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Assessment of wind and wave data measured at IJmuiden Munitiestortplaats

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Acknowledgement

This work has been carried out as part of the ECN project "O&M Cost Estimator" (project nr.: 7.4395), which has been defined within research line 5 (RL5) "Operation and Maintenance" of the consortium We@Sea.

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Summary

As part of the We@Sea project "Operation and Maintenance Cost Estimator" (OMCE) the 3-hour average wave and the 3-hour average wind data published by Rijkswaterstaat for the location "IJmuiden Munitiestortplaats" in the following denoted as YM6 have been analysed. Data measured over the period January 1990 - December 2001 have been considered. The co-ordinates of YM6 are 52º33'00" east and 4º03'30" north, and the water depth is 21 m. Besides the results over a period of 12 years also the four yearly seasons are considered separately, where these seasons are defined as follows:

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

To calculate the revenue losses due to downtime the capacity factor of the wind turbine has to be determined. For this purpose the wind speed distribution at YM6 is described by a 2-parameter Weibull distribution. Generally this Weibull distribution is based on 10-minute average wind speed data. However, 3-hour average data are available only so that the Weibull parameters of the wind speed distribution are based on these 3-hour average data. Although the parameters presented here are less accurate, they are still suitable to estimate the capacity factors and subsequently the revenue losses.

Weibull parameters of average wind speed distribution at YM6

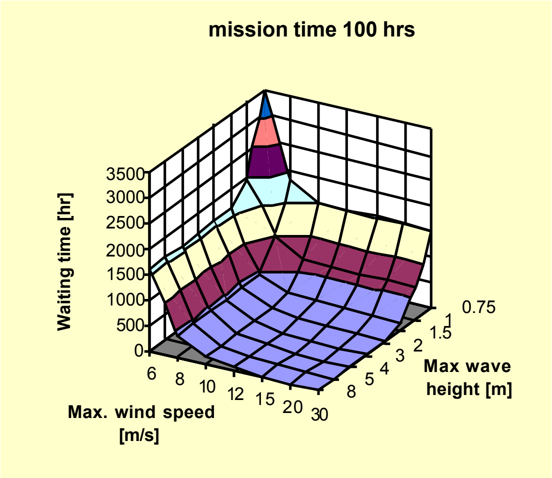
	Winter	**Spring**	**Summer**	**Autumn**	**Year**
shape parameter	2.16	2.27	2.29	2.16	2.16
scale parameter	8.90	7.41	6.98	8.07	7.84
mean wind speed [m/s]	7.88	6.57	6.18	7.15	6.94

The downtime of a wind turbine after a failure or the Time To Repair (TTR) is of importance to estimate different types of costs, f.i. the revenue losses and it appears that especially the waiting time due to bad weather conditions (T_wait) is of great importance for the total downtime. During this period an access system may be available but is not allowed to leave the harbour. The capabilities of an access system are particularly dependent on the weather window in which it can be operated. The weather window of an access system is characterized by the maximum significant wave height $H_{s,max}$ and the maximum wind speed $V_{w,max}$ during which a certain maintenance action can be performed. Besides the weather window the duration is of importance. For the weather windows specified in the table below the waiting time has been calculated as function of the duration of the mission, and the results are presented as 3rd order polynomials. The coefficients of these polynomials are presented in this report.

Overview of weather windows

Weather window number	$H_{s,max}$ [m]	$V_{w,max}$ [m/s]	Weather window number	$H_{s,max}$ [m]	$V_{w,max}$ [m/s]
1	0.75	6	16	2	15
2	0.75	8	17	3	8
3	0.75	10	18	3	10
4	1	6	19	3	12
5	1	8	20	3	15
6	1	10	21	3	20
7	1	12	22	4	12
8	1.5	6	23	4	15
9	1.5	8	24	4	20
10	1.5	10	25	4	30
11	1.5	12	26	5	15
12	2	6	27	5	20
13	2	8	28	5	30
14	2	10	29	8	20
15	2	12	30	8	30

The characteristic behaviour of the waiting time is shown in the figure below, where the waiting time is presented as function of the weather windows considered, viz. as function of the maximum allowable significant wave height and the maximum allowable wind speed.



Waiting time as function of the maximum allowable wave height and the maximum allowable wind speed

Logically the waiting time decreases when the weather windows become less harsh. It appears that this decrease is most significant for wave heights up to 1,5 - 2 m and wind speeds up to 10 - 12 m/s. So using access systems that can operate up to wave heights of 2 m and wind speeds up to 12 m/s will have a strong positive effect on the down time. On the other hand it is questionable whether an investment in access systems that can operate at wave heights above 2 m and at wind speeds above 12 m/s should be made for this location with these conditions. In general the advantage in terms of waiting time is only limited. However depending on the number of times and the duration a device is needed it might be advantageous in specific situations.

1. Introduction

1.1 Operation and Maintenance Cost Estimator

It is well known that the O&M costs of an offshore wind farm contribute to the total exploitation costs significantly [1]. The objective of the We@Sea project "Operation and Maintenance Cost Estimator" (OMCE) is to determine a methodology with which owners and operators of offshore wind farms are able to estimate and to optimise the future O&M costs [2]. This methodology together with monitoring of the wind farm should give owners and operators tools to support the decisions in O&M.

In the planning phase of a project a realistic estimate of the expected yearly O&M costs is made which is used together with other costs drivers for the economic assessment. To support the development of the Cost Estimator a realistic offshore wind farm will be considered and used in a case study. For this wind farm an initial O&M cost estimate will be made. This initial cost estimate must be considered as a reference for the case studies supporting the development of the Cost Estimator. Above all the initial cost estimate is used to make a comparison with the actual O&M costs and is the starting point to quantify the effects of modifications in the O&M strategy. For this purpose the calculation model in MS Excel developed by ECN [3, 4] will be used. This model enables to determine the long-term average effort and costs that are needed to maintain the wind farm and to calculate the associated downtime and revenue losses. The process of a maintenance action is depicted in Figure 1.1 and this process has served as the starting point for the development of the ECN model to calculate the initial costs of maintenance.

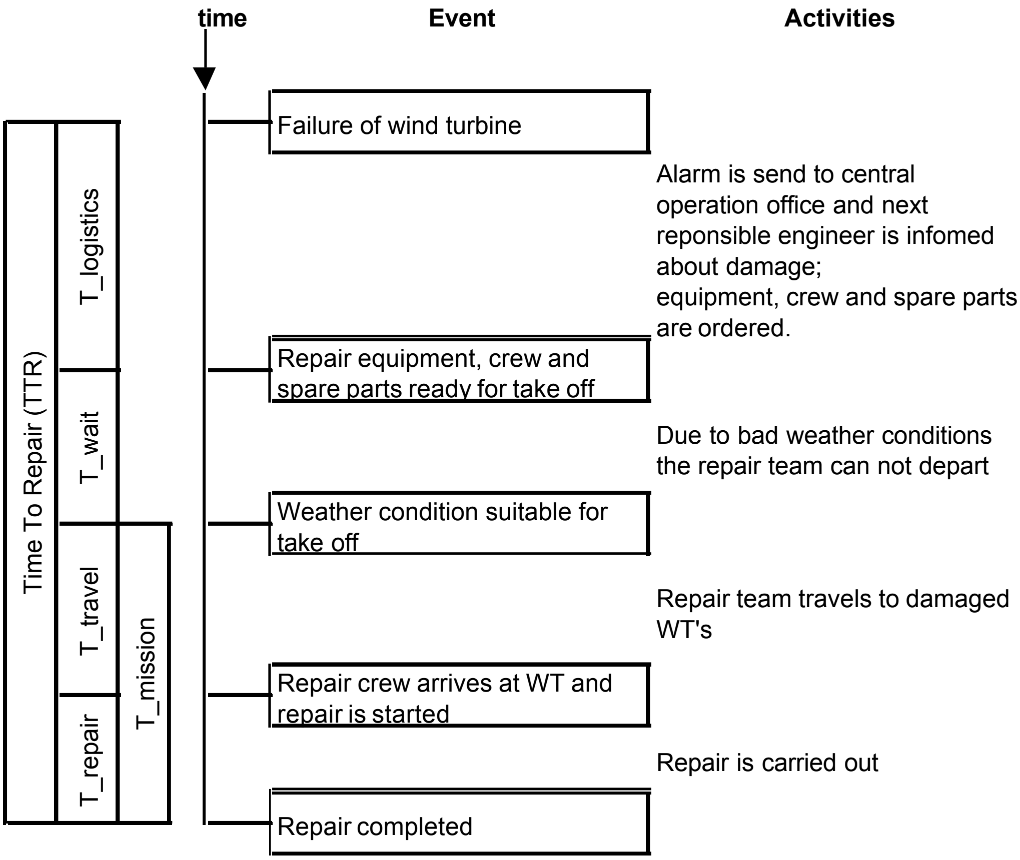


Figure 1.1: *Schematic overview of the repair process [3]*

As can be seen from Figure 1.1 the Time To Repair (TTR) can be split up into four different time intervals. Especially the waiting time due to bad weather conditions (T_wait) is of great importance for the total downtime and a lot of research is ongoing in the development of access system with the aim to reduce T_wait. An access system can be characterized by the weather window during which it can be used and the waiting time for a certain device is dependent on the weather window for that device and the duration of the mission (T_mission).

In the ECN model only the maximal allowable significant wave height and the maximum allowable wind speed are considered, other aspects like fog and ice might be of importance but are not taken into account. To determine the waiting time measured wind and wave data representative for the location of the wind farm have to be considered. To make these wind and wave data applicable for cost modelling the waiting time of a specific system characterised by the maximum allowable wave height and the maximum allowable wind speed has to be specified as a 3rd order polynomial of the mission time. For this purpose first the measured wind and wave measured at a certain location are characterized by means of Weibull distributions, which is described in Chapter 3. Next the waiting time for a specific weather window and the mission time are calculated by means of Monte Carlo simulations based on the previously obtained Weibull distributions, which is described in Chapter 4.

1.2 Climate data

For the development of the Cost Estimator climate data are obtained from the wave and wind data published by Rijkswaterstaat for the location "IJmuiden Munitiestortplaats" [5], in the following denoted as YM6, see Figure 1.2. The co-ordinates of YM6 are 52º33'00" east and 4º03'30" north, and the water depth is 21 m.

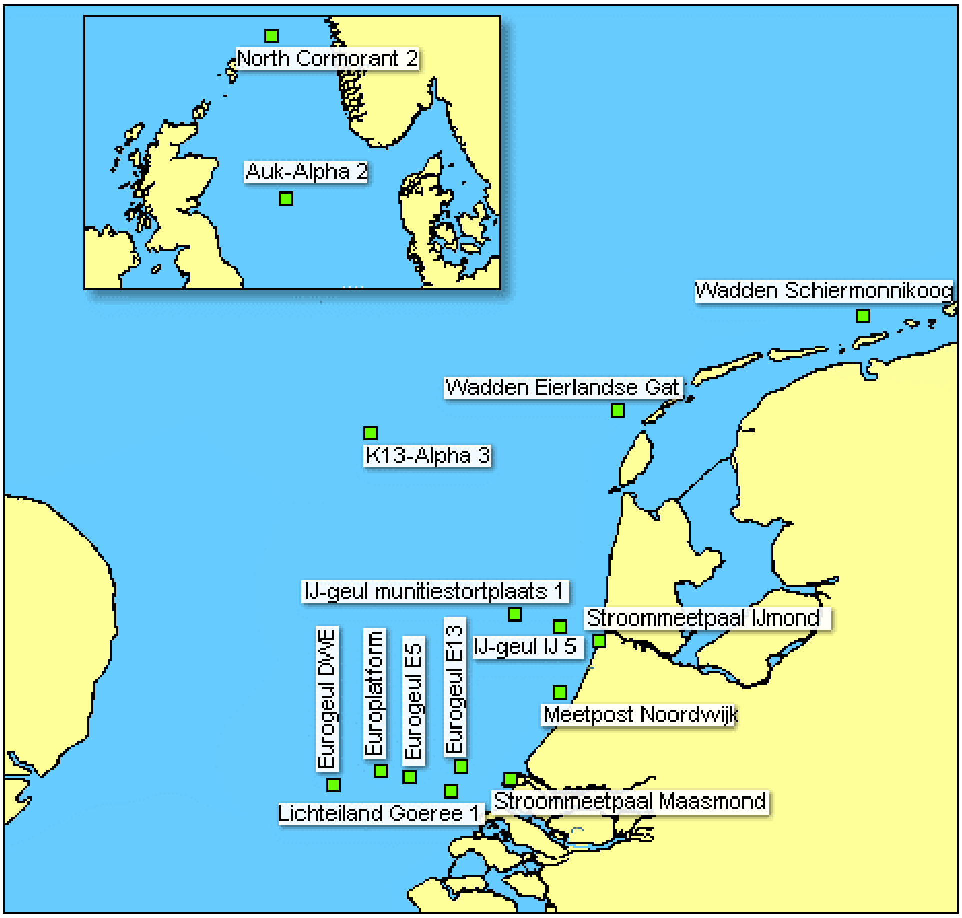


Figure 1.2: *Locations for which Rijkswaterstaat measures wind and wave data.*

These data are available as 3-hour average values and the wind speed V_w and the significant wave height H_s for a period of 12 years (January 1990 - December 2001) have been analysed. The measured data are presented in Chapter 2, where the correlation between the wind and wave data is considered also.

Besides the data over a period of 12 years, the four yearly seasons are considered separately, where these seasons are defined as follows:

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

Next these data have been processed to determine the parameters of the Weibull distributions characterising the weather windows specified in Table 1.1, see Chapter 3 and Annex C.

Table 1.1: *Overview of combinations of maximum wind speed and maximum wave height for which the measured time series of YM6 have been processed, the number denotes the weather window number.*

Maximum wind speed $V_{w,max}$ [m/s]	Maximum significant wave height, $H_{s,max}$ [m]							
	0.75	1	1.5	2	3	4	5	8
6	1	4	8	12				
8	2	5	9	13	17			
10	3	6	10	14	18			
12		7	11	15	19	22		
15				16	20	23	26	
20					21	24	27	29
30						25	28	30

Finally the coefficients of the 3rd order polynomials for the waiting time are calculated (see Annex D). An extended evaluation of the waiting times is presented in Chapter 4.

2. Evaluation of measured wind and wave data

2.1 Wind climate

The 3-hour average wind speed distribution at the location YM6 has been characterized by means of a 2-parameter Weibull distribution. For this purpose the @Risk functionality “Fit Distribution to Data” [6, 7] has been applied to the measured wind data over the period January 1990 up to December 2001. The fit has been made for all data (year) and furthermore the four yearly seasons have been analysed separately. A detailed description of the Weibull distribution is given in Annex A.

The results of the fit procedure are shown in Figure 2.1- Figure 2.5.

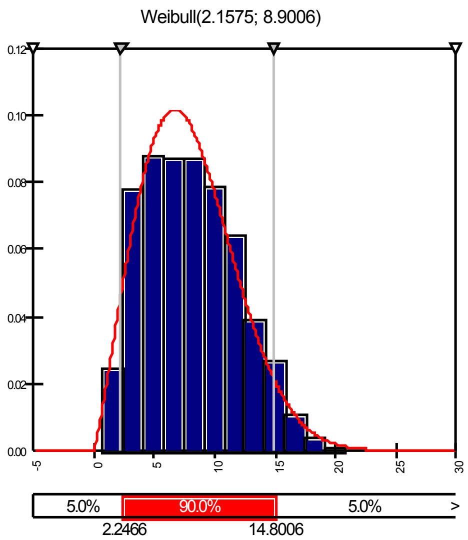


Figure 2.1: *Weibull fit of wind speed distribution in winter*

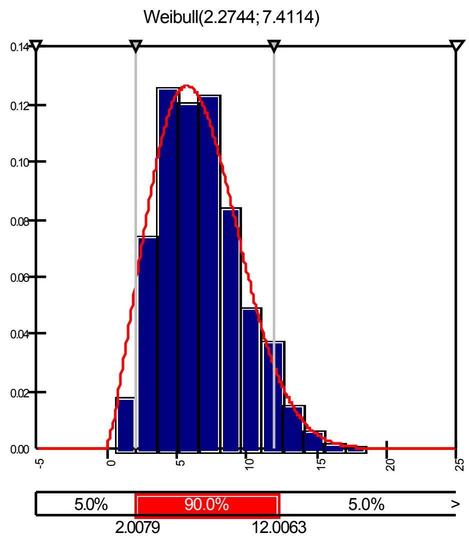


Figure 2.2: *Weibull fit of wind speed distribution in spring*

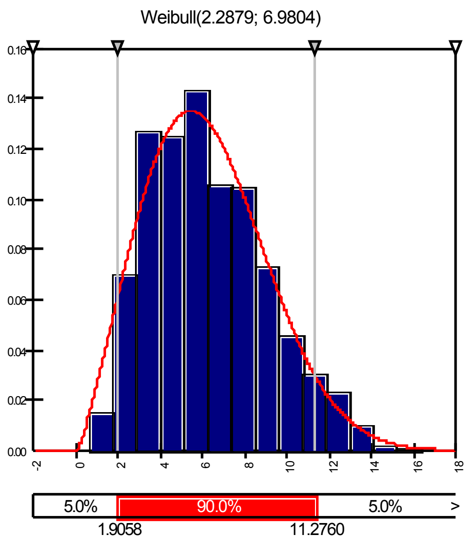


Figure 2.3: *Weibull fit of wind speed distribution in summer*

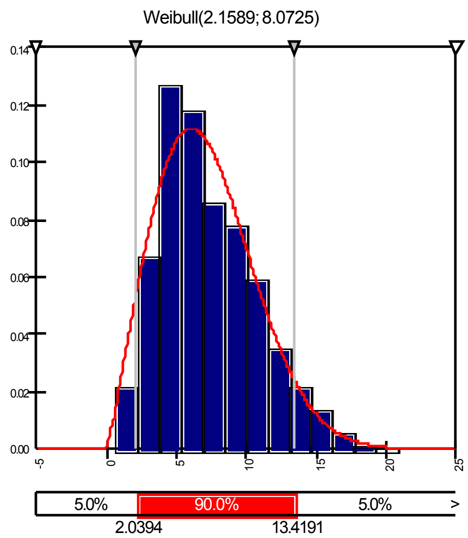


Figure 2.4: *Weibull fit of wind speed distribution in autumn*

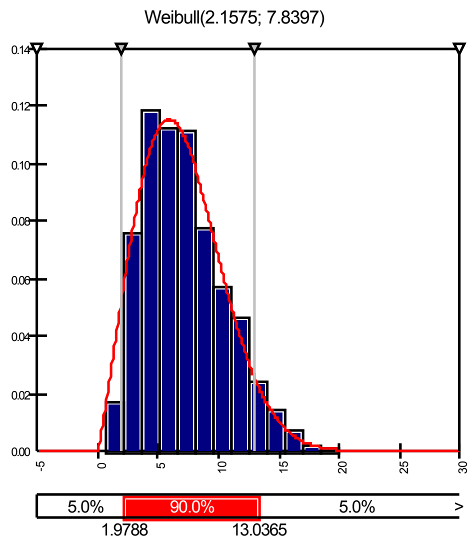


Figure 2.5: *Weibull fit of wind speed distribution over the whole year*

The corresponding cumulative distribution functions are depicted in Figure 2.6 and the calculated Weibull parameters are summarised in Table 2.1. It should be noticed that for an accurate prediction the Weibull parameters should be calculated based on 10-minute mean values. However, only 3-hour data are available for YM6. Although the parameters presented here are less accurate, they are still suitable to determine the capacity factors in the cost model.

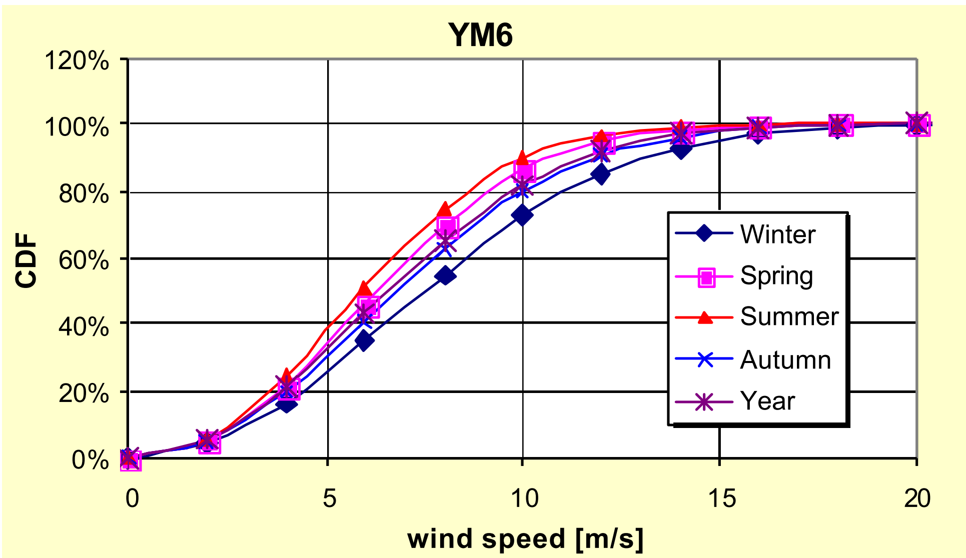


Figure 2.6: *Cumulative distribution functions of the average wind speed distribution at YM6*

Table 2.1: *Weibull parameters of average wind speed distribution at YM6*

	Winter	Spring	Summer	Autumn	Year
shape parameter	2.16	2.27	2.29	2.16	2.16
scale parameter	8.90	7.41	6.98	8.07	7.84
mean wind speed [m/s]	7.88	6.57	6.18	7.15	6.94

2.2 Wave climate

The 3-hour average significant wave height distribution at the location YM6 has been characterised by means of a 2-parameter Weibull distribution too. For this purpose the @Risk functionality “Fit Distribution to Data” [6, 7] has been applied to the measured significant wave height over the period January 1990 up to December 2001. The fit has been made for all data (year) and furthermore the four yearly seasons have been analysed separately. A detailed description of the Weibull distribution is given in Annex A.

The results of the fit procedure are shown in. Figure 2.7 - Figure 2.11

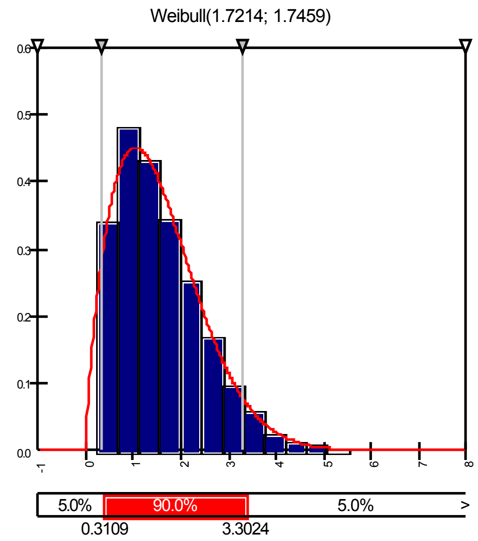


Figure 2.7: *Weibull fit of significant wave height distribution in winter*

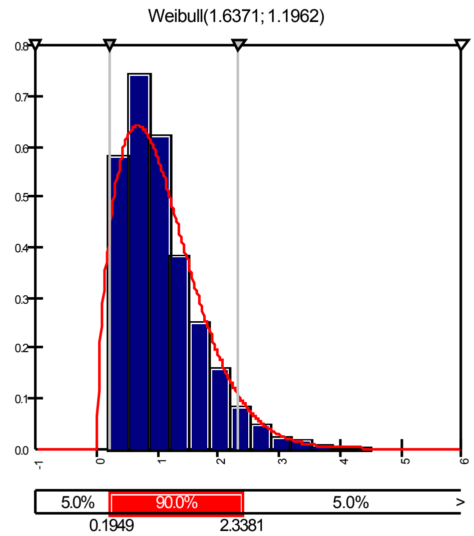


Figure 2.8: *Weibull fit of significant wave height distribution in spring*

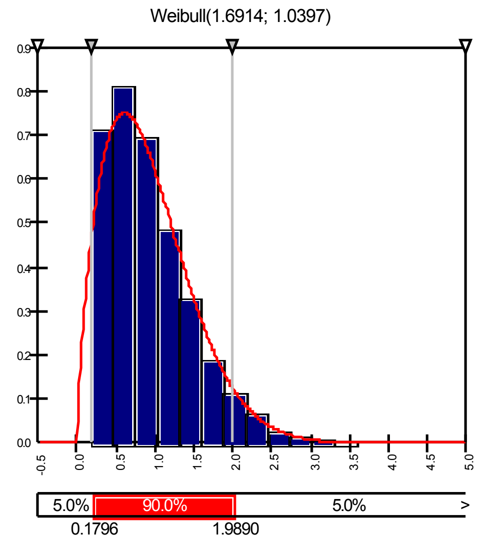


Figure 2.9: *Weibull fit of significant wave height distribution in summer*

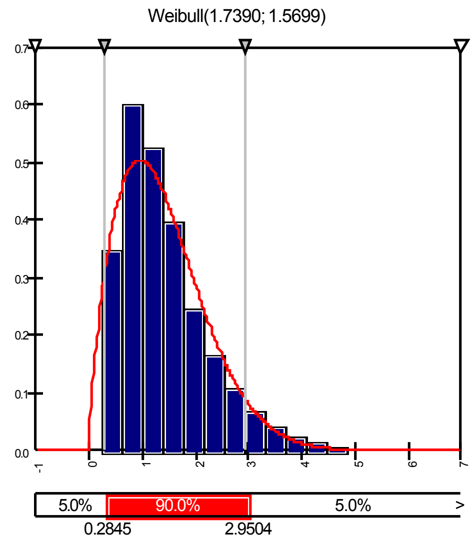


Figure 2.10: *Weibull fit of significant wave height distribution in autumn*

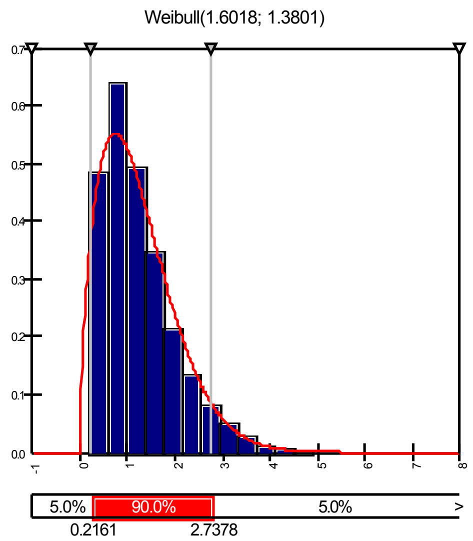


Figure 2.11: *Weibull fit of significant wave height distribution over the whole year*

The corresponding cumulative distribution functions are depicted in Figure 2.12 and the calculated Weibull parameters are summarised in Table 2.2

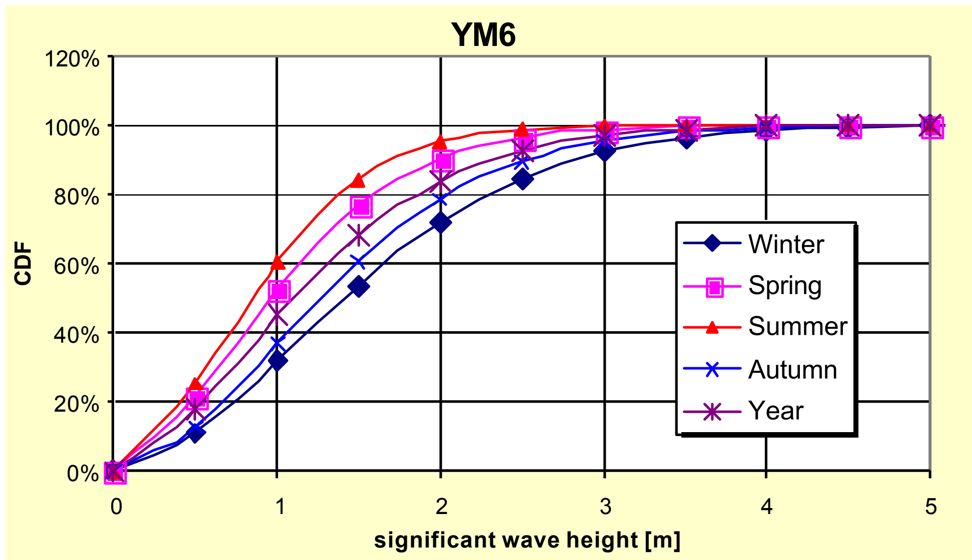


Figure 2.12: *Cumulative distribution functions of the significant wave height distribution at YM6*

Table 2.2: *Weibull parameters of the significant wave height distribution at YM6*

	Winter	Spring	Summer	Autumn	Year
shape	1.72	1.64	1.69	1.74	1.60
scale	1.75	1.20	1.04	1.57	1.38
mean wave height [m]	1.56	1.07	0.93	1.40	1.24

2.3 Combined wind and wave data

The correlation between the 3-hour average wind speed and the 3-hour average significant wave height over the period Jan. 1990 - Dec. 2001 is shown in Figure 2.13. Similar plots are obtained when the four yearly seasons are considered separately. It is clear that the wave height and the wind speed are strongly correlated. In Figure 2.13 two regions can be distinguished; the upper region where the wind speed is relative low and the wave height is relative high and the lower region where the wind speed is relative high and the wave height is relative low. In the upper region the wind speed will be the determinative parameter, while in the lower region it is the wave height. This can be explained as follows. For instance consider a wind speed of 10 m/s. It appears that for wind speeds up to 10 m/s the wave height will be less than 2.5 m with a very high probability. So variations of wave height in the interval greater than approximately 2.5 m will not influence the length of the weather windows. For the lower region it holds that very high wind speeds do not occur simultaneously with low wave heights, hence the wave height is the determinative parameter in this region.

In Annex B the frequency of occurrence of combinations of wind speed and significant wave height are given for the four yearly seasons and the whole year.

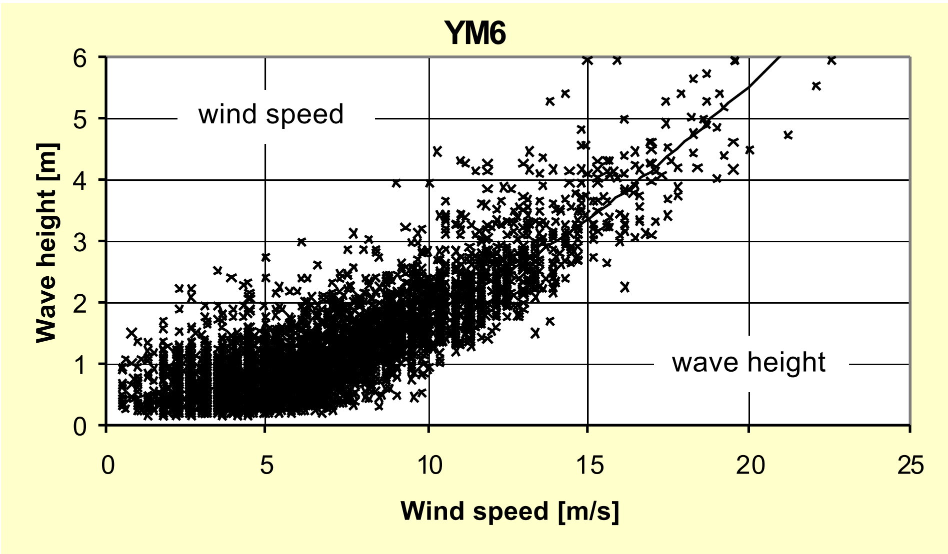


Figure 2.13: *Measured significant wave height as function of the measured wind speed for the period Jan. 1990 - Dec. 2001*

3. Weather Windows

3.1 General description

The maximum significant wave height $H_{s,max}$ and the maximum wind speed $V_{w,max}$ during which a certain maintenance action can be performed are of large influence on the downtime after a failure. If a failure occurs, the repair action can only be initiated if the weather conditions are suitable. If not, the repair has to be postponed. It is not only sufficient that the right weather window occurs, the duration should also be long enough to make sure that the repair can be carried out.

To illustrate this, a small part of a time series for the wind speed V_w and the significant wave height H_s are plotted in Figure 3.1. As an example it is assumed that a repair action can be carried out only if both $H_s \leq 1.5$ m and $V_w \leq 12$ m/s, hence the lines corresponding with $V_{w,max}$ = 12 m/s and $H_{s,max}$ = 1.5 m are drawn too. At the horizontal axis corresponding with the minimum y-value ($V = 0$ m/s) the low time intervals are indicated. During a low time interval $V_w \leq V_{w,max}$ and $H_s \leq H_{s,max}$ and repair is possible provided that the length of the interval is sufficient to complete the mission. At the horizontal axis corresponding with the maximum y-value ($V = 25.0$ m/s) the high time intervals are indicated. During a high time interval $V_w > V_{w,max}$ or $H_s > H_{s,max}$ and it is not allowed for the chosen device to leave the port or to be in operation. From Figure 3.1 it can be seen that if the failure occurs at $t = 0$, it takes approximately 96 hours before a repair action of 40 hours can be carried out. If the duration of the repair is only 20 hours, the waiting time is approximately 56 hours. Since the failure can occur at any point in time, the waiting time until a suitable weather window occurs in fact is a stochastic variable.

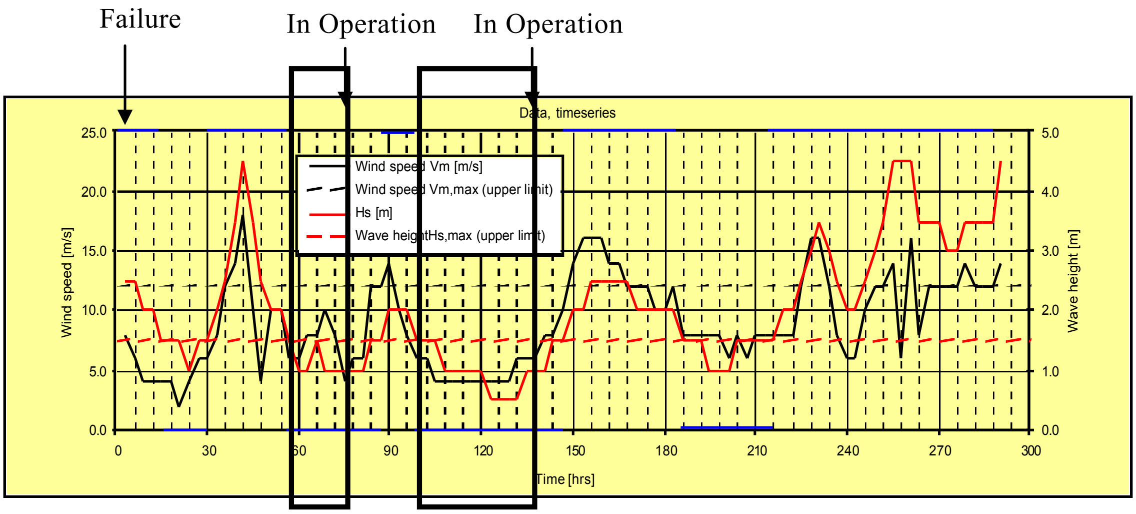


Figure 3.1: *Example of determination of waiting time for a maintenance action that can be carried out if H_s £ 1.5 m and V_w £ 12 m/s and the duration is 20 hrs or 40 hrs*

3.2 Characterisation of weather windows

Due to the stochastic behaviour of the waiting time it is not practical in the cost modelling to work with measured time series because of the amount of data to be handled repeatedly. To characterize long term wind and wave characteristics, data representative for the location of the wind farm should be analysed to search for the following variables:

- number of times that suitable weather windows occur, i.e. H_s and V_w are below the maximum values;
- duration of these suitable weather windows;
- number of times that weather windows occur during which maintenance cannot be carried out;
- duration of these weather windows that in fact determine the waiting time.

The length of the i[th] low interval is indicated by T_i^{low} and covers the time interval starting on $t_{i,1}^{\text{low}}$ and ending on $t_{i,2}^{\text{low}}$. The same definition holds for the high intervals.
The probability that a failure does occur in a low interval or a high interval is now given by

$$P_{\text{low}} = 1 - P_{\text{high}} = \frac{\sum T_i^{\text{low}}}{\sum T_i^{\text{low}} + \sum T_i^{\text{high}}}$$

To determine the first low interval in which a repair may be carried out it is not only of importance whether the interval in which the failure did occur is low or high, but the length of this interval is of importance also just as the length of the subsequent intervals. So the length of the 1st interval has be determined. As failures occur randomly one is interested in the probability that the point of time at which the failure occurs lies in an interval with a certain length. The probability that a failure occurs in a low interval with a certain length is determined by the fraction of the total duration of all low intervals with this length compared to total duration of all low intervals considered. For instance n_k^{low} low intervals with a length of T_k^{low} are found. In case the 1st interval is low the probability that this interval has length T_k^{low} is now

$$\frac{n_k^{\text{low}} \cdot T_k^{\text{low}}}{\sum T_i^{\text{low}}}.$$

The same holds for the high intervals. In this way the statistical distribution function of the length of the intervals can be determined for the low intervals as well as for the high intervals. The corresponding cumulative distribution function (CDF) is denoted by $F_D^{\text{low}}(T)$ for the low intervals and by $F_D^{\text{high}}(T)$ for the high intervals and gives the probability that a certain point in times lies in an interval with a length less than *T*.

The subsequent intervals do occur randomly, so the length is determined by the fraction of the number of intervals with a certain length compared to the total number of low or high intervals. The probability that the length of next low interval equals T_k^{low} is now given by

$$\frac{n_k^{\text{low}}}{\sum n_i^{\text{low}}}.$$

The same holds for the high intervals. In this way the statistical distribution function of the number of the intervals can be determined for the low intervals as well as for the high intervals. This cumulative distribution function (CDF) is denoted by $F_N^{\text{low}}(T)$ for the low intervals and by $F_N^{\text{high}}(T)$ for the high intervals and gives the probability that the length of a randomly chosen interval is less than *T*.

So, to determine P_{low} or P_{high} and the cumulative distribution functions $F_D^{\text{low}}(T)$, $F_D^{\text{high}}(T)$, $F_N^{\text{low}}(T)$ and $F_N^{\text{high}}(T)$ the quantities n_k^{low}, n_k^{high}, T_k^{low} and T_k^{high} have to calculated from the time series of the wind speed and the wave height.

For this purpose the times series of the wind speed and the wave height have to be processed to determine the low and the high intervals and subsequently corresponding cumulative distribution function.

For this purpose the computer program WeWiCDF has been developed at ECN [3]. In this program, which is implemented in an Excel workbook, time series of measured wind and wave data are processed to determine the low and the high intervals given the limit values $V_{\mathrm{w,max}}$ and $H_{\mathrm{s,max}}$. Furthermore these low and high intervals are processed by means of pivot tables to calculate the number of occurrences, finally resulting in tabulated cumulative distribution functions for $F_D^{\mathrm{low}}(T)$, $F_D^{\mathrm{high}}(T)$, $F_N^{\mathrm{low}}(T)$ and $F_N^{\mathrm{high}}(T)$.

The tabulated CDF's are fitted by a Weibull distribution by means of the @Risk function “Fit distribution to data” and the shape parameter and the scale parameter are obtained. Although several statistical functions showed a good agreement it appeared that the Weibull distribution could be used for all data sets (duration and length of intervals for both high and low) [8].

The parameters P_{low} and the parameters for the cumulative distribution functions $F_D^{\mathrm{low}}(T)$, $F_D^{\mathrm{high}}(T)$, $F_N^{\mathrm{low}}(T)$ and $F_N^{\mathrm{high}}(T)$ are calculated taking into account the wind speed and wave height data for all yearly seasons, resulting in yearly parameters. Furthermore the data of four yearly seasons are treated separately resulting in four sets of parameters valid for a certain season.

3.3 Data

The 3 hour mean wind speed and the 3 hour significant wave height published for YM 6 for the period 1991 - 2001 have been processed in the way described above for the combinations of maximum wind speed and maximum wave height listed in Table 1.1.

The calculated Weibull parameters for the weather windows specified in Table 1.1 are given in Annex B.

4. Waiting Time

4.1 Model description

To determine the duration of the waiting phase (T_wait) for a certain mission with length T_mission (see Figure 1.1) the Excel workbook *T_wait* has been developed at ECN [3]. In this workbook a stylistic time series consisting of alternately low and high intervals is constructed. For this purpose an @Risk model has been developed [3] based on P_{low} and on the Weibull distributions of $F_D^{\text{low}}(T)$, $F_D^{\text{high}}(T)$, $F_N^{\text{low}}(T)$, and $F_N^{\text{high}}(T)$, which are described in Chapter 3. The shape and the scale parameters for these Weibull distributions are summarized in Annex C. The construction is done according to the scheme shown in Figure 4.1. To determine whether the first interval is low or high the RiskBinomial function is applied, while the length of the intervals is determined by the @Risk function RiskWeibull together with the appropriate parameters.

The first low interval T_i^{low} with a length greater than T_mission is looked up and the waiting time now equals $t_{i,1}^{\text{low}}$.

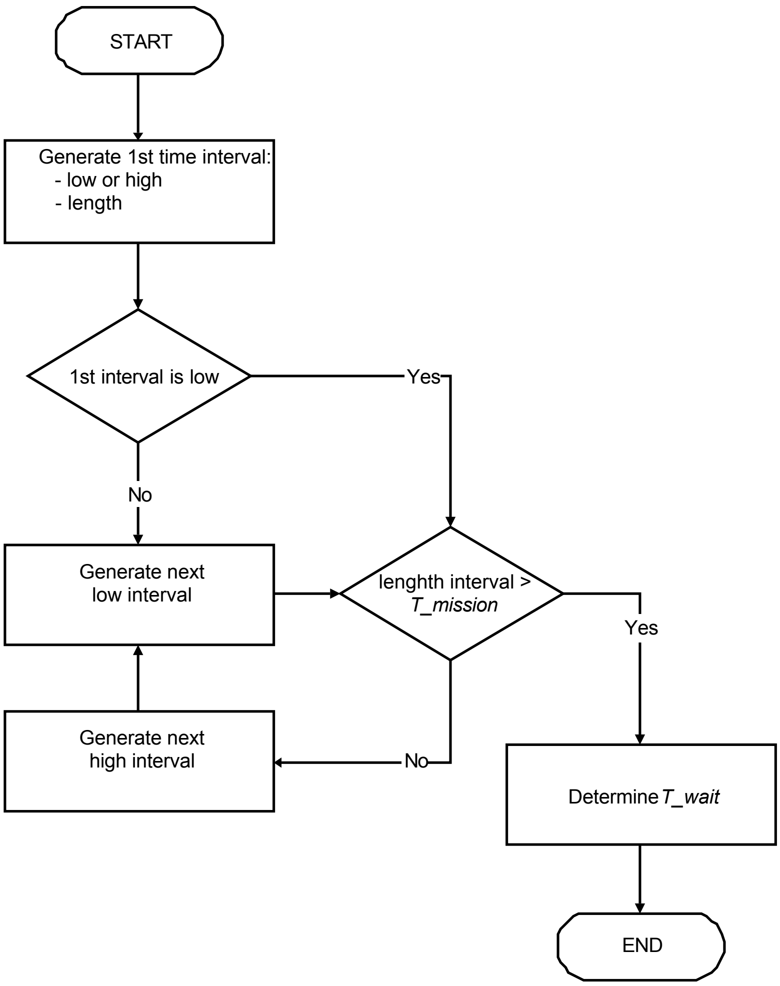


Figure 4.1: *Procedure for generating stylistic time series of alternately low and high intervals.*

As the input for this model is based on stochastic variables the result T_wait will be a stochastic quantity also, and the statistical parameters, like the mean value and the standard deviation of T_wait are of interest. The mean value and the standard deviation of T_wait for a certain value of T_mission are determined by means of Monte Carlo simulation available in @Risk, where the T_Wait is determined by the @Risk function RiskOutput.

After performing analyses for several values of T_mission the resulting mean values and standard deviation can be given as function of T_mission. The mean values and the standard deviation calculated for a certain weather window can now be fitted by a 2nd or 3rd order polynomial, so that the mean value and the standard deviation for a certain weather window are available as a continuous function of the duration of the mission. It is clear that the waiting time will increase when the duration of the mission increases, hence the polynomial fits should be continuously increasing function of the mission time. As an example the waiting time as function of the duration of the mission is shown in Figure 4.2 for a device that is able to operate for wind speeds up to 8 m/s and wave heights up to 1.5 m, where the wind and wave data over the whole year have been considered. Since the waiting time is a stochastic value, the standard deviation, the 5% value and the 95% value are given also. Furthermore the polynomial fitted through the calculated mean values and the calculated standard deviations are shown.

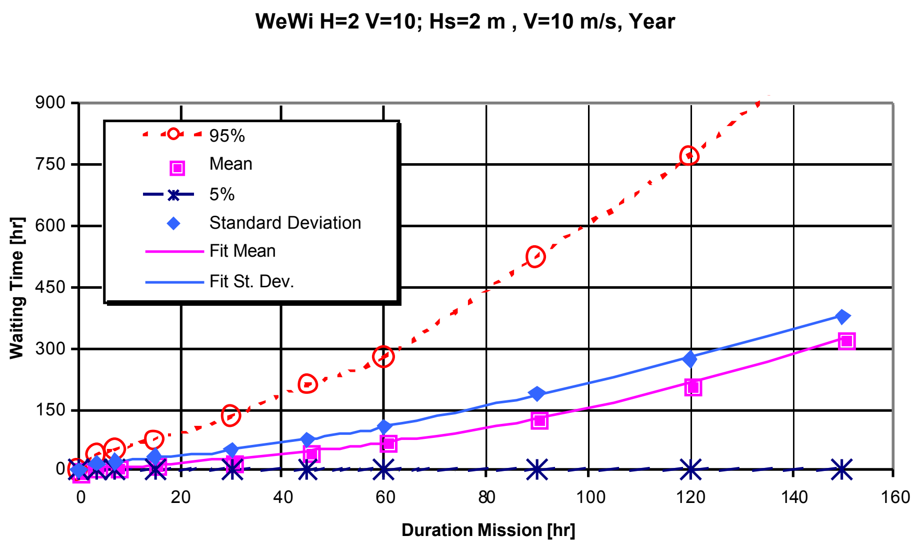


Figure 4.2: *Waiting time as function of the duration of the mission*

4.2 Results

For the combinations of H_s and V_w summarised in Table 1.1 the mean value of the waiting time has been calculated as function of the duration of the mission similar to Figure 4.2 and the results haven been fitted by a polynomial. The coefficient of these polynomials are summarised in Annex D for the four yearly seasons and for the whole year.

To show the characteristics of the waiting time it has been plotted as function of wave height for several different wind speeds in Figure 4.3 and as function of the wind speed for different values of the wave height in Figure 4.4. In both figures the duration of the mission is assumed to be 10 hours. These figure are based on the wind and wave data of the whole year for the period Jan. 1990 - Dec. 2001. The same results are presented in Figure 4.5 where the waiting time is given in a 3D plot as function of both the wind speed and the wave height. Besides a mission with duration of 10 hours missions with a duration of 25, 50 and 100 hours are depicted also. Similar results are obtained when the data for a specific yearly season is considered. In Figure 4.6 the influence of the seasons is shown

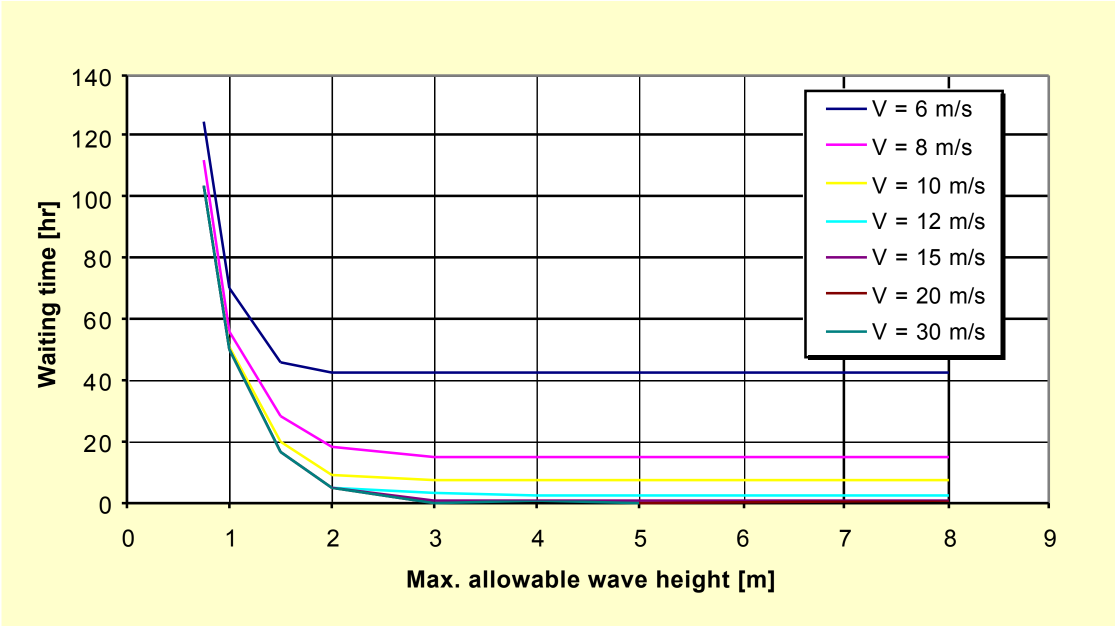


Figure 4.3: *Waiting time as function of the maximum allowable wave height for several values of the maximum allowable wind speed; duration of the mission is 10 hours, wind and wave data of the whole year*

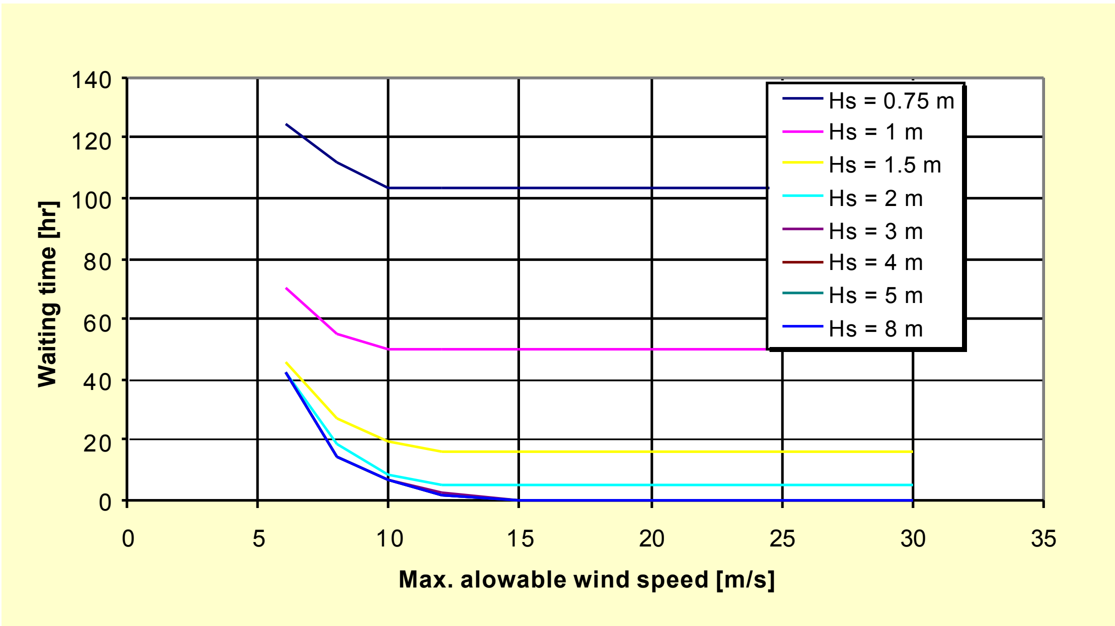


Figure 4.4: *Waiting time as function of the maximum allowable wind speed for several values of the maximum allowable wave height; duration of the mission is 10 hour, wind and wave data of the whole year*

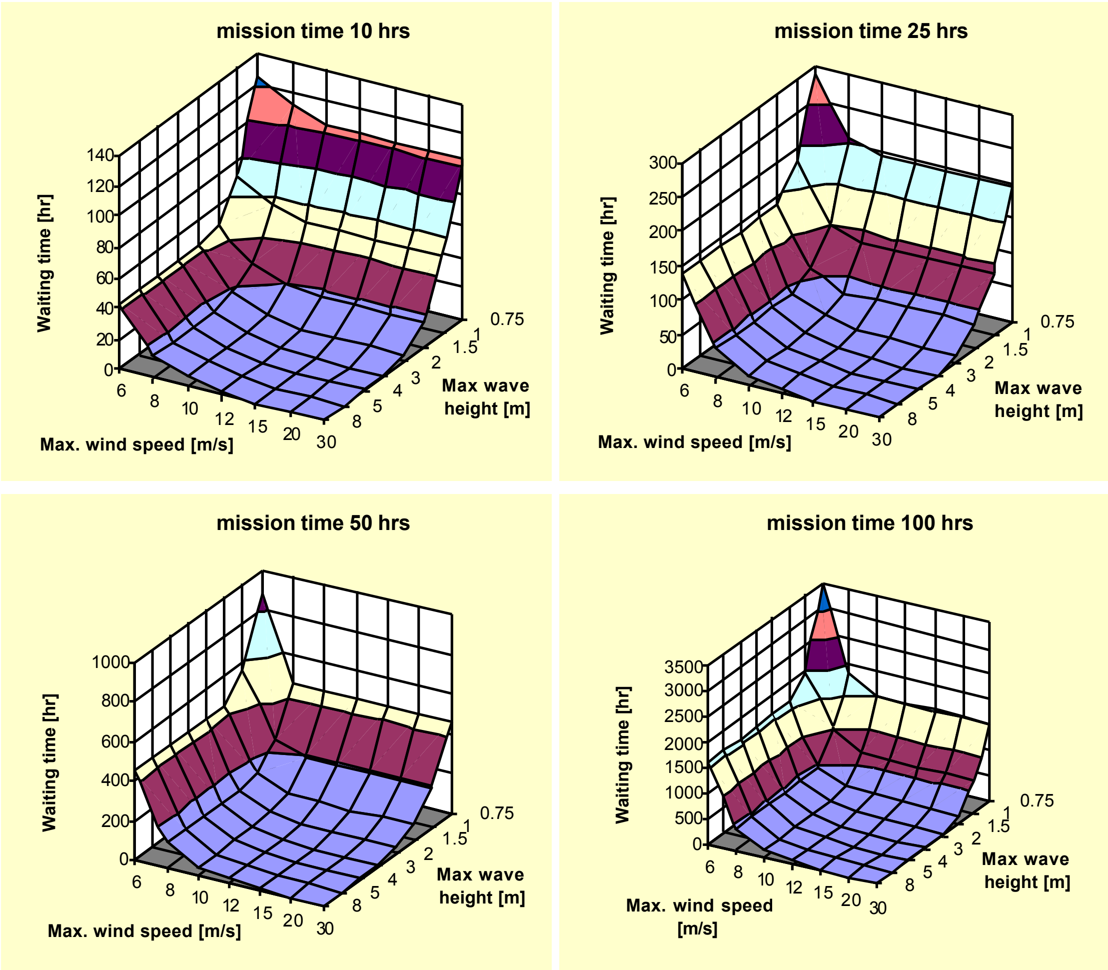


Figure 4.5: *Waiting time as function of the maximum allowable wave height and the maximum allowable wind speed for several values of the duration of the mission; wind and wave data of the whole year*

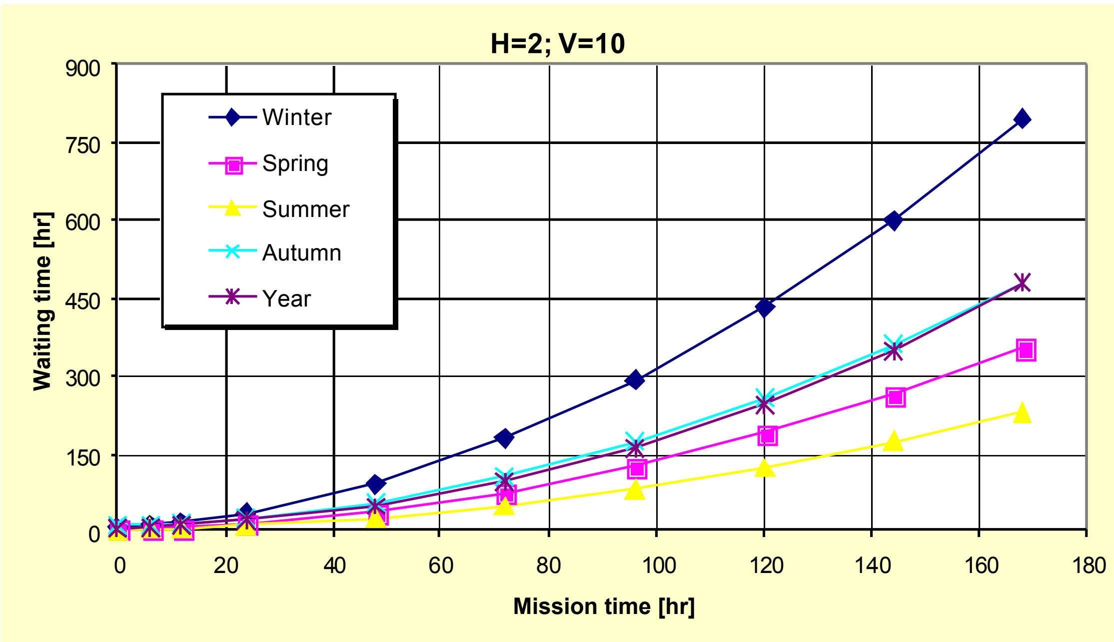


Figure 4.6: *Influence of the season on the waiting time*; *(Hs = 2 m; Vw = 10 m/s)*

As expected the waiting time decreases when the weather windows become less harsh. This decrease is most significant for wave heights up to 1,5 - 2 m and wind speeds up to 10 - 12 m/s. So using access systems that can operate up to wave heights of 2 m and wind speeds up to 12 m/s will have a strong positive effect on the waiting time. Investment in access system that can operate at wave heights above 2 m and at wind speeds above 12 m/s should be considered very careful for this location. In general the advantage in terms of waiting time is only limited. However depending on the number of times and the duration a device is needed it might be advantageous in specific situations.

5. Conclusions

After a failure, an offshore wind turbine may be out of operation for a significant period because it can not be accessed due to bad weather conditions. To be able to estimate this downtime the offshore weather conditions at the location of the wind farm have to be analysed. In this report the 3-hour average wind and wave data measured by Rijkswaterstaat for the location Munitiestortplaats IJmuiden (YM6) over the period January 1990 - December 2001 have been analysed.

To calculate the revenue losses due to downtime the capacity factor of the wind turbine has to be determined. For this purpose the wind speed distribution at YM6 is described by a 2-parameter Weibull distribution. Generally this Weibull distribution is based on 10-minute average wind speed data. However, 3-hour average data are available only so that the Weibull parameters of the wind speed distribution are based on these 3-hour average data. Besides the data over a period of 12 years also the four yearly seasons are considered separately.

The capabilities of an access system are particularly dependent on the weather window in which it can be operated. The weather window of an access system is characterized by the maximum significant wave height $H_{s,max}$ and the maximum wind speed $V_{w,max}$ during which a certain maintenance action can be performed. For a number of different weather windows the waiting time due to bad weather conditions has been calculated and logically the waiting time decreases when the weather windows become less harsh. It appears that this decrease is most significant for wave heights up to 1,5 - 2 m and wind speeds up to 10 - 12 m/s. So using access systems that can operate up to wave heights of 2 m and wind speeds up to 12 m/s will have a strong positive effect on the down time for this location. On the other hand it is questionable whether an investment in access system that can operate at wave heights above 2 m and at wind speeds above 12 m/s should be made for this location. In general the advantage in terms of waiting time is only limited. However depending on the number of times and the duration a device is needed it might be advantageous in specific situations.

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Annex A: Weibull distribution

The cumulative distribution function (CDF) of the Weibull distribution is defined as

$$F_X(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \quad , x > 0 \qquad \text{(A.1)}$$

where:

α : shape parameter (α > 0);
β : scale parameter (β > 0).

The mean value reads

$$\mu = \frac{\beta}{\alpha}\Gamma\left(\frac{1}{\alpha}\right) \qquad \text{(A.2)}$$

and the standard deviation reads

$$\sigma = \sqrt{\frac{\beta^2}{\alpha}\left[2\Gamma\left(\frac{2}{\alpha}\right) - \frac{1}{\alpha}\Gamma^2\left(\frac{1}{\alpha}\right)\right]} \qquad \text{(A.3)}$$

where Γ is the gamma function defined by

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt \qquad \text{(A.4)}$$

Integration by parts gives the important functional relation of the gamma function

$$\Gamma(x+1) = x\Gamma(x) \qquad \text{(A.5)}$$

Given the mean value and the standard deviation the Weibull parameters can be calculated as follows. From Eq. (A.2) and (A.3) it can be deduced that

$$\left(\frac{\sigma}{\mu}\right)^2 = \frac{\frac{2}{\alpha}\Gamma\left(\frac{2}{\alpha}\right)}{\left(\frac{1}{\alpha}\right)^2\Gamma^2\left(\frac{1}{\alpha}\right)} \qquad \text{(A.6)}$$

which gives the value for the shape parameter. Next the scale parameter is calculated with Eq. (A.2)

$$\beta = \frac{\mu}{\frac{1}{\alpha}\Gamma\left(\frac{1}{\alpha}\right)} \qquad \text{(A.7)}$$

Annex B: Correlation of wind speed and wave height

For the location YM6 the frequency of occurrence of combinations of wind speed and significant wave height over the period Jan. 1990 - Dec. 2001 are given below. Please note that these tables should not be mixed up with scatter plots in which the occurrence frequency of the significant wave height and the zero crossing period are plotted. In these type of scatter plots the wind speed is not considered.

Winter	significant wave height, Hs [m] - upper limi														
wind speed, Vw [m/s] - upperlimit	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	Grand Total
2	111	117	28	6	3	1									266
4	498	580	177	35	9	3									1302
6	214	751	431	105	19	3									1523
8	17	544	649	295	74	19	7								1605
10		91	454	507	208	56	19	4	2		1				1342
12		5	150	418	392	153	53	18	8		3				1200
14		1	5	113	267	245	111	45	15	4	3		1		810
16				5	53	114	121	55	32	19	10	3	1		413
18					1	18	55	25	19	10	7	4	3	1	143
20							5	7	12	12	4	5	1		46
22								2	2	6					10
24											1	2			3
26													1		1
Grand Total	840	2089	1894	1484	1026	612	371	156	90	51	29	14	7	1	8664

Spring	significant wave height, Hs [m] - upper limi														
wind speed, Vw [m/s] - upperlimit	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	Grand Total
2	191	128	21	7											347
4	715	633	159	19	3	2	1								1532
6	667	1111	416	75	7	3									2279
8	200	985	659	191	32	5	2								2074
10	25	315	517	350	95	21	4								1327
12		33	177	289	189	69	24	7	5						793
14		1	14	62	116	64	43	12	7	2					321
16				2	26	38	22	12	8	2					110
18						6	7	10	8		1				32
20						1	3	4	3						11
22										2	2				4
24						1									
26															
Grand Total	1798	3206	1963	995	468	210	106	45	31	6	3				8831

Autumn	significant wave height, Hs [m] - upper limi														
wind speed, Vw [m/s] - upperlimit	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	Grand Total
2	102	107	38	10	2										259
4	431	754	188	51	17	3	1	3							1448
6	291	1109	515	111	28	5	3	4	1						2067
8	38	548	827	317	63	17	3	2							1815
10	1	76	488	489	156	54	11	4	1						1280
12		7	86	350	313	113	47	12	4						932
14			6	37	180	203	71	35	15	5	1				553
16				7	14	58	90	46	24	11		1			251
18					1	7	28	31	19	8	1	1			96
20							3	8	9	7		2			29
22								1	1	2					4
24									1						1
26															
Grand Total	863	2601	2148	1372	774	460	257	146	75	33	2	4			8735

Year	significant wave height, Hs [m] - upper lim														
wind speed, Vw [m/s] - upperlimit	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	Grand Total
2	676	472	109	24	5	1									1287
4	2624	2663	648	112	29	8	3	3							6090
6	2039	4070	1733	325	57	13	3	4	1						8245
8	475	3044	2730	950	179	43	14	2							7437
10	56	798	2039	1647	512	134	36	8	3		1				5234
12		71	624	1339	1019	359	127	38	17		3				3597
14		2	31	261	689	560	253	100	37	11	4		1		1949
16				15	101	237	247	115	65	32	10	4	1		827
18					3	36	94	69	46	18	9	5	3	1	284
20						1	11	19	24	19	4	7	1		86
22								3	3	10	2				18
24						1			1		1	2			5
26													1		1
Grand Total	5870	11120	7914	4673	2594	1393	788	361	197	90	34	18	7	1	35060

Summer	significant wave height, Hs [m] - upper limi														
wind speed, Vw [m/s] - upperlimit	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	Grand Total
2	272	120	22	1											415
4	980	696	124	7			1								1808
6	867	1099	371	34	3	2									2376
8	220	967	595	147	10	2	2								1943
10	30	316	580	301	53	3	2								1285
12		26	211	282	125	24	3	1							672
14			6	49	126	48	28	8							265
16				1	8	27	14	2	1						53
18					1	5	4	3							13
20															
22															
24															
26															
Grand Total	2369	3224	1909	822	326	111	54	14	1						8830

Annex C: Weibull parameters weather windows

The calculated Weibull parameters of the CDF for the duration and the number of low and high intervals and the probability P_{low} are given in Table C.2 - Table C.6 for the weather windows specified in Table C.1.

Table C.1: *Overview of weather windows*

Weather window number	$H_{s\,max}$	$V_{w\,max}$	Weather window number	$H_{s\,max}$	$V_{w\,max}$
	[m]	[m/s]		[m]	[m/s]
1	0.75	6	16	2	15
2	0.75	8	17	3	8
3	0.75	10	18	3	10
4	1	6	19	3	12
5	1	8	20	3	15
6	1	10	21	3	20
7	1	12	22	4	12
8	1.5	6	23	4	15
9	1.5	8	24	4	20
10	1.5	10	25	4	30
11	1.5	12	26	5	15
12	2	6	27	5	20
13	2	8	28	5	30
14	2	10	29	8	20
15	2	12	30	8	30

Table C.2: Weibull parameters of the CDF for the duration and the number of low and high intervals and the probability P_{low} for the winter period

WINTER				Low intervals				High intervals			
				duration		number		duration		number	
Nr	$H_{s\,max}$	$V_{w\,max}$	P_{low}	α	β	α	β	α	β	α	β
	[m]	[m/s]	[%]	[-]	[hr]	[-]	[hr]	[-]	[hr]	[-]	[hr]
1	0.75	6	19.7%	1.1391	62.458	0.62875	14.515	1.1048	358.46	0.53700	51.469
2	0.75	8	21.7%	1.2755	66.906	0.67849	19.056	1.1342	339.00	0.57950	59.394
3	0.75	10	21.8%	1.2757	67.264	0.68480	19.397	1.1305	336.50	0.58807	60.177
4	1	6	27.6%	1.0938	66.179	0.62922	14.381	1.0771	220.01	0.56144	34.060
5	1	8	33.3%	1.1633	86.053	0.65980	20.806	1.1199	203.78	0.60692	39.097
6	1	10	34.2%	1.1174	96.232	0.66071	21.927	1.1805	197.16	0.63687	43.450
7	1	12	34.3%	1.1305	96.888	0.65471	21.996	1.1814	197.18	0.63896	43.680
8	1.5	6	35.2%	1.0008	65.086	0.63830	13.497	1.1366	126.24	0.61898	25.802
9	1.5	8	48.9%	1.0323	116.32	0.60404	20.976	1.2327	103.37	0.65593	25.692
10	1.5	10	55.2%	0.92679	169.51	0.60767	25.914	1.3473	91.249	0.73034	28.474
11	1.5	12	56.2%	0.90733	181.76	0.61029	26.771	1.3142	90.202	0.75194	28.724
12	2	6	36.8%	0.98818	63.346	0.63746	13.012	1.1274	108.09	0.65024	24.510
13	2	8	54.2%	1.0451	114.21	0.56521	18.194	1.1853	73.069	0.6954	19.655
14	2	10	67.2%	1.0002	181.18	0.56708	26.347	1.2766	55.387	0.74575	17.790
15	2	12	72.9%	1.0115	230.88	0.58872	35.341	1.3563	48.955	0.83567	18.772
16	2	15	74.2%	1.0272	242.68	0.57767	36.816	1.2974	47.900	0.84989	18.355
17	3	8	55.3%	1.0326	113.83	0.54634	16.616	1.2660	62.076	0.7262	18.672
18	3	10	71.5%	0.99459	183.18	0.53497	23.127	1.3453	38.545	0.78885	14.031
19	3	12	83.4%	1.0234	302.55	0.50162	32.051	1.3007	25.529	0.85939	10.463
20	3	15	91.3%	0.97594	582.59	0.55004	65.089	1.3962	21.848	0.90054	9.8686
21	3	20	92.0%	1.0060	637.70	0.52044	67.245	1.3607	22.328	0.8482	9.4015
22	4	12	84.5%	1.0268	305.33	0.50153	32.428	1.3256	22.799	0.87639	9.7045
23	4	15	95.4%	1.0503	769.51	0.53738	87.035	1.1925	14.500	0.79263	5.6746
24	4	20	97.8%	1.5514	1468.6	0.41175	212.94	1.2414	18.224	0.77433	6.8453
25	4	30	97.8%	1.5514	1468.5	0.42155	222.79	1.2577	18.393	0.76604	6.8835
26	5	15	96.1%	1.0432	799.91	0.56827	96.555	1.2056	12.065	0.85434	5.2727
27	5	20	99.7%	3.4045	8692.1	0.50093	1495.4	1.7930	12.741	1.0740	7.5706
28	5	30	100.0%								
29	8	20	100.0%								
30	8	30	100.0%								

Table C.3: Weibull parameters of the CDF for the duration and the number of low and high intervals and the probability P_{low} for the spring period

SPRING				Low intervals				High intervals			
				duration		number		duration		number	
Nr	$H_{s,max}$	$V_{w,max}$	P_{low}	α	β	α	β	α	β	α	β
	[m]	[m/s]	[%]	[-]	[hr]	[-]	[hr]	[-]	[hr]	[-]	[hr]
1	0.75	6	30.3%	1.0977	42.332	0.80666	14.091	1.1619	154.30	0.52317	23.047
2	0.75	8	37.1%	1.2912	66.887	0.73009	20.676	1.2671	146.88	0.56060	27.625
3	0.75	10	38.5%	1.1884	84.260	0.71124	23.271	1.2912	149.26	0.60702	33.227
4	1	6	38.7%	1.0934	44.198	0.79014	14.325	1.1524	98.898	0.56594	17.651
5	1	8	52.0%	1.3219	86.818	0.67667	23.949	1.1556	95.424	0.56994	17.944
6	1	10	55.3%	1.2286	126.79	0.64724	30.497	1.1956	98.063	0.65984	24.345
7	1	12	55.6%	1.2258	130.61	0.65511	31.909	1.2005	98.647	0.67266	25.277
8	1.5	6	45.5%	1.1501	44.163	0.75847	14.088	1.1230	66.548	0.61909	14.160
9	1.5	8	66.0%	1.3395	99.565	0.66313	26.353	1.0654	50.779	0.64329	11.702
10	1.5	10	75.7%	1.3054	197.37	0.63774	48.472	1.1424	51.658	0.7544	15.838
11	1.5	12	77.3%	1.3520	241.56	0.63323	61.196	1.1763	54.056	0.85255	19.244
12	2	6	46.7%	1.1416	44.082	0.75985	14.052	1.1526	60.285	0.63743	13.971
13	2	8	69.5%	1.3224	104.52	0.64072	25.580	1.1741	37.790	0.69946	10.92
14	2	10	82.9%	1.2651	239.90	0.58255	48.274	1.0681	33.354	0.80262	11.007
15	2	12	87.3%	1.3039	383.63	0.53714	68.277	1.1199	35.386	0.77920	11.406
16	2	15	87.9%	1.2017	446.49	0.54362	74.950	1.1458	37.041	0.79560	12.364
17	3	8	70.6%	1.3192	104.87	0.63575	25.229	1.2443	33.394	0.72754	10.722
18	3	10	85.4%	1.2495	245.95	0.54424	42.580	1.1398	22.202	0.90769	9.2395
19	3	12	93.4%	1.2071	565.43	0.48864	71.432	1.1581	17.597	0.81730	6.8725
20	3	15	96.0%	1.2581	890.93	0.49653	126.46	1.6648	15.590	1.0066	8.4253
21	3	20	96.4%	1.1819	1027.4	0.50074	137.51	1.5846	15.734	0.97082	8.1514
22	4	12	93.9%	1.2172	597.01	0.47958	70.806	1.1671	15.580	0.86567	6.5663
23	4	15	97.8%	1.1269	1326.6	0.55549	169.05	1.6815	10.052	1.0691	5.9752
24	4	20	98.8%	1.7779	1296.3	0.72420	527.79	2.1706	8.8823	1.4565	6.4690
25	4	30	98.9%	1.7746	1296.4	0.72580	526.97	2.1380	8.9686	1.3049	6.2151
26	5	15	98.1%	1.0153	1557.8	0.59635	182.49	1.5006	9.7827	1.0237	5.5323
27	5	20	100.0%								
28	5	30	100.0%								
29	8	20	100.0%								
30	8	30	100.0%								

Table C.4: Weibull parameters of the CDF for the duration and the number of low and high intervals and the probability P_{low} for the summer period

SUMMER				Low intervals				High intervals			
				duration		number		duration		number	
Nr	$H_{s,max}$	$V_{w,max}$	P_{low}	α	β	α	β	α	β	α	β
	[m]	[m/s]	[%]	[-]	[hr]	[-]	[hr]	[-]	[hr]	[-]	[hr]
1	0.75	6	38.8%	1.3481	46.127	0.82877	17.532	1.2378	109.44	0.56224	20.761
2	0.75	8	46.4%	1.2918	87.173	0.71924	26.150	1.3214	108.98	0.64585	28.537
3	0.75	10	47.7%	1.2269	103.31	0.71185	29.026	1.3434	109.72	0.70382	33.050
4	1	6	47.2%	1.2974	47.483	0.77409	16.341	1.1704	67.323	0.62394	15.314
5	1	8	59.8%	1.2138	100.65	0.70981	28.282	1.2476	67.612	0.65137	17.419
6	1	10	64.0%	1.2470	148.21	0.68387	39.289	1.2980	70.503	0.76852	23.676
7	1	12	64.2%	1.2438	154.57	0.67295	39.914	1.3036	70.740	0.77908	24.242
8	1.5	6	52.7%	1.2916	47.628	0.77884	16.388	1.1341	47.456	0.70626	13.319
9	1.5	8	72.1%	1.1947	110.57	0.69319	29.630	1.1778	37.183	0.68814	10.566
10	1.5	10	83.2%	1.3693	250.97	0.59720	57.875	1.2261	36.487	0.79834	13.000
11	1.5	12	85.7%	1.3242	347.13	0.55096	67.021	1.3362	36.947	0.81704	14.041
12	2	6	53.0%	1.2906	47.464	0.76994	16.113	1.1471	45.503	0.71640	13.174
13	2	8	74.0%	1.1862	111.14	0.68087	28.957	1.1106	31.989	0.70940	9.3961
14	2	10	88.6%	1.3053	311.82	0.54063	57.169	1.0864	26.305	0.69923	7.7655
15	2	12	94.2%	1.5523	624.89	0.50246	122.97	1.2008	24.460	0.75172	8.5239
16	2	15	94.8%	1.5395	748.00	0.49522	139.28	1.1843	24.750	0.80382	9.1413
17	3	8	74.2%	1.1934	111.40	0.67676	28.784	1.1294	30.957	0.72129	9.4364
18	3	10	89.5%	1.2634	339.21	0.52237	56.543	1.1236	23.078	0.72925	7.5175
19	3	12	96.5%	2.1183	686.82	0.48286	165.28	1.5367	13.419	0.97566	7.0559
20	3	15	99.1%	1.6426	1964.3	0.75140	810.32	1.9819	9.8907	1.1749	6.3990
21	3	20	99.2%	1.9935	2166.2	0.73143	1058.8	2.4335	10.803	1.3843	7.8001
22	4	12	96.6%	1.9682	711.90	0.46347	155.14	1.4672	13.026	0.96844	6.7305
23	4	15	99.6%	1.8043	2621.3	0.76868	1183.7	1.4123	5.4989	0.98159	3.2105
24	4	20	100.0%								
25	4	30	100.0%								
26	5	15	99.7%	2.0797	2767.7	0.81607	1370	1.4667	5.6487	1.0141	3.3769
27	5	20	100.0%								
28	5	30	100.0%								
29	8	20	100.0%								
30	8	30	100.0%								

Table C.5: Weibull parameters of the CDF for the duration and the number of low and high intervals and the probability P_{low} for the autumn period

AUTUMN				Low intervals				High intervals			
				duration		number		duration		number	
Nr	$H_{s,max}$	$V_{w,max}$	P_{low}	α	β	α	β	α	β	α	β
	[m]	[m/s]	[%]	[-]	[hr]	[-]	[hr]	[-]	[hr]	[-]	[hr]
1	0.75	6	23.1%	1.2420	42.390	0.75577	13.810	1.2050	228.43	0.51851	33.711
2	0.75	8	25.5%	1.1590	59.470	0.74458	17.619	1.2288	230.65	0.58471	44.717
3	0.75	10	25.6%	1.1113	61.630	0.74931	17.840	1.2327	230.80	0.59030	45.679
4	1	6	33.0%	1.2709	46.841	0.77664	15.901	1.3009	136.51	0.55012	25.265
5	1	8	39.9%	1.2532	83.471	0.71957	24.698	1.3253	137.95	0.65703	36.124
6	1	10	41.6%	1.1084	99.872	0.69395	24.982	1.2957	136.80	0.68107	37.229
7	1	12	41.6%	1.0841	102.00	0.68900	24.754	1.2961	136.44	0.68216	37.179
8	1.5	6	41.9%	1.2767	47.695	0.73649	15.048	1.2384	81.040	0.62502	18.548
9	1.5	8	57.3%	1.2451	105.09	0.64884	25.992	1.2250	72.913	0.70140	20.109
10	1.5	10	64.5%	1.1860	154.32	0.63487	34.747	1.2519	71.189	0.72615	20.844
11	1.5	12	65.6%	1.1273	172.18	0.63763	36.514	1.2726	72.265	0.73040	21.530
12	2	6	44.0%	1.2238	47.297	0.74198	14.736	1.1361	71.887	0.65591	17.206
13	2	8	62.9%	1.1442	109.71	0.63309	24.175	1.0757	55.212	0.72594	15.197
14	2	10	75.2%	1.1623	208.96	0.56353	35.709	1.1722	46.904	0.74041	14.183
15	2	12	80.2%	1.1988	315.20	0.55302	52.857	1.3095	47.254	0.82179	17.511
16	2	15	80.7%	1.2130	343.36	0.53594	54.259	1.3359	47.825	0.84359	18.457
17	3	8	64.5%	1.1350	108.53	0.63484	23.747	1.0374	51.742	0.71083	13.535
18	3	10	79.4%	1.1851	210.20	0.55902	35.975	1.0525	35.640	0.77435	11.072
19	3	12	89.5%	1.1137	464.10	0.52386	59.789	1.1620	25.713	0.88022	10.199
20	3	15	94.9%	1.1939	936.75	0.53173	145.67	1.1269	28.092	0.89718	10.734
21	3	20	95.8%	1.0667	1400.2	0.51234	159.02	1.1155	29.237	0.88855	11.019
22	4	12	90.6%	1.1408	482.92	0.50621	59.330	1.2257	22.269	0.89764	9.4577
23	4	15	97.8%	1.1987	1557.0	0.45048	207.10	1.0992	16.265	0.92806	6.8235
24	4	20	99.5%	2.8142	5333.0	0.29499	530.91	1.3356	12.262	0.89636	5.7529
25	4	30	99.5%	2.8171	5332.2	0.30405	579.88	1.3588	12.359	0.91602	5.9243
26	5	15	98.1%	1.2418	1645.7	0.45242	243.23	1.0645	15.486	0.84801	5.8758
27	5	20	99.9%	11.917	7056.1	1.9238	6318.0	1.2540	6.4261	0.79413	2.7200
28	5	30	100.0%								
29	8	20	100.0%								
30	8	30	100.0%								

Table C.6: *Weibull parameters of the CDF for the duration and the number of low and high intervals and the probability P_{low} for the whole year*

YEAR				Low intervals				High intervals			
				duration		number		duration		number	
Nr	$H_{s,max}$	$V_{w,max}$	P_{low}	α	β	α	β	α	β	α	β
	[m]	[m/s]	[%]	[-]	[hr]	[-]	[hr]	[-]	[hr]	[-]	[hr]
1	0.75	6	28.1%	1.1707	46.978	0.7667	15.170	1.0173	206.67	0.53304	27.503
2	0.75	8	32.8%	1.2172	72.661	0.71838	21.074	1.0498	205.54	0.58901	35.496
3	0.75	10	33.5%	1.1467	83.913	0.70497	22.486	1.0580	207.08	0.61976	39.642
4	1	6	36.7%	1.1512	49.578	0.74963	15.309	1.0462	126.50	0.56716	20.322
5	1	8	46.3%	1.2260	90.510	0.69483	24.675	1.0699	127.90	0.60487	24.358
6	1	10	48.8%	1.1403	123.91	0.65849	28.847	1.0988	130.08	0.66912	30.303
7	1	12	49.0%	1.1397	127.38	0.65450	29.219	1.1023	130.39	0.67575	30.880
8	1.5	6	43.9%	1.1491	49.629	0.73474	14.872	1.0594	79.328	0.62923	16.478
9	1.5	8	61.1%	1.2062	107.33	0.65737	25.989	1.0604	68.657	0.64752	15.321
10	1.5	10	69.7%	1.1651	200.06	0.60349	38.985	1.1566	68.443	0.71976	19.082
11	1.5	12	71.3%	1.1261	246.01	0.58015	42.204	1.1726	69.683	0.75167	20.880
12	2	6	45.2%	1.1346	49.269	0.73235	14.598	1.0764	70.438	0.65296	16.045
13	2	8	65.2%	1.1842	109.59	0.63306	24.332	1.0543	51.002	0.68872	13.048
14	2	10	78.5%	1.1514	242.01	0.55382	38.574	1.1293	44.086	0.72220	12.743
15	2	12	83.8%	1.1565	403.49	0.52123	54.737	1.2336	43.429	0.78636	14.850
16	2	15	84.6%	1.0988	461.34	0.51361	57.123	1.2356	43.641	0.80992	15.492
17	3	8	66.2%	1.1807	109.35	0.62518	23.581	1.1025	45.725	0.70528	12.568
18	3	10	81.4%	1.1349	248.98	0.53172	35.592	1.1428	32.020	0.77480	10.670
19	3	12	90.6%	1.1833	527.11	0.46844	55.306	1.1926	22.856	0.85666	9.1187
20	3	15	95.4%	1.0608	1167.4	0.48096	115.37	1.2562	21.591	0.92232	9.4615
21	3	20	95.8%	1.0310	1432.6	0.46164	116.86	1.2498	22.362	0.89772	9.4859
22	4	12	91.3%	1.1850	544.54	0.46075	54.574	1.2235	20.386	0.87401	8.5336
23	4	15	97.6%	1.0728	1663.9	0.46417	155.44	1.1228	13.886	0.86216	5.8275
24	4	20	99.0%	1.1782	3998.5	0.38286	372.23	1.1897	14.716	0.86911	6.2930
25	4	30	99.0%	1.1800	3991.9	0.39266	391.74	1.1989	14.877	0.85907	6.3111
26	5	15	98.0%	1.0629	1826.2	0.47750	175.21	1.1388	12.253	0.87572	5.2961
27	5	20	99.8%	2.3480	8909.6	0.51396	2385.7	1.5255	11.644	0.90364	5.9140
28	5	30	99.8%	1.4523	14844	0.50733	3080.6	2.2365	13.710	1.1173	8.6815
29	8	20	99.9%	2.0305	13604	0.53708	4467.5	1.9448	4.1807	1.5760	3.1724
30	8	30	100.0%								

Annex D: Time to wait results

The waiting time for a mission with duration of *t* hours is given by

$$T\_wait = C_0 + C_1 t + C_2 t^2 + C_3 t^3$$

For the weather windows specified in Table D.1 the polynomial coefficients C_i, i =0,..,3 are given in Table D.2.

Table D.1: *Overview of weather windows*

Weather window number	$H_{s\ max}$ [m]	$V_{w\ max}$ [m/s]	Weather window number	$H_{s\ max}$ [m]	$V_{w\ max}$ [m/s]
1	0.75	6	16	2	15
2	0.75	8	17	3	8
3	0.75	10	18	3	10
4	1	6	19	3	12
5	1	8	20	3	15
6	1	10	21	3	20
7	1	12	22	4	12
8	1.5	6	23	4	15
9	1.5	8	24	4	20
10	1.5	10	25	4	30
11	1.5	12	26	5	15
12	2	6	27	5	20
13	2	8	28	5	30
14	2	10	29	8	20
15	2	12	30	8	30

Table D.2: *Polynomial coefficients for waiting time*

Winter

weather window		polynomial coefficients			
$H_{s,max}$	$V_{w,max}$	C_0	C_1	C_2	C_3
0.75	6	127.836	13.35595	-0.125518	0.004006
0.75	8	116.5792	10.75958	-0.146188	0.003692
0.75	10	108.7434	10.00367	-0.090582	0.002693
1	6	90.75643	3.950768	0.140226	0.000628
1	8	69.07969	3.544768	0.087804	0.000116
1	10	71.52711	1.458832	0.114669	0
1	12	65.20972	1.778173	0.101413	0
1.5	6	49.13868	2.240212	0.139067	0
1.5	8	23.33379	1.748556	0.051853	0
1.5	10	25.5843	0.550888	0.042377	0
1.5	12	24.16063	0.793979	0.03555	0
2	6	43.42893	2.091328	0.130862	0
2	8	11.80419	2.263339	0.033966	0
2	10	6.150373	0.624626	0.024282	0
2	12	10.64462	0.209222	0.019331	0
2	15	10.13819	0.04213	0.018179	0
3	8	13.71656	1.540357	0.035554	1.55E-05
3	10	3.999631	1.158457	0.003601	0.000113
3	12	0	0.679058	0.000677	5.22E-05
3	15	0	0.206504	0.004351	0
3	20	0	0.013042	0.006164	0
4	12	0	0.238412	0.00965	0
4	15	0	0.213714	-0.002399	3.15E-05
4	20	0	0.066647	-0.000164	9.35E-06
4	30	0	0.033317	0.001416	0
5	15	0	0.049676	0.00328	0
5	20	0	0.027762	-2.91E-05	3.91E-07
5	30	0	0	0	0
8	20	0	0	0	0
8	30	0	0	0	0

Spring

weather window		polynomial coefficients			
$H_{s,max}$	$V_{w,max}$	C_0	C_1	C_2	C_3
0.75	6	41.52782	5.899317	-0.013608	0.005202
0.75	8	37.24326	3.915248	-0.010349	0.001654
0.75	10	39.24181	2.094214	0.082962	5.44E-05
1	6	34.16386	1.657042	0.118821	0.001942
1	8	21.04359	2.05153	0.005328	0.000491
1	10	18.09406	1.386803	0.004772	0.000283
1	12	21.29345	0.3671	0.040344	0
1.5	6	14.78555	3.18474	-0.017913	0.002961
1.5	8	11.05083	0.353914	0.035119	6.18E-06
1.5	10	7.313341	0.465182	0.006091	5.71E-05
1.5	12	6.533664	0.556066	0.00422	4.62E-05
2	6	11.0353	2.325534	0.030973	0.002285
2	8	6.124716	0.278781	0.033652	0
2	10	4.194705	0.121287	0.011694	0
2	12	2.194576	0.067626	0.007511	0
2	15	1.682272	0.043262	0.006568	0
3	8	6.504572	0.183829	0.035057	0
3	10	0.772581	0.159586	0.009513	0
3	12	0	0.020711	0.00397	3.32E-06
3	15	0	0.023446	0.001365	5.28E-06
3	20	0	0.10038	0.000848	0
4	12	0	0.005278	0.004266	2.16E-06
4	15	0	0.041309	0.0005	6.22E-06
4	20	0	0.044961	-0.000107	6.94E-06
4	30	0	0.091497	-0.000837	1.17E-05
5	15	0	0.060053	0.000379	7.89E-06
5	20	0	0	0	0
5	30	0	0	0	0
8	20	0	0	0	0
8	30	0	0	0	0

Summer

weather window		polynomial coefficients			
$H_{s,max}$	$V_{w,max}$	C_0	C_1	C_2	C_3
0.75	6	28.74454	3.635979	0.006345	0.002946
0.75	8	23.17037	3.750624	-0.05864	0.001406
0.75	10	20.37167	3.03021	-0.020759	0.000806
1	6	15.19936	3.201289	-0.028375	0.002174
1	8	9.471205	0.971495	0.024888	0.0002
1	10	8.463008	1.090568	0.006987	0.000141
1	12	7.445337	1.244904	-0.001747	0.000177
1.5	6	8.219994	2.209574	-0.007681	0.001924
1.5	8	3.559139	0.654996	0.016793	0.000141
1.5	10	1.982866	0.289328	0.006946	1.51E-05
1.5	12	1.372772	0.466275	-0.000617	3.54E-05
2	6	3.003118	2.97946	-0.038369	0.002149
2	8	2.446146	0.496041	0.024987	4.77E-05
2	10	1.244981	0.162984	0.006647	3.02E-06
2	12	0.911289	0.017303	0.001356	9.7E-06
2	15	0	0.046441	0.001661	2.73E-06
3	8	0	0.144084	0.033719	0
3	10	0	0.299664	0.004544	0
3	12	0	0.068018	0.002028	0
3	15	0	0.106364	0.000362	0
3	20	0	0.034981	0.000299	0
4	12	0	0.01016	0.002179	0
4	15	0	0.072709	-7.6E-05	1.09E-06
4	20	0	0	0	0
4	30	0	0	0	0
5	15	0	0.017054	9.52E-05	6.63E-07
5	20	0	0	0	0
5	30	0	0	0	0
8	20	0	0	0	0
8	30	0	0	0	0

Autumn

weather window		polynomial coefficients			
$H_{s,max}$	$V_{w,max}$	C_0	C_1	C_2	C_3
0.75	6	104.7626	0.89863	0.418606	0
0.75	8	99.53664	0.63713	0.284419	0
0.75	10	96.54334	0.800418	0.28246	0
1	6	51.81158	1.433948	0.241665	0
1	8	47.0512	1.334731	0.083931	0
1	10	44.07898	1.294558	0.08244	0
1	12	40.39507	1.695597	0.06924	0
1.5	6	27.96359	0.574589	0.163773	0
1.5	8	18.0074	0.453196	0.042619	0
1.5	10	15.04943	0.2885	0.030407	0
1.5	12	12.45818	0.305154	0.0268	0
2	6	20.74555	0.590623	0.15756	0
2	8	16.05795	0.213348	0.039599	0
2	10	9.011325	0.215292	0.015411	0
2	12	3.975207	0.304786	0.009134	0
2	15	1.431014	0.397343	0.007081	0
3	8	11.10633	0.471226	0.037004	0
3	10	6.351079	0.163329	0.015278	0
3	12	0	0.186681	0.005946	0
3	15	0	0.091074	0.001451	0
3	20	0	0.008288	0.001813	0
4	12	0	0.135089	0.004562	0
4	15	0	0.047898	0.001123	0
4	20	0	0.014416	0.000163	0
4	30	0	0.0329	0.000179	0
5	15	0	0.032843	0.000978	0
5	20	0	0.023417	5.08E-05	0
5	30	0	0	0	0
8	20	0	0	0	0
8	30	0	0	0	0

Year

weather window		polynomial coefficients			
$H_{s,max}$	$V_{w,max}$	C_0	C_1	C_2	C_3
0.75	6	82.60291	1.639936	0.246828	0.000772
0.75	8	60.38231	5.063425	-0.003153	0.001284
0.75	10	64.74088	3.141411	0.07206	0.000418
1	6	39.90952	1.232015	0.179169	0
1	8	32.62395	2.203921	0.001876	0.000736
1	10	34.17694	1.307912	0.028422	0.000203
1	12	31.46166	1.60121	0.02087	0.000227
1.5	6	23.0116	0.799259	0.151157	0
1.5	8	11.84377	1.38961	0.016352	0.000148
1.5	10	13.78605	0.496921	0.008513	8.19E-05
1.5	12	4.21224	1.192668	-0.000406	7.44E-05
2	6	14.65954	1.363067	0.144782	0
2	8	9.01333	0.73863	0.018882	0.000139
2	10	3.806602	0.376982	0.010137	2.68E-05
2	12	0.438803	0.388704	0.006093	0
2	15	1.635813	0.266962	0.004782	0
3	8	4.886275	0.595197	0.03551	0
3	10	3.542891	0.262555	0.007979	2.94E-05
3	12	0	0.222178	0.003489	0
3	15	0	0.043883	0.000849	8.92E-06
3	20	0	0.008134	0.001554	1.96E-06
4	12	0	0.180522	0.004315	0
4	15	0	0.037424	0.001387	0
4	20	0	0.019252	0.00039	0
4	30	0	0.038074	-0.00025	5.26E-06
5	15	0	0.021204	0.001261	0
5	20	0	0.013826	7.31E-05	0
5	30	0	0.022655	8.15E-05	0
8	20	0	0.038705	-0.00018	5.65E-07
8	30	0	0	0	0