

D8.3

Documentation of impact assessment model

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Nomenclature

Abbreviation	Description
CAPEX	Capital Expenditures
CLV	Cable Laying Vessel
D&C	Development and consenting
FINEX	Financial Expenditures
GUI	Graphical User Interface
KPIs	Key Performance Indicator
HV	High Voltage
ICC	Initial Capital Cost
ICM	Internal Cutting Manipulator
LCOE	Levelized Cost of Electricity
MTTF	Mean Time to Failure
MV	Mean Voltage
OPEX	Operational Expenditure
O&M	Operation and Maintenance
P&A	Production and Acquisition Phase
POF	Probability of Failure
ROV	Remotely Operated Underwater Vehicle
SOVs	Special Operations Vessels
WACC	Weighted Average Cost of Capital

1. Executive Summary

This report documents the background of the impact assessment model that has been developed as part of WP8 of the ROMEO project. This model will be employed in the remaining months of the project in order to evaluate the impact of scenarios that will incorporate innovations from other activities of the project compared to a base line case.

The main characteristics of this model is its modularity, the incorporation of the most updated parametric equations, the high fidelity of evaluation of key cost components, a detailed evaluation of O&M costs and associated KPIs, consideration of uncertain inputs and finally evaluation of environmental related KPIs.

The report, is linked to previous deliverables, D8.1 and D8.2, where the theoretical background of life cycle cost and environmental impact assessment modelling have been presented, and here the focus is the presentation of principles incorporated in this purpose-developed impact assessment model and associated tool.

After a short introduction stating the aim of the report, a high-level description of the impact assessment model, highlighting its key modules are presented. Subsequently, the fundamentals of the Life Cycle Cost (LCC) module, which is the backbone of the impact assessment model, the purpose-developed O&M module and the Environmental impact assessment module are discussed. Next, the interfaces of the different modules are presented, clearly listing the inputs and expected outputs. Finally, the report concludes with reference to next steps and future work that will link the work so far with consequent tasks of the project.

2. Introduction

The financial appraisal of offshore wind farms is a demanding task which requires a number of factors to be considered in order to ensure that relevant KPIs are estimated in a meaningful way. Key elements of Capital expenditures (CAPEX), Operating expenditures (OPEX), Financial expenditures (FINEX) and the amount of energy production should be modelled through appropriate methods, based on sound assumptions. In addition, consideration of the service life emissions of renewable energy projects are meaningful so as to evaluate their actual contribution to sustainable development.

For the purpose of the ROMEO project, these considerations have been taken into account and after review of available tools and published frameworks, which have been documented in a previous deliverable [1], a purpose-specific impact assessment tool has been developed and will be employed in the remaining 24 months of the project in order to quantify the impact of the technological advancements that will qualify through the project, based on a number of realistic scenarios that will be developed within the ROMEO consortium.

Following a detailed literature and market review, the specification of the impact assessment tool was determined and can be summarised as follows:

- Tool should be modular, with the individual steps having clearly defined interfaces (inputs/outputs);
- Users should be able to enter their input values manually or through parametric equations and, where required, new parametric equations should be developed based on data;
- The different phases of the service life of the asset should be mapped in sufficient detail (high fidelity) so as to account for the impact of sensitive parameters;
- Operation and maintenance (O&M) costs should be calculated in detail and utilising latest reliability data through appropriate engineering models;
- Uncertainties of key variables should be considered in a systematic way, assigning confidence levels on the expressions of estimated KPIs;
- The Environmental Impact throughout the service life of the asset should be assessed based on modern unit emissions databases.

As of month 36, all different modules of the impact assessment model have been developed and integrated, while indicative outputs have been produced in order to check that calculated KPIs are meaningful. For certain cases results have also been verified.

This report aims at presenting the key modules of the impact assessment model, documenting main assumptions and underlying theories, as appropriate. The remaining sections are organised as follows; Section 3 presents a high-level description of the impact assessment model, highlighting the key modules that are further presented next. Section 4 presents the fundamentals of the Life Cycle Cost (LCC) module, which is the backbone of the impact assessment model. Section 5, discusses the purpose-developed O&M module which has been modelled in such a level that allows the different operational management scenarios to be considered. In Section 6, the Environmental impact assessment module is discussed, linking quantities and processes to unit emissions from up-

to-date databases. Section 7, presents explicitly the interfaces of the different modules, listing the inputs and expected outputs. Finally, Section 8 concludes this report, highlighting next steps and future work that the authors are considering until the end of the project so as to enhance the tool for future use in commercial projects.

It should be noted, that this report does not aim to replicate what has been included in deliverables D8.1 and D8.2 and the reader is referred to these documents for relevant review of literature and basic theory behind cost and O&M assessment. Hence, the information included here refers to the concepts incorporated in the current version of the model.

3. High level description of the impact assessment model

The integrated Impact assessment model consists of the following independent modules, as illustrated in Figure 1:

- (i) CAPEX module, consisting of the D&C, P&A, I&C and D&D phases of the OWF;
- (ii) OPEX/O&M module incorporating data from the operational phase of the OWF;
- (iii) FinEx module with parameters on financing expenditures, such as WACC, inflation rate, equity and debt ratio;
- (iv) General site characteristics module detailing the weather conditions, site water depth, distance from port, vessels, cost of personnel etc.;
- (v) EIA module, which translates quantities of materials and types of processes to emissions-related KPIs.

On top of these modules, an additional layer of analysis introduces Monte Carlo Simulations, allowing for statistical representation of input variables and in turn assign confidence levels to KPIs of interest.

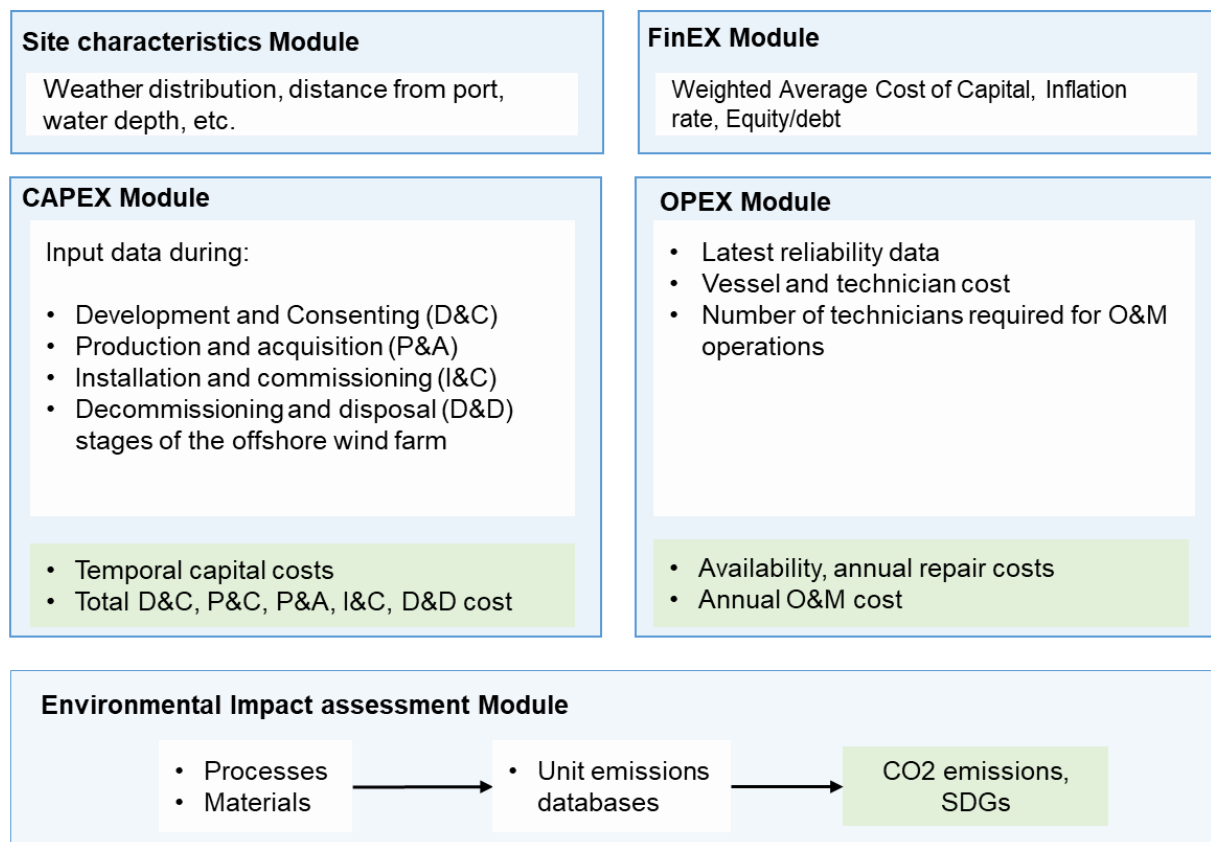


Figure 1: Methodological framework

In this section, the site characteristics module and the FinEx Module will be briefly presented as the remaining modules will be presented in more detail in subsequent sections.

3.1 FinEX module

3.1.1 Depreciation and tax

Tax depreciation is available through the capital allowances regime, according to which $d_{rate} = 18\%$ of qualifying expenditure on equipment is reduced [2]. Depreciation is a term used in accounting in order to spread the cost of the capital assets over the life span of the investment, so that the net profit in any year will reflect all the costs required to produce the output. The effect of depreciation is estimated by dividing the equipment cost of the wind farm, $C_{equipment}$, over the total life span of the asset and deducting the 18% of this annual cost from the tax payment. The net tax, t_{net} , can then be calculated by deducting the depreciation credit, d_{credit} , from the yearly tax payment, $t_{payment}$, as shown below:

$$d_{credit} = \frac{C_{equipment}}{n} \cdot d_{rate}$$

$$t_{net} = t_{payment} - d_{credit}$$

$$t_{payment} = t_c \cdot P_{gr}$$

where, $t_c = 17\%$ is the nominal corporate income tax rate paid every year and P_{gr} represents the gross profit. Accordingly, the Net profit, P_{net} , of the investment can be calculated as:

$$P_{net} = P_{gr} - t_{net}$$

3.1.2 WACC and inflation

Inflation and interest rates are used to account for the time value of money. Inflation accounts for the reduction in the purchasing power of a unit of currency between two time periods, while the interest rate is the rate earned from a capital investment. In financial analysis, the nominal interest rate is the interest rate quoted by the banks, stock brokers etc. which includes both the cost of capital and the inflation. Real discount rate (or else real WAAC) integrates the inflation adjustment and the discount of cash flows according to Fisher Equation [3]:

$$WACC_{real} = \frac{1 + WACC}{1 + R_{infl}} - 1 \approx WACC_{nom} - R_{infl}$$

The discount rate is determined by the source of capital as well as the estimation of the financial risks associated with the investment. Projects gather their capital by raising funds through debt and equity. These sources of financing demonstrate individual risk-return profiles; hence their costs also fluctuate. The cost of capital will correspond to the weighted average of cost of its equity and debt, with weights determined by the amount of each financing source. The WACC is calculated by the following expression [4]:

$$WACC = \frac{VE}{V} \cdot RoE + \frac{VD}{V} \cdot Rd \cdot (1 - tc)$$

where, VE is the market Value of Equity, VD is the market Value of Debt, $V = VE + VD$, RoE denoted the Return on Equity, and Rd the interest rate on debt. The risk of the project significantly influences the amount of return on investment required by the investor. External capital is cheaper and, thus, it is often desirable to obtain the highest possible amount of debt; however, the cost of debt depends on the specific investment risk, namely the highest the investment risk, the lower the amount that banks will be willing to lend. Further, the real WACC is calculated by taking into account the inflation rate.

3.2 Site characteristics module

This module outlines assumptions and characteristics of the wind farm that will be investigated and compiles data that are relevant to multiple phases of the service life of the asset, which are represented by the subsequent modules.

3.2.1 Wind farm related data

Data related to the wind farm include:

- Wind farm:
 - Total wind farm capacity, P_{WT}
 - Projected operational life of the wind farm, n
 - Construction years, T_{constr}
 - Number of turbines, n_{WT}
- General site characteristics:
 - Distance to port, D
 - Water depth, WD
- Wind turbine:
 - Rotor diameter, d
 - Hub height, h
 - Pile diameter, D_{pile}
 - Rated power
 - Cut-in speed
 - Cut-out speed

3.2.2 Weather data

Weather data are input in the format of 3-hourly data, which can be retrieved from the BTM ARGOS database [5] for modelling the installation and operational phase of the asset. Weather delays during the I&C and the D&D phases can be modelled through an appropriate adjustment factor.

3.2.3 Vessel data

In addition, vessel and personnel data should be considered here. Vessel data encompass the cost (and key characteristics) of vessels chartered for carrying out the I&C, O&M and D&D phases of the

project. The specifications of the vessels should include speed, day rates and mobilisation costs, while further data regarding the number and the type of vessels used per phase and task should also be included. The wind speeds are referenced at 10m above the mean water level, while the mobilisation and demobilisation activities comprise the cost and time allocated to the planning, preparing and modifying a vessel for a marine operation (mobilisation), and then to restoring it for release and reassignment to other operations (demobilisation). Data for different types of vessels are input for analysis Crew transfer vessel, Jack-up vessels, Heavy lift vessel, Helicopter, Diving support vessel (DSV), Cable laying vessel and Rock dumping vessel.

4. LCC module (CAPEX)

The CAPEX module includes costs during the D&C, P&A, I&C and D&D phases of the OW farm, and in this section the individual components are discussed with reference to appropriate parametric equations and reference values.

4.1 Development and consenting (D&C)

D&C costs relate to all costs prior to the point of financial close including project management, surveys, legal authorisation, front-end engineering and design and contingency cost. Costs during this phase of the wind farm vary significantly across different sites; thus, different values of costs can be obtained from literature. Considering the level of maturity of offshore wind energy, significant variation is observed between different installations and reported case studies. Such values are linked to the capacity of the wind farm and wind turbine unit in the numerical model.

4.2 Production and acquisition phase (P&A)

4.2.1 Wind turbines

The acquisition of a fully equipped turbine is one of the most expensive cost components of the P&A phase of the wind farm. Cost is usually expressed as a function of the turbine capacity and different parametric models have been developed to predict the cost of different sizes of turbines; it should be noted however that technological and modern commercial models can significantly affect these values. A typical expression for this cost can be obtained as [6]:

$$c_{T,pa} = (3 \cdot 10^6 \ln(P_{WT}) - 662,400) \times 1.11, \text{ in €/turbine}$$

where, P_{WT} is the capacity of the wind turbine (MW).

4.2.2 Foundations

Literature reports different parametric equations for monopile and jacket foundations, linking them to the wind turbine capacity, height and rotor diameter. Indicatively, the cost of foundation, $c_{F,pa}$, of a monopile can be obtained through the following parametric equation (hub height, h and rotor diameter, d) according to [7]:

$$c_{F,pa} = 320,000 \cdot P_{WT} \cdot (1 + 0.02 \cdot (WD - 8)) \cdot (1 + 8 \cdot 10^{-7} \cdot (h \cdot ((d/2)^2 - 100000)))$$

Since the project also considers jacket foundations, relevant parametric studies are included for this type of support structure linking similar deployment parameters to the overall cost of acquisition (plus potentially material usage and fabrication complexity).

4.2.3 Transmission system

The transmission system of the wind farm consists of the collection system of the generated power by means of array cables, the integration of the power through an offshore substation and the transmission of the electricity from the offshore substation to shore through the export cables. Two kinds of export cables are distinguished: the offshore export cables transmit the electricity from the offshore substation to the onshore substation, and the onshore export cable which transport the power to the grid connection point.

Array cables organise turbines in clusters adopting various different grid schemes, such as the radial design according to which, turbines of each cluster are interconnected in a ‘string’ ending at an offshore substation. Medium Voltage (MV) submarine cables are most frequently used as array cables, while High Voltage (HV) export cables carry the stepped up voltage from the offshore substation to the grid connection point. MV cable unit costs, similarly to HV cable unit costs vary according to the cable section and nominal voltage.

Export cables can be either high-voltage alternating current (HVAC) or high-voltage direct current (HVDC) depending on a number of factors and especially the distance from shore. Generally, if the distance from shore is less than 50 km, AC cables would be preferred while for longer distances and in more remote wind farms, DC cables are used since HVDC cabling has no reactive power requirements resulting in lower power losses.

In general, the total cost of the cables, $C_{cables,pa}$, is calculated by the product of the unit-length price of the cable, c_i (€/m), with the number of cables, N_i , and the average length of each cable, L_i (km). Protective equipment (such as J-tube seals, passive seals, bend restrictors etc.) is required to protect the cables [6].

$$C_{cables,pa} = \sum_{i=1}^3 (c_i \cdot L_i \cdot N_i) + C_{protection}$$

where, i denotes the cable type of the wind farm, namely: the MV array cables ($i=1$), the HV subsea export cables ($i=2$) and the HV onshore export cables ($i=3$).

The length of the subsea export cable, L_2 , is assumed equal to the distance between the centre of the OW farm (where the offshore substation is located) and the shore (where an onshore substation is located). Finally, the length of the onshore export cable, L_3 , is equal to the distance from the onshore substation to the grid connection point. The electrical system is typically comprised of 33kV array cables and two offshore substations of 336MW HVAC transmission system. Further, the transmission assets are considered connected to the onshore substation by three 800mm² 132kV subsea export cables.

The most cost efficient electric power transmission method to reduce cable losses is by means of an offshore substation, which is considered appropriate for projects located at a distance of more than 20km offshore. A realistic expression for the offshore substation cost, $C_{offSubst,pa}$, can be

estimated based on [8], which breaks down the cost of offshore substation to: 1) the MV/HV transformer cost, C_{TR} , 2) MV switchgear cost, $C_{SG,MV}$, 3) HV switchgear cost, $C_{SG,HV}$, 4) HV busbar cost, c_{BB} , 5) Diesel generator cost, C_{DG} to supply essential equipment when the OW farm is off, and 6) substation platform cost, $C_{offSubst,pa_f}$. The expressions of the individual cost components are the following:

$$C_{TR} = n_{TR} \cdot (42.688 \cdot A_{TR}^{0.7513})$$

$$C_{SG,MV} = 40.543 + 0.76 \cdot V_n$$

$$C_{DG} = 21.242 + 2.069 \cdot P_{WF}$$

$$C_{offSubst,pa_f} = 2534 + 88.7 \cdot P_{WF}$$

$$C_{offSubst,pa} = C_{TR} + C_{SG,MV} + n_{TR} \cdot (2 \cdot c_{SG,HV} + c_{BB}) + (C_{DG} + C_{offSubst,pa_f})$$

where, n_{TR} is the number of transformers, V_n is the nominal voltage and A_{TR} is the rated power of the transformers. The export cables connect the offshore substations with an onshore substation which further transforms power to grid voltage (e.g. 400MW). Onshore substation cost was assumed to be half the cost of the offshore substation according to assumptions from literature.

More recent wind farms have integrated supervisory control (including health monitoring) and data acquisition (SCADA) systems, with the view to optimise wind turbine life and revenue generation. Health monitoring of wind turbines is performed by means of sensors and control devices, gathering data that can be used for optimising operation and maintenance operations. Cost of monitoring was estimated $C_{SCADA,pa} = \sim 84$ k€/turbine [8].

4.3 Installation and commission phase (I&C)

I&C phase refers to all activities involving the transportation and installation of the wind farm components, as well as those related to the port, commissioning of the wind farm and insurance during construction. Once a suitable number of components are in the staging area, the offshore construction starts with installation of the foundations, transition piece and scour protection, followed by the erection of the tower and the wind turbines. Accordingly, the installation of the offshore substation, the array cables and finally the export cables and onshore substation takes place.

4.3.1 Foundation and wind turbine installation

Installation costs are a function of the vessel day rates, the usage duration and the personnel costs required for carrying out the operations. Vital components of both the wind turbine and the foundation installation cost are the vessel day rates and the duration of the installation processes. The total time per trip of an installation vessel is broken down to: the travel time, the loading time, the installation time and the intra-field movement time.

For the installation of monopiles a jack-up vessel can be employed with an assumed deck capacity of $VC_{F,JU} = 4$ foundations. After foundations are secured, the transition pieces are lifted and placed

on the top of the foundation pile and are then grouted. In the context of the present case research, it can be assumed that the installation of monopiles and the placement of transition piece can be realised by the same vessel. Appropriate provisions will be considered for the case of jacket type support structures.

Turbines are installed after foundations have been placed. The vessel used, both transports turbines in the installation site and performs installation. Turbines typically consist of seven components, namely nacelle, hub, 3 blades, and 2 tower sections. Onshore assembly of some of the parts of the OWT is usually performed in order to reduce lifts offshore, which can be considered risky and prone to cause delays due to wind speeds. The installation process of OW turbines is composed by the following time steps:

1. Travel/transportation time,
2. Lifting operation time,
3. Assembly operation time (onshore and offshore)
4. Jacking up operation time.

The pre-assembly (i.e. onshore assembly) strategy followed determines the total time of turbine installation, along with the distance from the port, the number of turbines, the nameplate capacity, etc.

4.3.2 Scour protection installation

Scour takes place around structures undergoing steady current conditions, and is associated with the increase in the sediment transport capacity and erosion. To ensure structural stability of the wind turbine foundation (as well as protection of cables), scour protection is usually applied. The scour protection option employed is site-specific, i.e. at some locations the amount of protection varies with sediment and current conditions, while in others scour protection may not be needed. The input data used for the estimated mass of scour protection [9], the vessel leased for installation and the total installation time can be adopted from [10]–[12].

4.3.3 Cables installation

A dedicated Cable Laying Vessel (CLV) needs to be leased for the installation of the inner array and export cables. Average installation rates of inner-array and export cables can be calculated by taking into account historic data from past projects on the total length (in km) of the cables and total installation time (in days) [12]. Average installation rates can be estimated approximately at 1.6 and 0.6km/day for export and inner array cables, respectively. For the installation of the subsea cables, a trenching ROV (Remotely Operated underwater Vehicle) is often employed for the post-lay burial of the cables with a typical daily charter rate of 92k€ [13]. The installation cost of export and array cables is estimated based on the total duration of the installation operation, and the day rates of the CLV and the trenching ROC. As such, the installation cost of array and export cables are calculated by the following expressions:

$$C_{C-array,ic} = T_{C-array,Inst} \cdot (V_{DR,CLV-array} + V_{DR,Trench}) + V_{Mobil,CLV}$$

$$C_{C-export,ic} = T_{C-export,Inst} \cdot (V_{DR,CLV-export} + V_{DR,Trench}) + V_{Mobil,CLV}$$

4.3.4 Substation installation

Substation is assumed to be barged on site and get installed by a Heavy-Lift vessel (HL). The installation time is comprised of the jacket foundation installation time, the grout application (if applicable) and, the installation of the substation topside.

The weight of the topside substation will determine the vessel that will be required with the appropriate crane capacity. The estimation of the installation cost of the substation is based on the total effective duration of the installation operation, $T_{Subst,Inst}$, and the HL vessel day rate, $V_{DR,HLV}$, and mobilisation cost, $V_{Mobil,HLV}$, as expressed below:

$$C_{OffSubst,ic} = T_{Subst,Inst} \cdot V_{DR,HLV} + V_{Mobil,HLV}$$

4.4 Decommissioning and disposal phase (D&D)

Energy companies are obliged to remove all structures and verify the clearance of the area upon the termination of the lease. Decommissioning activities relate to the removal of the wind turbine (i.e. nacelle, tower and transition piece) as well as the balance of the plant (substation, cables and scour protection). Removal of the wind turbine and tower is done using a reversed installation method while the removal of foundation is carried out by the use of a cutting tool that removes the transition piece, while an ICM (Internal Cutting Manipulator) is used to cut the monopile or the jacket piles at 2 meters below the mud-line [14]. Cranes are used to lift the cut pieces of the turbine. Removal of mud and internal cutting can be realised by means of a workboat, while the lifting of the structure is performed by a jack up vessel. Two jack up vessels with deck space to load 5 complete WTGs with foundations is a realistic assumption for monopile foundations while relevant provisions will be considered for jacket foundations. For the removal of the substation topside a heavy lift vessel is required while the jacket support structure of the substation also needs to be cut (the 4 piles) in order to get removed. As far as cables are concerned, they can be partially or wholly removed, depending on whether they are buried or not [15]. Cables can be cut in several sections while they are removed, hence, less expensive vessels can be employed, such as Special Operations Vessels (SOVs) or barges. The scour protection may also be left in situ in order to conserve the marine life that would have grown on it. Site clearance is the final stage during decommissioning and it encompasses the removal of the debris accumulated in a specified radius of the structure throughout the 25 years of life of the wind farm. Vessels employed for the decommissioning of the structures are assumed to have similar characteristics to the ones used for installation.

Further to the removal of the wind turbine components, the balance of the plant and the clearance of the area, removed items need to be transported and disposed. Cost of transportation is a function of the total mass of the wind farm components, $W_{components}$, the cost per ton-mile of the transportation truck, $C_{truckper\ ton-mile}$, the capacity of truck, W_{truck} , and the distance of port from the waste facility, $D_{port-facility}$, as follows [6]:

$$C_{transp,dd} = \frac{\sum W_{components}}{W_{truck}} \cdot D_{port-facility}$$

5. O&M module

5.1 Overview

With O&M costs accounting between 15-25% of life-cycle costs, it becomes pertinent to model related activities analytically, accounting for all downtime-contributing factors and at the same time incorporating in the analysis practicalities of operations. Related analysis should be able to account for the accurate prediction of weather data, classification of maintenance interventions and modelling of failure rates, and finally, apply realistic strategies with respect to planned and unplanned maintenance activities. This section presents the O&M module which allows the estimation of availability of a given wind farm with specified characteristics throughout its service life, allowing for the simulation of a number of scenarios related to reliability parameters, vessels specifications and availability, number of technicians etc, towards optimising a wind farm maintenance strategy.

An overview of the O&M analysis framework is illustrated in Figure 2 and in consolidated form in Figure 3. The main modules are: (1) the reliability module, (2) the weather forecast module, (3) the power module, and (4) the maintenance module. The input and output datasets are highlighted in blue and green colour respectively. It should be noted that the development of decisions for the different steps of the model have taken into consideration not only the accuracy of the calculation but also the computational efficiency required so as to allow a serial execution of simulations which can enable stochastic modelling and further sensitivity analyses. An important aspect in the development of such tools is that of validation, as complete data from operations of offshore wind farms are difficult to obtain; in this instance it is planned to perform a high-level validation based on consultations with experts from different parts of the supply chain.

The reliability module is further divided into mean time to failure (MTTF) (namely the uptime of the asset) estimation and the mean time to repair (MTTR) estimation throughout the maintenance operations (namely the downtime of the asset). The MTTR calculation is based on the annual failure rates, while the maintenance operations (planned and unplanned) require data related to the resources required for the repairs. The time to repair is calculated in the maintenance main module, and is used as input in the reliability module. Resulting downtime depends on the availability of the required vessels, technicians, weather window, spare parts, mission organisation time, duration of navigation and repair, as well as the required number of technicians' shifts.

The maintenance module covers planned and unplanned maintenance activities and takes consideration of the actual duration of all stages required to perform the repair and maintenance operations and uses vessel and crew day-rates, along with material costs to estimate the total O&M cost. Other outputs of the model are the time-based and production-based availability, and the power production losses.

The weather modelling module enables the forecasting of the future sea states, namely future significant wave heights and wind speeds. Weather conditions play an important role in the total downtime of the wind farm, as when the related parameters surpass the set wave height and wind speed limits of the vessels, travelling to wind turbines and accessing them becomes impossible.

Therefore, unfavourable weather conditions will delay repairs, thus increasing downtime and decreasing the wind farm's availability. Further, weather conditions also affect power production.

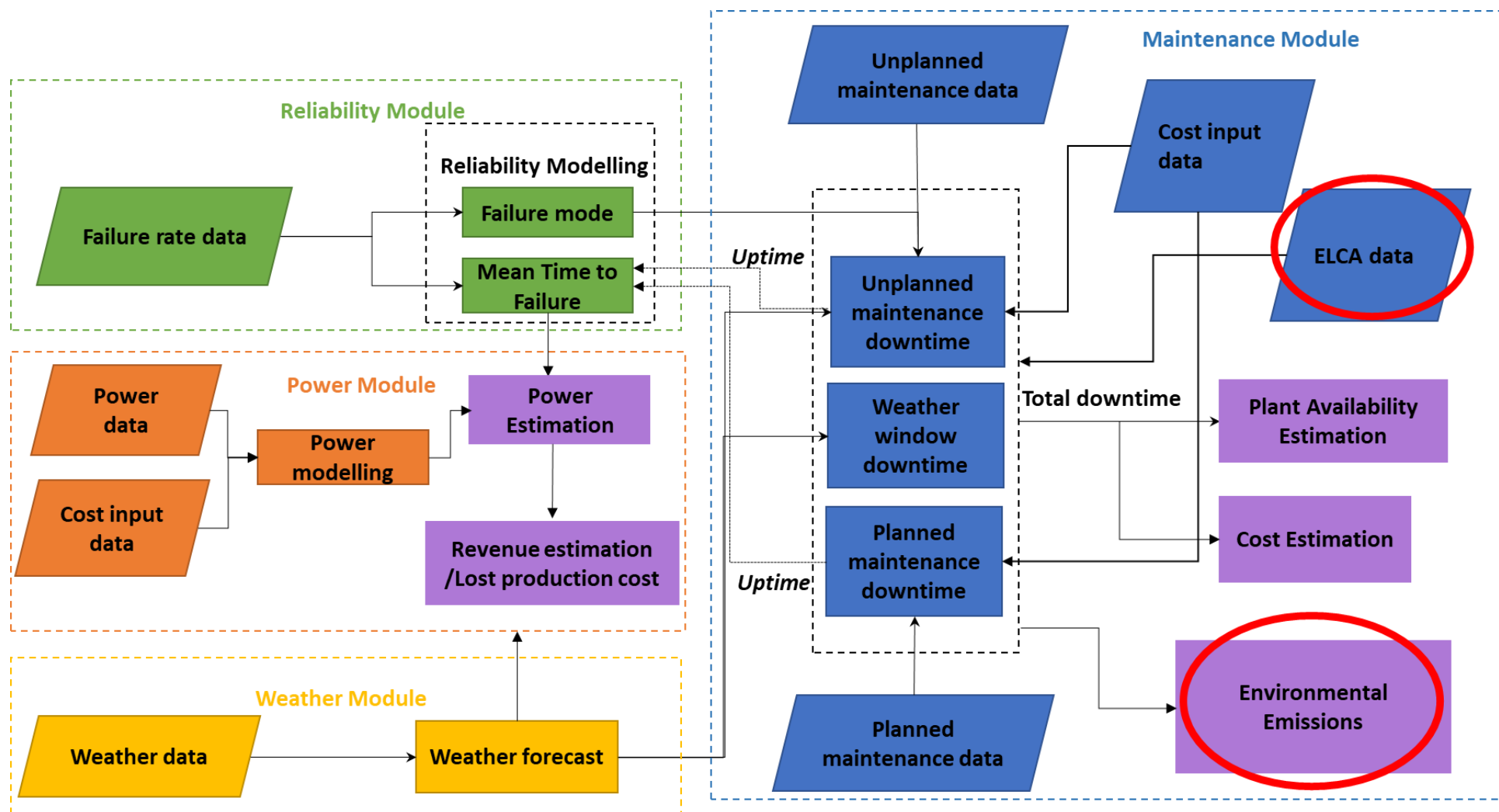


Figure 2: O&M lifecycle assessment model flowchart

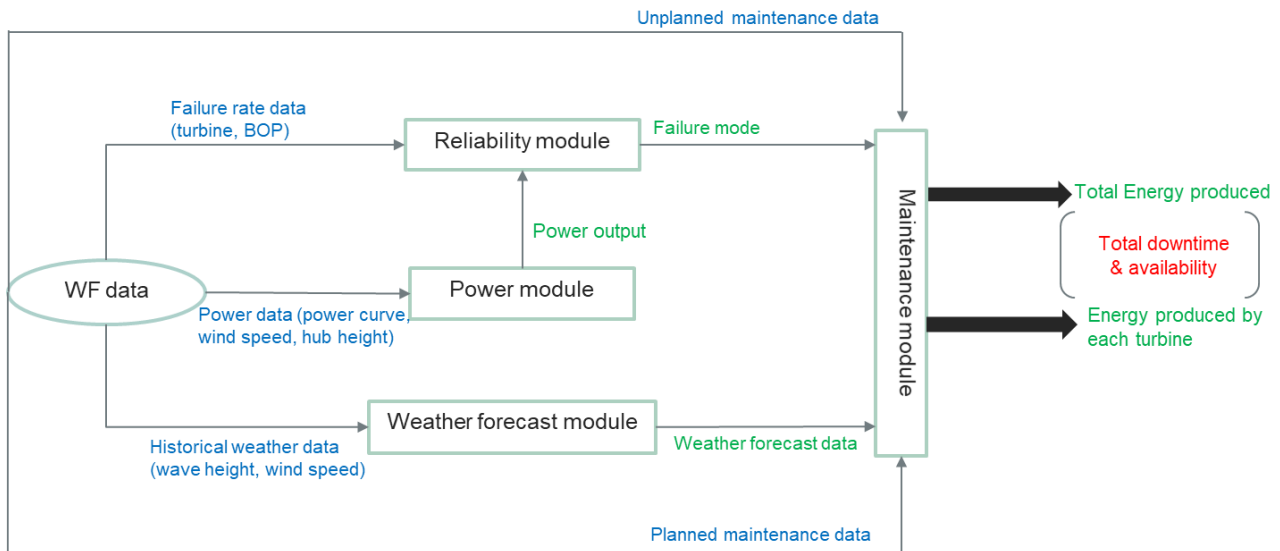


Figure 3: O&M cost module framework

Each (sub)module of the O&M module can be seen as a standalone module but some common interfaces have been developed in order to increase efficiency in modelling, which means that some inputs are related and most of their outputs are used to define the maintenance strategy.

The subsections below present the individual submodules in more detail.

Weather module

The weather module aims to provide forecast for wind and wave conditions, which is utilised in the power estimation module and the maintenance module in order to assess accessibility constraints. Historic met-ocean data representative of local conditions can be obtained and time-series forecasting models are trained.

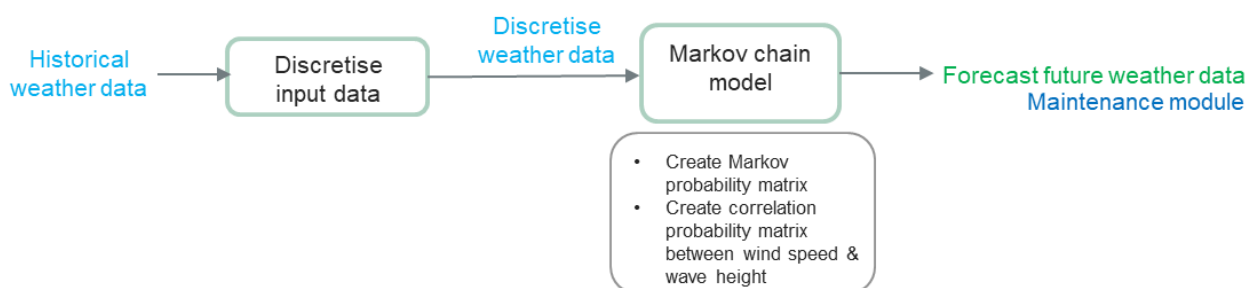


Figure 4: Weather forecast module framework

A Markov Chain is a stochastic process which defines a set of probabilities for the next possible set of states, given the current state. The historical weather data obtained from AGROSS database are discretised and then feed into the Markov chain model which will create a Markov probability matrix as well as establish a correlation probability matrix between weather data (wind speed and wave height), thereby estimating future weather time series data as illustrated in Figure 4. The set of probabilities for moving from one state to the next are called transition probabilities and are

dependant only on the state being moved from. In a regression problem, each possible discretised numeric value can be defined as a state. In Markov chains, the probability of any state at time t_n for a state, i , within a countable set of states, S , is independent of all previous states except for the last one, as shown [16]:

$$\Pr\{X(t_n) = i_n | X(t_1) = i_1, \dots, X(t_{n-1}) = i_{n-1}\} = \Pr\{X(t_n) = i_n | X(t_{n-1}) = i_{n-1}\}$$

Forecasting into the future is accomplished as a series of steps and any state in the future is dependent on all of the probabilities in between those states. With a given start time i , the probability of a certain state at time j which is r steps from the value, is given in the Chapman-Kolmogorov equation:

$$P_{ij} = \sum_{k=1}^r P_{ik} P_{kj}$$

Markov chains and how they work are described in detail in references [16]–[18].

The Markov Chain model used in this study is a first-order, observation driven model which generates a probability vector of wave height given the previous (t_{n-1}) wave height, with a separate matrix for each month. A probability matrix of wind speed, given wave height, is constructed as well as a matrix of wind direction given wave height. These are constructed by counting the number of occurrences within each matrix position and then normalising them by the total number. To determine each next iteration, the model samples from the probability matrices given the current state.

Reliability module

As regards the distribution of unforeseen failures in time, this information is modelled from the reliability module based on the reliability data from literature, as show in Figure 5. The input failure rates are grouped in minor repair, major repair and major replacement, according to the material cost as indicated by Carroll [19]. When a failure occurs, the turbine status varies depending on failure type. In minor repairs, the turbine is assumed to continue operation even after the failure detection, shutting it down only during the repair time. For major repairs and replacements, the turbine is stopped after fault detection, going back to service only after the fault is restored. The time to failure associated with each failure mode, for a particular subsystem i , is assumed to be distributed by an exponential probability density function $f(t)$, with parameter $\lambda_{i,mode}$ being the failure rate for subsystem the sub-system i under a particular failure mode (i.e. mr, Mr, or MR).

$$f(t) = \lambda_{i,mode} e^{-\lambda_{i,mode} t}$$

The cumulative distribution function is the probability of failure (PoF) of the subsystem according to the exponential statistical distribution and is given in the equation below. The PoF of the whole wind turbine is the PoF of all subsystems considering all failure mode classifications, as explained further in [20]. The probability of a subsystem to fail is randomly generated.

$$PoF = 1 - e^{-\lambda_{i,mode} t}$$

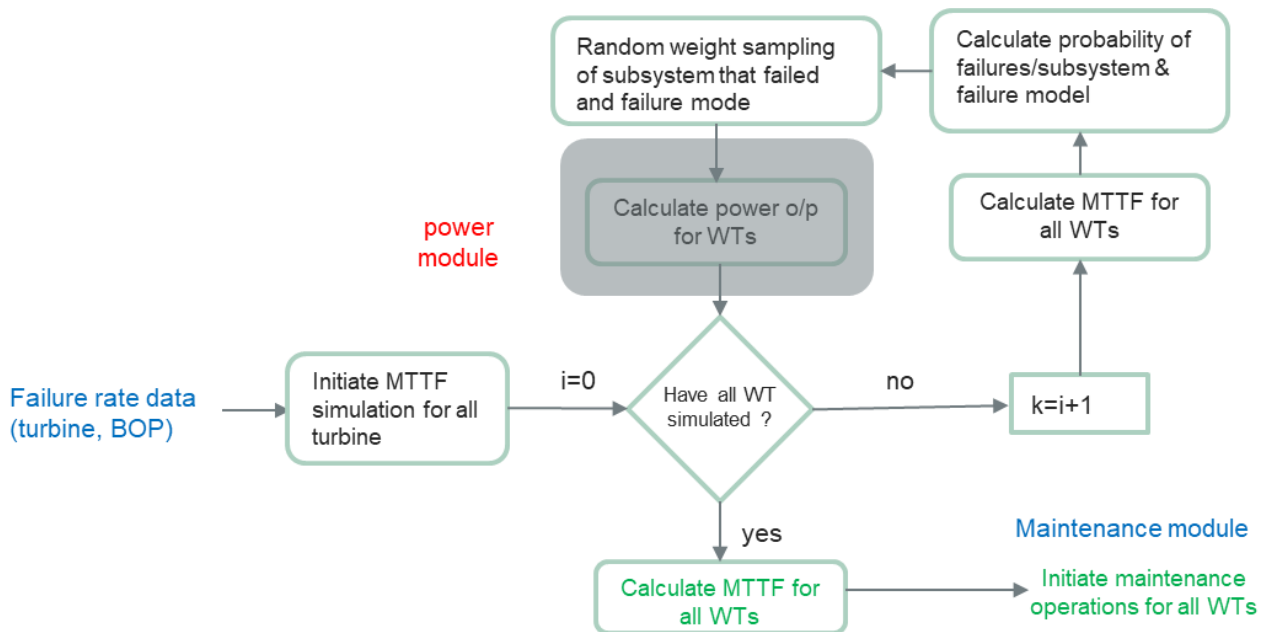


Figure 5: Reliability module framework

Maintenance module

This module takes into account the basic technical data of the wind turbine and the farm that the simulation uses in the analysis (Figure 6). The lifetime corresponds to the number of simulated years and the final availability is calculated as an average over the entire lifetime. The number of vessels, their crew capacity and their wave bearing capacity are included in the available means of transport considerations. If any of the requirements is not met, maintenance work is not completed and all remaining work is planned for the next suitable weather window. There are 2 types of maintenance activities considered in this model: planned and unplanned.

Planned maintenance is a scheduled service, whereas unplanned maintenance takes place as soon as a failure occurs. Downtimes are calculated accordingly, based on the maintenance duration, the weather conditions and the resource availability. It is assumed that for planned maintenance, workboats are filled to their maximum capacity, as they can perform operations to more than one turbine at once.

For unplanned maintenance, the O&M tool differentiates between failures which require a JUV (jack-up vessel) and failures which require a CTV (crew transfer vessel). In order to decrease downtimes, respective maintenance campaigns are implemented which do not only repair one turbine but store different maintenance tasks on a campaign list and follow this list during the campaign. While in one JUV campaign all turbines are maintained for which a failure occurred within the lead time of ordering a JUV, a CTV campaign repairs all failures which occurred during the night when technicians rest. This difference is due to the usage of vessel type. A JUV is costly and needs to be ordered at the market, and this takes time. Instead of just repairing one failure and ordering a JUV for another failure again, all pending turbines which need maintenance are served. Moreover, JUV campaigns

are performed in shifts to utilise the JUV to capacity. In comparison, CTV campaigns are only performed during day-shifts as no accommodation is available on this vessel type. All failures which occurred during the night are scheduled for the next day-shift. In case not all turbines can be served, the campaign continues the next day.

The O&M strategy is based on a decision tree that follows a system failure in one or more wind turbines. In the event of a failure, it is first checked whether a crew and a ship suitable for the type of repair required are already on site; component replacements are considered to require a crane vessel for - all other system repairs are assumed to require a crew transfer vessel. The absence of a suitable crew-ship combination on site leads to the activation of a ship or crane ship in port, if any are available. The activated vessel or barge will continue its transfer to the failed WT as soon as weather conditions permit; environmental restrictions are limited to a certain wave height limit.

The first parameter to check when launching a mission is availability of the spare parts. At the beginning of the simulation, the user defines the initial and minimum stock which defines when the spare parts orders are going to take place. In case there is no spare part available in stock, the tools check whether it has already been ordered and is expected to be delivered or whether a new material order should be placed. The waiting time until the required material is available is stored as spare part downtime.

Once the spare parts are available, the module needs to check the availability of vessels and crew. To be able to accomplish that, the module verifies whether a support vessel is required or not. In case it is needed, it checks the availability of both vessels (main and support), and accounts for the amount of time during which either of them is not available. This check is done against the number of vessels of each type, defined at the beginning of simulation by the users. Time for which the mission is postponed is stored as vessel downtime. Once the vessels are available, the module checks whether the required crew is ready for the mission, and in case it is not, the waiting time is stored as crew downtime.

With all the requirements ready to start the maintenance activity, a weather conditions check takes place to evaluate whether the conditions are suitable for the mission during the whole period; travelling to the wind turbine, resolving the failure and travelling back to the harbour. The verification of weather conditions can be summarised by checking the wind speed and wave height and comparing them to the maximum allowable values for each vessel. The threshold values are assigned by the user; however, the vessels' technical specifications should be taken into account. If the weather during this whole period is not suitable, the mission will be postponed and the delay is stored as weather downtime.

As soon as a failed system is put back into operation (status reached, as soon as a crew ship combination has been placed on the failed WT for the assigned repair duration), the next failure for this system is determined in the same way as the original TTF was generated. This process is repeated accordingly if a failed component is repaired or replaced.

Similar process to the one described to account for the turbines' downtimes is done for the Balance of Plant (BOP). The only difference being that only unplanned activities take place. In case the BOP

fails, all turbines connected to it are considered to be in non-operational mode at that time. Therefore, failures in this system are expected to considerably affect the wind farm's availability.

Once all the parameters directly affecting the availability during the whole simulation period have been considered, all downtimes can be summed, resulting in the total downtime. Total uptime is calculated by subtracting the total downtime from total simulation time, the latter being number of simulated years multiplied by the number of turbines. By dividing the total uptime by the simulation period, the total availability can be obtained. As well as this value, figures expressing the impact of each factor (spare parts, vessel and crew and weather) on the total downtime are also part of the outputs.

Since the aim of the wind farm is to produce energy, the module also calculates the amount of energy produced by each turbine and by the whole wind farm, which is a function of the weather conditions (wind speed). The calculation of this module is based on the power curve given by the OEM.

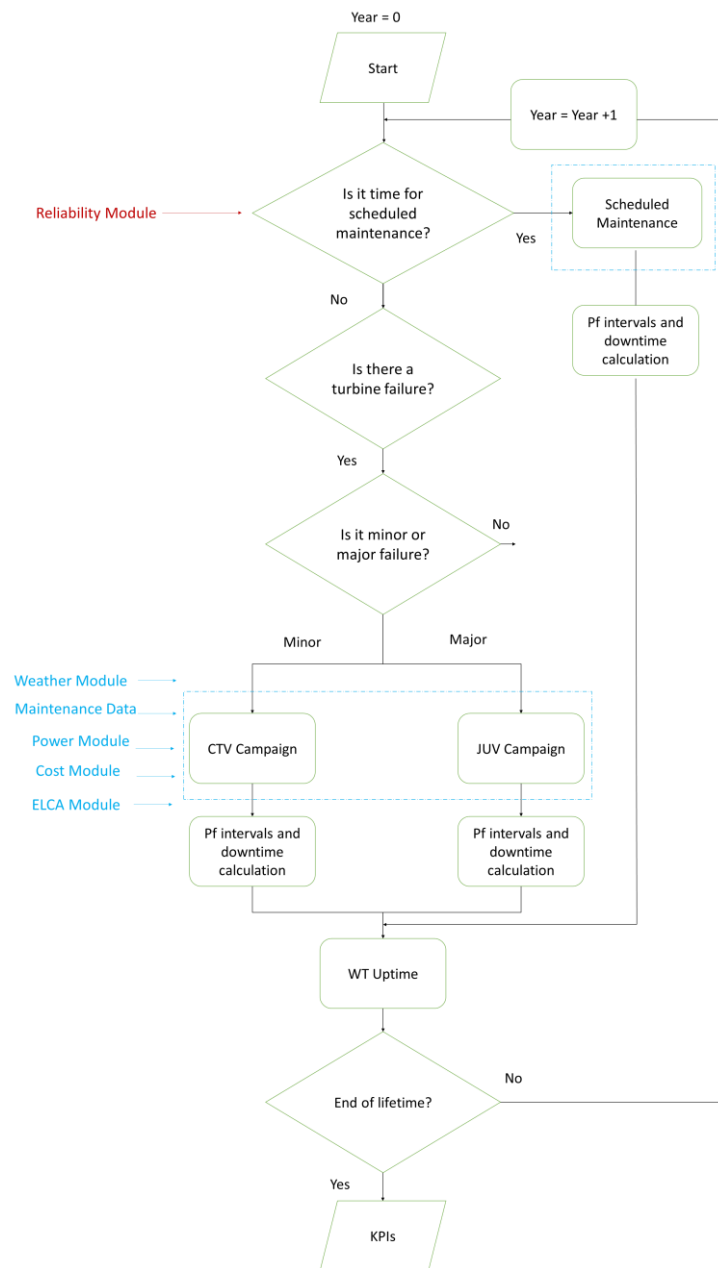


Figure 6: Maintenance module framework

Cost (OPEX) module

The cost module gathers the data recorded during each iteration, which are required to estimate the O&M cost. For unplanned maintenance of wind turbines, the time that a failure occurs is registered with reference starting point the beginning of operation of the wind farm. Further, the subsystem that failed and the type of failure will define the required main and support vessels (to match the correct day rates) and the number of crew members required for the repair. Downtimes of crew unavailability, spare parts unavailability, weather window, navigation time and demobilisation time

are taken into account and assigned to the respective day rates of vessels, crew, cost of materials, mobilisation and demobilisation costs, to estimate the total O&M cost.

The cost module is a subset of the maintenance module and it calculates all monetary flows during the offshore wind farm lifecycle. The costs for each maintenance activity take into account the material costs of the replaced parts, the repair costs, the vessel hire and fuel costs and the crew salaries based on their shifts. The revenue from the energy generated and sold (direct cost) and the lost production costs (indirect cost) are also calculated. The aforementioned cost estimations are based on a net present value, as shown below:

$$NPV = \sum_{r=1}^n \frac{R}{(1+i)^r}$$

Where R is the net cash inflows-outflows during a period r and i is the discount rate.

KPIs

Maintenance activities are carried out until the end of the lifetime of all WTs in the wind farm. Various key performance indicators (KPIs) are calculated thereafter. First, the downtimes of each turbine are added up, and the total wind farm availability is calculated, as shown below.

$$A = \frac{Lifetime_{wf} - Downtime_{wf}}{Lifetime_{wf}}$$

Where A is the calculated wind farm availability, $Lifetime_{wf}$ is the cumulative lifetime of all wind turbines in the wind farm and $Downtime_{wf}$ is the cumulative downtime.

Other key performance indicators calculated include the energy E generated from the wind farm as follows:

$$E = P \times t$$

Where t is the time given in *hours* and P is the power.

Other indicators are related to cost, such as the direct costs involved with operational activities, the indirect costs involved with lost power production and the revenue from the energy sold to the grid.

6. Environmental impact assessment module

Environmental life cycle assessment

Lifecycle assessment (LCA) is widely used to evaluate the environmental effects of industrial processes. For offshore wind applications, this includes the site construction, the site operation and maintenance and the decommissioning. The site construction accounts for the production of raw materials (composite materials for the blades, copper for the generator etc) as well as emissions during fabrication, transportation and installation of the units. Site operation includes emissions related to the transportation of staff and spare parts through vessels and helicopters. Finally, dismantling, or decommissioning accounts for the activities related to the end of life of the asset where components are taken apart and are partially recycled, reused or landfilled. The environmental lifecycle assessment (ELCA) module presented focuses on the operation and maintenance phase of the wind farm.

ELCA Module

The ELCA module of the O&M model calculates the direct and embodied emissions of the operational phase of the wind farm. The direct emissions come from the fuel consumption of the vessels that travel to the wind farm, while the embodied emissions come from the production of the spare parts that are replaced. Therefore, the total greenhouse gas emissions (GHG) is obtained as:

$$GHG_{total} = GHG_{direct} + GHG_{embodied}$$

The functional unit chosen for greenhouse gas emissions is kgCO₂ per kWh of electrical energy produced.

The GHG emissions for each stage can be calculated as

$$GHG = \sum input_i \times G_i$$

where G_i is the GHG-intensity coefficient of the i th input of wind turbine (including direct and indirect), and $input_i$ is the amount of the i th input.

Direct Emissions

The direct emissions are calculated based on the fuels consumptions of the vessels that travel to the wind farm for maintenance purposes. The emissions are a function of the type of vessel –and therefore its fuel consumption properties- as well as the speed and distance travelled. The fuel consumption properties of vessels are normally given in the manufacturer specifications.

Some indicative ship models and their consumption properties are shown in Table 1. MO4 is a typical wind farm service craft designed for light transits and heavy loads, while Seacor Puma is a CTV vessel. The cruising speed and dependent fuel consumption is given by the manufacturer. For a Diesel type of fuel the equivalent GHG emissions per distance travelled can be calculated through

a common conversion factor of 10,180 grams of CO₂ emissions per gallon of diesel consumed (Federal Register 2010).

Table 1: Vessel fuel consumption

Ship model	Cruising Speed (knots)	Fuel Consumption (L/Hr)
MO4	25	450
Seacor Puma	35	703

Embodied Emissions

Embodied energy is the sum of all the energy required to produce materials, which can vary depending on the equipment and exact procedures used. Some unified numbers that exist in the literature are used, in order to account for the GHG intensity of the various wind turbine components. The GHG-intensity coefficients for inputs are shown in Table 2.

Table 2: GHG Coefficients for materials

Material	GHG intensity (kgCO ₂ -eq/kg)
Aluminium	22
Aluminium alloys	22
Cast iron	1.25
Cast iron, ductile (nodular)	1.25
Cast iron, gray	1.25
Chromium steel	2.03
Concrete	0.22
Copper	4.7
Epoxy resin	3.07
GFRP, epoxy matrix (isotropic)	6.72
Glass fibre reinforced plastics	2.63
Lead	1.64
Low carbon steel	1.39
Lubricant	2.93
Polyethylene (PE)	2.4
PVC	2.14
Reinforcing steel	2.03
Rubber	3.18
Stainless steel	2.03
Steel, low alloyed	1.39
Zinc alloys	3.41
Diesel	0.45

The wind turbine consists of various components, which are made of a combination of materials. A broad breakdown is shown in Figure 7. For a reference wind turbine, the exact masses of these components are known and consequently the emissions can be calculated based on Table 2.

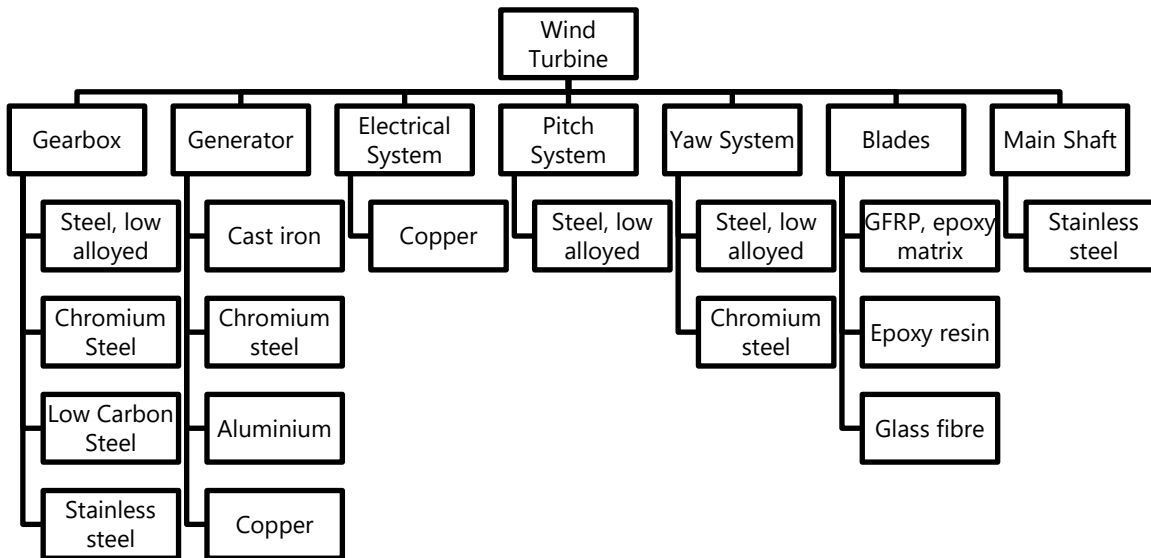


Figure 7: Components and materials breakdown

7. Inputs and outputs

As mentioned earlier, each of the modules have been coded as standalone with interfaces between them as well as global and local input. In this section these inputs and outputs are briefly presented.

Inputs to the model

7.1.1 Site characteristics and FinEx related costs

The inputs to the LCC module account initially for general site characteristics such as total wind farm capacity, Projected operational life of the wind farm, Construction years, Number of turbines, Distance to port, Water depth, Rotor diameter, Hub height, Pile diameter, Rated power, Cut-in speed, Cut-out speed. Further, vessel data are input, including for the different vessel types information such as technician space, vessel speed, significant wave height, wind speed, mobilisation/demobilisation costs and time and day rate. Personnel-related costs are also included. For FinEx input values for Weight Average Cost of Capital, inflation rate and Equity to debt ratio are considered.

7.1.2 LCC module

In D&C costs, the following are also included as fixed inputs; Legal costs, Environmental survey costs, Engineering costs, Contingency costs, Project management cost. In P&A costs, unit cost of cables are also introduced. For scour protection a number of inputs are considered such as Tonnage of scour protection per unit, Rock-dumping vessel capacity, Number of trips required to the installation of scour protection, Total transportation time of scour protection by rock-dumping vessel, Dumping time per trip, Loading time per trip and Mobilisation cost of rock-dumping vessel. Installation rates of export and array cables are also introduced. For the offshore substation the input required include Number of piles per substation foundation, Rate of piling the piles of the substructure, Depth of pile under the soil, Reposition time of the vessel, and Installation time of the substation's jacket.

7.1.3 O&M module

For the O&M module, failure data include failure rates, sub-system breakdown and failure categories. Relevant weather data include wind speed and wave height. For the cost estimation, Energy price, Interest rates, Material costs, Vessel costs and Crew costs are included. Data related to planned maintenance include: Maintenance times, Subsystem grouping, Required crew, Required main vessel type and Required support vessel type, while for unplanned maintenance input data include Repair times, Required crew number, Required main vessel type, Required support vessel type, Spare stock initial, Spare stock minimum, Spare wait time and Mission organization time.

7.1.4 EIA

For the Environmental impact assessment module, relevant inputs are Greenhouse gas emissions of materials (obtained from databases), Masses of materials (linked to the parametric equations), Vessel consumption (calculated considering site specific data) and Vessel speed.

Figure 8, summarises in a flow chart the input data required by the model.

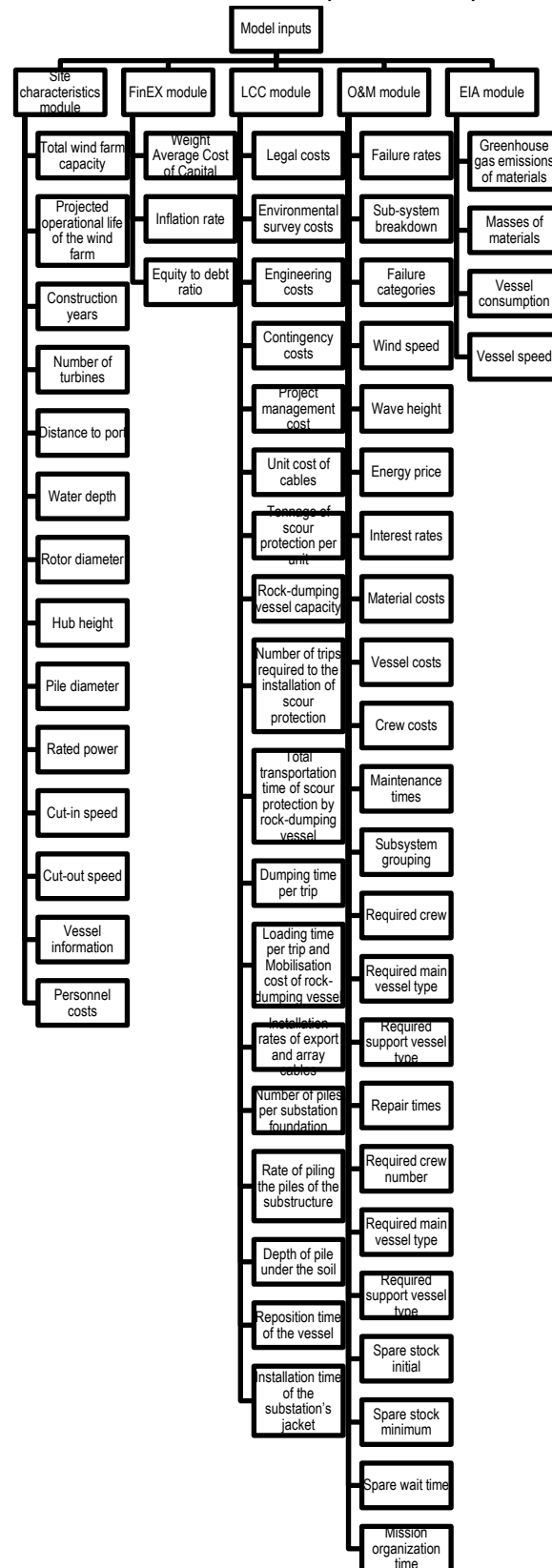


Figure 8: Inputs for the individual modules

Outputs from the model

7.1.5 LCC module (CAPEX only)

From the deterministic analysis, multiple KPIs can be obtained, the most common of which are the following:

- LCOE
- NPV
- IRR
- Detailed cost breakdown per phase
- Sensitivity analysis of key simulation variables
- Life cycle cost profiles

Results can also be expanded through stochastic assessment to express the above KPIs in terms of joint probability density functions, assigning confidence levels in the assessment.

7.1.6 O&M module

The O&M module returns a number of outputs including the following:

- Total energy produced by wind farm
- Production based and time based availability
- Power production losses
- Power output per each turbine
- Breakdown of downtimes
- O&M costs throughout the service life of the wind farm

7.1.7 EIA outputs

The EIA, calculates as main outputs CO₂ emissions per produced GWh, average missions or component, allowing for comparison of different scenarios.

Figure 9 to Figure 11 present indicative outcomes of the different modules.

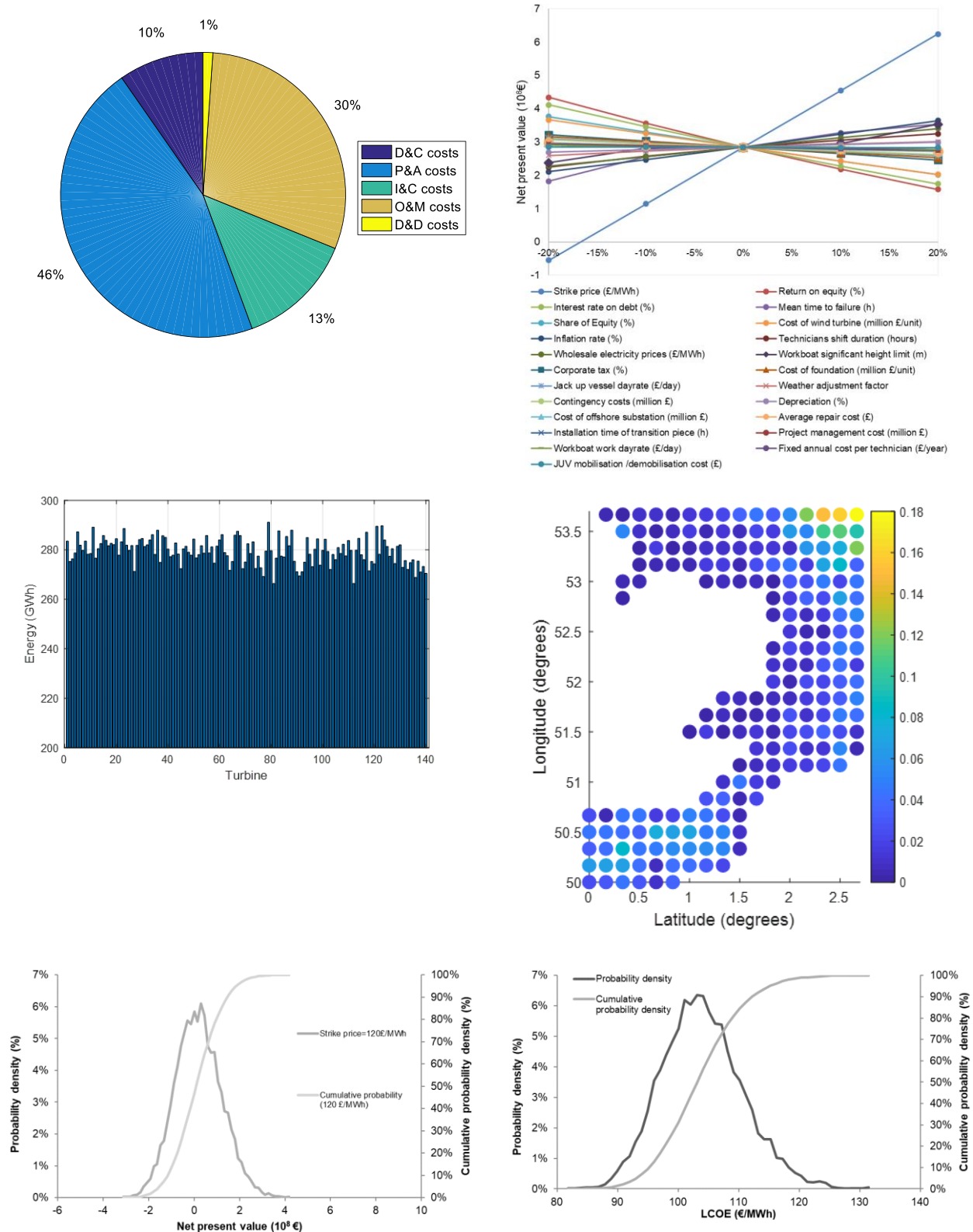


Figure 9: LCC module outputs (cost distribution per phase, sensitivity analysis, power production per unit, monthly power production)

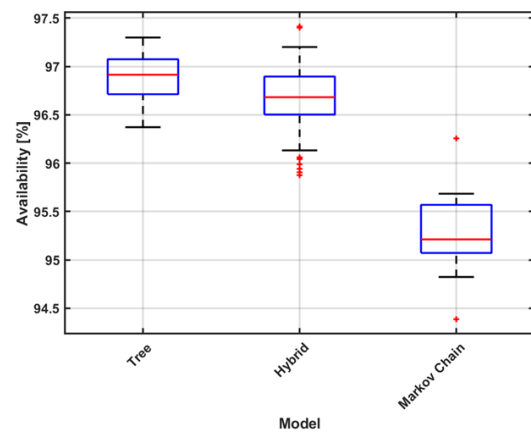
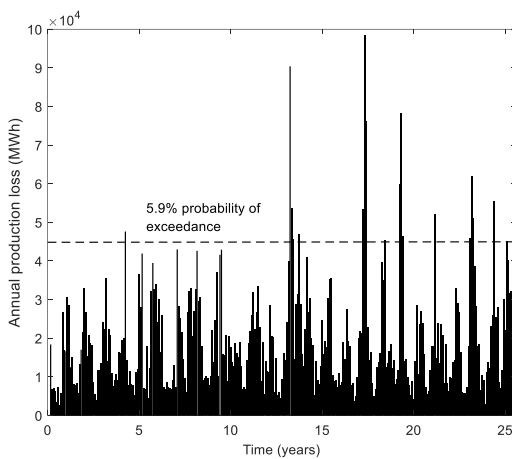
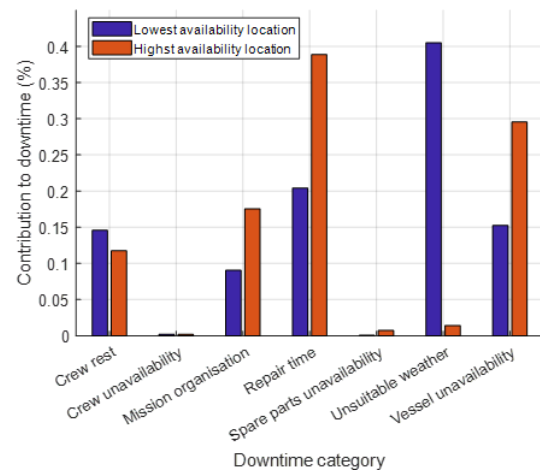
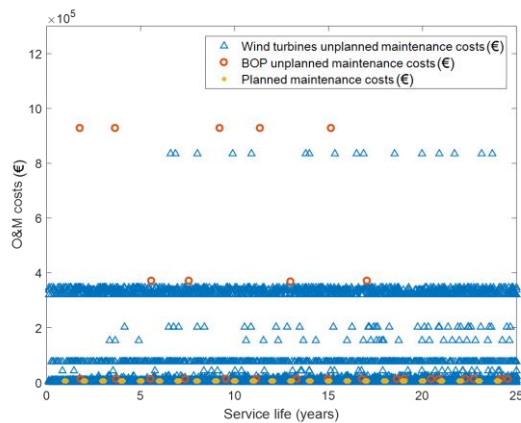
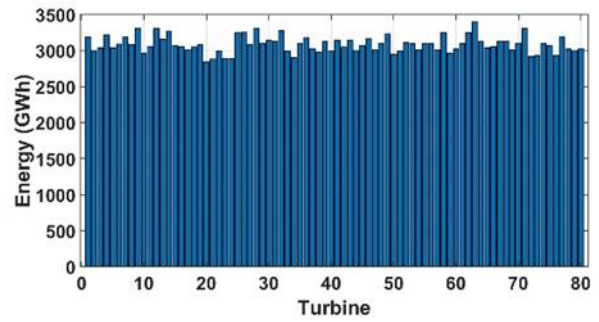
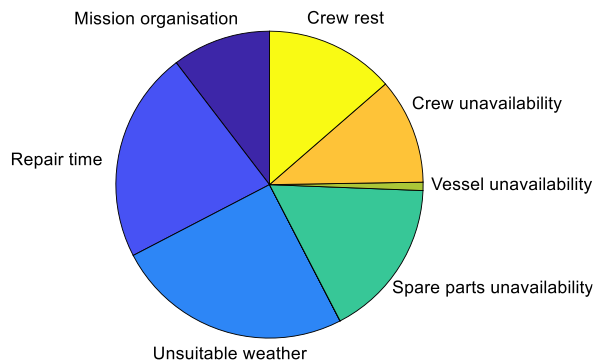


Figure 10: O&M related outputs (Energy generated by each wind turbine in its whole life, Breakdown of windfarm downtimes, O&M costs throughout the service life of the wind farm, contribution of downtime categories to the highest and lowest availability locations, Monthly power production losses as a function of time for the location with coordinates, Sensitivity analysis of key design inputs)

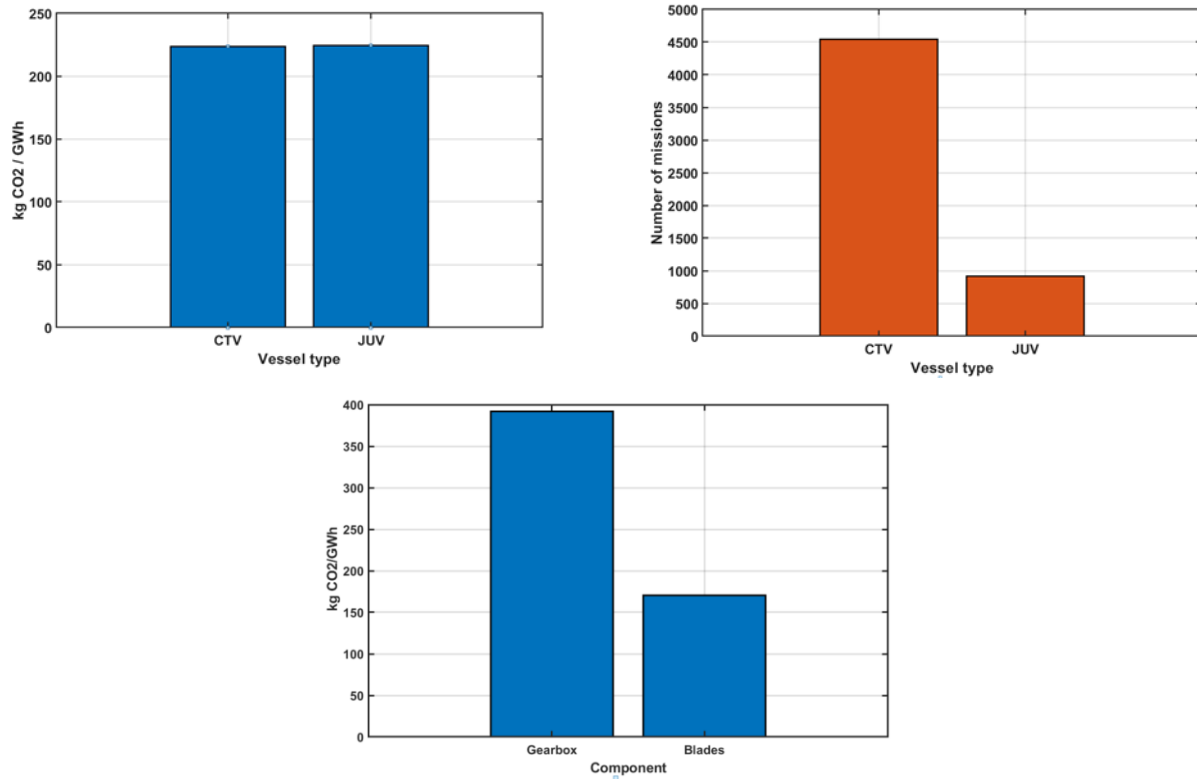


Figure 11: EIA related outputs (Direct emissions from transportation of equipment and crew, Emissions of gearbox and blade components)

8. Conclusions and further considerations

This report has presented the background of the theoretical concepts that have been incorporated in the current version of the impact assessment model. The main modules of the model which has been translated into a tool, include the site characteristics module, the FinEx module, the LCC module, the O&M module and the EIA module. Key assumptions made, inputs and indicative outputs are presented in detail. All modules of the model have currently been developed and individual case studies have been performed.

This deliverable and associated tool will stand as input for the remaining subtask 8.2.2: Benchmarking study results. The next steps on WP8 will be to determine the case studies that will be examined in order to evaluate benefits from the outcome of the ROMEO project, in consultation with the partners of the consortium and collect reliable input for this purpose.

In parallel, some additional modifications will be applied to the code, so as to allow for further benefits for the ROMEO partners:

- The tool is currently modelled in a MATLAB environment. Currently, it is been translated into python, to allow it to run without the need for a commercial software.
- An automated sensitivity analysis functionality will be incorporated to enable evaluation of the impact of key input variables.
- The potential of a GUI and cloud-hosted service will be investigated in order to facilitate input of data to the model.

It should be noted, that these activities are additional to the initially proposed scope, but to the WP leader's point of view will add significant value to the final version of the tool that will be developed.

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