Open Sea Operating Experience to Reduce Wave Energy Costs

Deliverable D6.2

Operational model for offshore operation of wave energy converters

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EXECUTIVE SUMMARY

This deliverable provides evidence of the development of an operational model for site accessibility, analysis and optimisation of maritime methods and calculation of cost of offshore operations as an aid in decision making in the OPERA project. This is the main outcome of the Task T6.2 (Improve offshore logistics and cost models).

Existing operational models for the estimation of the OPEX have been refined with data collected under real operating conditions. However, since most components are not expected to fail during the project life (2-3 years of operating data) service life has been estimated based on data collected, main drivers for components fatigue (e.g., operating temperature and peaks for the power conversion chain, loads in the mooring, etc.) and indications of the personnel involved in the operations (e.g. mariners, offshore crew, port authority etc.).

The operational model developed is focused on the cost of offshore operations, whereas the cost of components to be replaced and other running costs such as insurance will be integrated in the overall cost model in WP7 of the project.

Along T6.2 information from the rest of WPs has been collected on the probability of failure and the need for replacement of the equipment on board. Results have been used to feed into operational models for the OPEX calculation and O&M scheduling and will be validated against the effective failures and replacements occurring on site. UEDIN has contributed to reliability and O&M parameterisation with a view to developing WP7 models.

Modelling site accessibility assessment with estimation of weather windows and validation against real sea operations is also necessary to realistically assess the waiting time and costs. BiMEP has provided short term and long term statistics at the deployment site. UCC has analysed the historical metocean conditions for the implications of downtime on energy production.

The OPERA project has chosen a medium complexity OPEX modeling approach to account for the maturity of wave energy technologies. The model is detailed in terms of cost breakdown of vessels, personnel, equipment and consumables required per operation as well as device availability. Each maintenance operation could be classified as corrective or preventive depending on the uncertainties in estimating component failure rates. As a main conclusion, the model identifies the critical costs associated to O&M activities and help to improve OPEX strategies.

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ABBREVIATIONS AND ACRONYMS

CAPEX	Capital Expenditure Costs
COE	Cost of energy
BiMEP	Biscay Marine Energy Platform
EIA	Environmental Impact Assessment
FMEA	Failure Modes and Effects Analysis
HSSV	High Speed Safety Valve
IC	Initial Cost
LCA	Life Cycle Assessment
O&M	Operation and Maintenance
OPERA	Open Sea Operating Experience to Reduce Wave Energy Costs
OPEX	Operation Expenditures
OWC	Oscillating Water Column
PTO	Power Take-off (turbine-generator set)
TRL	Technology Readiness Level
WP	Work Package
WEC	Wave Energy Converter
WWWT	Weather Window Waiting Time

1. INTRODUCTION

1.1 Background

The development of wave energy technology finds itself at a crossroads. Some developers have started full scale testing programmes on their devices, but the economic feasibility of wave energy farms is not fully developed, especially in which logistics optimisation of Operations and Maintenance (O&M) is concerned.

Whereas operations refer to activities contributing to high level management and monitoring, maintenance focus on the up-keep and repair of the plant [1] . In general, O&M can be divided in two parts:

- Preventive maintenance: proactive replacements or repairs
- Corrective maintenance: replacement or repairs of failed components

In the context of wave energy, O&M is defined as all annual costs needed to maintain optimum performance of wave energy devices in the farm. O&M expenditure (OPEX) is commonly described by any of the three following metrics [1] :

- €/MWh: This metric provides a cost based on the relationship between the total initial cost of the project (CAPEX) and the annual energy output.
- % of Initial Cost (IC): O&M is calculated as a straight percentage of capital expenditure (CAPEX).
- % of Cost of Electricity (COE): This metric presents O&M cost as a percentage of the total COE for the project. It requires both the O&M and COE based in €/MWh.

O&M cost is estimated to be between 14%-30% of CAPEX [3] , [4] , [5] , for offshore wind and 17% of CAPEX for wave energy farms [6] . Although these values could be taken as an initial reference to compute total costs of the farm, it is still a significant percentage. Therefore, it is very important to understand the key factors that influence the OPEX and availability of the farm as well as to reduced uncertainties of the environmental conditions that contribute to higher costs.

Offshore operations also have a major impact on Life Cycle CO_2 emissions. Although similar importance can be expected in wave energy farms, the lack of open-sea experience shared across the sector introduces a significant uncertainty on OPEX and therefore a business risk in wave energy projects. Documenting and sharing information on offshore operations in OPERA is a major opportunity to achieve decisive progress on this front.

1.2 Objectives

The main objective of Work Package 6 is to reduce uncertainty on, and mitigate risk and cost of offshore operations. In this deliverable, existing operational models for the estimation of the OPEX will be analyzed to be used and refined with data collected under real operating conditions. Since most components are not expected to fail during the project life (2-3 years of operating data) service life will be estimated based on data collected (ej. From WP7 in the OPERA project), main drivers for components fatigue (e.g., operating temperature and peaks for the power conversion chain, loads in the mooring, etc.) and indications of the personnel involved in the operations (e.g. mariners, offshore crew, port authority etc.).

Moreover, deliverable D6.2 describes the operational model for a wave energy technology farm. Not only can this model be used for Operation and Maintenance, but also for the installation, and decommissioning phase.

Specific objectives of WP6 are:

- Improve operational models to more precisely reflect logistic requirements for floating OWC
- Identify maintenance and operational procedures to lower life-cycle costs.
- Perform, improve and document required offshore operations during the open-sea testing period
- Provide figures for OPEX calculation based on real open sea operations
- Produce guidelines and recommendations that minimize risk and cost of offshore operations for wave energy.

1.3 Description of work and role of each partner

In this deliverable Tecnalia is responsible of developing an OPEX operational model where all the operations will be quantified in terms of costs, emissions and the availability of the device. Information from all the other WPs on the probability of failure and the need for replacement of the equipment on board will be complete. Results have be used to feed into operational models for the OPEX calculation and O&M scheduling and has been validated against the effective failures and replacements occurring on site. University College of Cork has contributed with a Weather Window tool (see ANNEX II: WEATHER WINDOW WAITING TIME). University of Edinburgh has contributed to reliability and O&M parameterization with a view to developing WP7 models. OCEANTEC’s contribution has been related with the offshore operations planning and description.

The analysis of maritime strategies will be completed using models for the operational simulation of offshore renewable devices (Global Maritime, Iberdrola E&C) when it is not possible to gather this information directly from the open-sea experience (limited to a single unit). These tools might include optimization methods and techno-economic analysis to aid in the decision making and will be validated against the case offered by the real sea operations at BiMEP.

1.4 Structure

The key Sections of this deliverable are outlined below:

- Section 2: provides a description of different approaches to OPEX modeling.
- Section 3: gives a detailed OPERA OPEX model description.
- Section 4: shows a specific case study of the OPEX model.
- Annex I: introduction to random events generation to define maintenance scheduling.
- Annex II: consists on a description of weather window waiting time tool.

2. DESCRIPTION OF DIFFERENT APPROACHES TO OPEX MODELLING

Different approaches can be used to characterize the OPEX for both pilot and commercial farms of wave energy devices.

2.1 Simple models

The simplest approach to OPEX modeling is just to take OPEX costs as a percentage of CAPEX. The main advantages and disadvantages of this method are the following:

Advantages:

- Simple calculation method
- Estimations could be taken from similar sectors such as offshore wind
- Suitable for well-established sectors

Disadvantages:

- Operational costs depend on many different parameters such as the distance to shore, device type and number, or deployment location
- It does not give information to improve offshore operations and device design
- Limited experience of wave energy to define global costs

Basic techno-economic models implement this simple approach such as the one developed by Ms. Julia F. Chozas Consulting Engineer together with Aalborg University and Energinet.dk [8] . Other more sophisticated tools such as Exceedance Finance [9] allows OPEX to be entered in different complexity levels, ranging from the simplest where the user can enter one number to the most detailed where the user can customize a list of items for each area of the project and enter individual costs in each year for each item.

This simple approach could be used for initial guidance but it is not suitable in the framework of OPERA project, which requires a deeper definition of the operations to be done during the project life.

2.2 Complex models

The main advantages and disadvantages of a more advanced OPEX methods are the following:

Advantages:

- A more detailed definition of the different costs that make up the overall cost of each operation will help to identify the most critical ones
- Allow engineers to improve components design and operations requirements
- Depending on the level of detail resources can be optimized

Disadvantages:

- Deep knowledge on each operation and components must be required

These models typically have as an input the probability of failure for each component and/or sub-system. For the sake of simplification, these failures can be considered independent of one another. Other requirements such as personnel, vessel type, cost of repairs or weather conditions can be added in a more detailed description of each operation,. Historical metocean time series can used to obtain an average waiting time depending on the seasons or monthly.

The most complex models can apply some restrictions such as the number of vessels, operations per day, week, exactly data of the operation. These models are aimed at producing an optimal OPEX schedule and use of resources.

Some of the inputs are used in the model above can be refined as a result of the optimization process. This is the case of vessels since the optimization is done at a higher level bearing in mind overall resources. This approach is recommended for a commercial stage. Following the optimization phase, the model should obtain the optimal O&M definition and the planning of operations minimizing cost for the wave farm.

Different logistic models have been identified in this category. Table 1 summarizes the most interesting ones.

TABLE 1 SUMMARY LIST OF RELEVANT EXISTING TOOLS FOR SUPPORTING OFFSHORE LOGISTICS MANAGEMENT, [8]

Tools developer	Overview of the tool	Reference
Frauhnofer IFF	*Several tools to support logistic planning for the wind farm industry (onshore and offshore) in collaboration with ISL*	
Mojo Maritime Ltd.	*MerMaid-Marine Economic Risk Management aid is a software to consider the impact of scheduling and metocean conditions on complex marine operations*	[10]
Energy research Centre of the Netherlands (ECN)	*Offshore wind O&M optimization software. The tool can compare a large variety of maintenance scenarios and provides the impact on the techno-economic performance.*	[11]
National Renewable Energy Laboratory (NREL)	*Combination of a customized NREL offshore cost model BOS and the ECN O&M tool to optimize installation and O&M strategies for offshore wind*	[12]
EDF Group	*ECUME- Mean cost of operation of an offshore wind farm project and risk measurement of O&M operations (based on ECN's tool)*	[12]
SINTEF-NOWITECH	*NOWIcob- Life-cycle cost and O&M optimisation tool for offshore wind farms*	[13]
Overspeed GmbH Co. KG	*OutSmart – Offshore wind O&M strategy simulator. Based on the logistic scenario and historical weather data, the tool delivers the downtime and OPEX.*	[15]
University of Strathclyde	*StrathSim- Offshore Wind OpEx model*	[16]
University of Stuttgart	*Research code dealing with offshore wind O&M optimisation*	
DTOcean	*Is a project funded by the European Commission under the 7th Framework Programme for Research and Development, more specifically under the call ENERGY 2013-1. DTOcean that stands for Optimal Design Tools for Ocean Energy Arrays aims at accelerating the industrial development of ocean energy power generation knowledge, and providing design tools for deploying the first generation of wave and tidal energy converter arrays.*	[17]
NORCOWE	*The model simulates maintenance planning and execution, as well as marine logistics for the operation and maintenance life cycle phase.*	[17]
WES model	*This Microsoft Excel-based O&M tool uses the Monte Carlo method to simulate the occurrence of faults on each device in a wave energy array by utilising failure rate data. All the components of the device are represented by fault categories, assigned following a Failure Modes and Effects Analysis (FMEA)*	[18]

2.3 OPERA modelling approach

The OPERA project has chosen a medium complexity modeling approach to account for the maturity of wave energy technologies whereas opening the way to providing some useful design guidance and recommendations to developers in the prototype stage TRL3-6 [20] .

This approach is not as complex as some models of Table 1 in terms of resources optimization, but is detailed enough to identify the different costs centers. The objective is not logistic optimization during the project deployment lifetime, but the identification of cost reduction pathways for operations during the technology design phase.

The model to be used is going to be detailed in terms of cost breakdown of vessels, personnel, equipment and consumables requires per operation as well as device availability. Each operation could be classified as corrective or preventive maintenance depending on the uncertainties in estimating component failure rates (i.e. pre-exiting knowledge and experience on the operation of each element in the offshore environment and providing the intended function). The majority of the models presented above are not ready to be used in this way or cannot be modified and adapted during the project. Open source models such as DTOcean model [17] are unfortunately too detailed at this stage of development.

Those models however provide useful knowledge and data that can be integrated in a more versatile tool customized for the OPERA project.

3. OPERA OPEX MODEL DESCRIPTION

3.1 Model Architecture

The objective of the model is to quantify in terms of cost and CO2 emissions each operation carried out during the project and the device availability. The architecture of the OPEX model is represented in Figure 1.

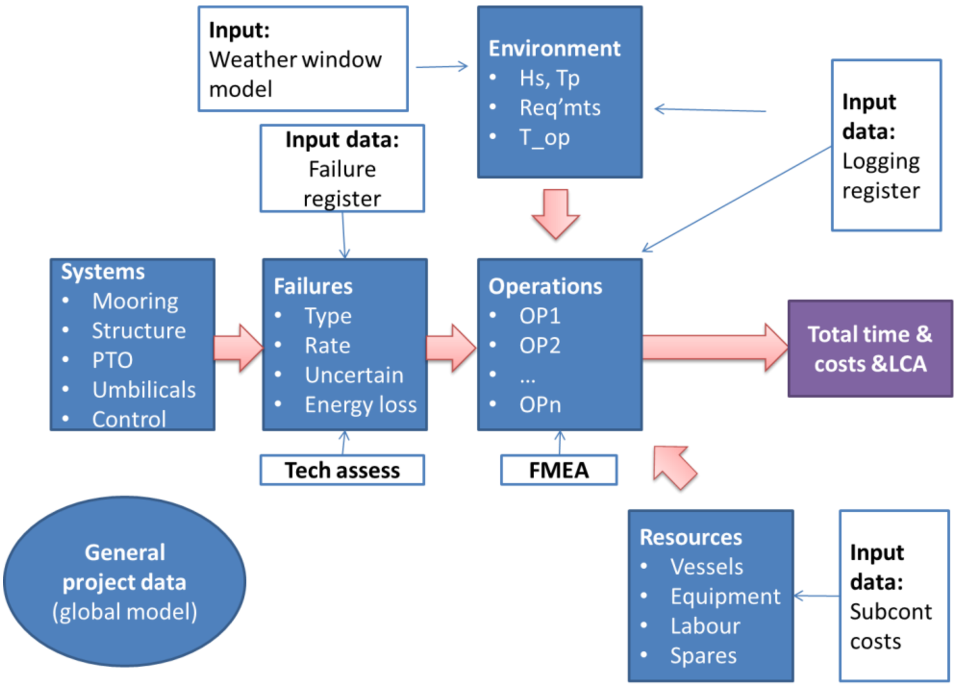


FIGURE 1 OPEX MODEL ARQUITECTURE

The first step of the model is to define different systems where the operations will be divided. Once general characteristics and operations (based on [20]) are defined, specific resources for each operation must be defined such as vessels (data from DTOcean [22] and local suppliers), equipment, labour and spares, duration of the operation, uncertainty level and mean time between failures [20] , planned operation (see [24]) OPERA experience will give inputs in the model such as failure rates and operations design.

The operations are either assigned as preventive or corrective actions (Figure 2) depending on the uncertainty level of the element that is considered as an input. High uncertainty operations will have a greater probability of being corrective, whereas well-known operations will have a preventive maintenance (see ANNEX I). Examples of preventive maintenance are inspections, calendar-based replacements and conditions monitoring operations.

All operations are considered independent of one another. However, the tool has the possibility to define a corrective operation as plannable in order to reflect the impact of monitoring in identifying potential maintenance needs.

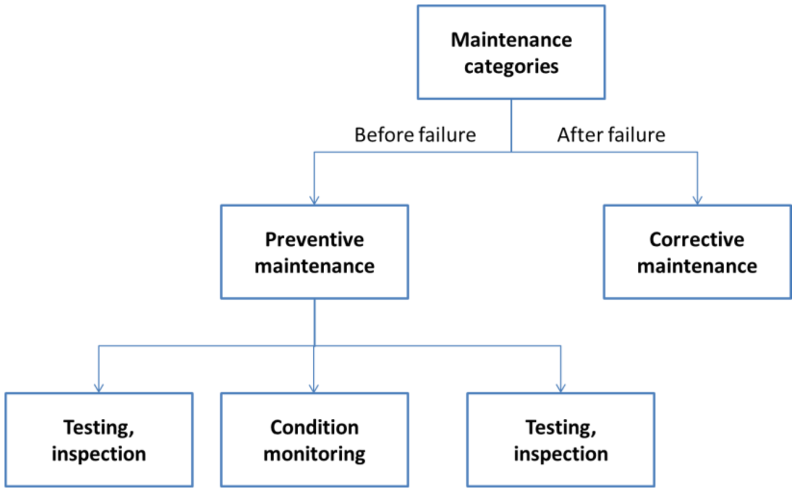


FIGURE 2 MAINTENANCE CATEGORIES FROM ISO 14224-2006 [23]

Two seasons have been considered to characterise farm accessibility, namely the summer season (March-August) and the winter season (September-February). Preventive operations will be schedule in the summer months leading to shorter waiting times. As a conservative measure, all corrective operations will be penalised in terms of waiting time and system availability.

Taking into account the failure rates of the different components and the maintenance plan, the full calendar of operations is generated along the farm project life. Once the operation time is estimated taking into account the different steps to complete each task, the total cost of each operation can be obtained.

3.2 Inputs required

The model requires some general input data for the cost estimation of the Operation and Maintenance plan developed for OCEANTEC's floating OWC buoy. The open-sea experience gained during the testing phase of the prototype will help improve the estimation of some of the inputs (e.g. operation time, maximum wave conditions for accessibility) and help optimize the design of the operations. Altogether this is expected to result in a better estimation of OPEX costs.

3.2.1 GENERAL INPUT

The following general parameters (Table 2) are needed to customise the O&M model:

TABLE 2 GENERAL PARAMETERS NEEDED TO CUSTOMIZE THE O&M MODEL

Parameter	Unit / description
Resource time series	Necessary for HMRC-UCC WWWT model "ANNEX II: WEATHER WINDOW WAITING TIME
Project life	Years
Distance to port	Km
Working day period	Hours
Initial year	-
Vessels data	See Table 3 below
Number of each operation type per farm	-

3.2.1.1 VESSEL DATA INPUTS

Regarding vessel data inputs, different references have been considered, starting from private quotations from suppliers, DTOcean project [22] and other literature sources. Table 3 shows the parameters for each vessel type. Some parameters are needed for the OPEX model and others as decision-making information in order to select vessel for a particular operation.

TABLE 3 VESSEL CHARACTERISTICS DATA

Name	Power (kW)	Normal speed (km/h)	Towing speed (km/h)	P nom % pot (0-1)	Consumption (Kg /kW)	Bollard pull (kG)	Deck (m^2)	Mobilization cost (€)	Day rate cost (€)	Waiting Day rate cost (€)	Base port
Tug boat #1	770	12,00	11,11	0,8	0,2	17000	50		6000		BILBAO
Tug boat #2	4698	12,00	17,04	0,8	0,2	91000	180	18000	8000	5000	SANTANDER
Tug boat #3	4388	12,00	20,74	0,8	0,2	100000	250		20000		BILBAO
Tug boat #4	3356	12,00	14,82	0,8	0,2	46000	100		7000		BILBAO
Multipurpose #1	2088	12,00	20,00	0,8	0,2	35000	150	25000	5650	2950	BILBAO
Multipurpose #2	2850	12,00	19,63	0,8	0,2	53400	180	29255	4700	3300	UK
Multipurpose #3	1791	12,00	18,52	0,8	0,2	33000	160	23720	3700	2600	UK
Multipurpose #4	895	12,00	17,22	0,8	0,2	15000	95	16000	3000	2000	UK
Multipurpose #5	403	33,34		0,8	0,2		20		2000		BILBAO
Boat #1		40,00		0,8	0,2				50		Armintza
Boat #2	130	46,30		0,8	0,2		12		1000		BILBAO
Boat #3	186	64,82		0,8	0,2		12		1000		BILBAO
ROV #1	186	64,82		0,8	0,2				2500		BILBAO
ROV #2	186	64,82		0,8	0,2			5500	4500		BILBAO

3.2.1.2 DESCRIPTION OF EACH OPERATION INPUT PARAMETER

At the beginning of Section 3, it was highlighted that each operation requires specific input data. Table 4 lists the different input parameters to describe each operation:

TABLE 4 DESCRIPTION OF INPUT PARAMETERS

<table>
<tr><th>Name of variable</th><th>Description</th></tr>
<tr><td>Item ref no.</td><td>Item name</td></tr>
<tr><td>Item details</td><td>Detail of the element, e.g. component or overall element (device; moorings and anchors; electrical equipment)</td></tr>
<tr><td>Planned operation (1/years)</td><td>Value between 0-1. Periodicity of interventions in a year (1 / year). There is no standardized way for defining a failure in the wind/wave energy industry. This analysis defines a failure as a visit to a turbine.</td></tr>
<tr><td>Uncertainty level</td><td>Probability of deviating from the average failure rate (1 - 4)
<table>
<tr><th>Uncertainty Levels</th><th>Standard Deviation / Mean [%]</th></tr>
<tr><td>1</td><td>0,001</td></tr>
<tr><td>2</td><td>10</td></tr>
<tr><td>3</td><td>50</td></tr>
<tr><td>4</td><td>Poisson - Exponential Distribution</td></tr>
</table></td></tr>
<tr><td>Mean time between failures (1/ years)</td><td>Average time between failures (1 / year)</td></tr>
<tr><td>Category</td><td>Three categories are typical for failure rates definition: Incipient, Critical, Degradation.</td></tr>
<tr><td>Failure mode</td><td>The manner in which an equipment or machine failure can occur. An example of a failure mode is corrosion, which might cause metal degradation and failure</td></tr>
<tr><td>Failure effect on the power production (0% -100%)</td><td>Impact of failure on energy production (0-1)</td></tr>
<tr><td>Action needed</td><td>Description of the intervention</td></tr>
<tr><td>Est. duration (hours)</td><td>Required duration time for action, excluding travel time</td></tr>
<tr><td>Location</td><td>Onsite or port maintenance</td></tr>
<tr><td>Vessels</td><td>Name of Vessel 1 required</td></tr>
<tr><td>Vessel aux 1</td><td>Name of Vessel 2 required</td></tr>
<tr><td>Vessel aux 2</td><td>Name of Vessel 3 required</td></tr>
<tr><td>Equipment</td><td>Necessary additional equipment for the repair</td></tr>
<tr><td>Equipment cost (€/h)</td><td>Equipment cost</td></tr>
<tr><td>Personnel</td><td>Additional Personnel description</td></tr>
<tr><td>Personnel cost (€/h)</td><td>Hourly personnel cost</td></tr>
<tr><td>Parts/consumables</td><td>Description of materials needed</td></tr>
<tr><td>Parts/consumables cost (€)</td><td>Material cost</td></tr>
<tr><td>Hs(m)</td><td>Maximum operational wave height</td></tr>
<tr><td>Towing required</td><td>Yes vs NO</td></tr>
<tr><td>Mounting time (h)</td><td>If one operation needs to be completed at port. Mounting and dis-mounting time of the element is considered</td></tr>
<tr><td>N operations</td><td>Number of operations of this type in a farm</td></tr>
<tr><td>Preparation Time (h)</td><td>Previous working time at port</td></tr>
</table>

3.2.2 DESCRIPTION OF INTERMEDIATE PARAMETERS OBTAINED IN THE MODEL

Some important parameters for each operation need to be assigned and/or computed for each operation during the project life:

- Preventive / corrective action
- Weather window waiting time
- Operation time of each operation

3.2.2.1 PREVENTIVE VS CORRECTIVE ACTIONS

Operations are defined as preventive or corrective actions depending on the uncertainty level, mean time between failures (1 / year) and planned operation (1/years) (see [24] and ANNEX III: COMPONENTS FAILURE RATES).

3.2.2.2 WEATHER WINDOW WAITING TIME

Weather window waiting time has been obtained taking into account the maximum operation wave height, H_S. A description in more detail of how this waiting time is calculated is presented in "ANNEX II: WEATHER WINDOW WAITING TIME". Two seasons have been considered to calculate waiting times depending on the type of operation (Figure 3): preventive operations in summer and corrective operations in winter. Summer If the operation is preventive (Figure 4). Winter (Figure 5) if the operation is corrective . If the weather window time increases waiting required time increases.

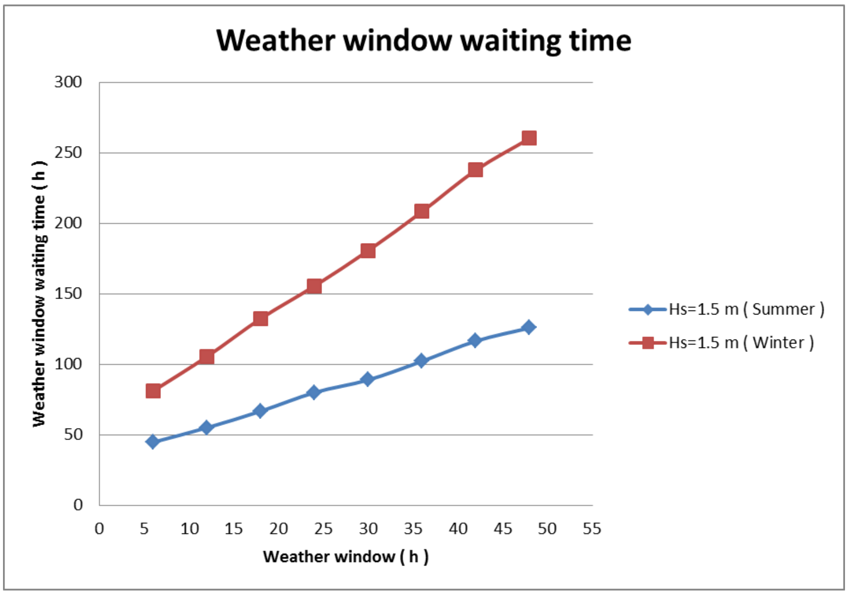


FIGURE 3 WEATHER WINDOW WAITING TIME IN BIMEP FOR H_S= 1,5M

The weather window length is considered to be equal to the operation and travel time when it is lower than working day period. Otherwise (when the time needed exceeds one working day), the required time is rounded up to the following expression:

$$n^{o}trips * travel\ time + working\ time\Big/_{24}$$

If more than one Vessel is required the most restrictive H_s limit is used to obtain the weather window waiting time (WWWT).

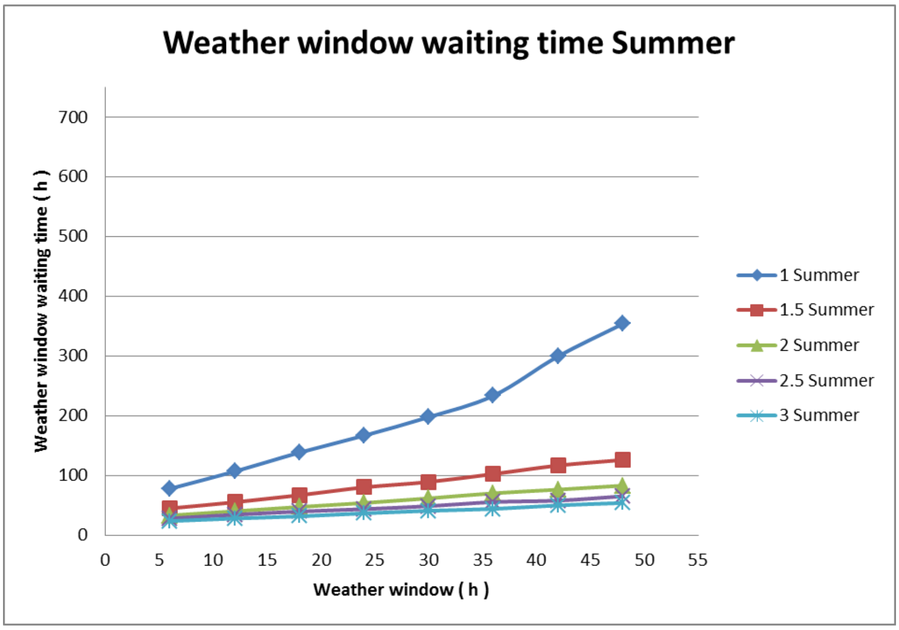


FIGURE 4 WEATHER WINDOW WAITING TIME SUMMER IN BIMEP

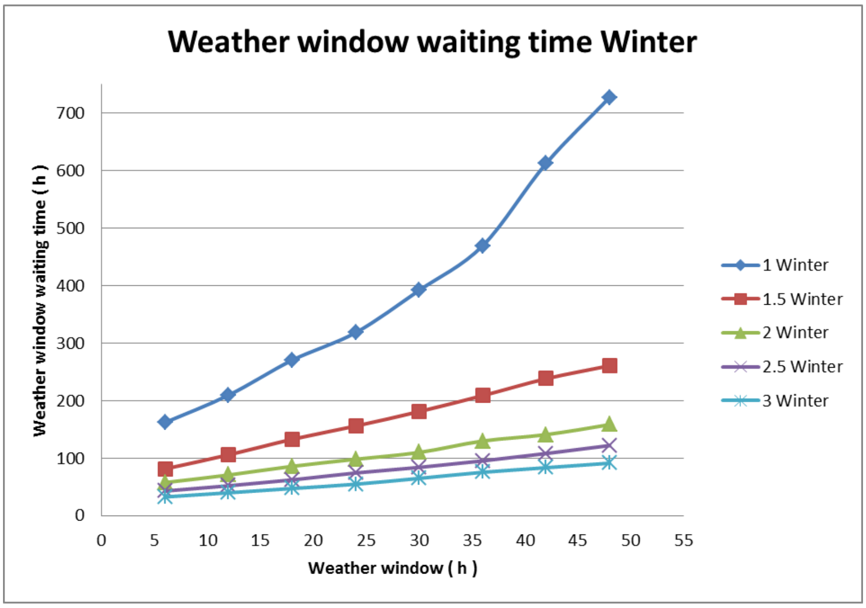


FIGURE 5 WEATHER WINDOW WAITING TIME WINTER IN BIMEP

3.2.2.3 OPERATION TIME OF EACH TASK

Time required for each operation (OT) has been obtained depending on whether it is corrective or preventive.

$$OT = WWWT + PT + TT + MT + DT$$

Where:

WWWT → weather window waiting time (considered when the operation is corrective)

PT → Preparation time (input)

TT → Travel time

MT → Mounting time (input if necessary)

DT → Duration working time (input)

For operations at port, Travel time or mounting and dismounting time is also considered.

The next flowchart (Figure 6) summarises the calculation of operation time depending on whether the operation is preventive or corrective, on site or at port.

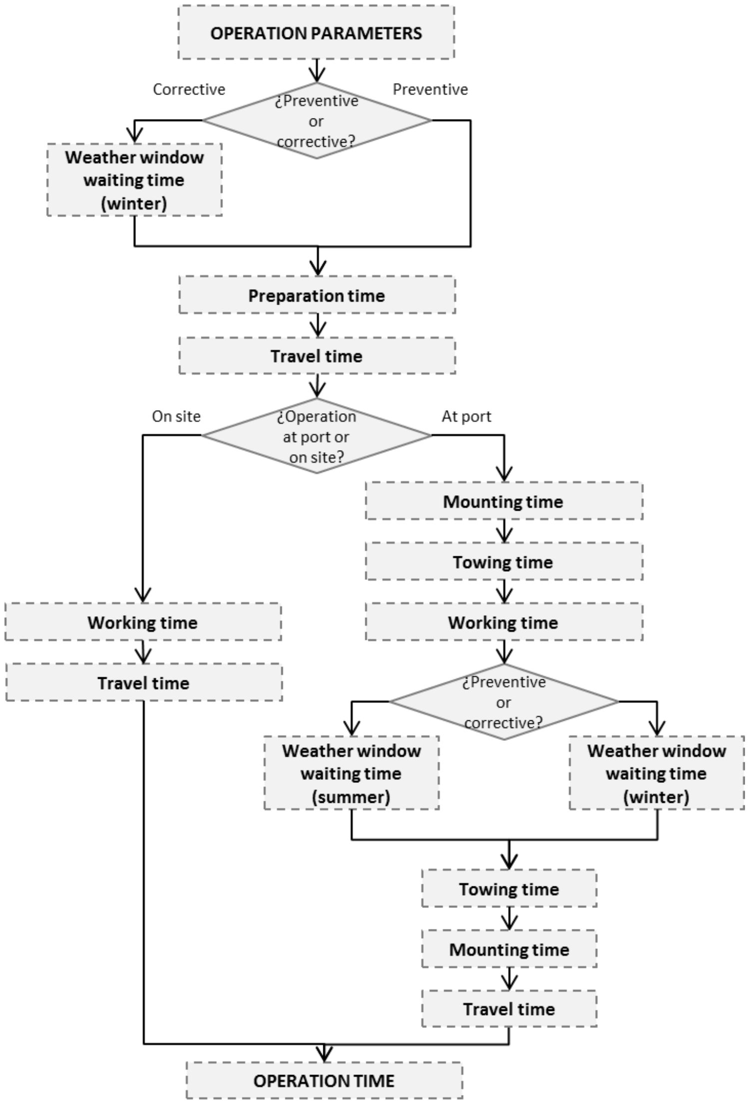


FIGURE 6 FLOW CHART REPRESENTING THE OPERATION TIME ESTIMATION DEPENDING IF THE OPERATION IS PLANNED, NON- PLANNED, ON SITE OR AT PORT.

3.3 Output parameters

There are three main output parameters that the global model will feed into the LCOE and LCA calculations.

- Operation cost. Total annually operation costs
- Availability. Uptime of farm over total time
- Litres of fuel consumption. Vessel emissions to perform the operations

3.3.1 OPERATION COST

Each operation cost has been obtained taking into account Vessels, Personnel cost and consumables costs (Figure 7).

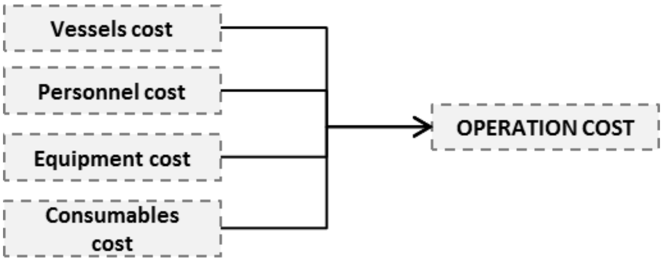


FIGURE 7 OPERATION COSTS DISTRIBUTION

The overall OPEX cost is the summation of each operation cost per year according to the following formula:

$$OPEX_{year} = \sum_{N=1}^{N} \left\{ N_{op} * \{V_C + P_c + C_c\} + N_{oc} * \{V_C + P_c + C_c\} \right\}$$

Where:

N_{op} → Number of preventive operations

N_{oc} → Number of corrective operations

V_C → Vessels renting cost

$V_C = \sum_{N=1}^{N} (OT + TT) * V_{RC}$

Where:

N → Number of vessels

V_{RC} → Vessels renting cost

TT → Travel time

OT → Operation time

P_c → Personnel cost

C_c → Consumables costs

3.3.2 AVAILABILITY

The profitability studies of the wave farm require an optimum balance between the operational expenditure and revenue lost because of downtime. The availability of a wave energy converter is the time that the device is producing energy.

In current offshore wind farms this value lies between 90%-95% ([1] , [25]), in onshore wind farms this value increase to 97% [1] , which is the target for Offshore wind farms. In wave energy farms the availability is estimated below these figures as we can observe in Figure 8.

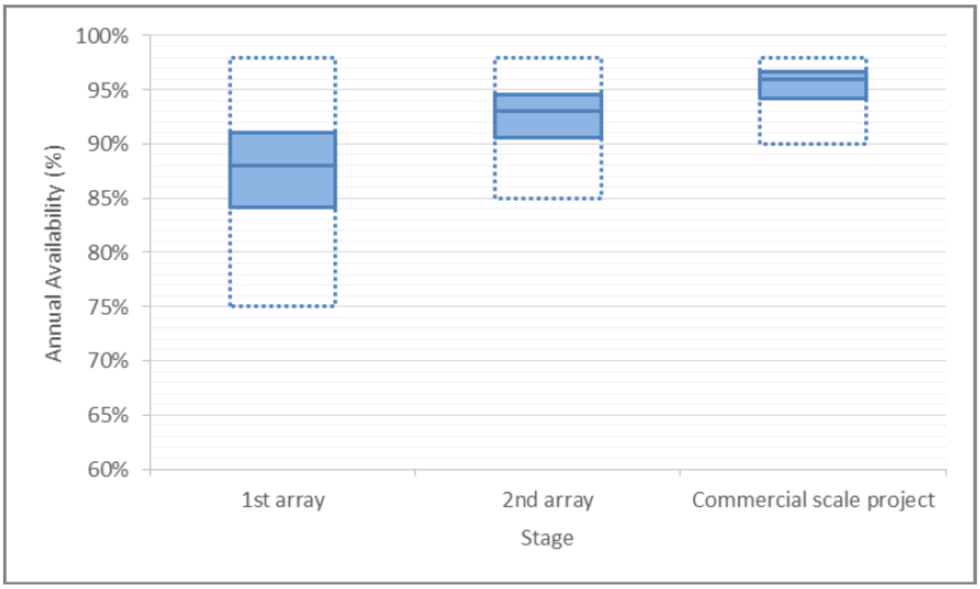


FIGURE 8 INDUSTRY AVERAGED AVAILABILITY AND LOCAL MAXIMUM AND MINIMUM VALUES (DOTTED LINES) AT EACH STAGE OF DEPLOYMENT [25]

The causes of reducing availability are:

- Harsh environmental conditions
- Limited accessibility
- More expensive maintenance
- Technology novelty

This is one of the main reasons to include environmental issues in the OPEX model. It is a key factor to optimize the marine operations.

Un-availability of the device has been obtained based on corrective and preventive maintenance Operation Times and Weather Window Waiting Times for corrective operation time.

$$A = \sum_{N=1}^{N} (Cm\, WWWT + OT) * Fe_{pp}$$

Where:

N → Number of operations

$Cm\ WWWT$ → Corrective maintenance Weather Window Waiting Time

Fe_{pp} → Failure effect on the power production (0%-100%)

OT → Operation time

Yearly revenues are obtained considering the total energy production and device availability.

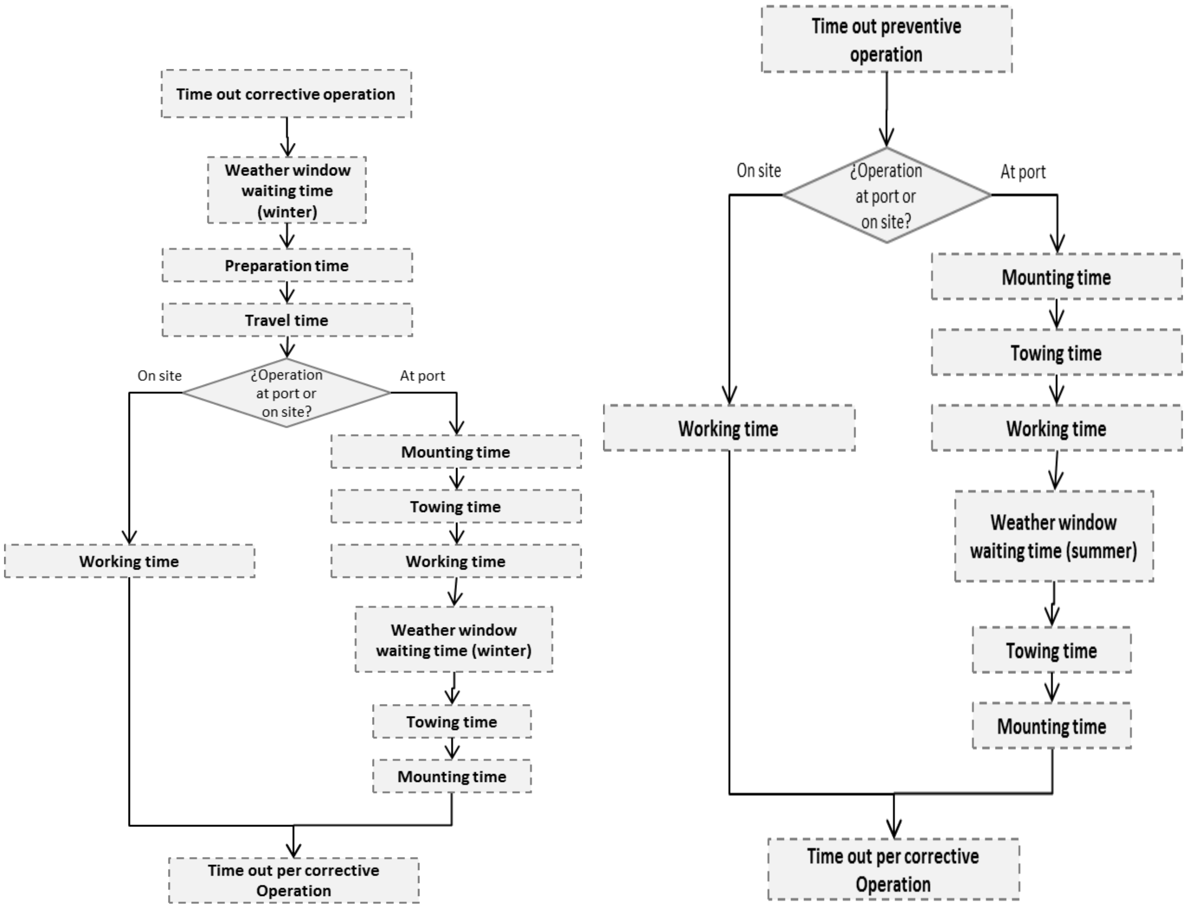


FIGURE 9 FLOW CHART REPRESENTING THE TIME OUT ESTIMATION FOR PREVENTIVE AND CORRECTIVE OPERATIONS

3.3.3 LITRES OF FUEL CONSUMPTION

Wave energy projects are subjected to Environmental Impact Assessment (EIA), consisting in the evaluation of the potential ecological effects. It is usual to apply the Life Cycle Assessment (LCA) methodology to define environmental impact in terms of $kgCO_2$ eq/kWh produced.

LCA is a methodology to calculate the environmental impacts resulting from the whole product life cycle steps, including impacts often ignored in traditional environmental analyses (e.g. raw material extraction, transportation, installation, maintenance process, operation, etc.) and considers the effects of the power production across its entire value chain. For this purpose, the model will obtain Installation, OPEX and Decommissioning If the time needed exceed than one working day fuel consumptions.

Litres of fuel consumed have been obtained taking into account the number of trips, speed and the type of vessel for each trip. The formula used is the following one:

$$Liters\ consumtion\ year = \sum_{N=1}^{N} \gamma * \sum_{V=1}^{V=3} \left\{ V_{np} * V_{CF} * V_c * \frac{D}{V_s} + V_{np} * V_{CF} * V_c * DT \right\}$$

Where:

γ → Number of same Operations

N → Number of operations

D → Distance from port to offshore site (km)

V → Number of vessels (maximum 3)

V_s → Vessel speed (km/h)

V_c → Vessel consumption (kG/kWh)

V_{np} → Vessel nominal power (kW)

V_{CF} → Vessel Capacity Factor (0-1)

DT → Duration (h)

Depending on the type of operation different capacity factors of the vessel motors can be taken into account:

- CF_NORMAL_SPEED = 0.8
- CF_TOWED_SPEED = 0.7
- CF_WORKING_TIME = 0.2 (CF of ship waiting at wave farm)

4. APPLICATION OF THE MODEL TO THE OFFSHORE OPERATIONS OF THE OPERA PROJECT

Since the prototype installation in October of 2016, several operations have been carried out related to the commissioning of the different systems of the Power Take Off (e.g. turbine, generator, power electronics or control). After the analysis of the operations that are currently being developed and with a better knowledge of the behavior of different components, the inputs of the OPEX model will be improved.

The case study model has been defined with 16 main Operations (Figure 10) classified in five groups (Figure 11):

- Structure
- Mooring
- PTO
- Electric
- Control

In each group there are at least three operations:

- Inspection: Preventive maintenance
- Minor repair: Preventive / Corrective
- Major repair: Preventive / Corrective

There are also some corrective repairs that are plannable as a result of the effective monitoring.

Item ref no.	Item details	Planable	Failure mode	Failure effect on the power production (0% -100%)
Item name	*e.g. component or overall element (device; moorings and anchors; electrical equipment)*		*i.e. what type of failure*	*i.e how does it impact production*
Structure - Structural	Structural component	NO	Major structural failure (Un-Planned)	1
Structure - Structural	Inspection	NO	Inspection (Planned)	0
Structure - Corrosion	All the structure	YES	Minor repariments due to marine growth, corrosion. Paint the structure (Planned)	1
Mooring - Connector	Connector or poliester rope	NO	Inspection (Planned)	0
Mooring - Buoys -Wire break	Mooring Wearout	NO	Anchor drag, Surface buoy loss, Cell wire break (Un-Planned)	0,5
Mooring -Mechanical Failure	Mooring mechanic failure	NO	Wearout (Un-Planned)	1
PTO - Power Electronics	Power electronics	YES	Mechanical failure (Un-Planned)	1
PTO - Generator	Generator, Mechanical components , Bearings	NO	Winding failure, or mechanic problems (Un-Planned)	1
PTO - Turbine	Turbine, Blade	YES	Broke a blade (Un-Planned)	1
PTO - Valves	Valves	YES	Valve repairment (Un-Planned)	0,5
PTO - Global	Turbine / Back to back / Generator / bilge ststem	NO	Inspection (Vibrations, Check the insulations, cleaning, thermography (Planned)	0,5
Electric - Umbilical	Umbilical degradation inspection	NO	Inspection (Planned)	1
Electric - Umbilical	Cable	NO	Absence of primary electricity, auxiliary electric network and communications to the WEC. Bend stiffner or restrictor damage Cable breaks or connector looses (Un-Planned)	1
Electric - Umbilical	Replace element	YES	Damage bend stiffener , buoy , bend restrictyor (un-planned)	1
CONTROL- Inspection	Inspection	NO	Inspection Problems on Safety system , loss of comunication (Planned)	0
CONTROL - Damage	Control & sensors / Protection function. Electric device problems	NO	Control damage problems (Un-Planned)	0,5

FIGURE 10 EXAMPLE OF 16 IDENTIFIED OPERATIONS

In order to demonstrate that the model is operational for the OPERA project, a case study is considered consisting in 72 devices located at 15km from shore with the following operations. Figure 11 shows a summary of different outputs of the model where green label means preventive and red label corrective operations.

OPERATION AND MAINTENACE (OPEX) MODEL

NUMBER OF OPERATIONS	1		2		3	
Structure - Structural	0	0	0	0	0	0
Structure - Structural	0	0	1	0	1	0
Structure - Corrosion	0	0	0	0	0	0
Mooring - Connector	0	0	0	0	0	0
Mooring - Buoys -Wire break	0	1	0	0	0	0
Mooring -Mechanical Failure	0	0	0	0	0	0
PTO - Power Electronics	0	0	0	0	0	0
PTO - Generator	0	0	0	1	0	1
PTO - Turbine	0	0	0	0	2	0
PTO - Valves	0	0	0	0	0	0
PTO - Global	0	0	2	0	2	0
Electric - Umbilical	0	0	0	0	0	0
Electric - Umbilical	0	0	0	0	0	0
Electric - Umbilical	0	0	0	0	0	0
CONTROL- Inspection	0	0	4	0	4	0
CONTROL - Damage	0	0	0	0	0	0

	1		2		3	
Structure - Structural	0	0	0	0	0	0
Structure - Structural	0	0	2269,423018	0	2269,423018	0
Structure - Corrosion	0	0	0	0	0	0
Mooring - Connector	0	0	0	0	0	0
Mooring - Buoys -Wire break	0	5734,989201	0	0	0	0
Mooring -Mechanical Failure	0	0	0	0	0	0
PTO - Power Electronics	0	0	0	0	0	0
PTO - Generator	0	0	0	3889,992801	0	3889,992801
PTO - Turbine	0	0	0	0	15779,9856	0
PTO - Valves	0	0	0	0	0	0
PTO - Global	0	0	4869,978402	0	4869,978402	0
Electric - Umbilical	0	0	0	0	0	0
Electric - Umbilical	0	0	0	0	0	0
Electric - Umbilical	0	0	0	0	0	0
CONTROL- Inspection	0	0	9159,971202	0	9159,971202	0
CONTROL - Damage	0	0	0	0	0	0

	1	2	3	4	5	6
Cost OPEX per year (€)	5734,989201	20189,36542	35969,35102	17668,79564	51749,33662	48954,30423
Liters fuel per year (L)	7854,145802	8670,324744	9119,454439	773,2588919	1861,565105	9359,490178
Total time out per year (h)	132,8384277	271,6768554	287,6768554	4	42	139,8384277
Total_time_out_per_year_prevenentive (h)	0	2	18	4	42	7
Total_time_out_per_year_corrective (h)	132,8384277	269,6768554	269,6768554	0	0	132,8384277
Total corrective cost per year (€)	5734,989201	3889,992801	3889,992801	0	0	5734,989201
Total preventive cost per year (€)	0	16299,37262	32079,35822	17668,79564	51749,33662	43219,31503
Total number operations	1	8	10	8	12	14
Total number corrective operations	1	1	1	0	0	1
Total number preventive operations	0	7	9	8	12	13

FIGURE 11 OPEX MODEL RESULTS EXAMPLE

The next figure is an example of fuel consumption evolution over the years of the project and comparative of number of preventive and corrective operations

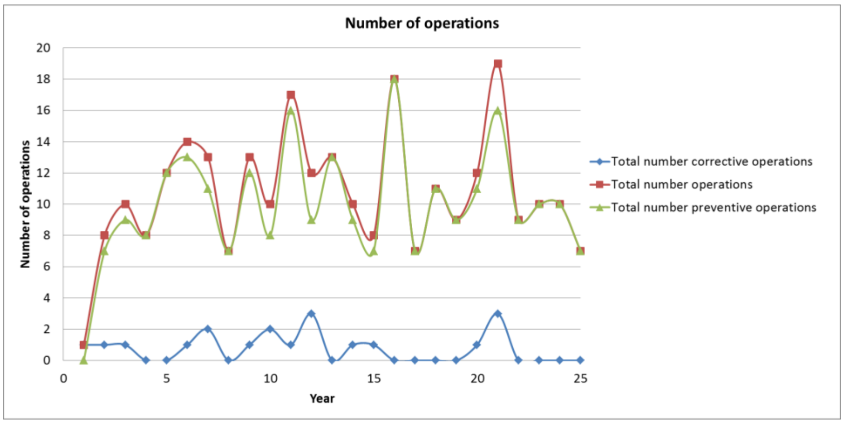


FIGURE 12 NUMBER OF PREVENTIVE AND CORRECTIVE OPERATIONS

The annual evolution of the OPEX cost also is obtained:

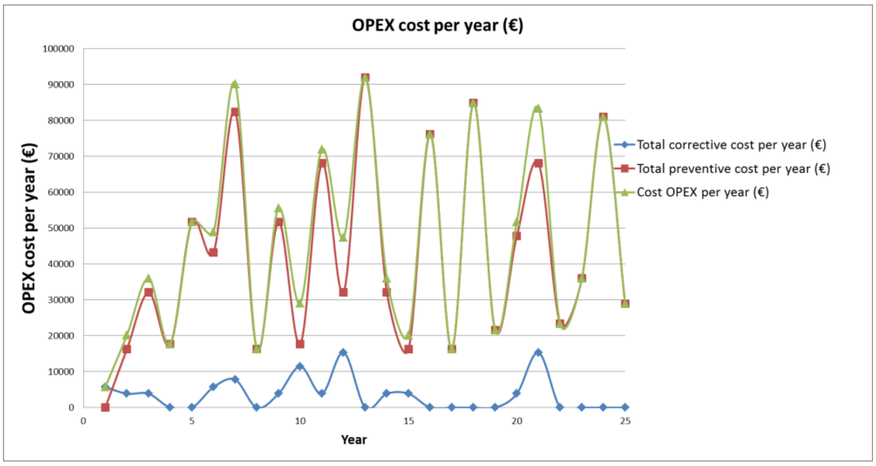
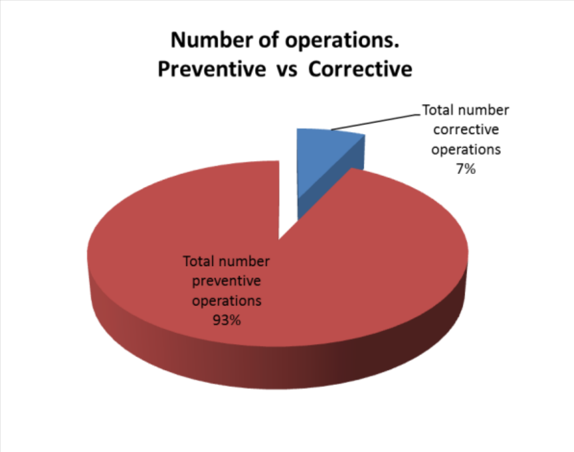


FIGURE 13 OPEX COST PER YEAR

Figure 14 shows that despite the number of corrective operations is considerably smaller the corrective downtime is quite significant. It is an important factor because the availability is a key factor in the annual economic balance of the farm. Corrective operations are completed in winter and preventive operations in summer with each weather window waiting time.



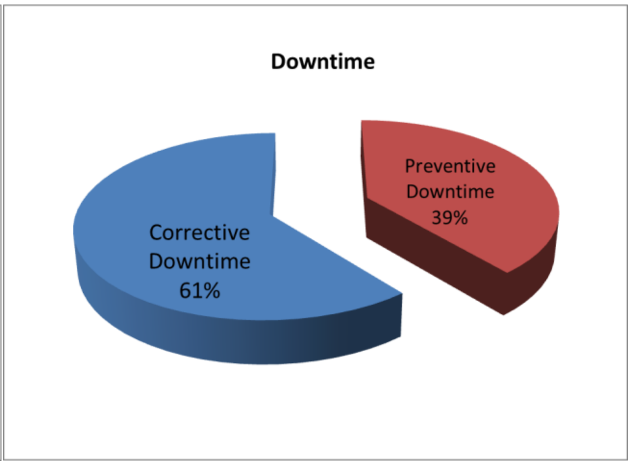


FIGURE 14 COMPARATIVE BETWEEN NUMBER OF PREVENTIVE AND CORRECTIVE OPERATIONS, AND TOTAL TIME OUT PREVENTIVE AND CORRECTIVE

The OPEX model developed did not optimize the resources, but modifying the inputs different O&M strategies can be applied and the effects on the cost can be analyzed. For example:

- Case 1: operations are performed in series, i.e. one trip per type of operation and device.
- Case 2: operations performed in a sequence, e.g. perform two operations of the same type in two different devices in the same travel. The ship cost will be halved and the working hours will be doubled.
- Case 3: operations performed in parallel, i.e. two different staff groups travel in the same ship to perform the same operation in parallel. This option can be reflected duplicating the personnel cost and dividing by two the operations.

In the next table there is a summary of the results obtained with the three different strategies where the same type of preventive operations has been grouped in pairs:

TABLE 5 CASE STUDIES RESULTS

	OPEX year per device k€	OPEX year farm (M€)	Total OPEX cost (M€)
Case 1	42,83	3,08	77,09
Case 2	37,26	2,68	67,07
Case 3	39,25	2,82	70,66

It can be seen that grouping operations of the same type (operations performed in a sequence) can have a significant impact in reducing the OPEX costs.

5. CONCLUSIONS

As a result of this work being carried out, the following conclusions can be drawn:

- A detailed OPEX model has been constructed and demonstrated as fit for purpose where all of OCEANTEC operations can be evaluated.
- The OPEX model has been adapted to be easily included in the global cost model that is being produced in WP7.
- The model is useful to obtain annual costs, availability and environmental parameters.
- The weather window time tool developed by HMRC-UCC has been integrated in the OPEX model.
- The model is fully operational.
- The model gives the opportunity to identify the critical costs and help to improve OPEX strategies.
- The most important parameters in terms of costs have been identified with this tool, such as the type and availability of vessels and downtime.

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7. ANNEX I: GENERATION OF RANDOM EVENTS FOR OPERATION AND MAINTENANCE SCHEDULING

A function in Visual Basic has been coded in order to generate random events/occurrences corresponding to each specific operation which is supposed to be carried out during the lifetime of the project.

The purpose of the function is to determine if during the lifetime of the project, a specific operation is required because of sudden failure of one or more components (corrective maintenance) or if the same operation can be planned (calendar based maintenance). The function is able to determine, therefore, how many corrective and/or calendar based maintenance operations are required per year. As an outcome, then, for each operation there will be a planning of operations in the time domain; being the approach totally stochastic, then, it is required to launch the function a bunch of times, in order to extract statistics out of the population of samples generated.

For each operation, when the function F_events is called, it requires the following inputs:

- Life [years]: it represents the lifetime of the project
- Planned Operation [years $^{-1}$] PO: it represents the frequency of the calendar based maintenance
- Mean time between failures [years $^{-1}$]: despite the name, it represents the failure rate of the specific components
- Uncertainty level [-]: it is an integer from 1 to 4. Each number corresponds to a level of "uncertainty" of the occurrence of the events, based on the experience and information about the components.

7.1 Probabilistic background for the generation of events

The variable which is generated randomly is the time between two different events. For this reason, the reciprocal of the input "mean time between failures" MTTF is considered. For uncertainty level from 1 to 3, such a variable is considered to be Gaussian distributed. The standard deviation of the process is calculated as a percentile of the mean time to failure, following the table:

Uncertainty Levels	Standard Deviation STD/ Mean Time to Failure MTTF [%]
1	0.001
2	10
3	50

TABLE 6 OPERATION UNCERTAINTY LEVEL DESCRIPTION

The probability density function pdf is Gaussian:

(1) $$pdf(\Delta t) = \frac{1}{STD\sqrt{2\pi}} exp\left[-\frac{(\Delta t - MTTF)^2}{2STD^2}\right]$$

The Visual Basic default generator of normal distributed samples is used; in case a negative number is generated, then a new sample is generated.

When the uncertainty level is equal to 4, then an exponential distribution (2) is adopted instead of (1).

(2) $$pdf(\Delta t) = \frac{1}{MTTF} exp\left[-\frac{\Delta t}{MTTF}\right]$$

7.2 Flowchart

1) The initial time is t_0 and the final time is $t_{end} = t_0 + life$
2) Start the counter $i = 1$
3) At the initial time, a random sample Δt_i is generated, following (1) or (2) according to the level of uncertainty and it is summed up to the initial time of the planning $t_i = t_{i-1} + \Delta t_i$.
4) It is checked if $t_i > t_{end}$. In this case, it terminates the execution of the planning loop.
5) If $t_i < t_{end}$ and $\Delta t_i < PO - \alpha MTTF$ (with α being a tolerance coefficient) then the maintenance is corrective and the event occurs and Δt_i is the one generated.
6) Otherwise if $\Delta t_i > PO - \alpha MTTF$, then the maintenance is planned and $\Delta t_i = PO$.
7) The counter is updated $i = i + 1$.

8. ANNEX II: WEATHER WINDOW WAITING TIME

The objective of the code developed by HMRC-UCC is to give statistical measures of wait times for a particular offshore site. Outputs of the executable are average wait times and standard deviation on said wait times for a user defined length of time (season).

The following text is a description of how to utilize the executable code, to yield these measures.

The input data is in the form of time series of hourly records. Properties such as significant wave height (Hs), peak period (Tp) wind speed & direction (Ws & Wd) and wave direction (α) are given for each hour. The user will define threshold limits on the aforementioned properties. If the parameters are beneath the limit (s) then the conditions are considered safe and there exists a weather window. The user will also define the length of weather window of interest, i.e. the number of consecutive hours in which the parameters lie below the threshold limits (6 hours 12 hours etc..).

The user interface is an Excel workbook which has three tabs.

1. Data
2. Variables
3. Results

The first tab contains the wave time series data for the particular site (i.e. BIMEP)

The second tab is for variables which the user can edit

The third sheet contains the outputs.

8.1 Methodology

The problem of whether all the hourly parameters lie below their associated threshold values is considered as a Boolean logic statement. If all the values are beneath their threshold values, then the output is 1 and there exists a window for that hour. If one or more physical parameter lies above the limit, then the output is 0 and there is no window. The problem of estimating weather windows (and associated wait times between windows) is then reduced to a familiar problem of counting sequences of 1's and 0's.

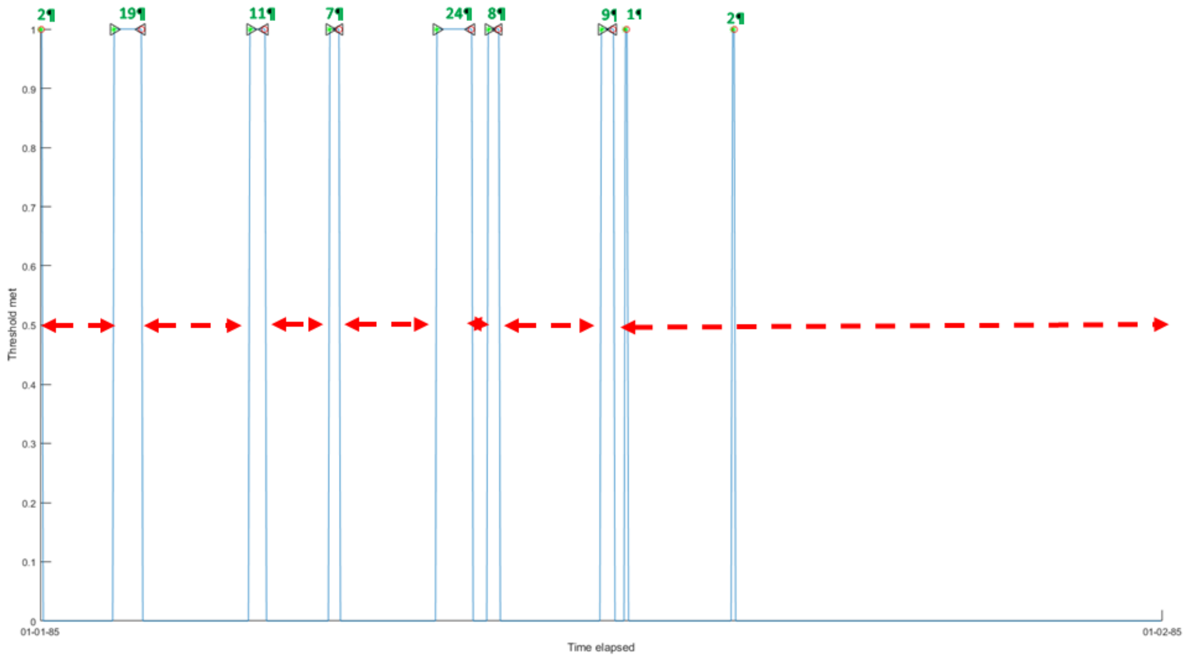

FIGURE 15: SAMPLE WEATHER WINDOW AND WAIT TIME PROCEDURE

As an example the figure on the previous page considers a single season as the month of January 1985. The example is for a single parameter study, Hs, however the methodology is identical for multi-parameter cases. The threshold statement in this example is Hs<1.0m and the window length of interest is six hours. There are nine instances where the conditions are below the threshold; however some of these are very brief (not remaining below the limit for the required 6-hour period). The number of hours below the threshold is written in green font above. The method of counting long windows is to take the nearest whole integer fraction i.e. in the example above.

There are 4 six hour windows in a 24-hour period, and there are 3 six-hour windows in a 19-hour period. Consequently, there are 11 six-hour weather windows during January 1985. The remaining time during the interval that is not a window is classified as wait time. It can be seen therefore that the percentage time waiting for a six-hour window is;

$$\frac{Total\ hrs\ in\ season - (number\ of\ windows\ x\ window\ length)}{Total\ hrs\ in\ season} = \frac{744 - (11x6)}{744} \approx 91\%$$

The average wait time is the total time spent waiting divided by the number of instances waiting. Referring to the previous figure there are seven separate intervals of waiting for a weather window such that the average wait time is;

$$\frac{Total\ hrs\ waiting}{Number\ of\ waiting\ instances} = \frac{744 - (11x6)}{7} \approx 96.8\ hrs$$

Since there are a number of years' worth of data, it is possible to estimate mean and standard deviation values for the percentage wait time and the average wait time. The mean is given by;

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n}$$

With $\overline{X}$ denoting the mean quantity, X_i the yearly value and n equal to the number of years. The standard deviation (S) is given by;

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left|X_i - \overline{X}\right|^2}$$

The outputs of the program are therefore the seasonal mean and deviation, taken over the number of years of data supplied by the user. This yields the percentage wait time and the average wait time for a given season and for a given window length (i.e. 6 hours). The next iteration is to repeat the procedure for the next window length (e.g. 12 hours) and so on, until results for all window lengths of interest have computed. Once all the window length results have been obtained for the initial threshold limit (Hs<1m in this example), the limit is advanced to the next user defined value (e.g. 1.5m) and the entire process is repeated.

8.2 Inputs

There are two input sheets for the user; the first 'Data' contains the time series data. The second sheet 'Variables' contains the user defined variables (number of seasons, window lengths … etc.).

8.2.1 DATA

The default data set used is the thirty-one years of hind cast data for the BiMEP site. The data is located in the first worksheet tab labelled 'Data'. Header columns are:

1. Time (datenum format)
2. Time (Julian format)
3. Day
4. Month
5. Year
6. Time (hh:mm)
7. Significant wave height (m)
8. Peak Period (s)
9. Wave Direction (^{o})
10. Wind speed at 10m height (m/s)
11. Wind direction (^{o})

Data from alternative sites can be inputted on this sheet, however the user is advised to ensure the new data is inputted into the correct column number, and to retain the same units (m, m/s etc.)

	A	B	C	D	E	F	G	H	I	J	K
1	Time (datenum format)	JD = Time + 1721058.5	Day	Month	Year	Time	Significant wave height (m)	Peak period (s)	Wave direction (0)	Wind speed at 10m height (m/s)	Wind direction (0)
2	725008	2446066.5	1	1	1985	00:00	0.007603722	2.0451	283.1991	3.0120858	339.72038
3	725008.04	2446066.54	1	1	1985	01:00	0.79720063	13.7578	321.6458	3.7220871	327.66476
4	725008.08	2446066.58	1	1	1985	02:00	1.3687357	13.7578	319.4391	4.8776087	326.34205
5	725008.13	2446066.63	1	1	1985	03:00	1.4834591	13.7578	318.1402	6.7807856	332.81577

FIGURE 16: SAMPLE DATA FROM BIMEP SITE

8.2.2 VARIABLES

The variables include:

num years the number of years' data to examine. The default value is 31 from the BIMEP data site however, if examining an alternative site; this figure should be set to the number of years of data available.

num seasons the number of seasons in each year. The user can select;

- 1 season (a year)
- 2 seasons (Summer and Winter)
- 4 seasons (Spring, Summer, Autumn & Winter)
- 6 seasons (season 1, season 2, …. season 6)
- 12 seasons (season 1, season 2, …. Season12)

The user must supply the date vectors for each initial season. i.e. the day the month and the year. The seasons need not start on the 1st day.

Each season will begin at midnight of the first season (i.e. 00:00 1st Mar) and end at the time stamp <u>immediately before</u> the next season (i.e. 23:00 31st Aug). The user should take account of which season will include leap year data. Be advised that the default site data begins in 01/01/1985 and ends 31/12/2015; therefore, in the likely event of a season starting later in the calendar year than the 1st of January some of the data at the beginning and end of the 31-year record will be 'lost'. To overcome this, the user must drop the number of years to 30.

window lengths(min,step,max)

By varying the three parameters below, the user selects a vector of window lengths of interest. In the example above the window length vector is [6:6:48] so that the windows of interest are [6 12 18 24 30 36 42 48] hours.

min window length The minimum window length of interest (e.g. 6 hours)

window length step the window length time step (e.g. 6 hours)

max window length the maximum window length (e.g. 48 hours)

The user must find a balance between more information and more time spent processing results. It is advised to use a longer time step to study broad trends and a finer time step to study more specific details.

num parameters the number of parameters to be studied (1-3)

Boolean Indicators For Hs, Tp Ws & Wd

Related to the previous parameter 'Num Parameters'; the indicators are switches to determine whether the associated parameter is of interest. 1=to be included, 0=not included.

For example, the set-up shown in the figure below would indicate a single parameter (Hs) study.

Num Parameters			
1			
Hs	Tp	Ws	Wd
1	0	0	0

FIGURE 17 EXAMPLE ONE PARAMETER STUDY

An example three parameter study is shown below; the parameters of interest are significant wave height, wind speed & direction.

Num Parameters			
3			
Hs	Tp	Ws	Wd
1	0	1	1

FIGURE 18: EXAMPLE THREE PARAMETER STUDY

Vectors for threshold limits of Hs, Tp, Ws & Wd.

the threshold limits for the various parameters in vector form.
Referring to Figure 3;

The significant wave height (Hs) vector is [1 1.5 2 2.5 3 3.5 4 4.5 5] meters.

The peak period (Tp) vector is [6 8] seconds, however the Boolean indicator for Tp is set to zero so Tp will not be considered in the calculations.

The Wind speed (Ws) vector is [6 8] seconds, however the Boolean indicator for Ws is set to zero so Ws will not be considered in the calculations.

The Wind direction (Wd) vector is between [340° > Wd < 20°] degrees and between [300° > Wd < 60°] degrees, however the Boolean indicator for Wd is set to zero so Wd will not be considered in the calculations.

A	B	C	D	E	F
Num Years	Num Seasons				
30	2				
Start Day	Start Month	Start Year			
1	3	1985		Run	
1	9	1985			
Min Window length (hr)	Window length Step (hr)	Max Window length (hr)			
6	6	48			
Lat	Long	Data_Import			
51.8969	-8.4863	1			
No Parameters					
1					
Hs	Tp	Ws	Wd		
1	0	0	0		
			greater than >	less than <	
1	6	6	340	20	
2	8	8	300	60	

FIGURE 19: DEFAULT VARIABLES SHEET LAYOUT

8.2.3 OUTPUTS

The third tab contains the results.

	A	B	C	D	E	F	G	H	I
1	Hm0	1 m							
2		Summer				Winter			
3		%WT	std(%WT)	avgWT {hr}	std(avgWT) {hr}	%WT	std(%WT)	avgWT {hr}	std(avgWT) {hr}
4	6	68.03892	6.180689	77.78026958	6.180689375	82.24217	4.98647	161.96183	4.986469956
5	12	70.99687	5.869937	106.5836547	5.869937495	84.0884	4.408921	209.45361	4.408921426
6	18	73.62081	5.876324	138.2858364	5.876323932	85.63536	4.405877	270.23298	4.405876529
7	24	76.11692	5.491222	166.6781566	5.491221964	87.14549	4.010192	318.18366	4.010191889
8	30	77.83649	5.041943	197.6099982	5.041942583	88.14457	4.075951	391.75795	4.075951015
9	36	79.59136	4.926292	233.4904481	4.926292171	89.33702	3.824023	469.31667	3.824022545
10	42	81.60392	5.152177	299.4117697	5.152177336	90.39595	4.09361	612.52795	4.093609961
11	48	83.24559	4.955036	353.6859341	4.955036272	91.86004	3.352594	727.28	3.352593829
12									
13	Hm0	2 m							
14		Summer				Winter			
15		%WT	std(%WT)	avgWT {hr}	std(avgWT) {hr}	%WT	std(%WT)	avgWT {hr}	std(avgWT) {hr}
16	6	17.02524	4.597866	32.83901443	4.597866064	41.21087	7.523066	57.39399	7.523066215
17	12	18.67161	4.843996	39.97101469	4.843996089	43.69245	7.674383	70.536689	7.67438342
18	18	20.19587	4.990448	47.15567209	4.990447853	46.03591	7.695084	85.624729	7.695083989
19	24	21.36741	5.351171	53.81574221	5.351170925	47.99263	7.649605	97.935777	7.64960467
20	30	23.03601	5.315953	61.57955534	5.315953074	49.56262	7.898088	109.73728	7.898087707
21	36	24.41598	5.768229	70.08783718	5.768228519	51.8232	8.013382	129.56834	8.01338152
22	42	25.33865	5.653722	76.24640014	5.653721641	53.13996	7.50954	140.70705	7.509539585
23	48	26.28848	6.2024	82.85910834	6.202400443	55.24862	7.871048	158.10584	7.871047895

FIGURE 20: SAMPLE RESULTS

The first row is the identifier of the particular threshold conditions. i.e. Hs<1m.

There is a row for each window length and for each window length;

- The average Percentage of the season spent waiting for the threshold (i.e. the average % over all n years)
- The standard deviation of the previous value (i.e. the standard deviation of all n yearly values)
- The average time (in hours) spent waiting for the threshold to be met
- The standard deviation of the previous value

These four values are given for each window length for the first season and for each subsequent season 2, season 3 … etc.

The next row is a left blank for space while the following row is the identifier for the next threshold condition. i.e Hs<2m.

The results are tabulated as before with rows of window length, and columns of seasonal results.

9. ANNEX III: COMPONENTS FAILURE RATES

The definition of Wave energy converters failure rates and requirements for repair is necessary for modeling and cost reducing Operation and maintenance. There is not data from commercial wave energy farms and few offshore wind farm failure rates have been published. The average failure rate for an offshore wind turbine levels out at approximately 10 failures per turbine per year by a wind farm's third operational year [25] .

Failure rates are simulated based on constant failure rates with the simplifying assumption that failures occur independently of each other.

TABLE 7 FAILURE RATES

	Failure rate	Reference
Structure	0,18	[1]
Auxiliary system Pumps		[27]
Power electronics	0,27	[29]
Mooring line 0,00225	0,00225	[24]
Generator mechanical components	0,26	[29]
Turbine blade	0,55	Same reference as turbine blade [30]
Valve	0,1	[31]
Umbilical	0,004	[32]
Cable	0,004	[32]
Electric control	0,77 (0,42 electrical components + 0,35 sensors)	[33]