.96%	21,422
option 2			€ 206,143	€ 216,183	€ 110,421	€ 88,536	€ 5,000	€ 800	5%	99.07%	21,522
option 3			€ 209,130	€ 214,472	€ 110,421	€ 93,108	€ 5,000	€ 600	2%	98.96%	21,512
Option 1	**Scenario 3 without weather constraint**	`H-M-L-M`	€ 101,201	€ 155,132	€ 60,162	€ 35,639	€ 5,000	€ 400	35%	99.12%	15,766
option 2			€ 99,372	€ 140,928	€ 60,162	€ 34,010	€ 5,000	€ 200	29%	98.96%	15,778
option 3			€ 108,265	€ 183,675	€ 60,162	€ 33,924	€ 5,000	€ 400	41%	98.96%	15,804
Option 1	**Scenario 4 without weather constraint**	`L-L-H-H`	€ 143,221	€ 252,563	€ 96,918	€ 40,603	€ 5,000	€ 700	43%	99.18%	13,543
option 2			€ 144,155	€ 243,441	€ 96,918	€ 41,537	€ 5,000	€ 700	41%	99.18%	13,496
option 3			€ 161,677	€ 175,761	€ 96,918	€ 59,059	€ 5,000	€ 700	8%	99.18%	13,543
Option 1	**Scenario 5 without weather constraint**	`M-H-H-M`	€ 192,416	€ 261,019	€ 120,266	€ 66,550	€ 5,000	€ 600	26%	99.07%	16,944
option 2			€ 184,218	€ 244,645	€ 120,266	€ 58,452	€ 5,000	€ 500	25%	99.07%	16,981
option 3			€ 200,989	€ 274,351	€ 120,266	€ 75,123	€ 5,000	€ 600	27%	99.07%	16,884
Option 1	**Scenario 6 without weather constraint**	`M-M-M-M`	€ 121,821	€ 163,864	€ 75,002	€ 41,219	€ 5,000	€ 600	26%	99.01%	13,825
option 2			€ 127,445	€ 265,663	€ 75,002	€ 46,843	€ 5,000	€ 600	52%	99.01%	13,843
option 3			€ 127,395	€ 232,743	€ 75,002	€ 46,793	€ 5,000	€ 600	45%	99.01%	13,838
Option 1	**Scenario 7 without weather constraint**	`H-L-M-L`	€ 63,000	€ 150,511	€ 32,186	€ 55,048	€ 5,000	€ 1,300	58%	98.36%	15,267
option 2			€ 63,438	€ 98,396	€ 32,186	€ 40,644	€ 5,000	€ 1,200	36%	99.12%	15,263
option 3			€ 66,352	€ 125,004	€ 32,186	€ 27,866	€ 5,000	€ 1,300	47%	99.12%	15,186
Option 1	**Scenario 8 without weather constraint**	`L-M-M-L`	€ 124,375	€ 203,842	€ 73,904	€ 44,970	€ 5,000	€ 500	39%	99.12%	10,357
option 2			€ 123,399	€ 189,560	€ 73,904	€ 44,094	€ 5,000	€ 400	35%	99.07%	10,184
option 3			€ 129,554	€ 193,354	€ 73,904	€ 50,149	€ 5,000	€ 500	33%	99.12%	10,190

Table 6.5.15: Summary of maintenance costs, for Location 1, 5WT, for 8 different scenarios, without weather restriction

To summarize, it is concluded that the savings than can be achieved using this model are higher when the restriction of the weather is included in the model are higher. Scheduling carefully the PM tasks shows that the total maintenance costs of a wind farm can also be improved and minimized.

The below figure the maintenance costs of the 4 different scenarios and for 3 different option reviewed in this report for the cases with and without weather restriction is illustrated. What is more, the total savings of the annual maintenance costs are also included.

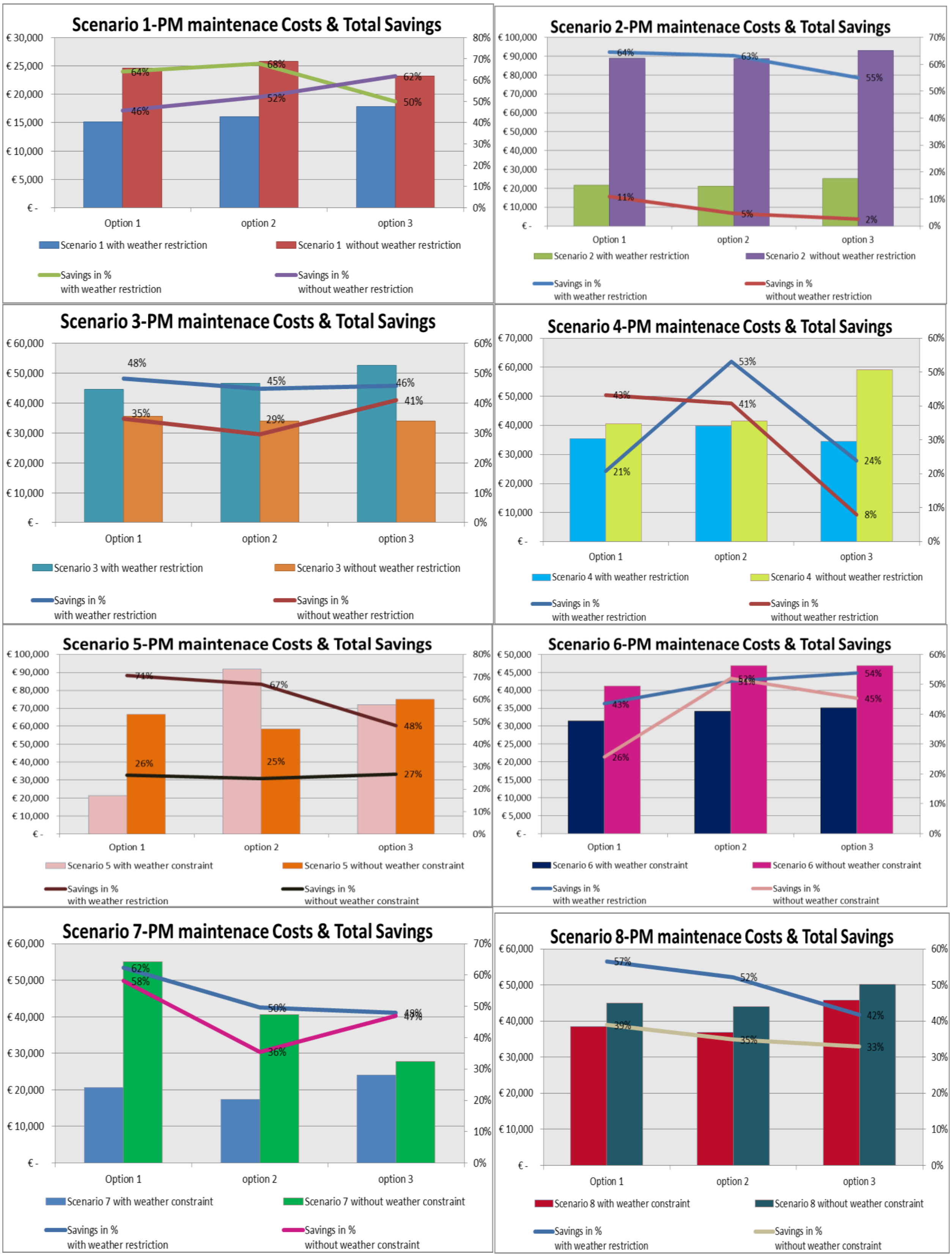


Figure 6.5.13: Summary of PM maintenance costs for 8 different scenarios, with and without weather restrictions and for 3 different options

To summarize, the conclusion drawn from this section is that scheduling wisely the PM tasks can save maintenance costs. The proposed model can achieve savings on average 52% when the weather constraint is included and 34% when there are no restrictions on max wind speed and wave height but the maintenance crew can always sail to the wind farm. In most case the maintenance costs for PM was higher on the case of no weather constraint and the saving were lower. Nevertheless, as shown in tables 6.5.14 and 6.5.15 the total annual availability is higher when the weather constraint is not included.

6.7 Influence of wind farm location on the maintenance costs

In order to determine and compare the difference on the maintenance costs depending on the location of the wind farms and weather restriction the model proposed was run for the locations proposed in this model and for four different scenarios. These scenarios are described in detail in section 6.1.

The table below presents the Annual Optimized Total Maintenance Costs for four different locations and scenarios. The highest optimized maintenance costs when the weather constraint is taken into account are encountered in Location 1 for all the different scenarios applied while the lowest maintenance costs are always between on location 1. When the weather constraint is excluded, there is no clear distinction on which location has always the minimum maintenance costs, but also in this case location 1 has the highest maintenance costs. The reason that location 1 has always the higher costs is due to higher energy losses driven by high wind speeds in that area.

		Location 1	*Location 2*	*Location 3*	*Location 4*
Option number	**Scenario number**	**Annual OTMC in €**	**Annual OTMC in €**	**Annual OTMC in €**	**Annual OTMC in €**
Option 1	**Scenario 1 with weather constraint**	€ 42,711	€ 17,062	€ 36,710	€ 35,846
option 2		€ 43,639	€ 17,714	€ 35,871	€ 32,726
option 3		€ 45,409	€ 20,198	€ 40,942	€ 39,145
Option 1	**Scenario 2 with weather constraint**	€ 58,827	€ 34,486	€ 57,568	€ 43,297
option 2		€ 58,315	€ 34,648	€ 55,253	€ 40,496
option 3		€ 62,262	€ 44,855	€ 59,625	€ 48,147
Option 1	**Scenario 3 with weather constraint**	€ 105,043	€ 27,625	€ 51,096	€ 27,982
option 2		€ 106,812	€ 27,854	€ 51,297	€ 29,248
option 3		€ 113,031	€ 30,808	€ 61,757	€ 44,354
Option 1	**Scenario 4 with weather constraint**	€ 83,860	€ 33,027	€ 46,563	€ 40,085
option 2		€ 88,181	€ 32,379	€ 47,126	€ 39,664
option 3		€ 103,950	€ 36,774	€ 59,174	€ 42,010

		Location 1	*Location 2*	*Location 3*	*Location 4*
Option number	**Scenario number**	**Annual OTMC in €**	**Annual OTMC in €**	**Annual OTMC in €**	**Annual OTMC in €**
Option 1	**Scenario 1 without weather constraint**	€ 99,406	€ 29,443	€ 33,344	€ 41,595
option 2		€ 100,658	€ 28,681	€ 33,348	€ 42,271
option 3		€ 103,118	€ 30,756	€ 37,546	€ 44,995
Option 1	**Scenario 2 without weather constraint**	€ 204,903	€ 76,700	€ 80,201	€ 131,354
option 2		€ 206,143	€ 75,380	€ 80,847	€ 111,271
option 3		€ 209,130	€ 75,273	€ 84,041	€ 137,594
Option 1	**Scenario 3 without weather constraint**	€ 101,201	€ 63,140	€ 29,139	€ 39,437
option 2		€ 99,372	€ 63,778	€ 29,295	€ 40,229
option 3		€ 108,265	€ 66,068	€ 38,848	€ 55,496
Option 1	**Scenario 4 without weather constraint**	€ 143,221	€ 42,198	€ 32,277	€ 32,253
option 2		€ 144,155	€ 42,405	€ 32,511	€ 33,040
option 3		€ 161,677	€ 42,878	€ 48,337	€ 33,813

Table 6.7.1: Total optimized maintenance costs for 4 different scenarios and locations, 3 different option with and without weather constraint

Based on the above annual OTMC, the below table was created in order to identify which location has the highest maintenance costs. As already explained, the annual maintenance costs are influence mainly from the energy losses thus, the higher the maintenance costs the higher the energy losses.

Option number	**Scenario number**	**Scenario Description**	**min ---------------------------------->max**			
Option 1 option 2 option 3	**Scenario 1 with weather**	L-L-L-L	**Location 2**	**Location 4**	**Location 3**	**Location 1**
Option 1 option 2 option 3	**Scenario 2 with weather**	H-H-H-H	**Location 2**	**Location 4**	**Location 3**	**Location 1**
Option 1 option 2 option 3	**Scenario 3 with weather**	H-M-L-M	**Location 2**	**Location 4**	**Location 3**	**Location 1**
Option 1 option 2 option 3	**Scenario 4 with weather**	L-L-H-H	**Location 2**	**Location 4**	**Location 3**	**Location 1**

Option number	**Scenario number**	**Scenario Description**	**min -------------------------------->max**			
Option 1 option 2 option 3	**Scenario 1 without**	L-L-L-L	**Location 3**	**Location 2**	**Location 4**	**Location 1**
Option 1 option 2 option 3	**Scenario 2 without**	H-H-H-H	**Location 2**	**Location 3**	**Location 4**	**Location 1**
Option 1 option 2 option 3	**Scenario 3 without**	H-M-L-M	**Location 3**	**Location 4**	**Location 2**	**Location 1**
Option 1 option 2 option 3	**Scenario 4 without**	L-L-H-H	**Location 4**	**Location 3**	**Location 2**	**Location 1**

Table 6.7.2: Ranking of the Total optimized maintenance costs for 4 different scenarios and locations from min to max

What is more, the availability of the each wind farm in the four different locations differs as it is impacted from the weather conditions. As mentioned in section 3.3 the availability of an offshore wind farm is influenced from the proximity to the shore. The availability of a wind farm is the percentage of time that is able to produce electricity thus an extra day of downtime due to weather conditions is influencing the total availability of the wind turbines and in whole of the offshore wind farm. From the below figure it can be verified that when the weather is not a constraint the availability of the wind farm is higher and stable at a rate above 99%.

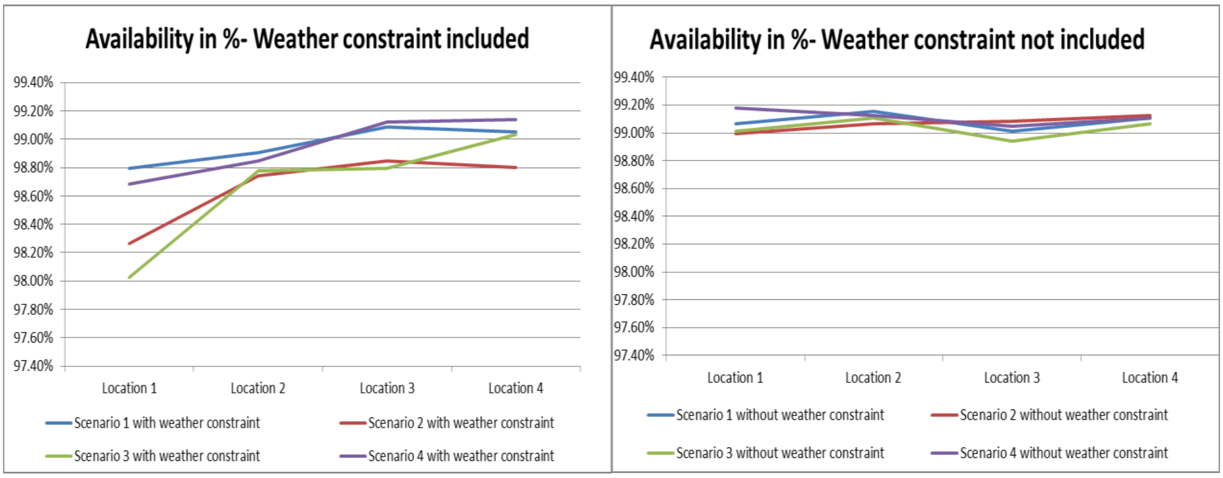


Figure 6.7.1: Annual availability for 4 different scenarios and 4 different locations, with and without weather constraint

Finally, more savings were gained when the weather constraint was included in the model run. Again, as the maintenance costs are determined by the energy losses, when the weather restriction was not in place, then when a failure occurred on a day with wind speed higher than the restriction of the weather the CM task as performed resulting to high energy losses. For example, if a failure occurred on day 45 with wind speed 8.5 m/sec, on the case when weather constraint was included then the CM task wouldn't take place as the max wind speed allowed to the vessel to sail is 8m/sec. The maintenance had to wait until a day with wind speed lower that 8m/sec. When weather restriction was neglected, CM task was performed on day with high wind speed which resulted in higher losses. This explains also the difference on the annual availability as the total downtime when no weather constraint applied was only during the days of maintenance activities. The below figure shows the difference on the total savings:

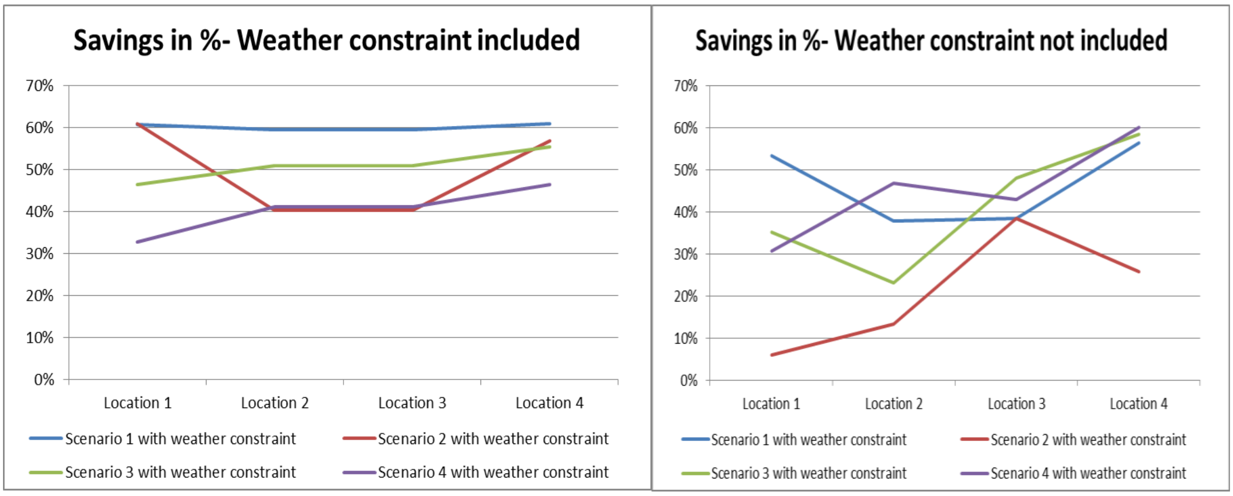


Figure 6.7.2: Annual savings for 4 different scenarios and 4 different locations, with and without weather constraint

To sum up, the results carried out from running the model for different scenarios and locations showed that the costs are influenced by the location of the wind farm in the sea which is driven from the different weather conditions. In appendix E, the results of each model run are presented in more details.

Chapter 7

7 Discussion

In this chapter the assumptions made as well as limitations of the model are discussed.

7.1 Assumptions

Assumptions made in these reports will be described. Specifically, assumptions made for the weather conditions, maintenance tasks and cost and determination of the timing that the maintenance needs to takes place can be found below.

7.1.1 General

The model was run for only one year as the purpose of this thesis was to test whether the maintenance costs of an offshore wind farm can be optimized by applying an opportunistic model. However the total lifecycle of an offshore wind farm is twenty years.

What is more, as explained above the model was run for the period of one year. The assumption for this model is that the year starts on the 1st of December and end on the 30th of November.

7.2.1 Weather

The assumptions made for the wind speed and the wave height is that their values will remain constant during the day and equal with the daily average value.

In order to determine the good weather windows when the offshore wind farm can be visited the maximum allowed average wind speed should be 8.0m/sec and the maximum allowed average wave height is 1.5m. This assumption is related as well to a specific maintenance category as presented in table 6.1 in chapter 6.

What is more, in this report the weather conditions are determined beforehand. In practice, maintenance actions have to be planned using weather forecasts. In order to incorporate unexpected weather circumstances during repairs weather scenarios were built for different values of wind speed and wave height.

Different weather inputs will change the model output and savings as the maintenance costs are associated with the energy output which is dependent on the wind speed. Moreover, the wave height is also influencing the maintenance costs as the higher the height the less opportunities to visit the wind farm will arise. Both wind speed and wave height have impact on the wind turbine's availability as when a failure occurs and the vessel cannot sail to the wind farm, the WT is producing energy.

7.2.2 Maintenance tasks and costs

Initially, before the model was run, both CM and PM maintenance tasks have to be pre-determined. As there is little information on the failure rates of the offshore wind farms, for this report the failures were determined randomly during the year. For every wind turbine it was assumed that two corrective maintenance task have to be performed per year and that they can be executed in at most a day. In chapter 6, section 6.2 the process of defining the CM works was described.

Number of preventive maintenance tasks in a year was assumed to be three per wind turbine. For PM activities the below further assumptions were explicitly made:

    - The first PM activity has to be performed before the first 100 days of operation of the WT
    - The second PM activity has to be performed between day 101 and before the 255 days of operation of the WT
    - The third PM activity has to be performed between day 256 and before 340 days of operation of the WT

In case the timing of the 3 PM tasks changes, the total annual optimized costs will be also different as the day that the PM will be perform will be different from the current assumption made, which means that the energy loss will be different. For example, if the first PM has to be performed within the first 77 days there is less time to wait for a failure to be performed and thus an opportunity to combine CM with PM.

In order to define the maintenance costs in € the below assumptions were made:

- Electricity price $C_{el} = 0.05€/kWh$
- Transportation costs including fuel and possible daily crew costs: 500€
- Penalty for extra working hours for a team of two maintenance technicians: 500€/hour
- Working hours per team: 7 hours
- Time to access the WT $\tau_{\omega} = 0.5$
- Number of corrective maintenance tasks in a year: 2 per WT

7.2.3 Logistics

It was assumed that upon a failure the spare parts were always available in the warehouse as well as the personnel for the maintenance activities as well as the vessel needed to transport the crew to the offshore wind farm.

In real life, there might be times when the vessel is not available at the requested day or the spare part needed for the repair is not in stock. Thus, the wind turbine might need to be down for more days than expected. This is affecting the capability of performing CM task, which has a direct impact on wind turbine's availability.

Chapter 8

8 Conclusions and Recommendations

In this chapter a summary of the model used in this thesis and the conclusions made will be presented. What is more, recommendations on further researched will be proposed.

8.1 Summary

As discussed in Chapter 2, the European Parliament and Council (2009), in an attempt to convert Europe in a low carbon and high energy efficiency economy was initiated. The European Union Heads of State and Government as a part of the project "Climate and Energy Package" has set the target of 20-20-20. The trend of highly energy-efficient, low carbon economies leads to high targets for renewable energy production. The plan to achieve this goal is to prepare a renewable plan which includes a breakdown of different types of renewable energy. One mean will be to build offshore wind farms. Thus, it is expected that in the European seas wind farms with total capacity of thousands of megawatts will be installed.

O&M costs for offshore wind farms are consisting of about 23% on the project's total costs (figure 2.1). For an equivalent onshore farm these costs of energy are estimated to be a lot lower with a percentage of 5-10% (Andrawus, Watson and Kishk (2007)). The reason of this difference can be attributed to the fact that offshore wind turbines are functioning under a harsh maritime environment and thus their accessibility for maintenance is influenced by sea-state (i.e. waves) and weather conditions(i.e. wind). What is more, visiting an offshore wind farm is more costly as their distance from shore creates problems in their accessibility.

For that reason, in this thesis an attempt to define the maintenance activities, optimize them and test whether savings can be achieved by its optimization was attempted. The main cost savings are related to the production losses and logistic costs including fuel and mobilization costs. The proposed model minimized the maintenance costs by decreasing production losses and transportation costs. Wind speed and Wave heights of the period 1993 until 2012 are used to simulate the wind and wave pattern. A cost comparison is made for the different locations and for different weather scenarios in order to prove the importance of both elements. The results showed that savings can be achieved with the proposed model even in harsh weather conditions.

8.2 Conclusion

In this section a general conclusion is given based on the research questions as defined in the Introduction chapter. The results are being analyzed and answers to the questions are given.

Combining corrective with preventive maintenance will drive to a reduction of total maintenance costs?

The proposed model for the optimization of maintenance planning is proposed to determine the optimal time for performing the scheduled maintenance activities, with consideration of the cost for transportation and production losses. The model is based on 20-year data for different locations for short term planning and Weibull distribution for weather forecasts, together with opportunities at corrective maintenance. With the data used for this thesis and the proposed maintenance simulation indicates that an economic benefit from 4,665€ up 20,000€ per wind turbine can be achieved.

The results show that maintenance costs can be significantly reduced through optimizing the maintenance strategies and the maintenance planning.

Is the impact of weather conditions considerable?

The model was applied for four different weather conditions as per described below:

Scenario 1: *Low* wind speed and wave height throughout the year (L-L-L-L)

Scenario 2: *High* wind speed and wave height during the year (H-H-H-H)

Scenario 3: *High* wind speed and wave height during the winter, *Medium* wind speed and wave height during the spring, *Low* wind speed and wave height during the summer and *Medium* wind speed and wave height during autumn. (H-M-L-M)

Scenario 4: *Low* wind speed and wave height during the winter, *Low* wind speed and wave height during the spring, *High* wind speed and wave height during the summer and *High* wind speed and wave height during autumn. (L-L-H-H)

		Location 1	*Location 2*	*Location 3*	*Location 4*			*Location 1*	*Location 2*	*Location 3*	*Location 4*
Option number	**Scenario number**	**Savings in %**	**Savings in %**	**Savings in %**	**Savings in %**	**Option number**	**Scenario number**	**Savings in %**	**Savings in %**	**Savings in %**	**Savings in %**
Average of 3 options	Scenario 1 with weather constraint	61%	59%	59%	61%	Average of 3 options	Scenario 1 without weather constraint	53%	38%	38%	56%
Average of 3 options	Scenario 2 with weather constraint	61%	40%	40%	57%	Average of 3 options	Scenario 2 without weather constraint	6%	13%	38%	26%
Average of 3 options	Scenario 3 with weather constraint	46%	51%	51%	55%	Average of 3 options	Scenario 3 without weather constraint	35%	23%	48%	58%
Average of 3 options	Scenario 4 with weather constraint	33%	41%	41%	46%	Average of 3 options	Scenario 4 without weather constraint	31%	47%	43%	60%

Table 8.1: Costs savings for 4 different locations and scenarios with and without weather constraint

The above table is confirming that the weather conditions are influencing the percentage of the costs savings. When the weather constrains is applied the savings are higher compared to the case when the weather constraint is neglected. What is more, every location has different weather conditions thus the savings are also influenced from this weather diversity. Generally, it was noticed that less savings achieved when the weather conditions assumed to be harsh (high wind speed and wave height during the year) compared to milder sea climate.

Location of offshore wind turbine influences the total annual maintenance costs?

In section 6.6 the influence of wind farm location on the maintenance costs is analyzed and compared. In the coming future offshore wind farms will be built further from the sea. The further from the coast the higher is the energy production thanks to higher wind speeds (figure 4.1) which results to higher maintenance costs due to higher energy losses. The results verify that the total optimized costs are differing per scenario and per location as well as the savings.

The figure below is showing the difference of the annual optimized maintenance costs for the different locations studied in this thesis. Total maintenance costs for both cases (with and without weather constraint) are included. It can be concluded that the location of the wind farm is indeed influencing the total maintenance costs.

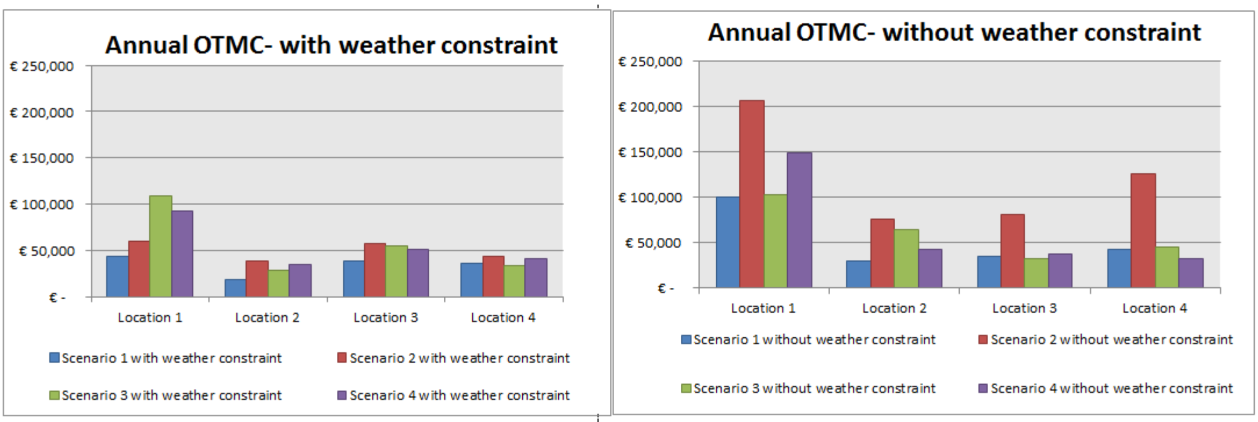


Figure 8.1: Annual OTMC for 4 different locations and scenarios with and without weather constraint

To summarize, in this section the questions raised in the introduction section are answered. The results o of the proposed model showed significant cost savings when the weather restriction is taken into account. In this case, savings are higher but there is an impact on the total annual availability of the wind farm. On the other hand, when weather conditions are not accounted for, then availability increased but cost savings are lower due to increased energy losses.

8.3 Recommended future work

In this final section some recommendations for future research are described. First some recommendations related on how to determine maintenance tasks and then regarding weather and logistics.

For the maintenance tasks the following recommendations are made:

- Corrective maintenance: As offshore wind farms are a new developed sector, data regarding the failure rates were not available. For that reason, in this report failures were generated randomly. Taking into account failure rate of the offshore wind farm will improve accuracy of the results.
- Preventive maintenance: As already mentioned above, due to lack of real life data, timing for PM tasks were determined based on assumptions. There will be also improvement in the results if assumptions made in this thesis will be replaced with real data.
- Maintenance category: Four maintenance categories were described but only one was used as the purpose of this model was not to test the impact on the costs of the different maintenance categories. Different maintenance categories can be tested to compare the results.

Recommendations for Logistics:

- In this report it was assumed that all vessels and maintenance crew was directly available when a maintenance had to be performed. Taking into account the impact of waiting until a vessel or maintenance crew is available will influence the cost of the maintenance actions and the availability of the wind turbines.

- Another enhancement that can be taken into account is spare part availability. It is assumed that the spare part needed to perform the maintenance is readily available which is not always applicable in real life situations.

Weather recommendations:

- As already concluded the weather impact is considerable on the maintenance costs of an offshore wind farm. In this report weather conditions were determined beforehand for the different scenarios proposed. Unexpected weather circumstances were tried to be captured using Weibull distribution to forecast wind data for the Long Horizon of the suggested model. …..

Appendix A
Probability distribution

A.1 Weibull distribution [38]

In probability theory and statistics the Weibull distribution is a continuous probability distribution with parameters α and β (α>0, β>0), where β is the shape parameter and α is the scale parameter. The probability density function of a Weibull random variable x is:

$$f(x,\beta,\alpha) = \frac{\beta}{\alpha}\ (\frac{x}{\alpha})^{\alpha-1} e^{(\frac{x}{\alpha})^{\beta}}, \quad x \geq 0$$

The distribution function for $x \geq 0$ is given by:

$$F_X(x,\beta,\alpha) = 1 - e^{-(\frac{x}{\alpha})^{\beta}}, \ \ x \geq 0$$

Generally, for larger values of α reveal reduced variability and larger values of β demonstrate higher median values. When β=1 the Weibull distribution equals the exponential distribution and when β=2 equals the Rayleigh distribution.

This distribution is regularly used for the lifetime distribution for the time shaping into a given technical device fails. If the failure rate (MTBF) of the unit decreases over time, is chosen β<1, which results in a decreasing density ***f*** . When the failure rate of the device is constant in the time, one chooses α=1, which again results in a decreasing density. If the failure rate increases over time, is chosen β>1 so that the probability density ***f*** first rises to a maximum and then decreases forever

The mean μ and standard deviation σ of Weibull distribution can be expressed by using the Gamma distribution as follows:

$$\mu = \frac{\alpha}{\beta}\Gamma\left(\frac{1}{\beta}\right) = \alpha\Gamma\ (1 + \frac{1}{\beta})$$

$$\text{and}\ \ \sigma = \sqrt{\frac{\alpha^2}{\beta}[2\Gamma(\frac{2}{\beta}) - \frac{1}{\beta}\Gamma^2(\frac{1}{\beta})]} = \sqrt{\alpha^2[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2(1 + \frac{1}{\beta})]}$$

The Weibull distribution can also be used to model the distribution of wind speeds at a particular location on earth. Again, each location is characterized by the shape and scale parameter.

Appendix B

B.1 Optimization Theory

Initially a general formulation of a mathematical problem will be presented. The objective of a classic mathematical problem is as follows:

$$min_{x \in X} f(x),$$

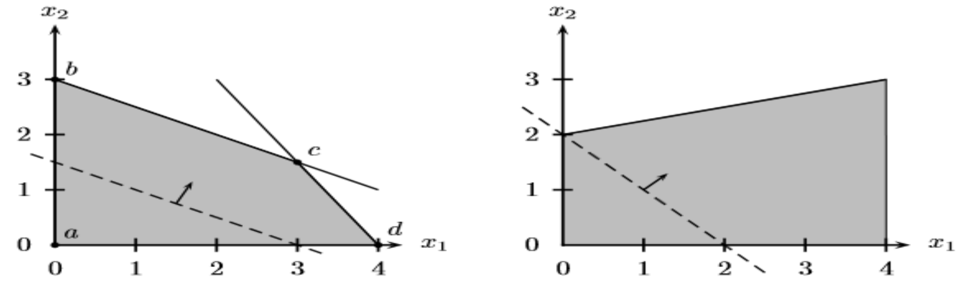
Where $x \epsilon R^n$ is representing the vector of decision variables, $f(x)$ is the objective function and the set of feasible solutions is represented by the set of X. In some case the s the feasible set of solutions can be defined by equality or inequality constraints such as:

$$g_i(x) = 0, i \in \mathrm{M},$$

$$g_i(x) \le 0, i \in \mathrm{N},$$

where M and N are indexed sets.

The optimal solution x^* is also a feasible solution if it satisfies: $f(x^*) \le f(x), \forall\, x \in X$. The method that can be used to obtain the optimal solution varies and it depends on the form of the objective function and the feasible set.



(a) Graphical representation of the problem min $-x_1 - 2x_2$ s.t. $x_1 + 2x_2 \le 6$. $3x_1 + 2x_2 \le 12$, $x_1, x_2 \le 0$. The extreme point c is the optimal solution.

(b) Graphical representation of the problem min $-x_1 - x_2$ s.t. $-x_1 + 4x_2 \le 12$, $x_1, x_2 \le 0$. There is no optimal solution in this case.

Figure B.1: Examples of two optimization problems with and without optimal solution, Bertsimas and Tsitsiklis (1997)

The above figure 3 shows two simple problems of the general form and their possibilities. In order to search and define the optimal extreme point, methods such as the simplex method have been developed.

B.2 Mixed Integer Linear Optimization

Bertsimas and Tsitsiklis (1997) argue that every linear problem that has the above mentioned form can be transformed as follows:

min $c'x$,

Subject to: Ax=B,

$x \geq 0$

Where $c \epsilon R^n$ is the cost vector and $A \epsilon R^{m*n}$ and $b \epsilon R^m$ are the parameters that represent the linear constraints of the problem.

If the feasible set $\{x \epsilon R^n | Ax = b, x \geq 0\}$ of the above formulated problem is non empty, then if there is a optimal solution that solution will be in the extreme points of the feasible set . There is also the possibility that the optimal solution is -∞.

The problem suggested for this thesis is formulated as a Mixed Integer Program (MIP). These types of problems have both integer and continuous variables. The standard form of a MIP optimization problem is:

Minimize: $c'x + d'y$,

Subject to: Ax+Bx=b,

x,y≥0, x integer

Where vectors c and d define the cost function and matrices A and B, and vector b define the linear constraints.

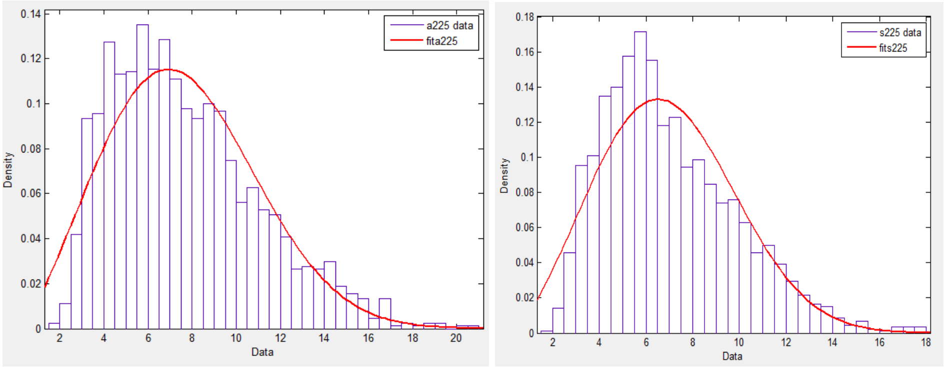
These problems are generally hard to solve. Most popular methods are those that are based on linear optimization and a sequence of linear problems have to be solved. Branch and bound and cutting planes are examples of exact methods. There are also sub-optimal methods such us local search or evolutionary but they don’t provide information on the quality of the solution.

Appendix C

C. Wind speed graphs

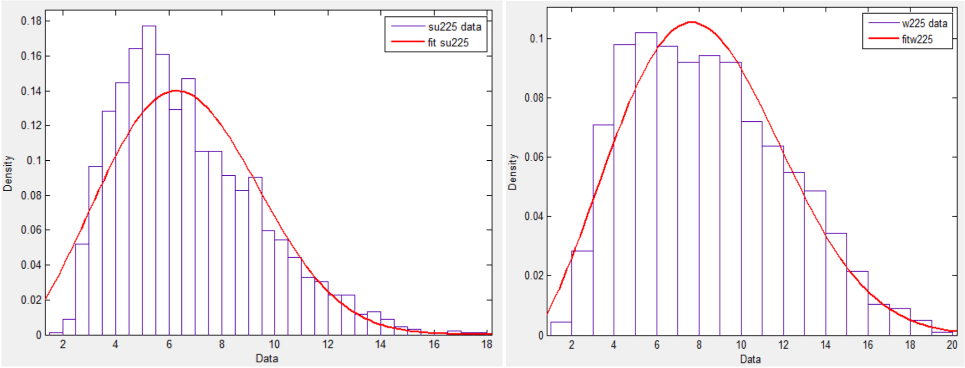
For the below graphs 1-hour average wind data for a period of 20 years (1993-2013) for different locations in the North Sea has been analyzed using Weibull distribution. Those data were published by the Royal Dutch Meteorological Institution (KNMI).

Figures C.1: Location Ijmuiden (225)



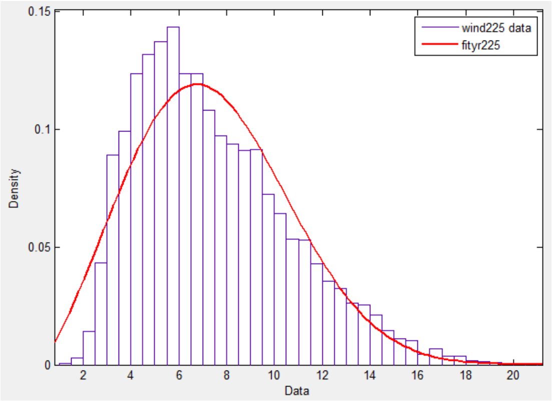
C.1 (a) Wind speed in the autumn (m/s)

C.1 (b) Wind speed in the spring (m/s)



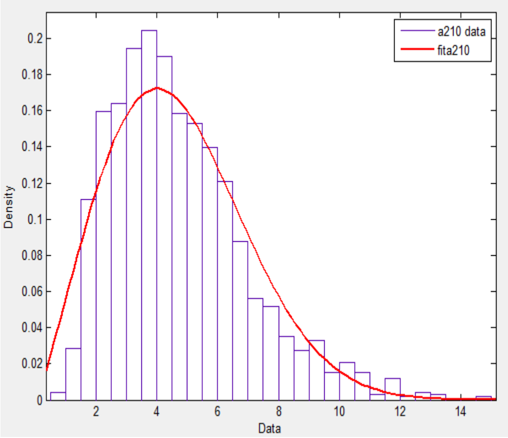
C.1 (c) Wind speed in the summer (m/s)

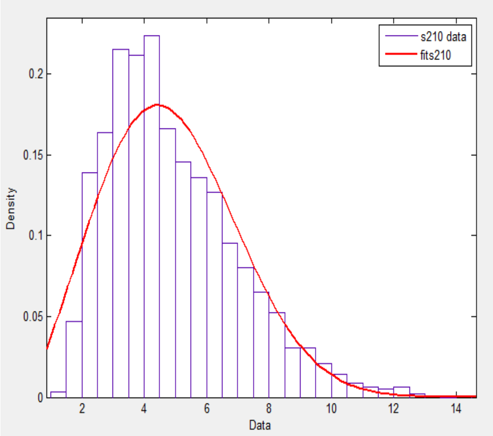
C.1 (d) Wind speed in the winter (m/s)



C.1 (e) Wind speed annual (m/s)

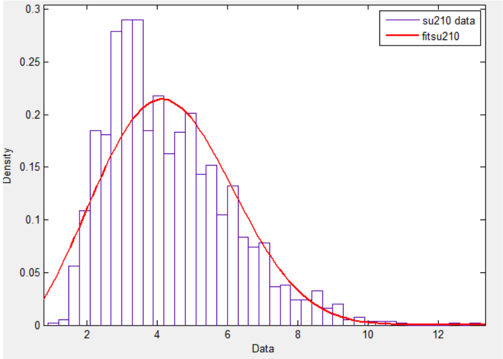
Figures C.2: Location Valkenburg(210)

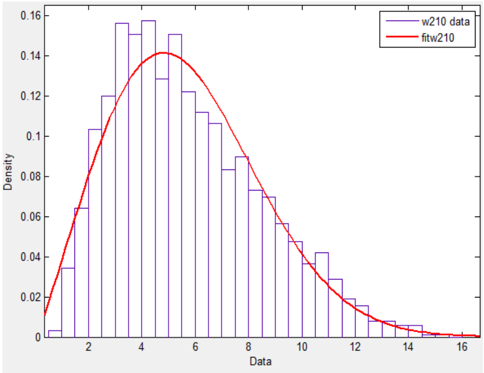




C.2(a) Wind speed in the autumn (m/s)

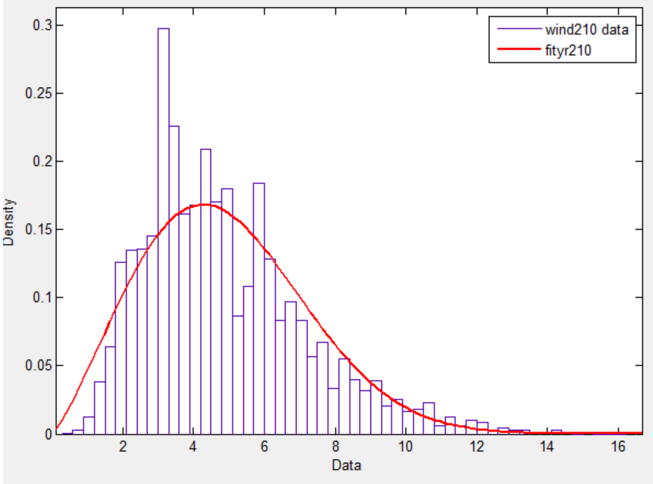
C.2 (b) Wind speed in the spring (m/s)





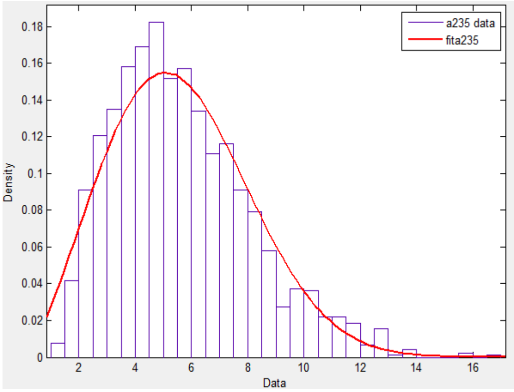
C.2 (c) Wind speed in the summer (m/s)

C.2 (d) Wind speed in the winter (m/s)

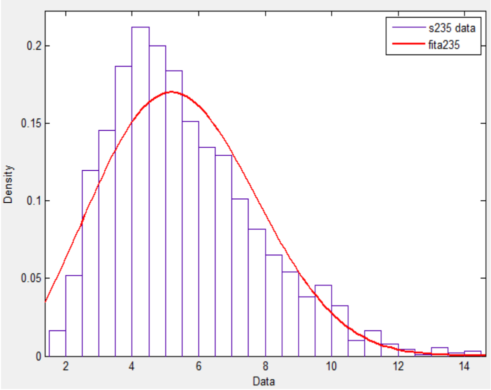


C.2 (e) Wind speed annual (m/s)

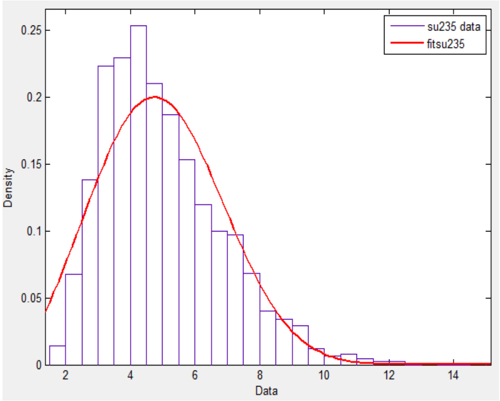
Figures C.3: Location De Kooy (235)



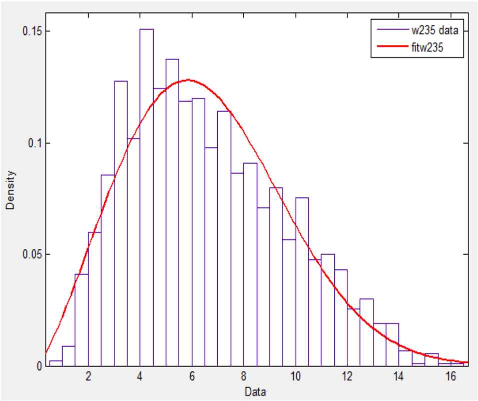
C.3 (a) Wind speed in the autumn (m/s)



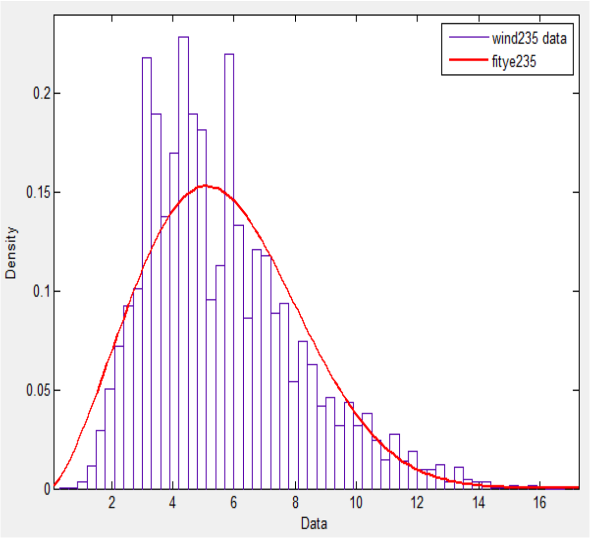
C.3 (b) Wind speed in the spring (m/s)



C.3 (c) Wind speed in the summer (m/s)

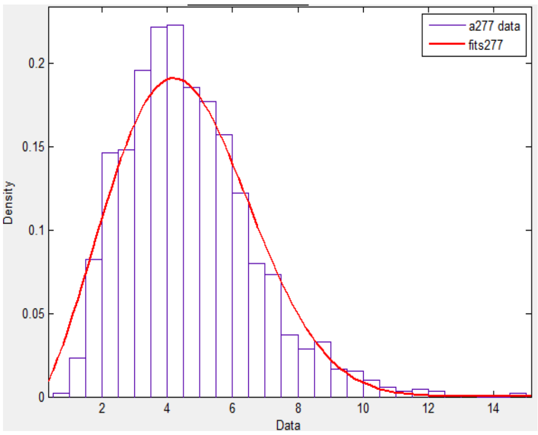


C.3 (d) Wind speed in the winter (m/s)

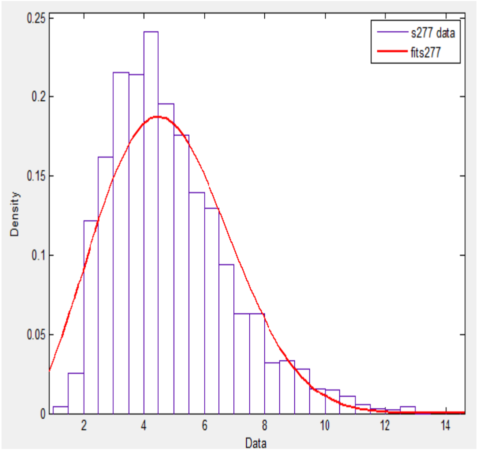


C.3 (e) Wind speed annual (m/s)

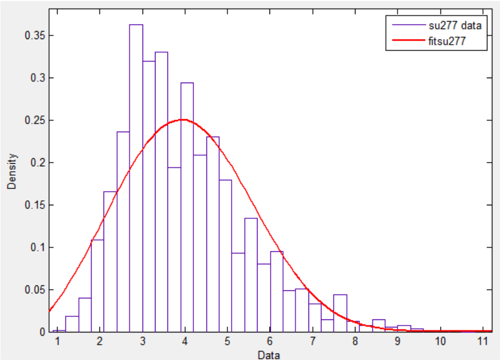
Figures C.4: Location Lauwersoog (277)



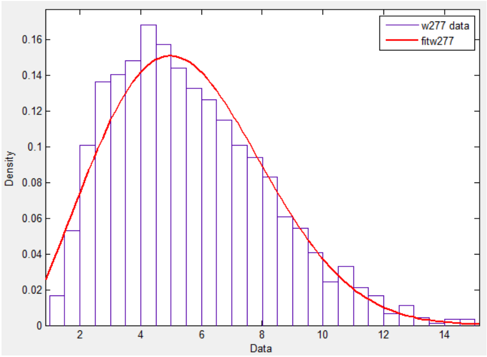
C.4 (a) Wind speed in the autumn (m/s)



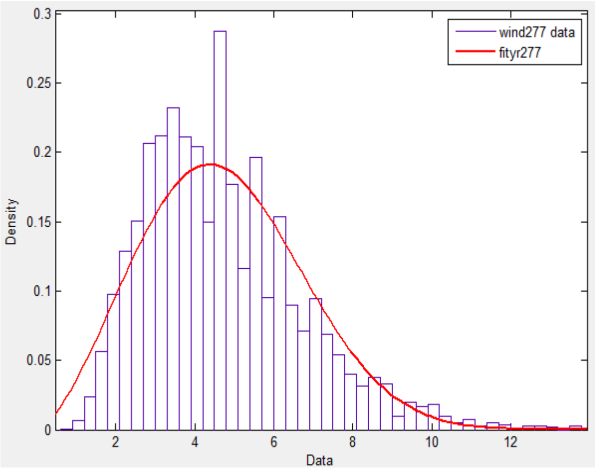
C.4 (b) Wind speed in the spring (m/s)



C.4 (c) Wind speed in the summer (m/s)



C.4 (d) Wind speed in the winter (m/s)



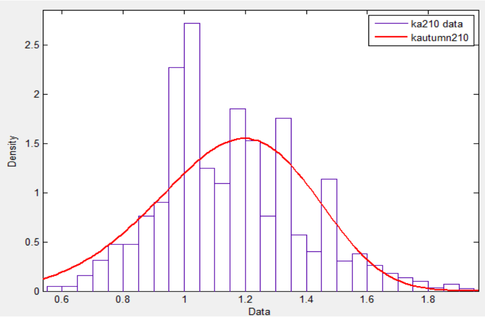
C.5 (e) Wind speed annual (m/s)

Appendix D

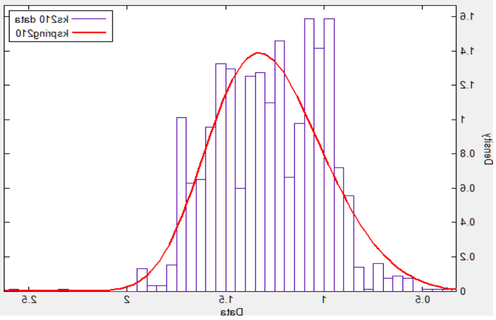
D. Wave height graphs

Data published by the “Rijkswaterstaat”, the website of the Dutch Ministry of Infrastructure and the Environment has been analyzed. 1-hour averages of the significant wave height for 4 different locations in the North Sea were used. The total period taken into account is: 1st of January 1995 until the 31st of December 2012 (both dates included).

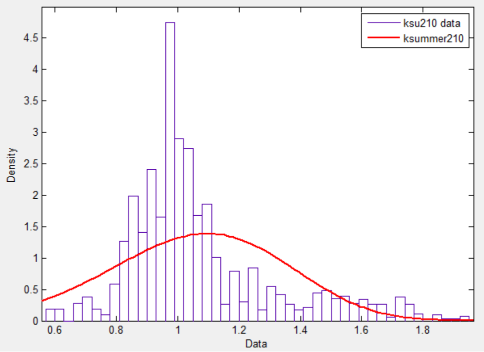
Figures D.1: Location K13 Platform



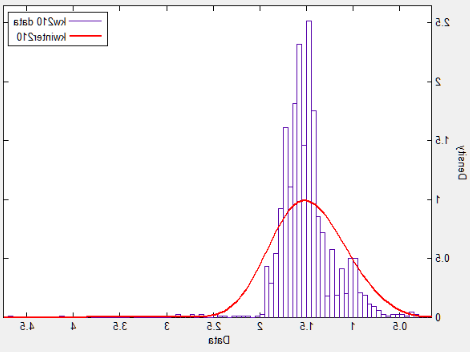
D.1 (a) Wave height in the autumn (m)



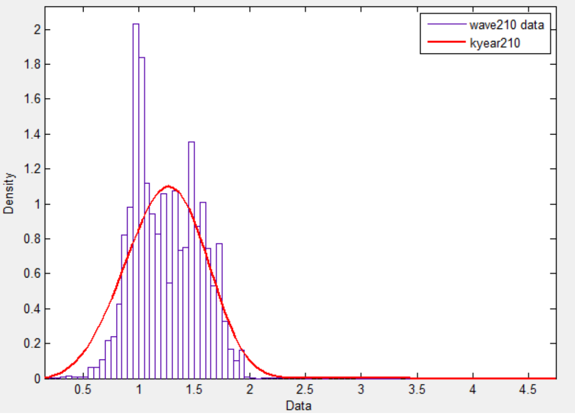
D.1 (b) Wave height in the spring (m)



D.1 (c) Wave height in the summer (m)

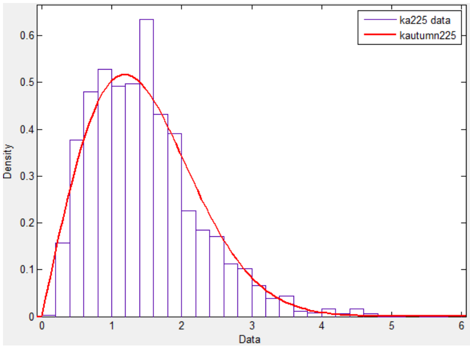


D.1 (d) Wave height in the winter (m)

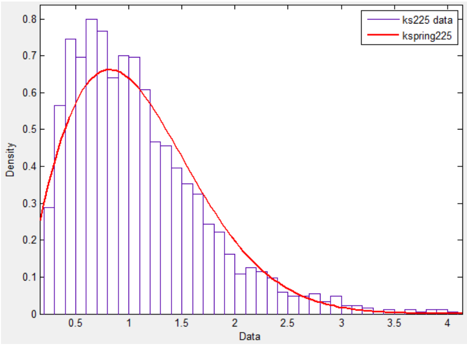


D.1 (e) Wave height annual (m)

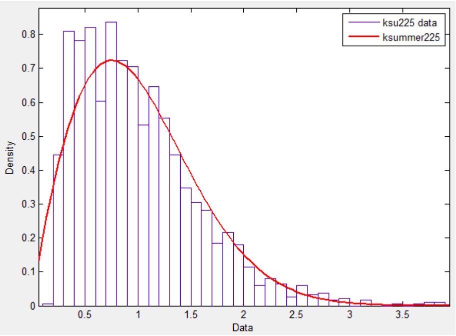
Figures D.2: Location Ijmuiden



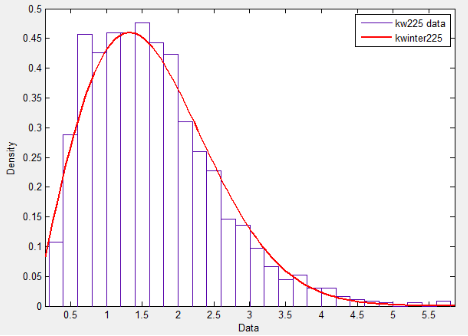
D.2 (a) Wave height in the autumn (m)



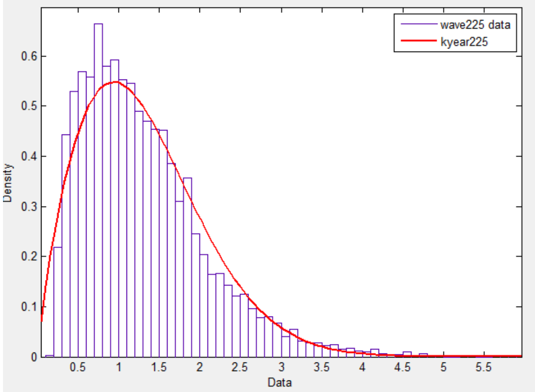
D.2 (b) Wave height in the spring (m)



D.2 (c) Wave height in the summer (m)

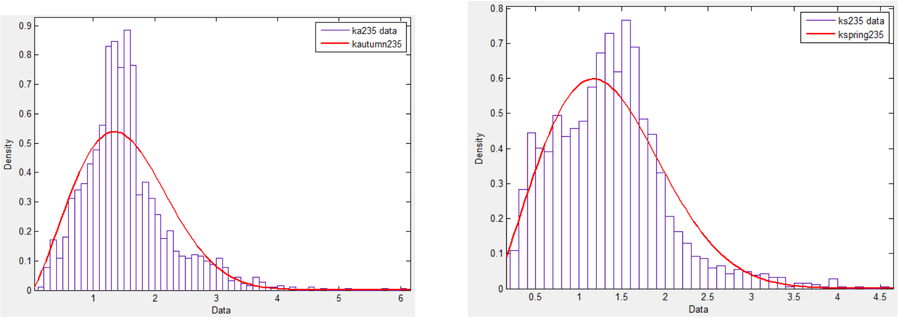


D.2 (d) Wave height in the winter (m)



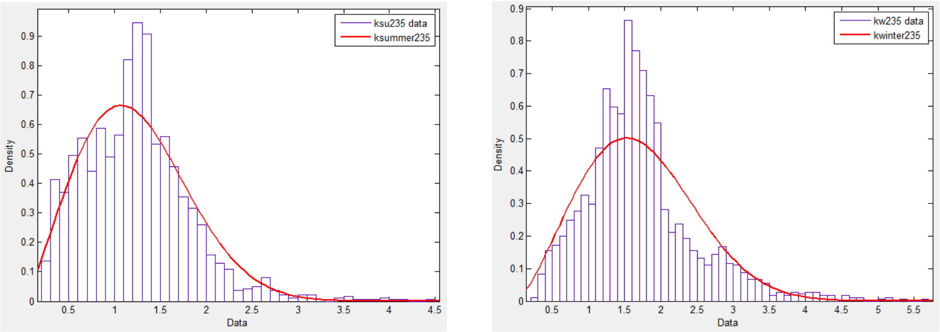
D.2 (e) Wave height annual (m)

Figures D.3: Euro platform



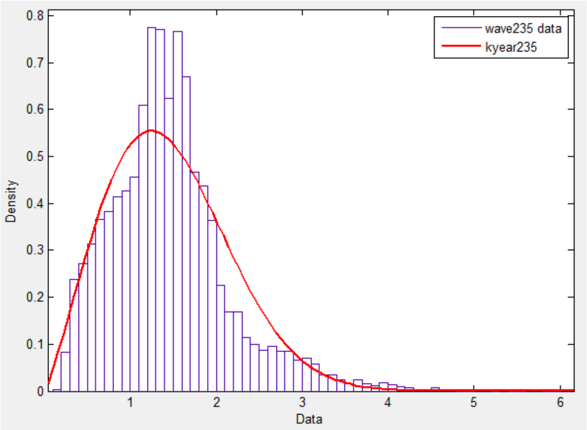
D.3 (a) Wave height in the autumn (m)

D.3 (b) Wave height in the spring (m)



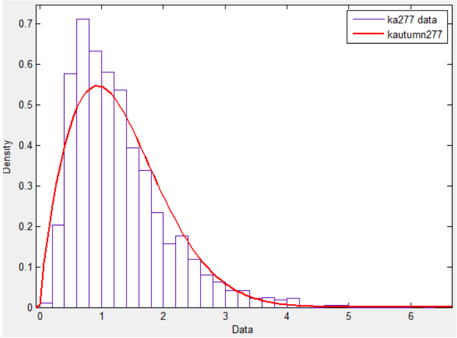
D.3 (c) Wave height in the summer (m)

D.3 (d) Wave height in the winter (m)

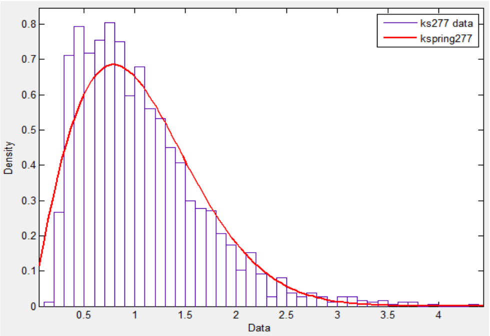


D.3 (e) Wave height annual (m)

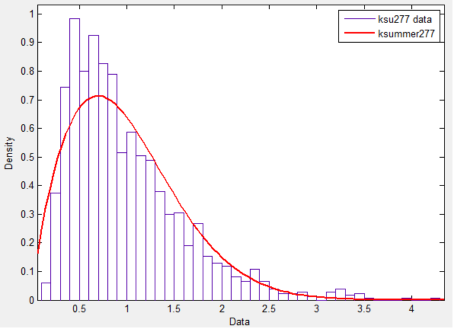
Figures D4: Wadden Schiermonnikoog



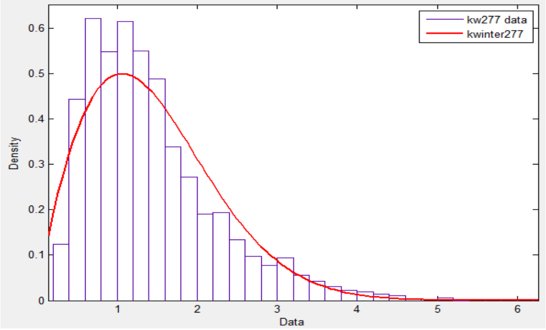
D.4 (a) Wave height in the autumn (m)



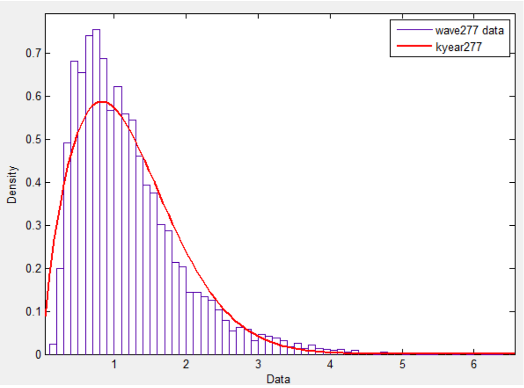
D.4 (b) Wave height in the spring (m)



D.4 (c) Wave height in the spring (m)



D.4 (d) Wave height in the winter (m)



D.4 (e) Wave height annual (m)

Appendix E- Results of the proposed model per location

E.1 Location 1 (Ijmuiden (225)- Ij-geul munitiestortplaats 1)

The below figures show the results of the model run for Location 1 on for the 3 different options, with and without the weather constraint.

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % with weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 with weather restriction	L-L-L-L	€ 42,711	€ 118,855	€ 21,888	€ 15,123	€ 5,000	€ 700	64%	98.79%	8,754
option 2			€ 43,639	€ 134,981	€ 21,888	€ 16,050	€ 5,000	€ 700	68%	98.79%	8,757
option 3			€ 45,409	€ 90,907	€ 21,888	€ 17,821	€ 5,000	€ 700	50%	98.79%	8,713
Option 1	Scenario 2 with weather restriction	H-H-H-H	€ 58,827	€ 165,360	€ 31,449	€ 21,578	€ 5,000	€ 800	64%	98.30%	21,319
option 2			€ 58,315	€ 158,470	€ 31,449	€ 21,165	€ 5,000	€ 700	63%	98.25%	21,356
option 3			€ 62,262	€ 138,674	€ 31,449	€ 25,013	€ 5,000	€ 600	55%	98.25%	21,352
Option 1	Scenario 3 with weather restriction	H-M-L-M	€ 105,043	€ 202,806	€ 54,770	€ 44,573	€ 5,000	€ 700	48%	98.03%	15,406
option 2			€ 106,812	€ 193,518	€ 54,770	€ 46,642	€ 5,000	€ 400	45%	98.03%	15,401
option 3			€ 113,031	€ 208,422	€ 31,449	€ 52,561	€ 5,000	€ 700	46%	98.03%	15,413
Option 1	Scenario 4 with weather restriction	L-L-H-H	€ 83,860	€ 105,792	€ 42,627	€ 35,533	€ 5,000	€ 700	21%	98.68%	13,464
option 2			€ 88,181	€ 188,424	€ 42,627	€ 39,854	€ 5,000	€ 700	53%	98.68%	13,543
option 3			€ 103,950	€ 136,709	€ 42,627	€ 34,483	€ 5,000	€ 700	24%	98.68%	13,434

Table E.1.1: Summary of maintenance costs, for Location 1, 5WT, for 4 different scenarios, with weather restriction

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % without weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 without weather restriction	L-L-L-L	€ 99,406	€ 183,485	€ 69,150	€ 24,556	€ 5,000	€ 700	46%	99.07%	8,767
option 2			€ 100,658	€ 209,413	€ 69,150	€ 25,808	€ 5,000	€ 700	52%	99.07%	8,768
option 3			€ 103,118	€ 270,602	€ 69,150	€ 23,174	€ 5,000	€ 700	62%	99.07%	8,714
Option 1	Scenario 2 without weather restriction	H-H-H-H	€ 204,903	€ 229,819	€ 110,421	€ 88,882	€ 5,000	€ 600	11%	98.96%	21,422
option 2			€ 206,143	€ 216,183	€ 110,421	€ 88,536	€ 5,000	€ 800	5%	99.07%	21,522
option 3			€ 209,130	€ 214,472	€ 110,421	€ 93,108	€ 5,000	€ 600	2%	98.96%	21,512
Option 1	Scenario 3 without weather restriction	H-M-L-M	€ 101,201	€ 155,132	€ 60,162	€ 35,639	€ 5,000	€ 400	35%	99.12%	15,766
option 2			€ 99,372	€ 140,928	€ 60,162	€ 34,010	€ 5,000	€ 200	29%	98.96%	15,778
option 3			€ 108,265	€ 183,675	€ 60,162	€ 33,924	€ 5,000	€ 400	41%	98.96%	15,804
Option 1	Scenario 4 without weather restriction	L-L-H-H	€ 143,221	€ 252,563	€ 96,918	€ 40,603	€ 5,000	€ 700	43%	99.18%	13,543
option 2			€ 144,155	€ 243,441	€ 96,918	€ 41,537	€ 5,000	€ 700	41%	99.18%	13,496
option 3			€ 161,677	€ 175,761	€ 96,918	€ 59,059	€ 5,000	€ 700	8%	99.18%	13,543

Table E.1.2: Summary of maintenance costs, for Location 1, 5WT, for 4 different scenarios, without weather restriction

E.2 Location 2 (Lauwersoog (277)- Wadden Schiermonnikoog)

The below figures show the results of the model run for Location 2 on for the 3 different options, with and without the weather constraint.

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % with weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 with weather restriction	L-L-L-L	€ 17,062	€ 42,179	€ 6,215	€ 5,247	€ 5,000	€ 600	60%	98.90%	2,461
option 2			€ 17,714	€ 48,645	€ 6,215	€ 5,899	€ 5,000	€ 600	64%	98.90%	2,453
option 3			€ 20,198	€ 44,993	€ 6,215	€ 8,384	€ 5,000	€ 600	55%	98.90%	2,460
Option 1	Scenario 2 with weather restriction	H-H-H-H	€ 34,486	€ 68,185	€ 14,828	€ 13,959	€ 5,000	€ 500	49%	98.74%	6,383
option 2			€ 34,648	€ 67,096	€ 14,828	€ 14,120	€ 5,000	€ 700	48%	98.74%	6,390
option 3			€ 44,855	€ 58,378	€ 14,828	€ 24,328	€ 5,000	€ 700	23%	98.74%	6,399
Option 1	Scenario 3 with weather restriction	H-M-L-M	€ 27,625	€ 70,433	€ 11,572	€ 10,452	€ 5,000	€ 600	61%	98.85%	4,749
option 2			€ 27,854	€ 52,929	€ 11,572	€ 10,882	€ 5,000	€ 400	47%	98.68%	4,747
option 3			€ 30,808	€ 55,129	€ 11,572	€ 13,636	€ 5,000	€ 600	44%	98.79%	4,729
Option 1	Scenario 4 with weather restriction	L-L-H-H	€ 33,027	€ 52,784	€ 16,478	€ 10,501	€ 5,000	€ 600	37%	98.90%	3,323
option 2			€ 32,379	€ 65,080	€ 16,478	€ 10,501	€ 5,000	€ 400	50%	98.79%	3,316
option 3			€ 36,774	€ 56,900	€ 16,478	€ 14,696	€ 5,000	€ 600	35%	98.85%	3,315

Table E.2.1: Summary of maintenance costs, for Location 2, 5WT, for 4 different scenarios, with weather restriction

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % without weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 without weather restriction	L-L-L-L	€ 29,443	€ 57,540	€ 13,047	€ 10,496	€ 5,000	€ 900	49%	99.17%	2,481
option 2			€ 28,681	€ 45,959	€ 13,047	€ 9,734	€ 5,000	€ 900	38%	99.12%	2,466
option 3			€ 30,756	€ 42,064	€ 13,047	€ 11,809	€ 5,000	€ 900	27%	99.18%	2,477
Option 1	Scenario 2 without weather restriction	H-H-H-H	€ 76,700	€ 82,568	€ 41,534	€ 29,765	€ 5,000	€ 400	7%	99.12%	6,483
option 2			€ 75,380	€ 89,368	€ 41,534	€ 28,445	€ 5,000	€ 400	16%	99.07%	6,454
option 3			€ 75,273	€ 90,564	€ 41,534	€ 23,701	€ 5,000	€ 400	17%	99.01%	6,459
Option 1	Scenario 3 without weather restriction	H-M-L-M	€ 63,140	€ 78,274	€ 33,839	€ 23,701	€ 5,000	€ 600	19%	99.12%	4,804
option 2			€ 63,778	€ 78,965	€ 33,839	€ 24,439	€ 5,000	€ 500	19%	99.07%	4,804
option 3			€ 66,068	€ 95,258	€ 33,839	€ 26,629	€ 5,000	€ 600	31%	99.12%	4,792
Option 1	Scenario 4 without weather restriction	L-L-H-H	€ 42,198	€ 76,601	€ 17,924	€ 18,674	€ 5,000	€ 600	45%	99.12%	3,366
option 2			€ 42,405	€ 83,106	€ 17,924	€ 18,881	€ 5,000	€ 600	49%	99.12%	3,364
option 3			€ 42,878	€ 79,952	€ 17,924	€ 19,354	€ 5,000	€ 600	46%	99.12%	3,361

Table E.2.2: Summary of maintenance costs, for Location 2, 5WT, for 4 different scenarios, without weather restriction

E.3 Location 3 (Valkenburg (210)-Europlatform)

The below figures show the results of the model run for Location 3 on for the 3 different options, with and without the weather constraint.

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % with weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 with weather restriction	L-L-L-L	€ 36,710	€ 48,993	€ 18,358	€ 19,729	€ 5,000	€ 700	25%	99.12%	2,459
option 2			€ 35,871	€ 75,191	€ 18,358	€ 11,912	€ 5,000	€ 600	52%	99.07%	2,453
option 3			€ 40,942	€ 53,598	€ 18,358	€ 16,884	€ 5,000	€ 700	24%	99.07%	2,449
Option 1	Scenario 2 with weather restriction	H-H-H-H	€ 57,568	€ 106,320	€ 31,539	€ 20,529	€ 5,000	€ 500	46%	98.90%	8,405
option 2			€ 55,253	€ 88,184	€ 31,539	€ 18,415	€ 5,000	€ 300	37%	98.79%	8,391
option 3			€ 59,625	€ 78,576	€ 31,539	€ 22,586	€ 5,000	€ 500	24%	98.85%	8,398
Option 1	Scenario 3 with weather restriction	H-M-L-M	€ 51,096	€ 70,737	€ 35,206	€ 10,390	€ 5,000	€ 500	28%	98.79%	5,869
option 2			€ 51,297	€ 115,246	€ 35,206	€ 10,591	€ 5,000	€ 500	55%	98.79%	5,909
option 3			€ 61,757	€ 97,934	€ 35,206	€ 21,051	€ 5,000	€ 500	37%	98.79%	5,968
Option 1	Scenario 4 with weather restriction	L-L-H-H	€ 46,563	€ 94,769	€ 27,780	€ 13,083	€ 5,000	€ 700	51%	99.12%	4,221
option 2			€ 47,126	€ 82,453	€ 27,780	€ 13,646	€ 5,000	€ 700	43%	99.12%	4,218
option 3			€ 59,174	€ 79,778	€ 35,206	€ 25,694	€ 5,000	€ 700	26%	99.12%	4,220

Table E.3.1: Summary of maintenance costs, for Location 3, 5WT, for 4 different scenarios, with weather restriction

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % without weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 without weather restriction	L-L-L-L	€ 33,344	€ 59,342	€ 18,259	€ 9,585	€ 5,000	€ 500	44%	99.01%	2,453
option 2			€ 33,348	€ 51,834	€ 18,259	€ 9,589	€ 5,000	€ 500	36%	99.01%	2,449
option 3			€ 37,546	€ 58,290	€ 18,259	€ 13,787	€ 5,000	€ 500	36%	99.01%	2,446
Option 1	Scenario 2 without weather restriction	H-H-H-H	€ 80,201	€ 130,840	€ 41,958	€ 31,944	€ 5,000	€ 1,300	39%	99.12%	8,373
option 2			€ 80,847	€ 134,055	€ 41,958	€ 32,690	€ 5,000	€ 1,200	40%	99.07%	8,366
option 3			€ 84,041	€ 132,606	€ 41,958	€ 35,783	€ 5,000	€ 1,300	37%	99.07%	8,368
Option 1	Scenario 3 without weather restriction	H-M-L-M	€ 29,139	€ 48,449	€ 15,033	€ 8,506	€ 5,000	€ 600	40%	99.07%	5,936
option 2			€ 29,295	€ 67,100	€ 15,033	€ 8,862	€ 5,000	€ 600	56%	98.96%	6,004
option 3			€ 38,848	€ 74,721	€ 15,033	€ 18,215	€ 5,000	€ 600	48%	98.79%	6,004
Option 1	Scenario 4 without weather restriction	L-L-H-H	€ 32,277	€ 60,800	€ 14,171	€ 12,506	€ 5,000	€ 600	47%	99.07%	4,231
option 2			€ 32,511	€ 68,053	€ 14,171	€ 12,740	€ 5,000	€ 600	52%	99.01%	4,228
option 3			€ 48,337	€ 68,644	€ 14,171	€ 28,566	€ 5,000	€ 600	30%	99.07%	4,230

Table E.3.2: Summary of maintenance costs, for Location 3, 5WT, for 4 different scenarios, without weather restriction

E.4 Location 4 (De Kooy (235) –K13 Alpha 3)

The below figures show the results of the model run for Location 3 on for the 3 different options, with and without the weather constraint.

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % with weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 with weather restriction	L-L-L-L	€ 35,846	€ 100,313	€ 15,066	€ 14,780	€ 5,000	€ 1,000	64%	99.12%	4,269
option 2			€ 32,726	€ 79,337	€ 15,066	€ 11,660	€ 5,000	€ 1,000	59%	99.01%	4,269
option 3			€ 39,145	€ 96,123	€ 15,066	€ 18,079	€ 5,000	€ 1,000	59%	99.01%	4,266
Option 1	Scenario 2 with weather restriction	H-H-H-H	€ 43,297	€ 109,316	€ 20,005	€ 17,592	€ 5,000	€ 700	60%	98.79%	10,299
option 2			€ 40,496	€ 111,984	€ 20,005	€ 32,976	€ 5,000	€ 600	64%	98.74%	10,194
option 3			€ 48,147	€ 89,794	€ 20,005	€ 22,443	€ 5,000	€ 700	46%	98.87%	10,202
Option 1	Scenario 3 with weather restriction	H-M-L-M	€ 27,982	€ 81,251	€ 11,573	€ 10,909	€ 5,000	€ 500	66%	99.07%	8,160
option 2			€ 29,248	€ 114,321	€ 11,573	€ 12,175	€ 5,000	€ 500	74%	99.01%	8,155
option 3			€ 44,354	€ 60,008	€ 11,573	€ 27,681	€ 5,000	€ 500	26%	99.01%	8,176
Option 1	Scenario 4 with weather restriction	L-L-H-H	€ 40,085	€ 134,631	€ 22,471	€ 11,914	€ 5,000	€ 700	70%	99.18%	5,987
option 2			€ 39,664	€ 57,845	€ 22,471	€ 11,594	€ 5,000	€ 600	31%	99.12%	5,944
option 3			€ 42,010	€ 67,328	€ 22,471	€ 13,839	€ 5,000	€ 700	38%	99.12%	5,939

Table E.4.1: Summary of maintenance costs, for Location 4, 5WT, for 4 different scenarios, with weather restriction

Option number	Scenario number	Scenario Description (winter-spring-summer-autumn)	Annual OTMC in €	Annual BTMC in €	Annual CM costs in €	Annual Total optimized PM costs in €	Transportation costs in €	Penalty costs in €	Savings in % without weather restriction	Availability in %	Energy Output in MW
Option 1	Scenario 1 without weather restriction	L-L-L-L	€ 41,595	€ 96,020	€ 20,983	€ 35,282	€ 5,000	€ 700	57%	99.12%	4,263
option 2			€ 42,271	€ 97,671	€ 20,983	€ 15,688	€ 5,000	€ 600	57%	99.07%	4,260
option 3			€ 44,995	€ 102,162	€ 20,983	€ 18,312	€ 5,000	€ 700	56%	99.12%	4,261
Option 1	Scenario 2 without weather restriction	H-H-H-H	€ 131,354	€ 186,134	€ 70,317	€ 55,337	€ 5,000	€ 700	29%	99.18%	10,337
option 2			€ 111,271	€ 167,938	€ 70,317	€ 35,354	€ 5,000	€ 600	34%	99.07%	10,218
option 3			€ 137,594	€ 160,044	€ 70,317	€ 61,577	€ 5,000	€ 700	14%	99.12%	10,320
Option 1	Scenario 3 without weather restriction	H-M-L-M	€ 39,437	€ 109,798	€ 20,011	€ 62,866	€ 5,000	€ 600	64%	99.07%	8,153
option 2			€ 40,229	€ 125,386	€ 20,011	€ 14,618	€ 5,000	€ 600	68%	99.07%	8,147
option 3			€ 55,496	€ 97,866	€ 20,011	€ 29,885	€ 5,000	€ 600	43%	99.07%	8,168
Option 1	Scenario 4 without weather restriction	L-L-H-H	€ 32,253	€ 109,773	€ 15,230	€ 11,423	€ 5,000	€ 600	71%	99.12%	5,989
option 2			€ 33,040	€ 63,084	€ 15,230	€ 12,210	€ 5,000	€ 600	48%	99.07%	5,950
option 3			€ 33,813	€ 89,280	€ 15,230	€ 12,982	€ 5,000	€ 600	62%	99.12%	5,968

Table E.4.2: Summary of maintenance costs, for Location 4, 5WT, for 4 different scenarios, without weather restriction

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